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CONTENTS

RESEARCH

FORUM - POLICY

AROUND THE WORLD

POLICY - PRACTICE

CO_2 CAPTURE BY SPIRULINA PLATENSIS RIA2 IN BUBBLE COLUMN PHOTOBIOREACTORS

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Abstract
Practical carbon capture options are needed alongside source abatement to meet mid century climate goals. Microalgae offer a biological route that operates at ambient conditions while generating valuable biomass; within this portfolio, Spirulina is robust under high pH/alkalinity and compatible with simple photobioreactors. This study evaluates CO_2 capture by Spirulina platensis RIA2 cultivated for 21 days in 8 L bubble column photobioreactors (working volume 5 L) under two aeration modes: ambient Air and CO_2 supplemented (≈10,000–30,000 ppm). We monitored biomass growth, nitrate and phosphate uptake, and CO_2 fixation (Level A, biomass equivalent). CO_2 enrichment accelerated early growth (doubling time ≈ 2.92 days) and produced an earlier biomass peak (1.576 g L^{-1} on day 11), whereas Air reached a higher peak (3.064 g L^{-1} on day 16) and maintained a substantially higher cycle average biomass. Over 21 days, cumulative fixed CO_2 was 1.047 g CO_2 L^{-1} with CO_2 supplementation versus 0.864 g CO_2 L^{-1} with Air, but peak CO_2 fixation productivity (PCO_2) was higher under Air (0.551 vs 0.395 g CO_2 L^{-1} day^{-1}). Nitrate decreased more strongly in Air (≈88.9%) than in CO_2 (≈54.5%), while phosphate removal was comparable. Overall, CO_2 supplementation trades early acceleration for reduced late phase stability unless pH/nutrient control is applied, whereas Air favors steadier long term performance. These findings clarify operational trade offs for low complexity bubble column systems and support pilot integration of algae based CO_2 capture near point sources.

Keywords: *Spirulina platensis, bubble column photobioreactor, CO_2 capture, biofixation, nutrient uptake, productivity.*
JEL Classifications: *Q42, Q55, Q54.*
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1. INTRODUCTION

Anthropogenic greenhouse-gas emissions remain high despite rapid expansion of renewables and efficiency measures, keeping atmospheric CO_2 on a trajectory inconsistent with mid-century climate targets. Most credible mitigation pathways therefore pair deep source reductions with carbon-capture options that can be deployed across diverse contexts and scales. Within this portfolio, microalgae-based CO_2 capture is a compelling biological complement to engineered systems because it operates at ambient conditions, can co-remove nutrients from wastewater, and yields biomass that can be valorized as food, feed, pigments, or bio-based materials-attributes that improve practical deployability near dispersed point sources (Tripathi et al., 2023). Vietnam provides a particularly pertinent setting: the Government has announced a net-zero greenhouse-gas target for 2050 and submitted an updated Nationally Determined Contribution in 2022 that raises ambition toward 2030, creating policy space to pilot biological capture alongside abatement in power and energy-intensive industries. In such a landscape, modular, low-complexity systems that integrate with existing utilities and offer co-benefits are especially valuable.

Among microalgae, Spirulina is well suited for practical deployment. It thrives at high pH and alkalinity (≈9–10), conditions that naturally suppress contamination, and it accumulates high-value compounds such as phycocyanin and proteins while sustaining robust growth (Vonshak & Tomaselli, 2013; Delrue et al., 2017). Pairing Spirulina with bubble-column photobioreactors (BCBRs) further matches the need for simplicity and effective gas–liquid contact: BCBRs have no internal moving parts, are straightforward to construct and operate at laboratory or pilot scale, and provide adequate mixing and CO_2 dispersion for shear-sensitive cultures (Bégu et al., 2019; Zhao et al., 2023). Nevertheless, operation entails trade-offs. CO_2-supplemented aeration increases inorganic carbon supply and can accelerate early growth, but it also perturbs pH and carbonate–bicarbonate speciation; without control of pH and nutrients, late-phase decline may occur. Conversely, ambient air aeration often enhances long-term stability but may constrain peak productivity. Prior studies report mixed outcomes for A. platensis under CO_2 enrichment or real exhaust, highlighting the need for strain- and system-specific evidence and for transparent carbon accounting that enables comparison across studies (Dębowski et al., 2024; Petrova et al., 2023).

To address these gaps in a context relevant to Vietnamese point sources, this study evaluates CO_2 capture by Spirulina platensis RIA2 cultivated for 21 days in 8-L bubble-column photobioreactors (working volume 5 L) operated under two aeration modes: ambient Air and CO_2-supplemented (approximately 10,000–30,000 ppm). We quantify growth kinetics, CO_2 fixation reported at Level A (biomass-equivalent) using a single explicit conversion factor (1.83 g CO_2 g^{-1} dry weight, corresponding to a 0.50 carbon mass fraction), and nutrient uptake (nitrate and phosphate) with clear units and dilution factors. By providing a controlled comparison of aeration strategies in a low-complexity BCBR and by linking carbon capture with nutrient dynamics, the study clarifies the balance between early-phase acceleration and long-term stability and offers practical guidance for pilot-ready integration of algae-based CO_2 capture with Vietnamese point sources and emerging carbon-credit mechanisms.

2. RESEARCH METHODS

2.1. Time and place of research

Time and Place of Research was conducted from February 10th, 2025 to September 30th, 2025 at the laboratory of the Faculty of Natural Resources and Environment, University of Technology - Vietnam National University, Ho Chi Minh City. The experiments were conducted in parallel on two Spirulina platensis microalgae culture models in a Bubble Column Photobioreactor (BCBR). The analytical parameters in all chemicals used in this study were of analytical grade and imported from certified suppliers. The study included temperature, light, pH, phosphate concentration (PO_4^{3-}), nitrate (NO_3^-) and microalgae biomass, measured and analyzed at the Laboratory of the Faculty of Natural Resources and Environment, University of Technology.

2.2. Research subjects

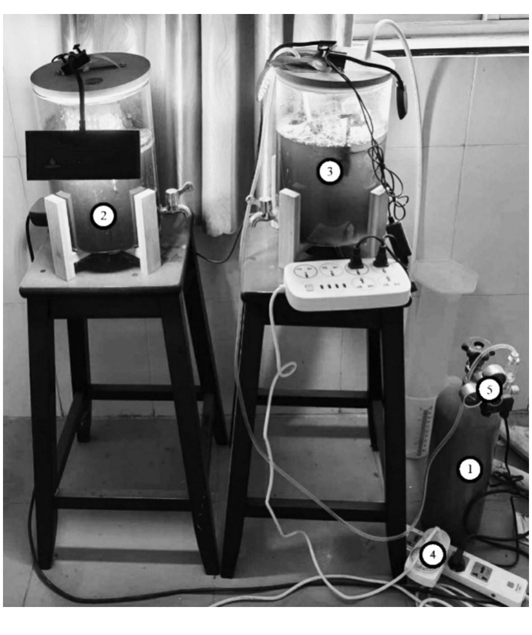
The source of algae used in the study was the ability to determine CO_2 in biomass, the microalgae strain strain Spirulina platensis RIA2 cultured at the Research Institute for Aquaculture II, selected based on its outstanding characteristics of fast growth rate, high CO_2 fixation efficiency and tolerance to high CO_2 concentrations (10,000–30,000 ppm). This microalgae strain has been shown in many previous studies to have great potential in converting CO_2 from industrial emissions into high-value biomass.

The CO_2 gas used in the study was a simulated gas, with concentrations ranging from 10,000 to 30,000 ppm. To evaluate the CO_2 absorption kinetics, a Bubble Column Photobioreactor (BCBR) system with a design capacity of 8 L and a working volume of 5 L was designed and fabricated, ensuring optimal operating conditions for the growth of Spirulina platensis RIA2.

2.3. Prepare of the experiment

2.3.1. Experimental model

The study was conducted on 2 experimental models designed as Bubble Column Photobioreactor (BCBR) systems with a total capacity of 8 L, of which 5L is used as the working volume containing the Spirulina platensis RIA2 microalgae suspension. The tank is made of transparent glass, vertical cylinder, height 30 cm, convenient for observing and monitoring the growth of microalgae during the experiment. The



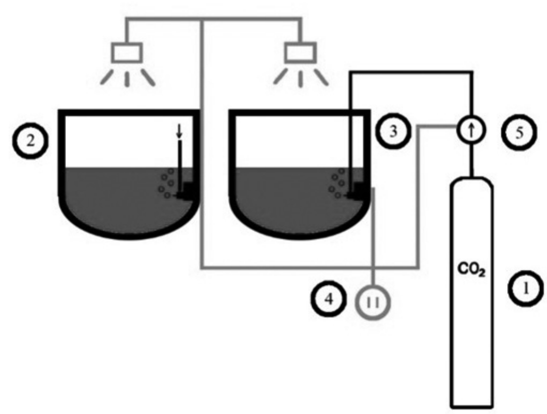


Figure 1. PhBR-B system with CO_2 source: 1- CO_2 tank, 2- The hermetic photobioreactor-biofilter (PhBR-B), 3- PhBR-B with CO_2 supply, 4-electrical systems, 5-one-way valve

model consists of the main parts: reaction column, air supply system, lighting system (Figure 1).

Operating parameters such as temperature (30–35°C), light intensity (5000 lux), CO_2 concentration (10,000–30,000 ppm), and pH (9–11) were maintained stable throughout the experiment. The culture period was 21 days, during which the biomass was allowed to settle and samples were collected every 2 days at 10:00 a.m. to monitor growth rate and CO_2 uptake efficiency.

From the dimensions of the model, the tank characteristics are calculated as follows:

Cross-sectional area:

$$A = \frac{V_{total}}{H} = \frac{0{,}008}{0{,}30} = 0{,}0267\ m^2$$

Tank diameter:

$$D = 2\sqrt{\frac{A}{\pi}} = 0{,}184\ m\ (18{,}4\ cm)$$

Liquid layer height:

$$H_l = \frac{V_w}{A} = \frac{0{,}005}{0{,}0267} = 0{,}189\ m\ (18{,}9\ cm)$$

Air clearance height: H_h=0,30-0,189=0,111 m

Illuminated surface area (lateral area):

$$A_{lat} = 2\pi r H_l = 0{,}1085\ m^2$$

Area/Volume Ratio (A/V):

$$\frac{A_{lat}}{V_w} = 21{,}7\ m^{-1}$$

Geometric ratio:

$$\frac{H}{D} = 1{,}63$$

Effective optical path (light path): ≈ 18.4 cm

The above parameters show that the tank has a high area/volume ratio, which is favorable for light absorption and photosynthesis of microalgae; at the same time, the H/D ratio is reasonable, helping to increase the efficiency of gas dispersion and CO_2 absorption during the culture process.

2.3.2. Adaptation for Microalgae

Before the formal cultivation, the Spirulina platensis RIA2 strain underwent an acclimatization period to ensure stable growth under experimental conditions. This period lasted for 3 days in standard Zarrouk medium (Zarrouk, 1966), under continuous illumination of 4,000–5,000 lux and room temperature ranging from 30–35°C.

During the acclimation process, the pH was maintained in the range of 9.0–11.0. The biomass density was monitored daily by filtration and drying to constant mass, then converted to dry biomass concentration (g/L). When the biomass reached a stable value (~0.5 g/L), the inoculum was considered well acclimated and ready for formal experiment.

Before inoculation into the BCBR system, the algae samples were examined under a light microscope to identify the correct species of Spirulina platensis RIA2 as well as to assess the purity. Only samples that met the purity standards and had stable density were used for the main culture.

Table 1. Nutritional composition of Zarrouk's medium for cultivating Spirulina spp

Ingredient	Content
NaCl	1.00 g/L
$CaCl_2 \cdot 2H_2O$	0.04 g/L
$NaNO_3$ (KNO_3)	2.50 g/L
$FeSO_4 \cdot 7H_2O$	0.01 g/L
EDTA (Na)	0.08 g/L
K_2SO_4	1.00 g/L
$MgSO_4 \cdot 7H_2O$	0.20 g/L
$NaHCO_3$	16.8 g/L
K_2HPO_4	0.50 g/L
Trace elements A_5: H_3BO_3, $MnCl_2 \cdot 4H_2O$,	
$ZnSO_4 \cdot 4H_2O$, $NaMoO_4$, $CuSO_4 \cdot 5H_2O$	1.00 mL

The initial inoculation ratio was set at 10% of the working volume, equivalent to 0.5 L of algal seed suspension for every 5 L of culture medium in the BCBR system (Table 1).

Prior to inoculation into the system, the algal culture was examined under a microscope to confirm the species identity and assess purity.

2.4. Experimental procedure

The study was conducted in the following order:

Step 1: Prepare the experiment

Standard Zarrouk medium (Zarrouk, 1966) was prepared according to the composition in Table 1. The BCBR reactor (design capacity 8 L, working volume 5 L) was cleaned and sterilized with 70% alcohol, then rinsed several times with sterile distilled water. The lighting and aeration equipment were checked and calibrated before operation.

Step 2: Acclimatize the algae and perform preliminary trials.

Spirulina platensis RIA2 strain was acclimatized for 3 days (light conditions 4,000–5,000 lux, room temperature 30–35°C , pH 9.0–11.0). Biomass density was monitored by filtration and drying. When the biomass reached a stable value (~0.5 g/L), the algae were checked for purity under a microscope and inoculated into the BCBR at an initial inoculation ratio of 10% of the working volume (0.5 L/5 L).

Step 3: Conduct the official experiment

The experiment was carried out in parallel on two

Table 2. List of chemicals used in the research

Chemicals name	Chemical formula	Country of origin
2,6-Dimethylphenol	$C_8H_{10}O$	China
Acetic acid (glacial)	CH_3COOH	China
Sulfuric acid	H_2SO_4	China
Phosphoric acid	H_3PO_4	China
Aminosulfonic acid	NH_2SO_3H	China
Glycerol	$HOCH_2CHOHCH_2OH$	China
Tin(II) chloride dihydrate	$SnCl_2.2H_2O$	China

BCBR systems with identical rearing conditions, differing only in the air supply: the first system (control) was aerated with normal air through an aerator placed at the bottom of the tank, while the second system (treatment) was aerated with compressed CO_2 (10,000–30,000 ppm) from an air tank through pipes and aerators. The experiment lasted 21 days. Samples were collected periodically every 2 days at the same time frame to ensure uniformity. The collected biomass was used to evaluate growth rate and performance CO_2 absorption efficiency.

2.5. Methods and analytical procedures

All chemicals used in this research were of analytical grade and imported from certified suppliers. Category chemical matter main serve service stool nitrate (NO_3^-) and phosphate (PO_4^{3-}) are released in the list of chemicals is presented in Table 2.

Determination of microalgae biomass

Microalgal biomass was determined by thedry weight method. For each sampling, two replicate samples (25 mL/sample) were taken using a 25 mL volumetric flask, then filtered through a glass fiber filter paper with a known mass. The filter paper and biomass were dried at 105°C to a constant mass. The biomass concentration (X, g/L) was calculated according to the formula (Tang et al., 2011):

$$X = \frac{m_2 - m_1}{V}$$

In there $m_1$is the mass of dry filter paper before filtration (g), $m_2$is the mass of filter paper after drying with biomass (g), and V is the volume of filtered sample (L).

Determination of nitrate (NO_3^-)

The NO_3^- concentration in the culture medium was determined by the colorimetric method using 2,6-dimethylphenol according to TCVN 6180:1996. After the reaction to form a yellow compound, the optical density of the solution was measured at a wavelength of λ = 342 nm using a UV-Vis spectrophotometer. The NO_3^- content was calculated based on the standard curve and expressed as mg/L.

Determination of phosphate (PO_4^{3-})

PO_4^{3-} content was analyzed according to TCVN 6202:2008, using the colorimetric method with ammonium molybdate and the reducing agent $SnCl_2$, forming a blue complex measured at a wavelength of λ = 690 nm. PO_4^{3-} concentration was determined from the standard curve and expressed in mg/L.

Determination of pH and temperature

The pH of the medium was determined directly using a standard pH paper (range 1–14). Temperature was monitored using a glass thermometer throughout the experiment.

Calculation of CO_2 fixation efficiency

The amount of CO_2 fixed by microalgae was estimated based on the dry biomass mass, assuming the biomass contained an average of 50% carbon by mass. The conversion formula (Tang et al., 2011):

$$CO_2 fixed\ (g/L) = X \times 1{,}88$$

Where X is the dry biomass concentration (g/L) and the factor 1.88 is the conversion factor from carbon content to equivalent CO_2 mass.

2.6. Data processing and analysis methods

All data obtained from the experiment were processed using Microsoft Excel 2019 software. The biomass index was sampled twice (n = 2), the results were expressed as mean ± standard deviation (mean ± SD) to reflect the experimental variability (Zar, 1999). For the NO_3^- and PO_4^{3-} indices, only one sample was analyzed at each collection, so the values were reported in single form (mg/L).

Specific growth rate (μ, day^{-1}) of Spirulina platensis RIA2 was determined by the biomass variation over the time interval $[t_1,t_2]$ (Griffiths & Harrison, 2009):

$$\mu = \frac{\ln X_2 - \ln X_1}{t_2 - t_1}$$

In there X_1 and X_2 is the biomass concentration (g/L) at time point t_1 and t_2.

CO_2 fixation capacity in biomass (Level A – biomass-equivalent).

As shown in the table, dry biomass is assumedto contain on average X_C=50% carbon by mass (Tang et al., 2011; Lim et al., 2021). From this, the conversion factor is determined:

$$Y_{CO_2/X} = X_C \times \frac{44}{12} \approx 1{,}83\ g\ CO_2/g\ DW$$

Fixed CO_2 accumulated between two points in time$t_1 \rightarrow t_2$(g CO_2/L):

$$\Delta CO_2 = (X_2 - X_1) \times 1{,}83$$

Average CO_2 fixation yield (g CO_2/L/day):

$$P_{CO_2} = \frac{(X_2 - X_1) \times 1{,}83}{\Delta t}$$

When system-scale conversion is required, the above value is multiplied by the working volume V_w=5 Lto express in g CO_2/day/device.

Net CO_2 equivalent (Level C – Net CO_2e). To reflect the system-wide carbon balance, net CO_2e is calculated using the formula (Lim et al., 2021; Wang et al., 2019):

$$NET\ CO_2e = CO_{2,fixed}^{(A)} - E_{elec} - E_{chem} - E_{cons} - E_{trans} \pm Credit_{prod}$$

In there:

$CO_{2,fixed}^{(A)}$: CO_2 fixed in biomass (Level A).

E_{elec}: emissions from electricity consumption (kWh × grid emissions factor).

E_{chem}: emissions from chemicals, including CO_2-eq equivalent from bicarbonate/carbonate salts (e.g. $NaHCO_3$: $0{,}542\times m_{NaHCO_3}$).

E_{cons}: emissions from consumables.

E_{trans}: emissions from transport.

$Credit_{prod}$: product substitution credit when biomass is used as a substitute for another commercial product.

Statistical testing: The differences between the two systems (control – air aeration and treatment – CO_2 aeration) were analyzed using a two-sample independent t-test, with a significance level of $p < 0.05$ (Ruxton, 2006).

The results are illustrated with line graphs (showing trends in biomass, NO_3^-,PO_4^{3-},and PCO_2over time) and bar graphs (comparing mean ± SD values between the two systems). In this study, CO_2 results are reported in parallel at both Level A (biomass-equivalent) and Level C (Net CO_2e), to reflect both biologically fixed CO_2 and net emissions of the entire system.

2.7. Analysis of equivalent CO_2 absorption capacity

In this study, the equivalent CO_2 uptake capacity of Spirulina platensis RIA2 was evaluated based on two different calculation levels following the guidance of Lim et al. (2021):

Level A (biomass-equivalent): reflects the amount of CO_2 fixed in biomass through photosynthesis, calculated from the increase in dry mass. This is the most direct index to describe the biological performance of the system.

Level C (Net CO_2e): considers all life-cycle emissions and credits, including emissions from electricity, chemicals, consumables, transport, as well as credits when biomass replaces another commercial product. This indicator reflects the net emission reduction of the system, linked to the carbon credit development target.

The CO_2 results in the study are reported in parallel at both Level A and Level C , to both describe the CO_2 uptake capacity of microalgae at the experimental scale and to provide a basis for comparing potential applications to carbon markets.

3. RESULTS AND DISCUSSION

3.1. Biomass growth dynamics

Spirulina platensis RIA2 biomass monitoring in two systems (Air and CO_2) are shown in Figure 3.1. Both systems showed a strong growth trend in the first half of the experiment and a decline in the final stage, however the dynamics were clearly different.

CO_2 system (Figure 3.1b), biomass increased rapidly from 0.0099 g/25 mL (0.40 g/L) on day 1 to 0.0394 g/25 mL (1.58 g/L) on day 11, earlier than in Air, but then decreased to 0.0242 g/25 mL (0.97 g/L) on day 21.

Comparing growth coefficients showed that the CO_2 system peaked earlier (~3.98 times on day 11) but lower in absolute value, while the Air system peaked later (~3.20 times on day 16) and accumulated higher biomass. After the peak, biomass decreased more strongly in Air (53.3% decrease from day 16→21) than in CO_2 (38.6% decrease from day 11→21).

The specific growth rate (μ, day^{-1}) calculated by the formula in Section 2.6 shows:

Early stage (1–7 days): μAir = 0.122, μCO_2 = 0.107.

Acceleration phase: μAir (days 4–7) = 0.202, μCO_2 (days 9–11) = 0.258.

The doubling times (t_d = ln2/μ) at these stages are 3.44 days (Air) and 2.68 days (CO_2), respectively.

Late stage (14–21 days): both systems have negative μ, reflecting growth retardation.

Analysis of the area under the biomass curve showed that the average biomass over 21 days in Air was ~1.96 g/L, which was approximately 2.04 times higher

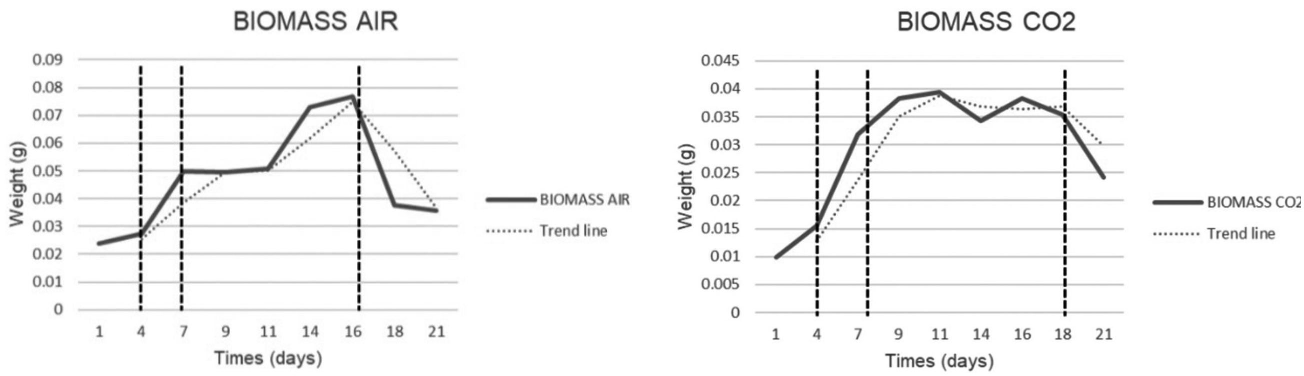


Figure 3.1. Spirulina platensis RIA2 biomass dynamics during 21 days of culture: (a) Air system and (b) CO_2 system. Solid lines show experimental values, dashed lines show trend lines; vertical bars indicate main observation periods

than that in CO_2 (~0.96 g/L). This demonstrates that the CO_2 system offers an advantage in growth rate and early peaking, while the Air system maintains a stable biomass and accumulates more in the long term.

The above results are consistent with the trend reported in previous studies (Singh & Dhar, 2011; Ho et al., 2017), suggesting that CO_2 supplementation increases initial growth rates but requires nutrient and pH management to maintain the effect over the long term (Figure 3.1) .

CO_2 fixed efficiency

The CO_2 fixation capacity of Spirulina platensis RIA2 was calculated using the biomass-equivalent method (Level A), with a conversion factor of 1.83 g CO_2/g DW (Tang et al., 2011). The results showed that the two systems Air and CO_2 had clear differences in dynamics and total amount of CO_2 fixed during the 21-day experiment.

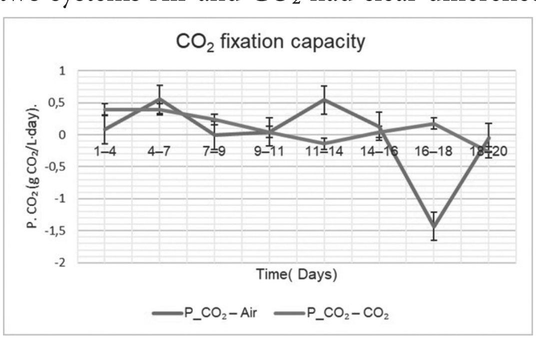


Figure 3.2. Dynamics of CO_2 fixation productivity (PCO_2, g $CO_2 \cdot L^{-1} \cdot day^{-1}$) of Spirulina platensis RIA2 in two Air and CO_2 systems. Values are calculated according to Level A from the variation of biomass concentration, with a conversion factor of 1.83 g CO_2/g DW

Fixed CO_2 Productivity Value (PCO_2) The highest PCO_2 was recorded at the 4–7 day period. The Air system reached a peak of 0.551 g $CO_2 \cdot L^{-1} \cdot day^{-1}$, which was higher than the CO_2 system (0.395 g $CO_2 \cdot L^{-1} \cdot day^{-1}$). However, the CO_2 system had a cycle-averaged PCO_2 of 0.052 g $CO_2 \cdot L^{-1} \cdot day^{-1}$, which was slightly higher than the Air system (0.043 g $CO_2 \cdot L^{-1} \cdot day^{-1}$), reflecting the short-term growth advantage of the CO_2 system.

Figure 3.2 shows that the PCO_2 of the CO_2 system increased sharply in the early stages but decreased rapidly after day 11, even showing negative values reflecting biomass decomposition. In contrast, the Air system maintained a more stable PCO_2 until day 16 before decreasing. This result is consistent with the biomass dynamics (Figure 3.1), demonstrating that CO_2 supplementation accelerates growth but is difficult to maintain in the long term without balancing nutrients and pH (Table 3.2).

The CO_2 system has the advantage of speed and total CO_2 fixation, while the Air system remains more stable and sustainable. This result emphasizes that CO_2 supplementation is only effective when accompanied by strict management of nutrients and operating conditions, otherwise it will lead to C/N imbalance and biomass loss in the late stage.

3.2. Fluctuations in NO_3^- and PO_4^{3-} concentrations

The variation of inorganic nutrient concentrations is shown in Figure 3.3 (NO_3^-) and Figure 3.4 (PO_4^3).

Table 3.2. CO_2 fixation efficiency (Level A) of Spirulina platensis RIA2 in two Air and CO_2 systems

System	Peak CO_2 (g $CO_2 \cdot L^{-1} \cdot day^{-1}$)	Average PCO_2 (g $CO_2 \cdot L^{-1} \cdot day^{-1}$)	Net CO_2 (g CO_2/L, 21 days)	Net CO_2/device (g, 5 L)
Air	0.551	0.043	0.864	4.32
CO_2	0.395	0.052	1,047	5.23

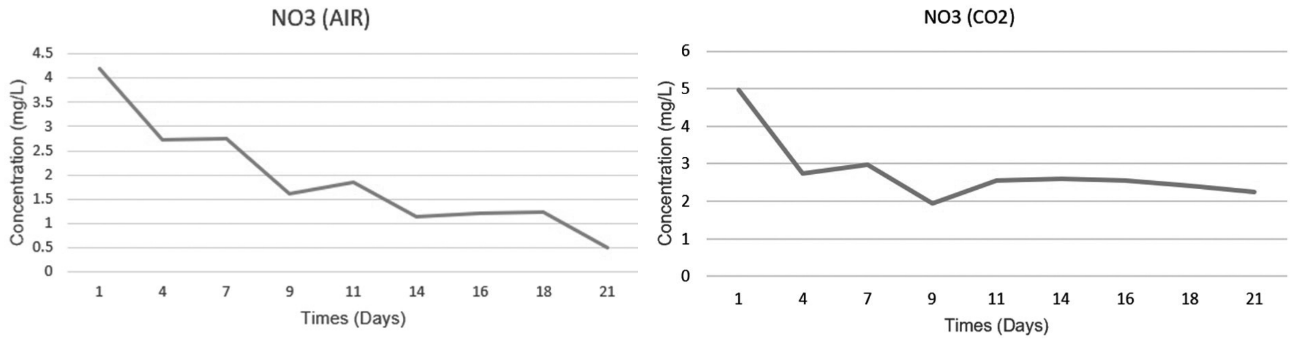


Figure 3.3. Changes in NO_3- concentration (mg/L) of Spirulina platensis RIA2 in two Air and CO_2 systems over culture time

Both systems show a decreasing trend over time, however the consumption rates are significantly different between Air and CO_2.

In the Air system, NO_3^- concentration decreased from 4.40 mg/L (day 1) to 0.49 mg/L (day 21), corresponding to 88.9% consumption. Meanwhile, in the CO_2 system, NO_3^- decreased from 4.97 mg/L to 2.26 mg/L after 21 days, a consumption of only 54.5%. This shows that the Air system used nitrate almost completely, while the CO_2 system still had a significant nitrate residue at the end of the period. This trend is consistent with the biomass dynamics: the Air system maintained stable growth thanks to the efficient use of nitrate sources, while the CO_2 system, although growing rapidly at the beginning of the period, could not utilize nitrate in the long term due to the C/N imbalance.

PO_4^{3-} concentrations decreased slightly in both systems. In the Air system, PO_4^{3-} decreased from 0.0115 mg/L to 0.00836 mg/L (a decrease of 27.2%). Meanwhile, in the CO_2 system, it decreased from 0.0123 mg/L to 0.00737 mg/L (a decrease of 39.9%). Thus, the phosphate consumption between the two systems was not significantly different and was not the decisive factor for the difference in growth dynamics between Air and CO_2.

The above results show that nitrate (NO_3^-) is the main limiting nutrient, determining the ability to maintain growth and fix CO_2. The Air system with the ability to fully utilize nitrate achieved an average biomass and a more stable CO_2 fixation ability. In contrast, the CO_2 system, although having an abundant carbon source, due to the incomplete utilization of nitrate, growth was concentrated in the early stage and declined rapidly in the late stage. Phosphate (PO_4^{3-}) decreased at a similar rate in both systems, so it had little effect on the overall difference.

3.3. Relationship between nutrient consumption and CO_2 fixation capacity

The changes in inorganic nutrients in the culture medium were closely related to the biomass dynamics and CO_2 fixation efficiency (PCO_2) of Spirulina platensis RIA2. The experimental results showed that nitrate (NO_3^-) was the main limiting nutrient, while phosphate (PO_4^{3-}) did not make a significant difference between the two systems.

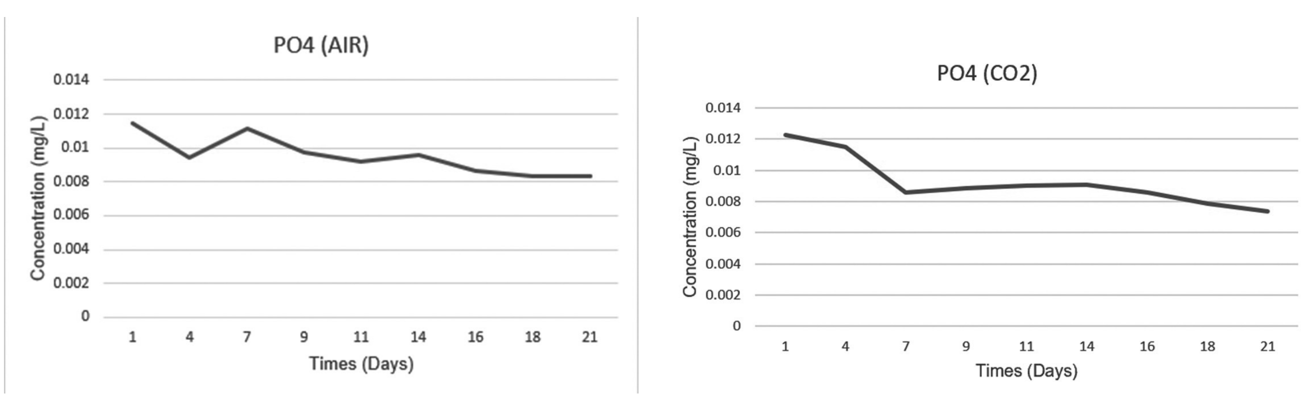


Figure 3.4. Changes in PO_4^{3-} concentration (mg/L) of Spirulina platensis RIA2 in two Air and CO_2 systems over culture time.

In the Air system, the sharp decrease in NO_3^- from 4.40 to 0.49 mg/L (88.9% reduction) was accompanied by a steady increase in biomass, reaching a plateau X_ max = 3,064 g/Lby day 16. This also reflected a more sustained CO_2 uptake efficiency, with PCO_2 remaining positive until day 16 before declining. In contrast, in the CO_2 system, despite a high initial growth rate (μ_max= 0.237 day^{-1}, maximum PCO_2 of 0.395 g $CO_2 \cdot L^{-1} \cdot day^{-1}$ on days 4–7), NO_3^- concentrations remained relatively high at the end of the cycle (2.26 mg/L). This suggests that the abundant carbon source was not sufficient to sustain biomass accumulation if nitrate was not fully utilized, resulting in a decline in PCO_2 after day 11.

PO_4^{3-} consumption was relatively uniform in both systems (27.2% reduction in Air and 39.9% in CO_2), with no clear correlation to the differences in biomass and CO_2 fixation. Thus, phosphate was not the main limiting factor under these experimental conditions.

In summary, the relationship between nutrition and CO_2 fixation capacity is shown in:

Nitrate is the main controlling factor, high nitrate consumption is associated with increased biomass and stable CO_2 fixation capacity (Air).

Additional CO_2 sources can only be effective if accompanied by proper nitrate management, otherwise it will lead to C/N imbalance, causing a decline in biomass and CO_2 (CO_2) uptake efficiency.

These results confirm the importance of carbon and nitrogen synchronization strategies in photobioreactor system design, and suggest directions for optimizing nutrient combinations to enhance CO_2 uptake efficiency and reduce net emissions at industrial scale.

3.4. Summary and outlook

The experimental results showed that the growth dynamics and CO_2 uptake capacity of Spirulina platensis RIA2 were strongly dependent on the culture conditions. The CO_2 system provided high growth rates and carbon fixation in the early stages, but was unstable in the long term due to C/N imbalance. In contrast, the Air system maintained a moderate biomass and higher CO_2 uptake efficiency throughout the entire cycle, thanks to its ability to fully utilize nitrate.

These results are consistent with previous studies (Tang et al., 2011; Singh & Dhar, 2011; Ho et al., 2017), confirming that CO_2 addition is only effective when accompanied by nutrient and pH management. This has important implications for the operation of industrial-scale microalgae cultivation systems, where the costs of aeration and pH adjustment can significantly increase indirect emissions.

At Level A (biomass-equivalent), the CO_2 system had a higher total net CO_2 fixation (1.047 g/L) than the Air system (0.864 g/L). However, when scaling up to Level C (Net CO_2e), indirect emissions from electricity (aeration, lighting) and chemical addition need to be taken into account. Recent studies (Lim et al., 2021; Wang et al., 2019) show that electricity consumption is often the largest source of emissions in closed microalgae systems. This means that although the CO_2 system has a speed advantage, it may not necessarily result in a higher net emission reduction than the Air system, especially under experimental conditions with continuous electricity consumption.

Application prospects.

Scientifically: This result provides evidence that the optimal combination of carbon and nitrogen is key to enhancing biological CO_2 fixation efficiency.

In terms of technology: To achieve a positive net efficiency (Net CO_2e), improvements are needed in two main directions: (i) reducing energy consumption (optimizing aeration, using high-performance LEDs or natural light sources), and (ii) taking advantage of reusable nutrient sources, for example, nitrate/ phosphate-rich wastewater from the food industry.

Economic and environment: This result can be used as a basis for building a biocarbon credit model. In an industrial-scale scenario, the amount of CO_2 fixed by microalgae can be converted into carbon credits, contributing to the reduction of greenhouse gas emissions and bringing additional economic value to the energy and food processing industries.

CO_2 addition offers a speed advantage but does not guarantee sustainability, while airs systems are slower but more stable and efficient in the long term. When integrated into a life cycle analysis (Level C), Air systems can provide better Net CO_2e performance. This highlights the need for microalgae systems targeting carbon credits to be designed to optimize carbon, nutrients and operating energy simultaneously.

4. CONCLUSION AND RECOMENDATIONS

4.1. Conclusion

The study demonstrated the feasibility of a CO_2 capture model based on the microalga Spirulina platensis RIA2 with two different culture systems. The results showed that the CO_2 system had a fast growth rate in the early stages, with μ_max = 0,237 day^{-1}a doubling time of only 2.92 days, but the maximum biomass was lower and declined earlier than the Air system. In contrast, the Air system, although growing slower, reached the highest maximum biomass (3.064 g/L on day 16) and maintained an average biomass throughout the cycle that was almost twice as high as the CO_2 system, reflecting superior long-term sustainability. The CO_2 fixation efficiency calculated at Level A showed that the CO_2 system captured a total of 1.047 g CO_2/L (5.23 g/device), approximately 21% higher than the Air system (0.864 g CO_2/L; 4.32 g/device). However, the Air system achieved a higher peak PCO_2 yield and maintained a positive value for longer. In addition, nutrient analys is showed that nitrate was the main limiting factor, with a consumption of 88.9% in the Air system compared to 54.5% in the CO_2 system, while phosphate decreased similarly in both systems and had little effect on the growth dynamics differences. In terms of Net CO_2e, the Air system has the potential to deliver higher net emission reductions due to the full nitrate utilization and stable biomass maintenance.

4.2. Recommendations

Based on the results obtained, the study recommends that larger-scale and longer-duration trials be conducted to verify the system's stability, and that the assessment be extended to Level B and Level C to more accurately quantify the net emission reduction. Optimization of operating conditions, including light, pH, aeration rate, and initial density, is necessary to improve both the growth rate and sustainability of CO_2 fixation. In terms of applications, the microalgae model can be directly integrated with CO_2-rich sources such as thermal power plants or the food processing industry, combining the use of recycled nutrients from nitrogen- and phosphorus-rich wastewater to reduce costs and increase sustainability. At the same time, indirect emission reduction through energy optimization and the application of renewable energy sources will contribute to improving the Net CO_2e balance. In terms of economic and environmental aspects, the study proposes the development of a life cycle database to serve as a basis for biocarbon credit valuation, and the linkage of microalgae biomass production with value-added products to improve economic efficiency. These orientations will help the microalgae model become a potential solution in the strategy of reducing greenhouse gas emissions and developing a green economy.

Regarding application prospects, it is necessary to propose the possibility of using renewable energy sources such as solar power and wind power to operate pumping, aeration, lighting systems, etc. in the environmental treatment and management process. Integrating these clean energy sources will help improve operating efficiency, reduce energy costs and increase autonomy in operations. At the same time, the use of renewable energy also plays an important role in reducing greenhouse gas emissions, ensuring sustainability throughout the entire life cycle of the system. This is a direction in line with the green development trend, friendly to the environment and meets the criteria for minimizing negative impacts on the global climate.

Aeration systems consume a lot of electricity, especially in shrimp farms or wastewater treatment. Using solar or wind power helps reduce operating costs, increase equipment durability and almost eliminate CO_2 emissions. In the Southwest region, many farms have applied solar power systems to operate oxygen pumps, maintaining stable oxygen levels without the need for diesel generators. In the field of urban lighting, LED projects combined with solar panels in Hanoi are proving to be clearly effective: saving electricity, operating independently and reducing pressure on the grid. When considering the whole life cycle, these systems have a long life, low maintenance costs and almost no emissions, superior to traditional solutions.

Despite the great potential, the deployment of renewable energy still faces many challenges: the instability of energy sources, high initial investment costs and complex technical requirements. To overcome this, there needs to be supportive policies from the government, development of electricity storage technology and training of specialized human resources. Coordination between the government, businesses and the community is the key to promoting this transition. In the context of Vietnam moving towards green development goals, applying renewable energy to aeration and lighting systems is not only an inevitable trend but also a driving force for a sustainable future.

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SUSTAINABLE DEVELOPMENT OF MARINE SHRIMP FARMING IN VINH LONG: AN ANALYSIS COMBINING ENVIRONMENTAL FACTORS AND ECONOMIC DEVELOPMENT POLICIES

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Abstract
Marine shrimp farming plays a vital role in Vietnam's economy but is increasingly threatened by environmental change and climate variability. Vinh Long province, formerly Ben Tre, was selected as the study site because it is both a major shrimp farming hub and one of the regions most severely affected by salinity intrusion, drought, and extreme weather. These conditions make it representative for examining sustainability challenges in aquaculture. This study aims to assess the current status of shrimp farming, identify key factors influencing its sustainability, and propose solutions that integrate environmental and economic perspectives. A mixed-method approach was applied, combining secondary data from local reports with primary surveys of 52 farming households in Binh Dai, Ba Tri, and Thanh Phu districts. The Sustainable Livelihood Framework (DFID) and the Livelihood Capitals Index (LCI) were employed, with normalized indicators and radar charts used to compare strengths and vulnerabilities. Findings reveal that financial and social capitals are the strongest supports, while human and natural capitals remain the main constraints. The study proposes targeted training, adaptive water infrastructure, expanded credit access, and strengthened farmer organizations to enhance resilience. The results provide evidence for sustainable aquaculture policies in Vinh Long and the wider Mekong Delta.

Keywords: *Aquaculture technology, climate change, policy support, shrimp farming, sustainable development.*
JEL Classifications: *Q22, Q54, Q56, O13.*
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1. INTRODUCTION

Vietnam's fisheries sector, particularly marine shrimp farming, continues to play a pivotal role in the national economy. According to the General Statistics Office and the Vietnam Association of Seafood Exporters and Producers, by 2022 the country's aquaculture production reached 4.6 million tons, and seafood exports attained a historic milestone of USD 11 billion, with shrimp remaining the leading contributor to export value. The fisheries sector as a whole accounts for approximately 4–5% of Vietnam's GDP and provides livelihoods for millions of rural and coastal households (Van Quang et al., 2023).

However, the rapid development of aquaculture has been increasingly threatened by climate change and environmental degradation. Vietnam is among the countries most vulnerable to climate change, facing rising sea levels, salinity intrusion, droughts, and extreme weather events(Tuyet Hanh et al., 2020). The Mekong Delta, which produces more than 60% of Vietnam's farmed shrimp, is particularly exposed, with large areas experiencing saline intrusion during the dry season and flooding in the wet season. These phenomena have directly reduced water quality, lowered shrimp yields, and increased production risks (Bhowmik et al., 2023).

Within this context, Vinh Long province (formerly Ben Tre) represents a critical case. This region has long been a major shrimp farming hub, with approximately 36,661 ha of ponds in 2025, accounting for more than 80% of its aquaculture area. Yet production has not kept pace with expansion, peaking at 55,946 tons in 2015 before declining to 45,479 tons in 2025, largely due to environmental stress, disease outbreaks, and seed quality constraints (Nguyen et al., 2021). Ben Tre (now incorporated into Vinh Long) was chosen as the research site not only because of its significant shrimp farming area and contribution to the Mekong Delta economy, but also because it is one of the provinces most severely affected by salinity intrusion, drought, and climate variability (Tran, Thuan, et al., 2025). These conditions make it a representative and urgent case for analyzing the sustainability of shrimp aquaculture.

Sustainable development in fisheries must go beyond increasing output to ensure environmental protection and improvements in community livelihoods. As defined by the Food and Agriculture Organization (Hamilton, 2019), sustainable aquaculture involves managing natural resources rationally to meet human needs without compromising the ability of future generations to meet their own. Studies on shrimp farming in Vietnam have identified key sustainability constraints (Engle et al., 2017), including overuse of antibiotics and chemicals, environmental pollution, and inadequate infrastructure. Research in Vinh Long has further highlighted that while shrimp farming areas continue to expand, productivity remains unstable due to climate impacts and disease risks (Tran, Duong, et al., 2025).

Although previous studies have addressed the economic and environmental aspects of shrimp farming, few have systematically examined the combined role of environmental change, economic development policies, and technological adoption in shaping sustainability pathways. Moreover, integrated frameworks that assess the interaction between livelihood capitals and policy support remain limited in the Mekong Delta context

The objective of this research is therefore threefold: (i) to analyze the current status of marine shrimp farming in Vinh Long (formerly Ben Tre); (ii) to assess the key factors influencing sustainability, with particular emphasis on the impacts of climate variability and livelihood capital vulnerabilities; and (iii) to propose policy-relevant solutions that integrate environmental resilience, technological innovation, and economic development. The novelty of this study lies in its application of the Livelihood Capitals Index (LCI) and radar chart analysis to comprehensively evaluate sustainability across multiple dimensions. Its significance extends beyond Vinh Long, offering evidence-based insights for designing resilient shrimp farming models in the Mekong Delta and informing national strategies for sustainable aquaculture development.

2. METHODOLOGY

2.1. Research area

This study was carried out in the coastal districts of the former Ben Tre province (Nguyen et al., 2021), namely Binh Dai, Ba Tri, and Thanh Phu, which were the major centers of marine shrimp farming in the Mekong Delta. These districts were administratively merged into the newly established Vinh Long province in July 2025, following Resolution No. 1687/NQ-UBTVQH15 on the reorganization of commune-level administrative units in Vinh Long province. Although now part of Vinh Long, the geographical and ecological conditions of these areas remain those of the former Ben Tre, characterized by extensive wetlands, coastal ecosystems, and large shrimp farming zones (Figure 1).

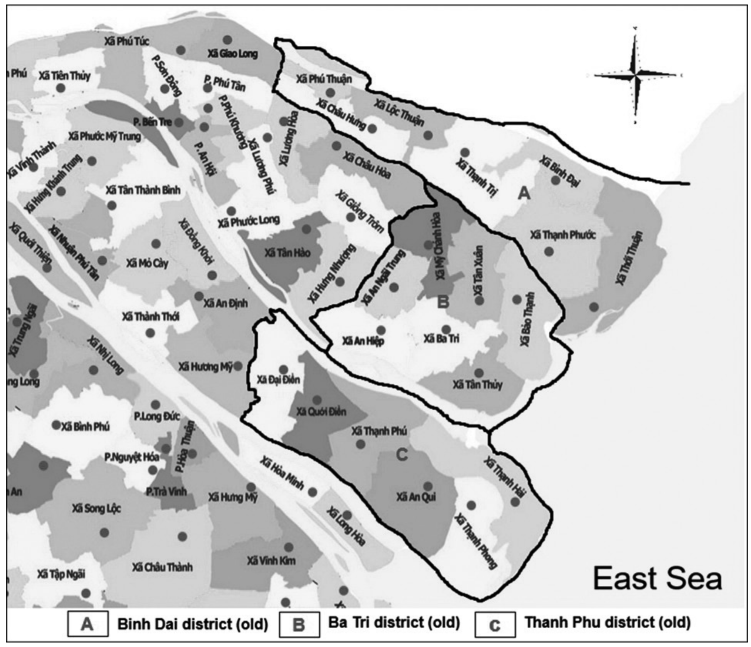

Figure 1. Research area with Binh Dai, Ba Tri, and Thanh Phu districts (former) on the new map of Vinh Long province (after the 2025 merger)

The field survey specifically targeted shrimp farming households in these three coastal districts prior to the administrative merger. A total of 52 structured questionnaires were collected, distributed as follows: 16 from Binh Dai, 21 from Ba Tri, and 15 from Thanh Phu. These districts were chosen as the research focal points due to their significant shrimp farming areas, their exposure to critical challenges such as climate change and salinity intrusion, and their continuous growth in aquaculture activities over recent years. Such characteristics provided a robust basis for assessing environmental, social, and economic factors influencing the sustainable development of the shrimp farming sector in the region.

2.2. Data collection

2.2.1. Questionnaire Content Based on the Sustainable Livelihood Framework (DFID)

The household survey was developed on the basis of the Sustainable Livelihood Framework (SLF) proposed by DFID (1999), which emphasizes the interactions among five key livelihood capitals: human, social, physical, financial, and natural. The questionnaire was structured to operationalize these capitals in the context of marine shrimp farming, capturing both socioeconomic and environmental dimensions that influence sustainable development.

Human capital: number and education of main laborers engaged in shrimp farming; ratio of active laborers to household members; highest educational attainment of family members.

Social capital: household perceptions of local infrastructure (electricity, transportation, irrigation, education, healthcare); participation in local organizations (farmer associations, aquaculture cooperatives, women's unions); frequency of training or extension workshops; and shrimp marketing channels.

Physical capital: household economic conditions reflected in housing and living standards; changes in aquaculture land over the past five years; ownership of aquaculture equipment and communication technologies (internet access).

Financial capital: household investment in shrimp farming; net income from aquaculture after deducting costs; main production model (type, scale, yield per hectare); monthly expenditures; and household financial capacity to sustain farming under environmental stress.

Natural capital: perceived impacts of drought, salinity intrusion, flooding, prolonged heat, and heavy rainfall on shrimp farming, assessed on a five-point scale from "no impact" to "very severe impact."

By aligning the survey content with the DFID framework, this study systematically integrates both policy-relevant socioeconomic aspects and environmental challenges into the assessment of sustainable shrimp farming in Vinh Long.

2.2.2. Livelihood Capitals Index (LCI)

The calculation of LCI followed the balanced weighted-average approach proposed by Sullivan et al. (2002). In this method, each sub-component contributes equally to the overall index, regardless of differences in the number of sub-components under each major component. The methodology is adapted from Hahn et al. (2009), with modifications to fit the local context. Since each indicator was measured on different scales, all sub-components were normalized into a comparable index using the following equation (1):

$$\text{Indexs}_r = \frac{S_r - S_{min}}{S_{max} - S_{min}} \quad (1)$$

where Sr represents the original value of a sub-component in the study area, while Smin and Smax are the minimum and maximum values, respectively.

After normalization, the sub-components were averaged to calculate the value of each major component (Mri) using equation (2):

$$M_{ri} = \frac{\sum_{i=1}^{n} \text{indexsr}}{n} \quad (2)$$

where Indexsri denotes the indexed values of the sub-components, and nnn is the number of sub-components in each major component.

Finally, the composite Livelihood Capitals Index (LCIr) was calculated as in equation (3):

$$\text{LCI}_r = \frac{\sum_{i=1}^{5} W_{Mi} M_{ri}}{\sum_{i=1}^{5} W_{Mi}} \quad (3)$$

where WMi is the weight of each major component, defined as the number of sub-components that constitute it, following the balanced weighting principle of Sullivan et al. (2002).

This methodological framework enables an integrated evaluation of how environmental, social, and economic dimensions jointly influence the sustainability of shrimp farming households. By applying both LCI and radar chart visualization, the study provides a comparative assessment of the vulnerabilities and strengths across the surveyed communes, thereby informing strategies to align environmental resilience with economic development policies for sustainable aquaculture in Vinh Long.

2.3. Data Analysis Methods

This study draws upon both primary and secondary data sources to analyze the sustainable development of marine shrimp farming in Vinh Long. The analytical framework integrates the Livelihood Capitals Index (LCI) with Radar Chart visualization to assess the combined effects of five livelihood capitals and to compare the relative impacts across two surveyed communes.

Secondary data were collected from commune and district-level reports within the study area, providing background information on environmental, economic, and social conditions. Primary data were obtained through household surveys, in which information was recorded based on structured questionnaires targeting shrimp farming households. All collected data were systematically compiled, summarized, and analyzed using Microsoft Excel (version 2010).

The LCI framework evaluates sustainable livelihoods through five major components: (i) human capital, (ii) social capital, (iii) physical capital, (iv) financial capital, and (v) natural capital. Each major component is further divided into several sub-components, which were identified based on household surveys and interviews in the study area.

3. RESULTS AND DISCUSSION

3.1. Assessment of the current status of marine shrimp farming in Vinh Long, former Ben Tre area

Marine shrimp farming in Vinh Long (formerly Ben Tre) has expanded significantly in recent years, making an important contribution to the fisheries sector of the Mekong Delta. According to the report of the Vinh Long Department of Agriculture and Rural Development, as shown in Figure 2, the marine shrimp farming area of the province reached approximately 36,661 ha in 2025, accounting for 81.2% of the total aquaculture area. Coastal districts such as Ba Tri, Binh Dai, and Thanh Phu represent the largest shrimp farming zones, contributing the bulk of the province's output. While the farming area has steadily increased, production and productivity have not followed a consistent upward trend. In particular, production rose from 29,208 tons in 2010 to 55,946 tons in 2015, but then declined to 45,479 tons in 2025, reflecting the impacts of environmental stressors and other external factors.

The structure in Figure 3 illustrates that shrimp output is highly concentrated in three coastal districts: Binh Dai accounts for 46.86%, Thanh Phu for 31.10%, and Ba Tri for 18.46%, while other areas contribute only 2.97%. Such spatial concentration implies that risks of disease transmission and environmental disturbances are particularly severe in these districts, highlighting the need for prioritized investment in irrigation, electricity supply, and disease management, as shown in Figure 2. One of the main factors affecting the sector is climate change, particularly salinity intrusion(Bhowmik et al., 2023). The coastal districts with large shrimp farming areas frequently face saline intrusion during the dry season. Prolonged droughts and abnormal weather patterns have further reduced freshwater availability, making water supply for shrimp ponds increasingly difficult. Salinity intrusion not only reduces shrimp yield but also degrades shrimp quality by creating unsuitable water conditions. In practice, many farmers in salinity-affected areas have reported mass shrimp mortalities due to substandard water quality.

Beyond environmental issues, disease outbreaks remain one of the most serious challenges for marine shrimp farming in Vinh Long. Diseases such as white spot syndrome and acute hepatopancreatic necrosis, caused by bacterial and viral agents, have resulted in significant production losses. Statistics indicate that mortality rates in previous production cycles reached 30-40%, reducing both productivity and efficiency. Although farmers have implemented preventive measures such as pond renovation, antibiotic use, and stricter water management, disease outbreaks continue to occur due to unstable pond environments and insufficiently effective disease control.

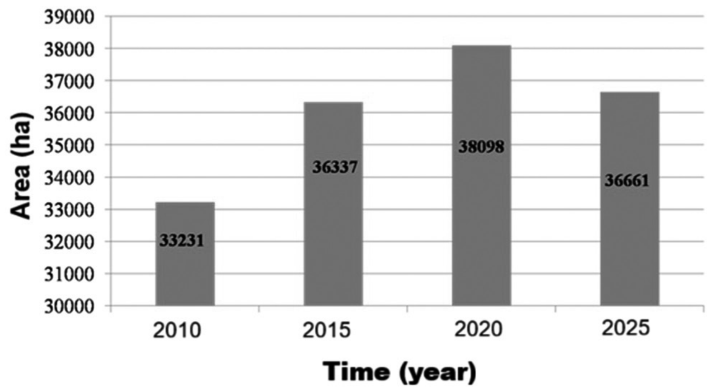

Figure 2. Statistics on marine shrimp area in Ben Tre region of Vinh Long province

Seed quality is another crucial factor influencing productivity and product quality (Ngo et al., 2022). In Vinh Long, however, seed quality remains problematic. Most seed is supplied by hatcheries within the province and neighboring regions, but not all hatcheries meet high-quality standards. As a result, seed quality is inconsistent in size and growth performance, reducing the effectiveness of production cycles. Poor-quality seed often leads to higher mortality rates and slower growth, thereby diminishing final yields.

Despite ongoing efforts to improve seed quality and adopt advanced farming technologies, the application of modern practices remains limited. High-tech models, such as lined ponds and two-stage farming, have been piloted in some areas of the province. These systems help increase productivity and reduce disease risks, but their initial investment costs are prohibitively high (Tran, Thuan, et al., 2025). Many smallholder farmers cannot adopt such systems due to limited access to capital. Credit support and loan programs remain insufficient, restricting the wider diffusion of these advanced models.

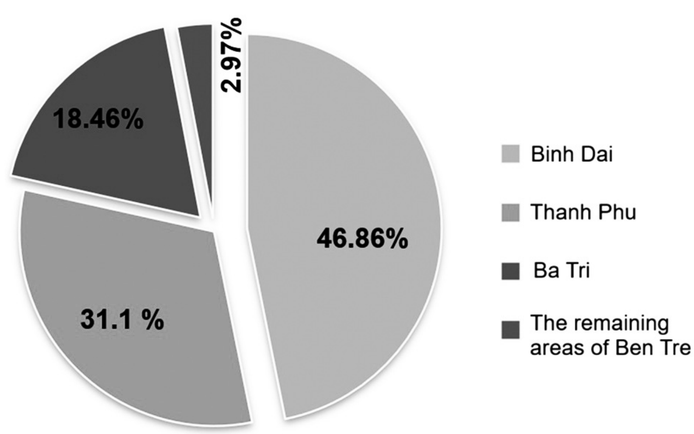

Figure 3. Structure of marine shrimp output by district and town in Ben Tre region (Vinh Long province)

Infrastructure for shrimp farming in Vinh Long also remains inadequate. Although improvements have been made in recent years, many coastal areas still lack effective water supply and drainage systems. This deficiency makes it difficult to maintain water quality in ponds, especially during the dry season when freshwater is scarce. In addition, challenges in waste treatment and pollution from shrimp farming activities need to be addressed to protect the environment and sustain the long-term development of the sector.

Overall, marine shrimp farming in Vinh Long continues to face significant challenges, particularly with respect to environmental pressures, seed quality, and disease outbreaks. Nonetheless, with improved infrastructure, the adoption of new technologies, and the development of sustainable farming models, shrimp farming can continue to grow and make a positive contribution to the provincial economy. Coordinated solutions are required to overcome current limitations, alongside enhanced application of science, technology, and supportive policies to raise productivity and efficiency in the sector.

3.2. Factors affecting the sustainable development of marine shrimp farming

3.2.1. Livelihood capital assessment across districts

The analysis of the Livelihood Capitals Index (LCI) highlights both strengths and weaknesses in the shrimp farming households across the three surveyed districts of the former Ben Tre province, now part of Vinh Long.

In Binh Dai district, the LCI results indicate that financial capital (0.68) was the most favorable component, reflecting relatively strong household income and financial resources to sustain aquaculture. Social capital (0.572) and physical capital (0.59) also reached moderate levels, suggesting adequate social networks and infrastructure. However, human capital (0.511) and especially the sub-component of labor experience and availability (0.3005) were comparatively weak, while natural capital was the lowest at 0.50, revealing vulnerabilities to environmental stresses (Table 1).

In Ba Tri district, the pattern differed somewhat. Here, social capital was highest at 0.65, indicating strong household participation in local organizations and satisfaction with infrastructure, particularly the sub-component of social networks (0.77). Financial capital (0.603) also played a critical role in supporting shrimp farming households. By contrast, human capital was lowest at 0.46, with relatively low scores in both knowledge/skills (0.48) and labor resources (0.44). Natural capital scored 0.526, reflecting moderate exposure to salinity intrusion and climatic variability, while physical capital was also relatively weak (0.505) (Table 2).

Table 1.Values of the main components of the LCI index in Binh Dai district

Key elements	LCI index	Key components	LCI index
	Binh Dai district		Binh Dai district
Human capital	0.511	Knowledge and skills	0.722
		Experience and labor resources	0.3005
Social capital	0.572	Demographics	0.547
		Social networks	0.597
Physical capital	0.59	Housing, land, and infrastructure	0.59
Financial capital	0.68	Finance and income	0.68
Natural capital	0.5	Natural resources	0.5
		Climate	0.5

Table 2.Values of the main components of the LCI index in Ba Tri district

Key elements	LCI index	Key components	LCI index
	Ba Tri district		Ba Tri district
Human capital	0.46	Knowledge and skills	0.48
		Experience and labor resources	0.44
Social capital	0.65	Demographics	0.53
		Social networks	0.77
Physical capital	0.505	Housing, land, and infrastructure	0.505
Financial capital	0.603	Finance and income	0.603
Natural capital	0.526	Natural resources	0.5
		Climate	0.553

In Thanh Phu district, the LCI profile revealed a more balanced situation. Financial capital remained strong at 0.66, supported by social capital (0.657), which highlighted the role of community participation and demographic structure. Human capital reached 0.544, slightly higher than Ba Tri, largely due to strong knowledge and skills (0.75), though labor resources were

Table 3. Values of the main components of the LCI index in Binh Dai district

Key elements	LCI index Thanh Phu district	Key components	LCI index Thanh Phu district
Human capital	0.544	Knowledge and skills	0.75
		Experience and labor resources	0.338
Social capital	0.657	Demographics	0.674
		Social networks	0.641
Physical capital	0.529	Housing, land, and infrastructure	0.529
Financial capital	0.66	Finance and income	0.66
Natural capital	0.554	Natural resources	0.5
		Climate	0.608

again limited (0.338). Natural capital showed improvements with a score of 0.554, driven by better adaptation to climatic conditions (0.608), while physical capital was somewhat modest at 0.529 (Table 3).

Overall, these findings suggest that financial and social capitals consistently emerged as the most supportive factors for sustainable shrimp farming across all three districts. In contrast, human capital and natural capital represent the main constraints, particularly the shortage of skilled labor, dependence on family workforce, and vulnerability to environmental stressors such as drought, salinity intrusion, and flooding. The results highlight the need for policies that strengthen human capital (e.g., training, extension services) and enhance environmental resilience (e.g., adaptive infrastructure, water resource management) to ensure the long-term sustainability of marine shrimp farming in Vinh Long.

3.2.2. Comparative analysis of strengths and vulnerabilities

The radar charts in Figure 4 illustrate the relative strengths and weaknesses of the five livelihood capitals across the three districts. A consistent pattern emerges in which financial and social capitals are the strongest dimensions in all districts, particularly in Ba Tri and Thanh Phu, where social capital exceeds

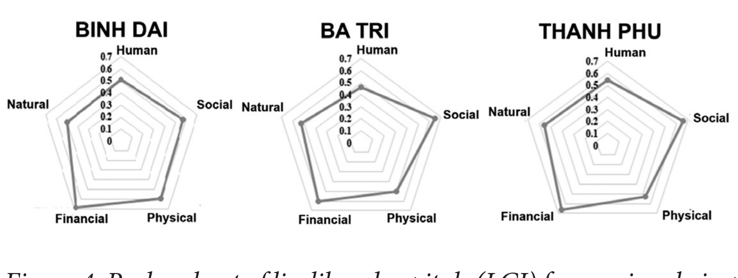

Figure 4. Radar chart of livelihood capitals (LCI) for marine shrimp farming households in Binh Dai, Ba Tri, and Thanh Phu districts

0.65. These results reflect the importance of household income and the role of social networks, organizations, and infrastructure in supporting shrimp farming.

By contrast, human capital and natural capital appear to be the most constrained factors. Human capital remains below 0.55 in all districts, with the lowest in Ba Tri (0.46), indicating limited skills, education, and labor resources available for shrimp aquaculture. Natural capital also shows vulnerability, with Binh Dai scoring the lowest at 0.50, highlighting exposure to salinity intrusion, climatic variability, and resource depletion. Physical capital is relatively moderate across the three districts, fluctuating between 0.50 and 0.59, suggesting an ongoing need for improved infrastructure and farming facilities.

The comparative profile shows that while Binh Dai faces the greatest vulnerability in natural and human capitals, Ba Tri performs better in social networks but remains weak in physical conditions, and Thanh Phu presents a relatively balanced but still constrained profile in human and natural aspects. These variations point to the need for location-specific strategies that address both socio-economic and environmental challenges.

3.3. Proposed solutions for the sustainable development of marine shrimp farming

Based on the LCI analysis, several policy and management solutions can be proposed to enhance the sustainability of marine shrimp farming in Vinh Long:

Strengthening human capital, training and capacity-building programs should be prioritized to improve farmers' technical knowledge and aquaculture management skills. Extension services, farmer field schools, and collaboration with research institutions can help reduce the gap in human resources, particularly in Ba Tri where human capital is the weakest.

Enhancing natural capital resilience, adaptive strategies are needed to mitigate the risks of climate change, salinity intrusion, and resource degradation. Investments in water management infrastructure, such as salinity control sluices and sustainable water reuse systems, can strengthen resilience. Ecological approaches, including mangrove-shrimp integrated systems and environmentally friendly farming practices, should be promoted.

Consolidating financial capital, access to credit and financial services should be expanded to support household investments in technology and adaptive practices. Policies that encourage cooperative models or collective financing can reduce risks and stabilize income for small-scale farmers.

Upgrading physical capital, infrastructure improvements, such as reliable electricity, roads, and cold-chain facilities, are essential to reduce post-harvest losses and improve market access. Adoption of digital monitoring systems (IoT, water quality sensors) should also be supported to optimize farming operations.

Leveraging social capital, the strength of community networks in Ba Tri and Thanh Phu suggests that local organizations and cooperatives can serve as effective platforms for knowledge exchange, collective action, and sustainable certification programs (e.g., ASC, VietGAP). Encouraging wider farmer participation in associations will enhance resilience and bargaining power in the market.

In summary, while financial and social resources currently underpin the viability of shrimp farming, the long-term sustainability of the sector requires significant investments in human capital development and environmental resilience. Tailored solutions at the district level – focusing on the weakest livelihood dimensions – will be critical for ensuring sustainable development under changing ecological and socio-economic conditions.

4. CONCLUSION

The findings highlight that financial and social capitals currently provide the strongest support for farming households, while human and natural capitals remain the most critical constraints. Specifically, labor resources, skills, and environmental vulnerability to salinity intrusion and climate variability continue to undermine long-term sustainability. The novelty of this research lies in its integration of livelihood capital assessment with policy-oriented analysis, providing a multidimensional view of shrimp aquaculture that combines environmental resilience and economic development strategies. This approach offers practical implications for policymakers, particularly in designing adaptive infrastructure, expanding credit access, and strengthening farmer training and community-based organizations.

The study's significance extends beyond Vinh Long, offering lessons for sustainable aquaculture in other climate-vulnerable regions of the Mekong Delta. Future research should focus on testing adaptive models that integrate technological innovation (e.g., IoT-based water management), ecological practices (e.g., mangrove–shrimp systems), and participatory governance, thereby strengthening both household resilience and sectoral sustainability under accelerating climate change.

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BIOPLASTIC FROM SHRIMP SHELLS COMBINED WITH GREEN TEA EXTRACT AND ITS APPLICATION IN FOOD PRESERVATION

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Abstract
The growing environmental burden of plastic waste highlights the urgent need for sustainable alternatives in food packaging. Chitosan, a natural polymer derived from shrimp shell waste, offers excellent film-forming and biodegradable properties, while green tea extract (GTE) provides bioactive compounds with antibacterial activity. In this study, bioplastic films were prepared by blending chitosan with polyvinyl alcohol (PVA) and varying amounts of GTE (5, 7, and 10 mL). The biofilm synthesized with chitosan and green tea extract exhibited a smooth surface morphology, with tensile strength ranging from 12.51 ± 0.25 to 26.66 ± 0.53 MPa, elongation at break ranging from 388.3 ± 7.8% to 546.8 ± 10.9%, and can inhibit the growth of Escherichia coli (E. coli) bacteria. Incorporation of GTE reduced solubility, improved tensile strength, and enhanced antibacterial activity against Escherichia coli, with inhibition zones increasing proportionally with GTE content. Fourier transform infrared spectroscopy (FTIR) confirmed hydrogen bonding interactions between chitosan and phenolic compounds in GTE, while scanning electron microscopy (SEM) revealed uniform, compact surfaces. Biodegradability tests showed rapid degradation, with films losing over 90% of mass within 53 days. These findings suggest that chitosan–PVA–GTE films are promising eco-friendly packaging materials with improved mechanical durability, antibacterial functionality, and environmental sustainability.

Keyword: *Chitosan, shrimp shells, green tea extract, bioplastic films.*
JEL Classification: *Q53, Q55, L66.*
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1. INTRODUCTION

Plastic is one of the most widely used materials in the global economy, becoming indispensable in modern life with applications in packaging, medicine, and construction, etc. Currently, growing concern exists over the increasing global production of plastics. Plastic waste clogs drainage systems, canals and rivers, threatening marine and coastal ecosystems. This has negative impacts on important sectors of the economy, including tourism, shipping, and aquaculture (Franco-Trecu et al., 2017; Hermabessiere et al., 2017; Issac et al., 2021). In 2015, Vietnam generated about 5 million tons of plastic. In 2018, plastic production increased by 7%, reaching 8.3 million tons. Of the total processed plastic waste, nearly 12% of plastic is recovered or recycled, the rest is treated by incineration, landfill, or will leak into the environment (Ministry of Natural Resources and Environment, 2019). The majority of plastic comes from households (~70.4%), followed by markets (~16.9%) and other sources (Giang et al., 2023). Notably, the leakage into aquatic life accounts for 335 tons/year (~8.9%), mainly due to uncollected waste, poor trash and drainage systems, as well as waste spilled during transportation. A similar situation has been reported in major Vietnamese cities such as Ho Chi Minh City (11.3%), Da Nang (8.3%), and Quang Ninh (8.9%) (Tran et al., 2020) (Tran et al., 2020).

In order to address this issue, bioplastics were created in the beginning of the twenty-first century. Commercial polymer products made from natural or renewable resources are known as bioplastics (Rudin et al., 2013). Certain renewable materials derived from bioplastics may be regenerated through biological processes, and certain bioplastics are biodegradable under the right circumstances (Harnkarnsujarit et al., 2021). Vegetable oils, sugar, cellulose, proteins, and other natural and renewable materials are frequently utilized in the production of bioplastics. The manufacturing capacity of bioplastics was 1075 per 1000 tons in 2022, according to the European Bioplastics Association, and is predicted to rise to around 2453 per 1000 tons by 2024 (European Bioplastics, 2020). The need to switch from traditional plastics to bioplastics is growing as environmental conservation and protection become more widely recognized. About 1% of plastics produced worldwide each year are bioplastics, and current trends indicate that the market for bioplastics is expanding steadily across a range of sectors (Siracusa et al., 2020). Bioplastics are now widely used in many different industries due to their flexibility in design and the ability to improve material properties through the use of additives such as plasticizers, compatibilizers, cross-linkers and coupling agents to optimize thermo-mechanical performance, biodegradability and processability (extrusion, injection molding, blow molding, etc.) (Negrete-Bolagay & Guerrero, 2024). In addition, bioplastics are also used in the pharmaceutical and medical industries (biodegradable implants, bioactive films, drug delivery systems), construction and automotive (lightweight materials, non-load-bearing interior parts), coatings, adhesives and small electronic devices (Martínez et al., 2013).

Therefore, interest in bioplastic films has increased among consumers and the food industry due to growing environmental concerns along with concerns about the potential negative impacts of food packaging that will harm and poison human health, affect hormones causing endocrine disruption and cause some breast cancers (de Paula & Alves, 2024; Amato-Lourenço et al., 2021, Thoene et al., 2020). In addition, there is growing scientific evidence of the environmental friendliness and effectiveness of bioplastics in reducing the environmental impact (Kumar et al., 2024; Coppola et al., 2021; Dilkes-ho et al., 2019). Recently, many researches have been conducted on value–added products from seafood industrial waste such as chitin are being utilized to synthesize chitosan. Due to its affordable price, availability and diverse properties such as antibacterial activity, biodegradability, complexation, film–forming ability and good mechanical strength, chitosan stands out from other biopolymers, showing great potential in application as food packaging material (Priyadarshi & Rhim, 2020; Ahmed et al., 2025; Hasan et al., 2020). Along with the application of creating tensile films, to support the improvement of the mechanical strength of the product, chitosan is mixed with plasticizers such as PVA (Polyvinyl alcohol) and some additives. In addition, chitosan is also combined with some biological active substances in fruit peels, leaves, seeds, etc. to increase the antibacterial, antifungal and antioxidant properties of the film (Yun et al., 2021; Zhang et al., 2021). In this research, chitosan was combined with green tea leaf extract (GT), a compound with high antioxidant and antibacterial properties thanks to polyphenols in tea, to create a coating with effective antibacterial properties. Catechin is the predominant polyphenol in green tea, the antioxidant activity of which is a result of the neutralization of nitrogen and oxygen free radicals, as well as the ability to form complexes with metal ions in redox reactions (Musial et al., 2020). The specific chemical structure of polyphenols (presence of at least five hydroxyl groups) present in green tea has a significant impact on the antioxidant capacity (Koch et al., 2018). Tea Polyphenols (TPs) are non–toxic, antibacterial polymers that slow down the oxidation process and prevent the growth of bacteria in some foods (Liu, Liang et al., 2018; He et al., 2016).

This research highlights the importance of developing bioplastic films from chitosan extracted from shrimp shells, blended with PVA, as a sustainable alternative to conventional plastic packaging aligned with the UN Sustainable Development Goals (SDGs). A comprehensive characterization was conducted, including antibacterial activity, biodegradability, Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and mechanical testing. The results obtained from the study contribute to promoting orientation in the design and development of sustainable bio-packaging, while meeting urgent requirements related to environmental protection and ensuring food safety. In this article, the aim is to explore the potential of bio-waste (shrimp shells) as a renewable raw material in combination with green tea extract and its application in food preservation. The conversion of agricultural and aquatic waste into useful materials contributes to sustainable development strategies and a circular economy.

2. MATERIALS AND METHODS

2.1. Materials and chemicals

Waste shrimp shells were obtained from a local fish market in Ho Chi Minh city, Vietnam, and transported to the laboratory within one hour of collection. Upon arrival at the laboratory, shrimp shells scraped clean of loose tissue and washed individually in mild salt water to remove dirt and impurities. The shells are then dried at 70°C until crisp. Green tea leaves and nutrient agar were purchased from local supermarkets. Antimicrobial activity was assessed using Escherichia coli (ATCC25,922). All reagents, glycerol ($C_3H_8O_3$ - 99%), acetic acid ($C_2H_4O_2$ – 99.5%), LB Broth (Miller), and Polyvinyl alcohol (PVA) were supplied by commercial vendors (Ghtech, HiMedia Laboratories, and Sigma - Aldrich). All chemicals were used as received without further purification. Distilled water was used throughout the experiments.

2.1.1. Synthesis of Chitosan from chitin of Shrimp Shells (SS)

The chitin extraction procedure was adapted from Percot et al. (2024) with modifications to suit the experimental conditions.

Demineralization (DM)

Demineralization was conducted using HCl solution

(2%) to remove inorganic salts ($CaCO_3$, $Ca_3(PO_4)_2$). Shrimp shells were soaked in HCl (ratio 1:12 w/v) at 30°C while stirring continuously for 1 hour (until no CO_2 bubbles). Then, filtered, washed several times with distilled water. The resulting demineralized shrimp shells were washed until the pH was neutral (~7).

Deproteinization (DP)

The deproteinization process was performed to remove organic protein from demineralized shrimp shells. Shrimp shell protein was recovered by the classical deproteinization process on demineralized shrimp shells in NaOH solution (3.5%; washing in a 15:1 w/v solution layer) to ensure safety and no chitin hydrolysis. The NaOH solution was heated to 75°C, and the demineralized shells were soaked at a 1:10 w/v ratio and stirred for 3 hours. Finally, the product obtained was crude chitin after being filtered, washed with hot and cold water until the pH was neutral.

Decolorization

Prior to deacetylation, decolorization was performed to remove any pigments such as astaxanthin and melanin from the chitin. The following decolorization procedure is based on Iñiguez–Moreno et al., 2024; Xiong et al., 2023, but has been modified to be compatible with the experimental conditions. This procedure is performed by immersing the sample in a hydrogen peroxide solution H_2O_2 3% (v/v) for 25 min at 65°C. Finally, the sample was rinsed with distilled water to achieve neutral pH and then dried in an oven at 60°C for 24 hours.

Conversion of chitin to chitosan

The deacetylation of chitin to chitosan was carried out by hydrolysis of the acetyl groups using concentrated sodium hydroxide (NaOH, 40 wt%). The deacetylation vessel was refluxed at 100°C under ambient pressure for up to 40 hours; this reaction was accompanied by a vigorous decomposition of the chitin to produce chitosan (Ghanem et al., 2025; Al Sagheer et al., 2009). High concentrations should be used in a safe and suitable process to avoid polymer degradation.After deacetylation, the chitin was washed until neutral pH (pH = 7) was achieved, and then dried in a UN30 drying oven at 70°C for 4 hours (Sree et al., 2020). The crude chitosan obtained exhibited an ivory to light-yellow color.

Preparation of green tea extract

Green tea leaf extract was prepared based on the method of Yang, et al (Yang et al., 2022). Green tea leaves were heated for 10 minutes at 90ºC with a ratio of 2gr to 10mL of distilled water and filtered using Whatmann No.1 filter paper to obtain the extract. The extract was stored at 4ºC for the next experiment.

Manufacturing of Bioplastic

To prepare the film-forming solution, chitosan was dissolved in 2% (v/v) aqueous acetic acid and stirred for 4 hours. Polyvinyl alcohol (PVA) was dissolved separately in distilled water at 90°C under stirring at 250 rpm for 2 hours. Then, PVA solution was poured into chitosan solution and mixed using a magnetic stirrer at 250 rpm for 1 hour (Fadia Zatalini et al., 2023). Chitosan - PVA mixtures were prepared at weight ratios of 1:1, 1:3 and 3:1 (w/w), which would correspond to M11, M13, M31 films, respectively. After mixing, 0.5 mL of additives was added to each solution, followed by stirring for 15 min to obtain a homogeneous, thickened solution. Finally, the resulting mixtures were cast into Petri dishes, ensuring that no air bubbles remained on the surface, and then dried at 80°C for 3 hours.

Film formation process from chitosan and green tea

Green tea extract at a concentration of 10% was mixed with chitosan solution and poured into petri dishes. After drying in an oven at 45°C for 2 hours, the film was peeled off from the petri dish and stored in an airtight container at 23°C for further testing (Amankwaah et al., 2020).

Characteristics of Bioplastic

The bioplastic characteristic tests include film thickness, SEM, FTIR, film tensile strength, water solubility, testing antibacterial ability by agar hole punching method and biodegradation test.

2.1.2. Mechanical properties

Determination of film thickness and tensile strength (ASTM D882-18)

The mechanical properties of the bioplastic films such as film thickness and tensile strength at break were determined using a PTA MTC 500 Testing Machine (Spain) connected to a Registra3 software on the computer. Measurements were made with a 1000N force sensor, a 500 mm/min clamping speed and a 50 mm clamping distance. Five measurements were taken randomLy from two locations on each film. The average value from five measurements was reported.

Scanning electron microscopy (SEM)

Scanning Electron Microscopy (SEM) was employed to examine the surface morphology of the synthesized membrane using a Hitachi S–4800 FESEM with a magnification of 6000× at an accelerating voltage of 10 kV.

Fourier transform infrared spectroscopy (FTIR)

Fourier–transform infrared spectroscopy (FT–IR) served as the analytical method to investigate chemical bonds within composite sheets, employing a Frontier FT–IR/NIR spectrometer (PerkinElmer, serial number

105667). This state–of–the–art equipment facilitated high-resolution spectroscopy with a precision of 4 cm-1 , enabling detailed examination of molecular interactions and vibrations in the material. IR spectroscopy measurements spanning from 4000 cm-1 to 400 cm-1 allowed for a thorough analysis of functional groups, chemical compositions, and bonding configurations present in the bioplastic composite

Determination of solubility in water (%)

According to the method described by Rubilar et al, the water solubility of the film was determined. The solubility was defined as the dry mass fraction dissolved after 48 hours of immersion in water using the following equation (Rubilar et al., 2013):

$$\text{Solubility in water (\%)} = \frac{Mi-Mf}{Mi} \text{ x } 100$$

Where Mi is the initial mass and Mf is the final mass (g) of the sample. Five replicates were taken for each sample.

Testing antibacterial ability by agar hole punching method

Chitosan film formulations containing green tea extract and Chitosan – PVA film mixtures were prepared at weight ratios of 1:1, 1:3 and 3:1 (w/w) were tested for antibacterial activity against Escherichia coli bacteria. The experiment was conducted by pipetting 100μl of the Escherichia coli bacteria solution into a petri dish containing LB agar under sterile conditions. Using a glass triangular inoculating rod, spread it evenly over the agar surface, then punch a hole and fill the hole with the sample solution. Incubate immediately at 37°C for bacteria to grow for 48 hours. Observe and measure the diameter of the sterile zone on the agar plate (Rai et al., 2017).

Determination of biodegradation time

The biodegradability of chitosan films was evaluated by soil burial method. For the soil burial test, film samples were buried to a depth of 9 cm in moist soil and then periodically removed weekly, washed, dried, and reweighed to determine the rate of mass loss over time (ASTM 5336).

3. RESULTS AND DISCUSION

3.1. Film thickness and water solubility

The appearance of packaging plays a crucial role in shaping consumers' perception of the contained food. The basic properties of the film including thickness (mm), water solubility (%) are shown in Table 1. Film thickness is an important parameter that determines the final physical, mechanical and barrier properties of biodegradable films. Thickness values ranged from 0.051 to 0.065 mm, with the green tea chitosan film had the thickest thickness of 0.065 mm. The film thickness under all conditions was not significantly different ($p>0.05$). This may be because the film thickness was controlled by a defined film solution volume and a constant diameter of the petri dish. In addition, film thickness is also influenced by the solid content of green tea extract (GTE). According to Kasai et al., the thickness of the film directly affects its mechanical strength and overall performance in packaging applications. These important factors for preserving the freshness and quality of perishable products require thicker films to provide a barrier against oxygen and moisture (Kasai et al., 2018). The incorporation of GTE into chitosan/PVA films improved the mechanical properties, thickness and water vapor barrier, enhanced the polyphenol content and antioxidant activity of the films (Siripatrawan & Harte, 2010). The appropriate thickness can prolong the shelf life of foods and maintain optimal conditions during storage and transportation. In addition, the thickness of the film also affects the puncture resistance and durability of the film, which are important during handling and transportation (Roy et al., 2023).

The water solubility values of different films were presented in Table 1. The results showed that the water solubility of the film decreases with the addition of green tea extract. In general, higher solubility indicated lower water resistance. Therefore, GTE film had higher water resistance as its water solubility is 54.2%. This may be due to the OH- groups of the phenolic compound in GTE forming H-bonds with the NH^{3+} groups of the chitosan backbone (Bourtoom and Chinnan, 2008; Siripatrawan and Harte, 2010). Stronger intermolecular H-bonds, between the OH- groups of GTE and the NH^{3+} groups of chitosan, reduced the affinity of the GTE film for water and led to a decrease in water solubility.

3.2. Tensile strength (TS) and Elongation at break (E)

Usually, the TS and E were desired properties for a packaging film to keep and maintain its integrity to tolerate external stress and tightness. The arrangement

Table 1. The thickness and water solubility of the prepared films with different compositions

Film samples	Thickness (mm)	Water Solubility (%)
M11	0.051	95.08
M13	0.051	97.40
M31	0.052	89.15
GTE	0.065	54.16

and compactness of the inter- and intra-molecular connections between polymer chains in the film structure usually determined the film's mechanical properties (Murugan et al., 2024). In general, high molecular weight PVA produced blend films with high tensile strength and low elongation at break. The TS and E of the prepared films were shown in Table 2. The mechanical properties of chitosan films incorporated with different ratios of Chitosan/PVA concentrations and GTE were statistically compared. The results showed that GTE significantly affected the mechanical resistance and extensibility of the chitosan-based films. As can be seen in Table 2, the TS of Chitosan/PVA blended films ranged from 12.50 to 26,66 MPa and the values increased with increasing PVA content. The M11 film exhibited a TS of 25.04 MPa and an E of 459.6%, respectively. In contrast, the M31 film decreased TS by 50% (12.51 MPa) but increased E sharply by 84% (546.8%). The TS and E of M13 film were 26.66 MPa and 388.3%, respectively. The addition of plasticizers such as glycerol and sorbitol has been reported to improve polymer flexibility. Cerqueira et al. created the plasticizers by looking at how adding glycerol/sorbitol affected them (Cerqueira et al., 2012). In general, high molecular weight PVA produces blend films with high tensile strength and low elongation at break. Adding the right amount of PVA to the films can make them stronger. Blending causes intermolecular interactions between the two polymers, which increases the mechanical strength of the blended film. Blending these two polymers improves their mechanical properties by interacting with their -OH and $-NH_2$ groups. In fact, The mechanical strength of the film increases with increasing molecular weight and deacetylation of chitosan (Hajji et al., 2016).

Table 2. The tensile strength and elongation at break of the prepared films with different compositions

Film samples	Tensile strength (MPa)	Elongation (%)
M11	25.02	459.6
M31	12.51	546.8
M13	26.66	388.3
GTE	23.73	422

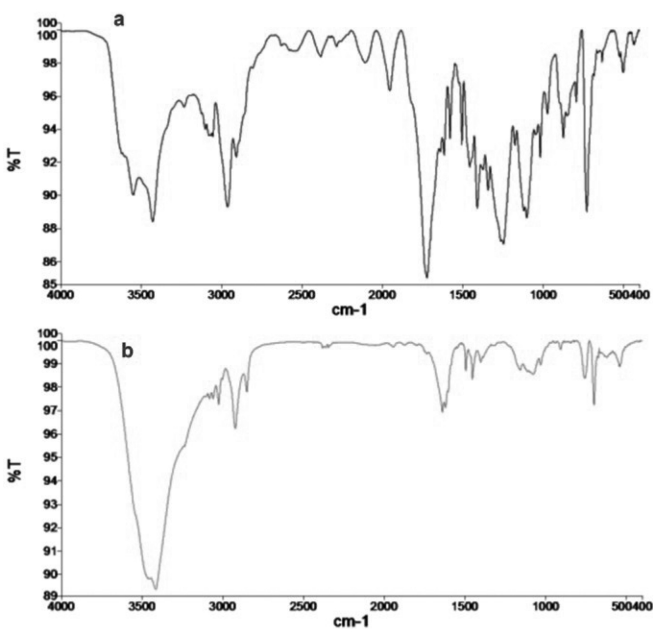

Fig 1. Fourier-transform infrared spectroscopy analysis: a. Chitosan - PVA membrane, b. Chitosan - PVA membrane immersed in green tea extract

The TS of the films increased as the GTE concentration increased. However, the E showed an opposite trend compared to TS, as shown in Table 2. The increase in TS value with increasing GTE content may be due to the formation of hydrogen bonds between OH- groups of polyphenolic molecules and NH_3^+ reactive groups of chitosan backbone. This interaction contributed to the enhanced strength of the films. When GTE was added, the E value decreased, indicating that the film became less flexible. The decrease in extensibility of the film may be the result of the restricted movement of the chain due to the interaction between chitosan and GTE (Detduangchan et al., 2014).

3.3. FTIR spectra results

The characteristic peaks corresponding to the bending and stretching vibrations of functional groups in the synthesized chitosan-PVA film and the chitosan-PVA film immersed in green tea extract illustrate significant chemical interactions within these materials, as shown in Figure 1. The FTIR spectrum of the synthesized chitosan-PVA membrane displayed characteristic peaks, confirming the presence of functional groups from both polymers (Fig 1a). Broad absorptions at 3552–3430 cm^{-1} were assigned to O-H and N-H stretching vibrations, indicating hydroxyl and amine groups capable of hydrogen bonding. Peaks at 2964 and 2910 cm^{-1} corresponded to aliphatic C-H stretching, while a strong band at 1725 cm^{-1} was attributed to C=O stretching from ester or carbonyl groups. The amide I (1643 cm^{-1}) and amide II (1549 cm^{-1}) bands reflected the characteristic vibrations of chitosan, and additional peaks between 1316 and

1087 cm^{-1} were assigned to C-O stretching, confirming the presence of alcohol and ether functionalities in both chitosan and PVA (Jasrotia et al., 2025). After immersion in green tea extract, notable spectral changes were observed, indicating interactions between polyphenolic compounds and the Chitosan–PVA matrix (Fig 1b). The broad O-H/N-H stretching shifted to 3441 cm^{-1}, suggesting stronger hydrogen bonding due to the incorporation of tea polyphenols. New peaks at 3084-3027 cm^{-1} appeared, corresponding to aromatic C–H stretching, while additional signals at 1619 and 1493 cm^{-1} were associated with aromatic C=C skeletal vibrations, confirming the integration of green tea-derived aromatic compounds. Furthermore, C-O stretching bands at 1156–1029 cm^{-1} were intensified, reflecting contributions from ether and alcohol groups in both the polymer and tea extract. The presence of low-wavenumber bands at 906–538 cm^{-1} further supported aromatic skeletal vibrations from green tea constituents. Collectively, these findings demonstrate that immersion in green tea extract introduced new functional groups and enhanced hydrogen bonding, evidencing strong chemical interactions between the bioactive polyphenols and the chitosan–PVA membrane (Peng et al., 2013).

3.4. Scanning electron microscopy (SEM)

The morphology of the synthesized shrimp chitosan membranes at various chitosan – PVA compositions were studied using SEM techniques (Fig 2). The surface of the chitosan: PVA (1:1, w/w) membrane exhibited a relatively homogeneous and compact morphology with a fine nodular texture and a few isolated aggregates, indicating reasonable miscibility between the two polymers (Fig 2a). In contrast, the PVA–rich (1:3, w/w) membrane revealed pronounced phase separation, characterized by plate–like domains, sharp rims, and micro–fissures that are likely associated with crystallization of PVA during solvent evaporation (Fig 2b). Meanwhile, the chitosan–rich (3:1, w/w) membrane displayed a comparatively smooth and continuous surface matrix with minor ridges, suggesting improved structural uniformity. These observations highlight that the relative chitosan/PVA ratio governs the extent of phase separation and surface texture, with higher PVA contents favoring crystallization–induced heterogeneity and higher chitosan contents promoting a smoother, more uniform film structure (Fig 2c) (Le Ba Thai et al., 2024). Interestingly, the 1:1 w/w membrane after immersion in green tea extract exhibited a layered and striated surface pattern, distinct from the nodular morphology of the untreated film (Fig 2d) . This modification may be attributed to the adsorption and possible interaction of tea polyphenols with chitosan and PVA chains, which may alter hydrogen bonding and surface packing, thereby enhancing surface roughness and introducing a more ordered microstructure (Westlake et al., 2023).

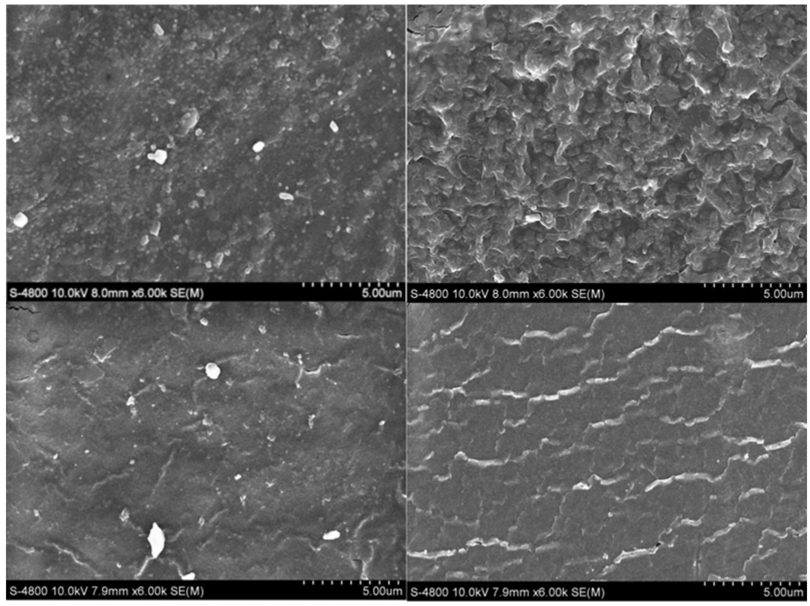

Fig 2. SEM micrographs of composite films: a. Chitosan – PVA 1:1 w/w, b. Chitosan – PVA 1:3 w/w, a. Chitosan – PVA 3:1 w/w, a. Chitosan – PVA 1:1 w/w with 7mL green tea extract

3.5. Testing antibacterial ability by agar hole punching method

As shown in Figure 3, the pure Chitosan membrane was observed clear antibacterial ability against Escherichia coli strain. At a high Chitosan ratio (3:1 w/w), the inhibition zone reached 10 mm and 9 mm (Fig 3a), which was larger than that observed at a 1:1 w/w ratio (6 mm and 7 mm) (Fig 3b), indicating that higher chitosan content enhanced antibacterial effectiveness. In constract, at a 1:3 w/w ratio (lowest chitosan content), almost no inhibition zone was observed (Fig 3c), suggesting insufficient chitosan to exert antibacterial activity, thus allowing E. coli proliferation. When green tea extract (GTE) was incorporated into the chitosan membrane at concentrations of 5, 7, and 10 mL, the inhibition zones against E. coli were 12 mm (Fig 4a), 13 mm (Fig 4b) and 14 mm (Fig 4c) respectively. The analysis results show that when chitosan and green tea leaf extract are mixed to create a film with good antibacterial properties, this suggests that the synergy between chitosan and polyphenol compounds in green tea (such as catechin) significantly enhances antibacterial activity (Musial et al., 2020). Chitosan already has natural antibacterial properties, but the combination with green tea extract increased the effectiveness of inhibiting E. coli bacteria (Rahayu et al., 2022), opening up the potential application of Chitosan–green tea films in food packaging to prolong the preservation time and improve food safety and hygiene.

3.6. Determination of biodegradation time

As mentioned earlier, biodegradable active packaging is the main focus of current food packaging research and development. Accordingly, the aim of this study is to develop an environmentally friendly active film from chitosan combined with aqueous green tea extract as a natural antioxidant. The possibility of improving the antioxidant properties of chitosan films is to combine with antioxidant agents (Muñoz-Tebar et al., 2023). The results of the biodegradation test in Table 3 and Fig 5 showed that each sample had a clear tendency to decrease in mass and there were significant differences at each time point. The Chitosan – PVA sample

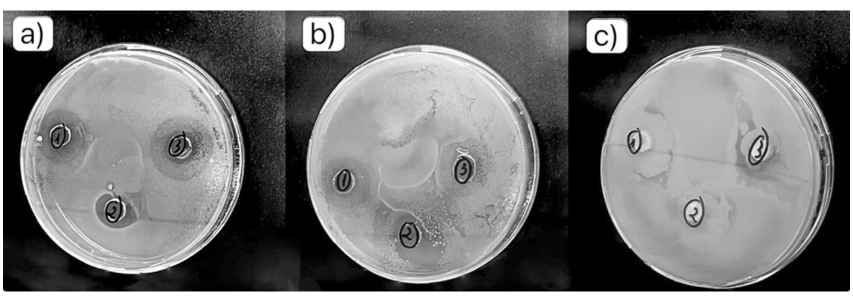

Fig 3. Image of measuring the diameter of the E. coli sterile zone of Chitosan – PVA film mixtures with scale bars of a) 3:1 w/w, b) 1:1 w/w, c) 1:3 w/w

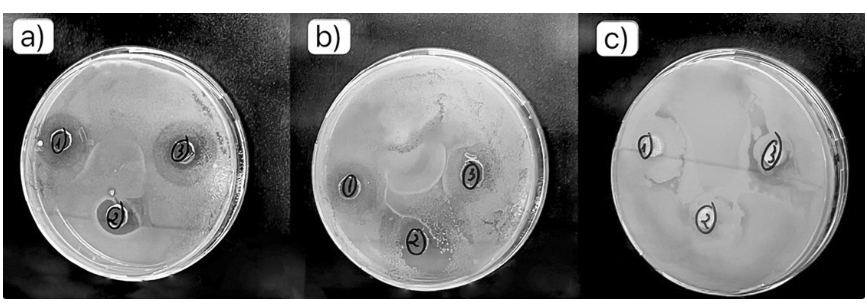

Fig 4. Image of measuring the diameter of the E. coli sterile zone of Chitosan with green tea extract with scale bars of a) 5mL, b) 7mL, c) 10mL

Table 3. Biodegradation time (days) and weight loss (g) survey of chitosan film

Time (days)	Sample M13 (g)	Sample M11 (g)	Sample M31 (g)	Sample GTE (g)
0	0.1850	0.1887	0.1916	0.1965
30	0.074	0.0813	0.0891	0.0603
53	0.0192	0.0203	0.0217	0.0165

with a ratio of 1:3 w/w, M13, after 30 days, the mass decreased from the initial 0.1850g to 0.0740g, equivalent to 60% decomposition and only 0.0192g on day 53, reaching 89.62% decomposition. The Chitosan – PVA sample with a ratio of 1:1 w/w, M11, decreased from 0.1887g to 0.0813g after 30 days (56.92% decomposition) and 0.0203g after 53 days (89.24% decomposition). The Chitosan – PVA sample with a ratio of 3:1 w/w, M31, had a mass of 0.1916g, after 30 days had a decomposition rate of 53.5% (0.0891g) and decomposed to 88.67% in the next 23 days (remaining 0.0217g) Notably, the GTE sample had the highest initial mass of 0.1965g but after being buried in the ground, the sample mass decreased the fastest, only 0.0603g on day 30 (69.31% decomposition) and 0.0165g on day 53 (91.60% decomposition). This shows that the MGTE film showed the highest early decomposition rate but the largest decrease rate in the later phase, suggesting that as a good source of polyphenols, GTE can be used as an active agent and incorporated into the film. This biodegradability is due to cellulose and glycerol, which contain O–H groups that can bond together and are able to bind moisture from the air, helping them to degrade quickly (Mashuni et al., 2022). It can be concluded that the biodegradable plastic from Chitosan, PVA and GTE has met the standard because the biodegradation test met the international standard (ASTM 5336).

4. CONCLUSION

This study indicated that an active film from chitosan-based film can be effectively developed through the incorporation of green tea extract (GTE) as a

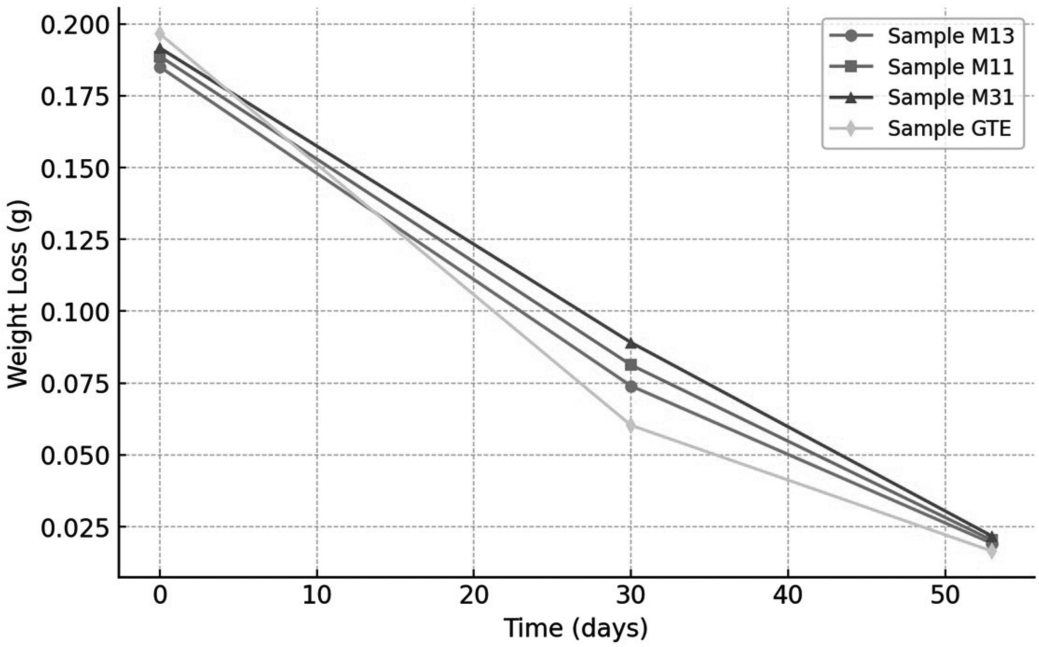

Fig 5. Biodegradation time and weight loss survey of chitosan film

natural antioxidant. Addition of GTE improved high antioxidant and antibacterial properties thanks to polyphenols in tea, to create a coating with effective antibacterial properties. Catechin is the predominant polyphenol in green tea, the antioxidant activity of which is a result of the neutralization of nitrogen and oxygen free radicals, as well as the ability to form complexes with metal ions in redox reactions. These changes, as verified by FTIR analysis, could be attributed to the interactions between functional groups of chitosan and GTE polyphenolic compounds. To assess the overall performance of the films, comprehensive characterization was conducted, including SEM imaging, biodegradability testing, antibacterial assays, and mechanical evaluations. By simultaneously addressing food safety concerns and environmental protection requirements, the findings highlight the strong potential of chitosan–GTE films in guiding the design and development of sustainable bio-packaging solutions.

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KOH-MODIFIED DURIAN PEEL BIOCHAR FOR ENHANCED REMOVAL OF SYNTHETIC DYES FROM AQUEOUS ENVIRONMENT

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Abstract

Large quantities of durian peel residues are produced as by-products of consumption and processing, creating a challenge for sustainable waste management. The production of synthetic dyes is on the increase due to their high demand, most especially in the textile and clothing industries. These chemicals (dyes) are massively produced annually in thousands of tons worldwide. Specifically, the annual industrial production of dye compounds is ~ 7x105 tons (Katheresan et al., 2018). A few examples of synthetic dyes are aniline blue, alcian blue, basic fuchsin, methylene blue, crystal violet, toluidine blue, and congo red. Synthetic dyes remain in the physical environment since most of them are difficult to biodegrade and are not usually eliminated during the conventional water treatment processes. Therefore, they cause persistent pollution and ecological risks in aquatic environments. Methylene blue (MB), a representative cationic dye widely used in textile and printing industries, was selected in this study as a model pollutant because of its high stability, intense coloration, and toxicity even at low concentrations.

In this study, durian husk was valorized into biochar and applied as an adsorbent for methylene blue (MB) removal from aqueous solution. The production process was systematically optimized with respect to pyrolysis temperature and residence time. Preliminary tests revealed that biochar prepared at 600°C exhibited markedly higher decolorization efficiency compared with those obtained at 400 and 500°C. Further investigation showed that extending the residence time from 3 to 5 hours enhanced adsorption performance, with the 600°C 5-hour biochar demonstrating the best results. Subsequently, a saponification pretreatment using 5% KOH, with immersion times, the optimized material achieved a maximum MB removal efficiency of approximately 98% and an equilibrium adsorption capacity of about 8.9 mg.g⁻¹. Overall, these results highlight the potential of durian peel biochar, especially after KOH saponification, as a cost-effective and eco-friendly adsorbent for dye-contaminated wastewater.

Keyword: *Biochar, durian husk, KOH saponification, methylene blue, adsorption, wastewater treatment.*

JEL Classification: *Q53, Q55, Q25.*

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1. INTRODUCTION

In recent years, rapid urbanization, industrial expansion, climate change, and upstream alterations in river flow have significantly deteriorated water quality in many regions, particularly within the Mekong Delta (Doan et al., 2025). Increasing discharges of organic matter, nutrients, and synthetic dyes from industrial and domestic activities have raised serious concerns regarding aquatic pollution, with profound risks to both human health and ecosystem integrity. In response to these challenges, sustainable and low-cost adsorbents have attracted considerable attention for wastewater treatment. Among them, biochar has emerged as a promising candidate owing to its unique properties, as it not only valorizes abundant agricultural by-products but also offers a renewable, economical, and environmentally friendly option for contaminant removal.

Biochar is a stable, highly aromatic, carbon-rich porous material produced through the pyrolysis of biomass (e.g., crop residues, livestock, and poultry manure) under anaerobic or oxygen-limited conditions, and it generally exhibits alkaline characteristics under natural environments (Xu et al., 2017). As an organic amendment, biochar can not only modify the physical and chemical properties of soils but also demonstrates strong adsorption capacity owing to its large specific surface area and well-developed pore structure. Consequently, it has attracted increasing attention in recent years for applications in carbon sequestration, soil improvement, pollution control, and other environmental management practices (Sakhiya et al., 2020b; Ravindiran et al., 2024). The adsorption of pollutants by biochar is influenced by multiple factors, among which its intrinsic characteristics, such as pore size distribution and types of surface functional groups, play decisive roles (Oliveira et al., 2017). Numerous studies have highlighted that the pyrolysis temperature significantly alters the specific surface area, pore architecture, surface functionalities, and aromaticity of biochar, thereby modulating its adsorption efficiency toward various contaminants (Raj et al., 2021b; P. Zhang et al., 2019b). For instance, G.Zhang et al. (2011) reported that biochar prepared at higher temperatures exhibited a greater degree of aromatization, larger surface area, more complete pore structure, reduced abundance of polar surface groups, and enhanced adsorption capacity for simazine.

The environmental burden of industrial wastewater from textile manufacturing is substantial, as it is characterized by high concentrations of auxiliary chemicals, heavy metals, and dyes. This effluent is a significant contributor to water degradation, with the dyeing and finishing phase alone accounting for approximately 20% of all pollution in clean water sources. The composition of textile dyeing wastewater includes high concentrations of recalcitrant organic molecules, notably synthetic dyes like indigo blue and indigo carmine, which are chemically stable and difficult to degrade (Yaseen & Scholz, 2018). Furthermore, the effluent's toxicity is intensified by the presence of heavy metals, including chromium, copper, zinc, and lead, which are employed to fix dyes. This poses a risk to both human health, daily life and the aqueous environment, including the potential for skin irritation and carcinogenic effects. In order to alleviate this issue, numerous sophisticated treatment technologies have been implemented. Ozone oxidation has demonstrated significant potential for the purification of textile wastewater, and the efficacy of COD and color removal has been enhanced through the integration of AOPs or UV treatment with coagulation pretreatment.

MB is extensively used for dyeing fabrics, papers, and leathers in textile and garment industries, leading to the discharge of large volumes of dye-laden effluents into aquatic environments. According to Oladoye et al. (2022), MB poses ecological and health risks owing to its monoamine-oxidase inhibitory properties that can induce serotonin toxicity in humans at doses above 5 $mg.kg^{-1}$. Its complex aromatic and heterocyclic structure renders it highly resistant to biodegradation, oxidation, and even photolysis (Shahinyan et al., 2019), allowing persistence in water bodies where it reduces light penetration and disrupts aquatic ecosystems. Consequently, the effective removal of MB from wastewater is of critical environmental significance. The adsorption of MB onto biochar occurs through a combination of physicochemical mechanisms, including electrostatic attraction between MB^+ cations and negatively charged oxygen-containing groups, ion exchange with alkali or alkaline-earth cations (K^+, Ca^{2+}, Mg^{2+}), π–π stacking between aromatic domains, π–cation interactions, and hydrogen bonding (Xu et al., 2017; Sakhiya et al., 2020). Owing to its well-defined structure, planar geometry (~1.4 × 0.6 × 0.4 nm), and strong absorption peak at 664–665 nm, MB is widely used as a benchmark molecule to probe adsorption pathways and evaluate biochar performance, offering mechanistic insights relevant to a broader range of persistent organic pollutants and heavy metals.

Vietnam has emerged as one of Southeast Asia's leading durian producers, driven by strong domestic demand and booming exports, particularly to China. In 2023, the country's durian cultivation area exceeded 110,000 hectares, producing over 850,000 tons of fruit and generating export revenues surpassing 2.1 billion USD (Khanh, 2025). However, alongside this impressive growth lies a pressing environmental challenge. Structurally, durian fruit comprises three main parts: the edible aril (20–35% of total weight), the seeds (5–15%), and the husk, which constitutes the majority fraction at 55–66% (Nordin et al., 2017). Consequently, most of the durian biomass remains as an underutilized by-product. With the sharp rise in production, husk disposal has become a serious concern. For instance, durian farming in the Philippines generates over 22,000 tons of husks annually (Phoung, 2012), while in Vietnam, the figure exceeded 150,000 tons in 2023 and is projected to reach 300.000–450.000 tons in the near future (Khanh, 2025). Current disposal practices are largely unsustainable, as the husks are often dumped into landfills or left to decompose in open areas, releasing unpleasant odors, attracting pests, and emitting methane (CH_4), a greenhouse gas with a global warming potential 25 times greater than CO_2, thereby compounding the environmental burden of the durian industry.

From the perspective of a circular economy, the valorization of durian husk waste presents a promising pathway for sustainable waste management. Compared with other agricultural residues, durian husk offers both economic and technical advantages. It is abundantly available and has an extremely low market value, while its composition, rich in cellulose, hemicellulose, and lignin, makes it particularly suitable for thermochemical conversion into biochar. In contrast, other residues such as bamboo and coconut shells are often repurposed for higher-value applications (e.g., handicrafts, paper, or organic fertilizers), leaving durian husk as a low-cost yet underexploited feedstock ideal for developing biochar-based adsorbents within a circular economy framework.

Building upon this context, the present study evaluates the adsorption performance of biochar prepared (i) at 400, 500, and 600°C for a fixed residence time of 4 h; (ii) at 600°C with varied residence times of 3, 4, and 5 h to identify the optimal duration; and (iii) with KOH pretreatment under the optimal condition compared with its non-pretreated counterpart.

2. MATERIALS AND METHODS

2.1. Materials and chemicals

Durian husks were collected from local markets, thoroughly washed to remove impurities, and oven-dried for further use. Methylene Blue (MB, 82% purity), potassium hydroxide (KOH, 5% solution), and distilled water were employed as chemical reagents.

2.2. Preparation

In the preliminary optimization stage, durian husks were pyrolyzed at different temperatures (400, 500, and 600°C) under fixed residence time conditions. The results indicated that biochar obtained at 600°C exhibited superior performance compared to lower pyrolysis temperatures. At the selected temperature of 600°C, residence times of 3, 4, and 5 hours were further evaluated, and 5 hours was found to be optimal.

For chemical pretreatment, the husks were immersed in 5% KOH solution for 30 minutes, lightly rinsed with distilled water, oven-dried, and subsequently pyrolyzed at 600°C for 5 hours.

2.3. Sample names

C 400/500/600 : Biochar (without KOH) produced at 400/500/600°C with fixed residence time.

C600-3/4/5 : Biochar is produced at 600°C for 3/4/5 hours, respectively.

C306005 : Biochar pretreated with 5% KOH for 30 minutes, then pyrolyzed at 600°C for 5 hours.

2.4. Adsorption experiment

2.4.1. Adsorption dynamics experiment

Batch adsorption experiments were conducted to investigate the adsorption dynamics of methylene blue (MB) onto the prepared biochar samples. A fixed amount of biochar (0.50 g) was added into MB aqueous solutions of known initial concentration (C_0 = 100 mg.L^{-1}, V = 45 mL). The mixtures were agitated in an orbital shaker at a constant speed of 120 rpm (ambient temperature, 28°C, pH ≈ 10). At predetermined time intervals, aliquots were withdrawn, filtered, and analyzed for the residual MB concentration using a UV-Vis spectrophotometer at λ = 664 nm.

The adsorption capacity (q_t, mg.g^{-1}) at time t was calculated according to:

$$q_t = \frac{(C_0 - C_t) \times V}{m}$$

where: C_0 and C_t are the initial and residual dye concentrations (mg.L^{-1}), respectively, V is the solution volume (L), and m is the adsorbent mass (g).

The adsorption kinetic experimental data were fitted and analyzed using the Pseudo-first-order (PFO), Pseudo-second-order (PSO), and Intra-particle diffusion (IPD) models. The corresponding linearized equations are presented below:

Pseudo-first-order (PFO):

$$\ln(q_e - q_t) = \ln q_e - k_1 t$$

Where: q_e (mg.g^{-1}) and qt (mg.g^{-1}) are the adsorption capacities at equilibrium and at time t (min), respectively, and k_1 (min-1) is the rate constant of the PFO model.

Pseudo-second-order (PSO):

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

Where: k_2 (g.mg-1.min-1) is the rate constant of the PSO model.

Intra-particle diffusion (IPD):

$$q_t = k_i t^{0.5} + C$$

Where: k_i (mg.g^{-1}.min$^{-1/2}$) is the intra-particle diffusion rate constant, and C reflects the boundary layer thickness.

2.4.2 Isothermal adsorption experiment

Equilibrium adsorption isotherm studies were carried out by contacting a fixed mass of biochar (0.50 g) with MB solutions of varying initial concentrations (C_0 = 20-200 mg.L^{-1}) at a constant volume (45 mL) and pH (≈10). The suspensions were shaken at 150 rpm and 28°C until adsorption equilibrium was attained (after 180 min, as determined from the kinetic experiments). The supernatants were filtered, and the residual MB concentrations were measured using a UV-Vis spectrophotometer at 664 nm.

The equilibrium adsorption capacity (q_e, mg.g^{-1}) was calculated according to:

$$q_e = \frac{(C_0 - C_e) \times V}{m}$$

Where: C_0 and C_e are the initial and equilibrium dye concentrations (mg.L^{-1}), respectively; V is the solution volume (L), and m is the adsorbent mass (g).

The isothermal adsorption experimental data were fitted and analyzed using the Langmuir, Freundlich, and Temkin models. The linearized forms of the equations are expressed as:

Langmuir model:

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e}$$

Where qe (mg.g^{-1}) is the adsorption capacity at equilibrium and C_e (mg.L^{-1}) is the equilibrium concentration. q_{max} (mg.g^{-1}) represents the maximum adsorption capacity; K_L (L.mg^{-1}) is the Langmuir adsorption constant;

Freundlich model:

$$q_e = K_F C_e^{\frac{1}{n}}$$

Where K_F[(mg.g^{-1})(L.mg^{-1})$^{-1/n}$] is the Freundlich constant; n is the Freundlich heterogeneity factor.

3. RESULTS AND DISCUSSION

3.1. Initial properties and Preliminary optimization

The preliminary experiments were conducted to evaluate the effect of pyrolysis temperature and residence time on the adsorption performance of the biochar toward methylene blue (MB).

Figure 1 illustrates the integrated effect of pyrolysis temperature (400, 500, and 600°C) and residence time (3, 4, and 5 hours) on the MB removal efficiency of biochar. The removal percentage increased substantially with temperature, reaching more than 98% at 500°C and nearly complete removal at 600°C. This improvement would be due to catalyzing the decomposition of such compounds as well as generating more stable aromatic carbon structures. This trend is consistent with previous findings for MS and SG. The observed increases in surface area and pore volume are attributed to the thermal degradation of organic components such as hemicellulose, cellulose, and lignin, along with the development of vascular bundles or channel-like structures during pyrolysis (Kim et al., 2013; Li et al., 2012). According to Lee et al., 2013, cellulose and hemicellulose in MS begin to decompose around 500°C. When the pyrolysis temperature rises above 500°C, the breakdown of hemicellulose and other organics promotes the generation of additional micropores in biochar (Jeong et al., 2015). Furthermore, the decomposition of lignin accompanied by the rapid release of H_2 and CH_4 leads to a marked increase in surface area and pore volume between 500 and 600°C. In addition, extending the residence time from 3 to 5 hours at 600°C enhanced MB removal, with

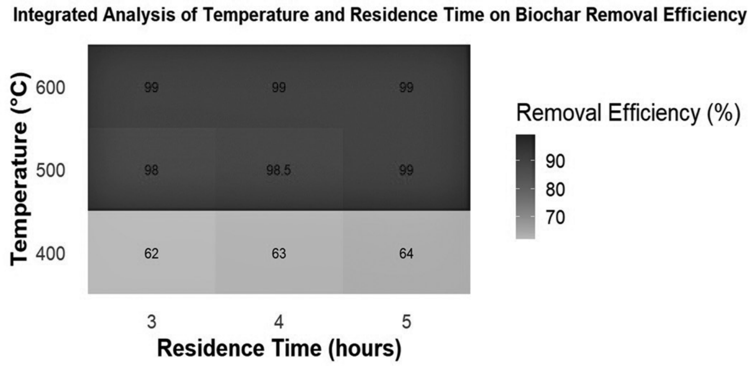


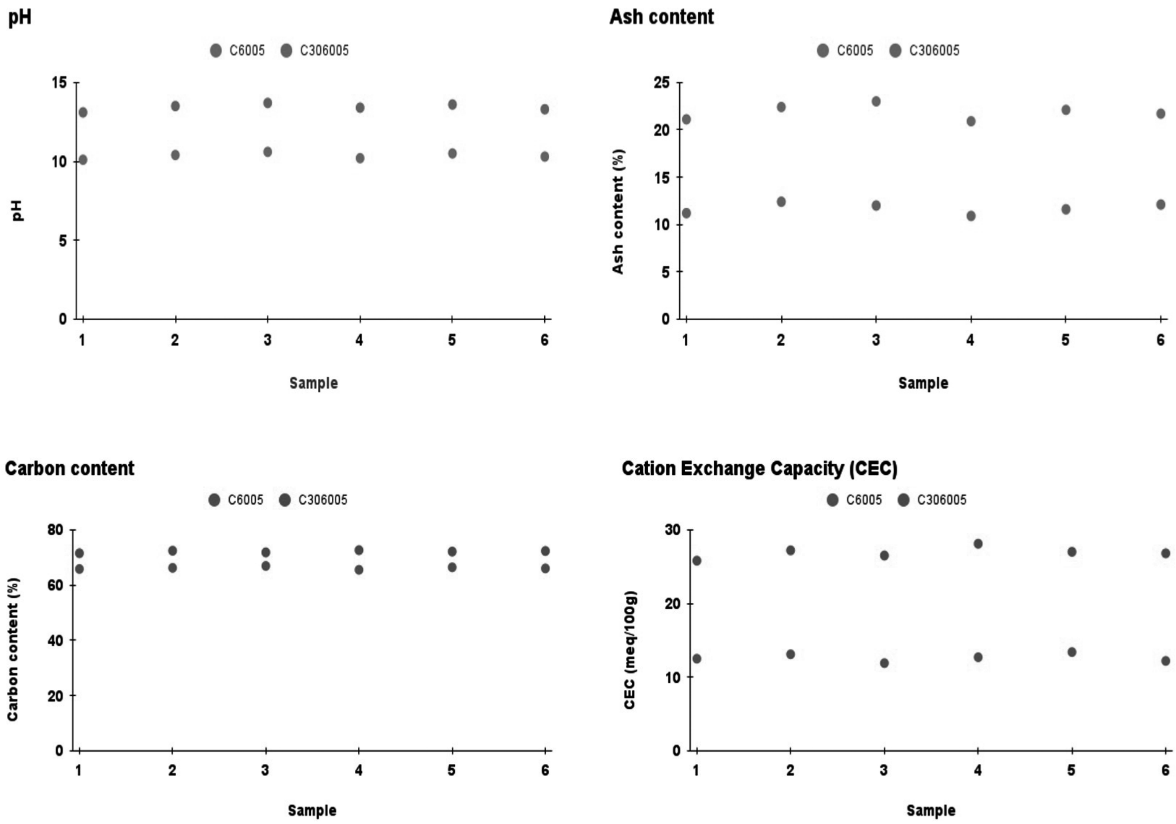
Figure 1. Integrated effect of pyrolysis temperature and residence time on MB removal efficiency of biochar

optimal performance (~98%) achieved after 5 hours. The slight increase can be attributed to the reduction of volatile matter and the increase of fixed carbon, along with higher surface pH and a greater abundance of basic functional groups, which provide more favorable adsorption sites. However, after about 4 to 5 hours, the structure and surface properties of the biochar became nearly stabilized, resulting in only a minor improvement and a tendency to level off (Sun et al., 2016).Therefore, a residence time of 5 hours was selected as the optimal condition to ensure high and stable adsorption performance.

3.2. Effect of KOH

Analysis results indicated that the addition of KOH altered the composition of the biochar. In terms of ash content, the untreated sample exhibited a markedly higher value of about 25%, whereas the KOH-saponified sample showed a reduced level of approximately 10%. Moreover, the moisture content decreased significantly during dry storage and under high-temperature conditions, and water retention was further diminished after KOH modification compared to the initial state. In contrast, KOH reacts with the carbon network through activation processes, leading to the consumption of carbon and a subsequent decline in its content (Wahyu et al., 2025). In addition, biochar activated with KOH solution exhibited higher values in cation exchange capacity (CEC), which is also dependent on the biomass feedstock and pyrolysis conditions (Loc et al., 2018). With the increase of pH from 10 to nearly 14, the removal efficiency of MB rose significantly, reaching its maximum at pH 13.5. According to Gurav et al. (2021), as the pH value increases, the electrostatic attraction between the negatively charged biochar surface and the cationic dye MB^+ becomes stronger, resulting in a higher adsorption capacity.

The comparison of non-activated and activated biochars reveals a clear difference in removal efficiency. Activated biochars exhibited an increase from 90.5–91.7% to over 98% compared with the non-activated sample. This improvement is attributed to the greater number of active-binding sites generated on the surface after chemical modification, together with the formation of new functional groups and enhanced ion-exchange properties that facilitate adsorption.



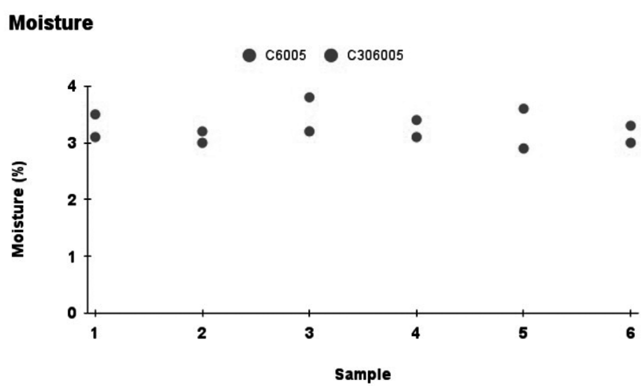


Figure 2. Comparison of physicochemical properties (pH, ash content, carbon content, moisture, and cation exchange capacity) between C6005 and C306005 biochars

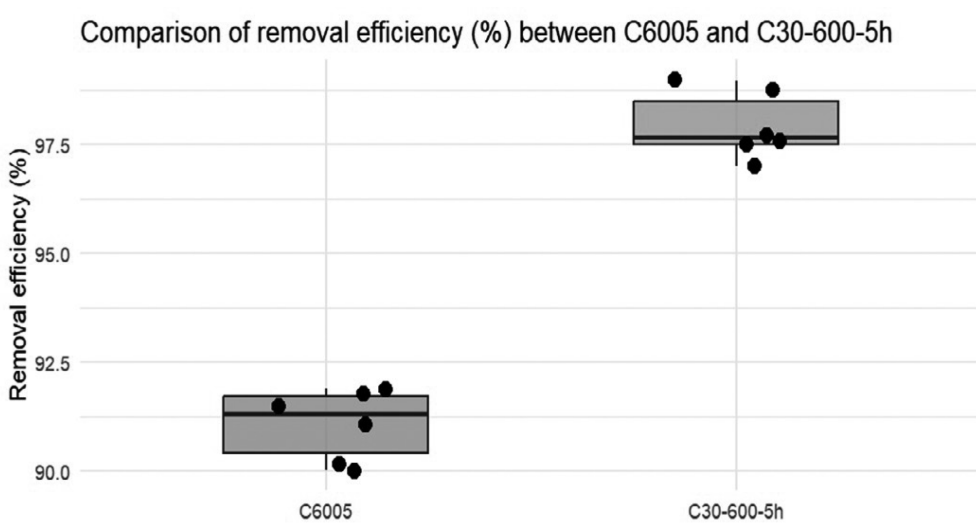


Figure 3. Comparison of removal efficiency (%) between C6005 and C306005

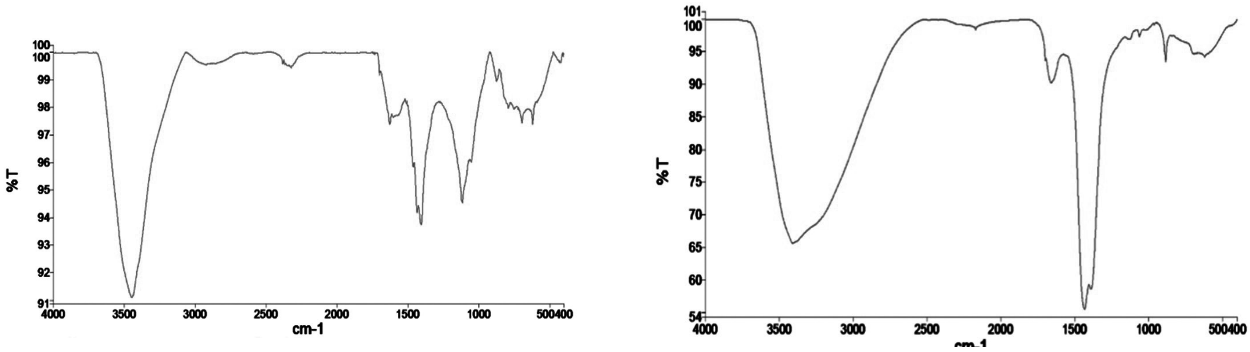


Figure 4. FTIR spectra of biochars: (a) C6005 and (b) C306005

3.3. Material properties

The FTIR spectra of the two biochars reveal clear structural differences between the C6005 and C306005. In C6005, weak aliphatic C–H stretching vibrations at 2960, 2926, and 2852 cm^{-1} are still detectable, suggesting the persistence of residual hydrocarbon chains, while the absorption band at 1700–1627 cm^{-1} corresponds to C=O and aromatic C=C groups. Several out-of-plane bending vibrations of aromatic C–H are observed at 893, 872, 789, and 748 cm^{-1}, together with signals below 600 cm^{-1} attributed to Si–O or metal–O bonds, reflecting the contribution of mineral phases. By contrast, the spectrum of C306005 is dominated by a broad O–H stretching band at 3346 cm^{-1}, accompanied by the disappearance of aliphatic C–H peaks, indicating a more complete carbonization process. A distinct absorption at 1432 cm^{-1}, along with additional bands at 1389 and 1329 cm^{-1}, is assigned to CO_3^{2-} vibrations, confirming the presence of surface carbonate after KOH pretreatment. Strong absorptions at 1248 and 1136 cm^{-1} are related to C–O stretching of phenolic and ether groups, while the peaks at 836 and 816 cm^{-1} further confirm the aromatic backbone of the biochar. Overall, C6005 retains some aliphatic and carbonyl functionalities and shows a stronger contribution from mineral phases, whereas C306005 exhibits a more stable aromatic framework enriched with hydroxyl and carbonate groups. These modifications render the surface more alkaline and polar, thereby increasing the number of active adsorption sites and facilitating multiple adsorption mechanisms, including electrostatic interactions with cationic MB, hydrogen bonding with hydroxyl functionalities, and π–π interactions between the aromatic rings of the biochar and the dye.

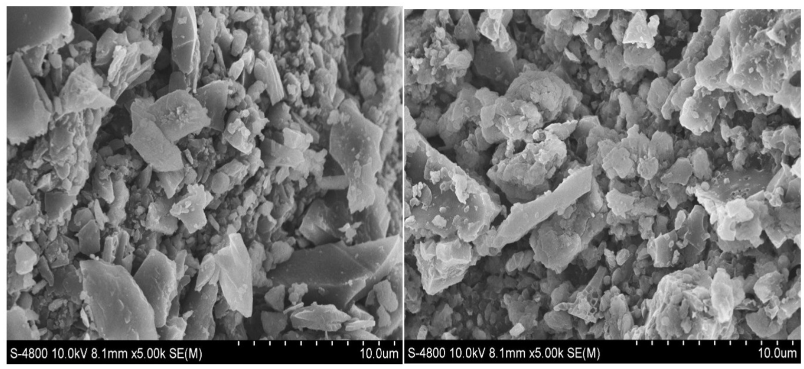


Figure 5. SEM images of (a) C6005 and (b) C306005

The SEM micrographs recorded at 10 kV and ×5000 magnification reveal clear morphological differences between C6005 and C306005. The pristine C6005 sample Figure 5a exhibits a relatively compact surface structure with stacked plate-like particles and limited pore development. In contrast, the KOH-pretreated C306005 Figure 5b shows a rougher texture with extensive fragmentation, micro-cracks, and a higher density of cavities. This structural transformation can be attributed to the alkaline saponification process, during which KOH penetrates the biomass matrix and reacts with hemicellulose and lignin, promoting partial dissolution of inorganic components and weakening the carbon framework, resulting in the formation of a well-developed porous structure on the biochar surface, with a predominance of micropores and the appearance of active functional groups (Ding & Liu, 2020; Jedynak & Charmas, 2023). The internal components of the biomass are revealed, and a uniform chemical reaction is facilitated by the presence of KOH, which is highly effective. Subsequent pyrolysis further enhances the release of volatile matter, leaving behind a more disordered and porous network.

3.4. Kinetic and adsorption isotherm

The kinetic parameters of MB adsorption onto C6005 and C306005 are summarized in Table 1. For C6005, the PSO model provided a better fit (R^2 = 0.9993; qe,cal close to qe,exp, suggesting

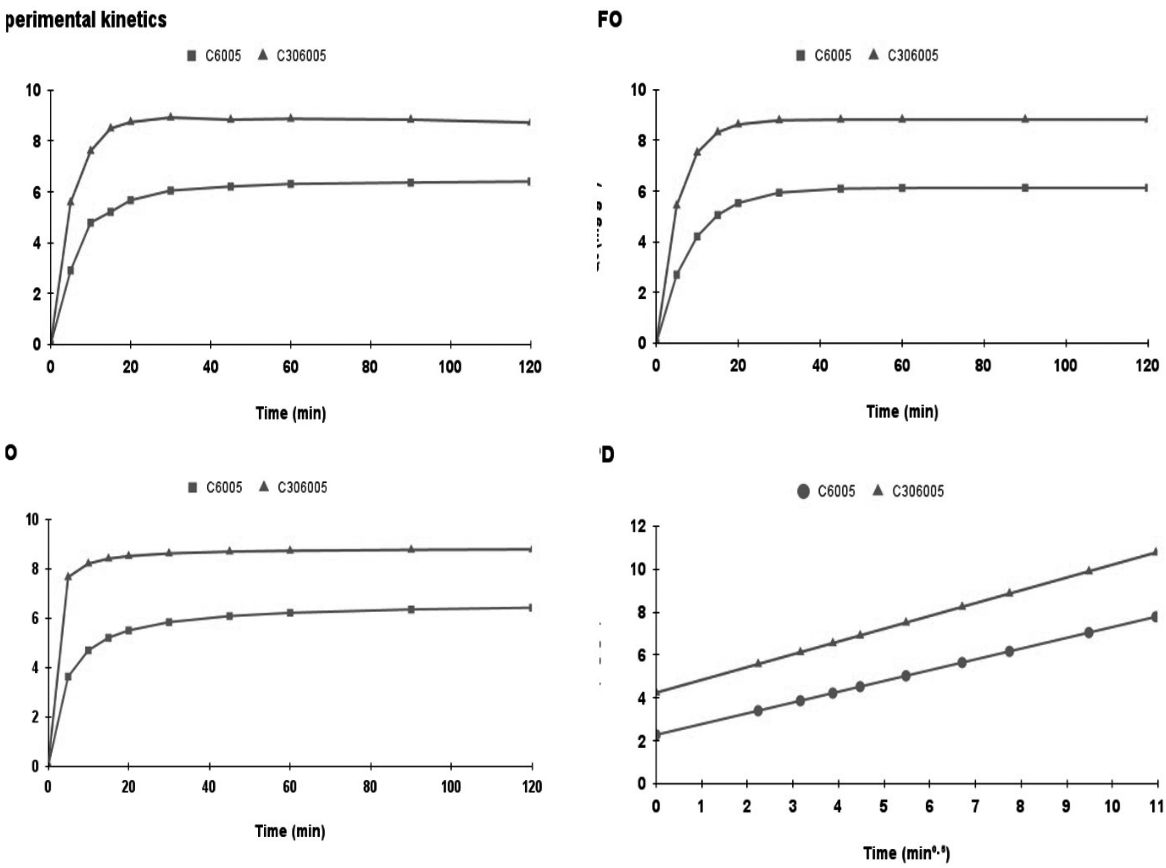


Figure 6. Adsorption kinetics of methylene blue onto C6005 and C306005 biochars: (a) experimental data, (b) pseudo-first-order (PFO) model, (c) pseudo-second-order (PSO) model, and (d) intra-particle diffusion (IPD) model.

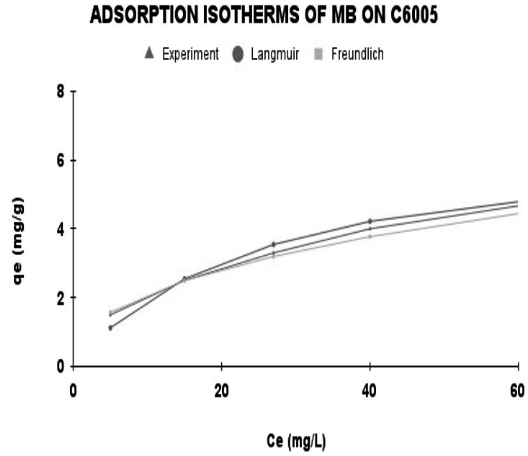
Table 1. Parameters k_1, k_2, q_e, R^2, RMSE

Sample	Model	k_1(1/min)	k_2(g.mg^{-1}.min^{-1})	q_e, exp	q_e, cal	R^2	RMSE
C6005	PFO	0.1162		6.4050	6.1275	0.9749	0.2489
	PSO		0.0364	6.4050	6.6684	0.9993	0.2512
C306005	PFO	0.1912		8.9200	8.8206	0.9998	0.1014
	PSO		0.0364	8.9200	8.8648	0.9993	0.7035

that the adsorption process is mainly governed by chemical interactions (chemisorption) between MB and surface functional groups.

In contrast, for C306005, the PFO model showed superior agreement (with a markedly lower RMSE), which is typically observed when adsorption kinetics are dominated by film or intraparticle diffusion and physical adsorption. The biochar treated at 600 °C for 5 hours with alkali pretreatment exhibited increased surface area and porosity, suggesting that adsorption is primarily governed by rapid diffusion and pore-filling mechanisms. Furthermore, the superior fit of the Freundlich isotherm compared to the Langmuir model indicates the heterogeneous nature of the surface, thereby reinforcing the suitability of the PFO model for describing the kinetics, while not excluding the contribution of electrostatic and π–π interactions.

The isotherm parameters of MB adsorption onto C6005 and C30-600-5h are summarized in Table 2. For C6005, the Langmuir model exhibited a higher correlation coefficient and lower RMSE, with the calculatedq_{max} being close to the experimental value, indicating that adsorption primarily occurred on a homogeneous surface through monolayer coverage. In contrast, for C306005, the Freundlich model provided a better fit, reflecting the heterogeneous surface characteristics of the modified biochar. This suggests that adsorption on C306005 is governed by multiple



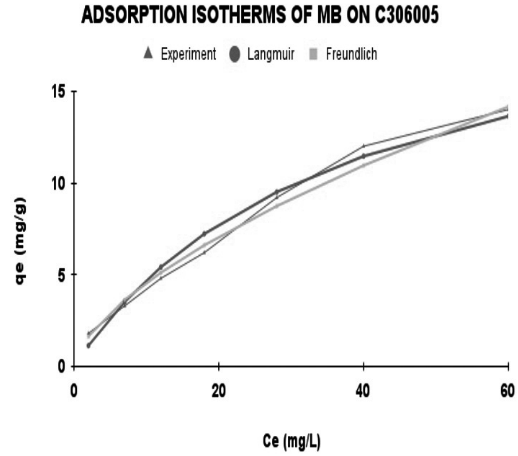


Figure 7. Adsorption isotherms of MB on C6005 and C306005: experimental data and model fittings

Table 2. Parameters of q_{max}, K_L, K_F, n, R^2, RMSE

Sample	Model	q_{max} ($mg.g^{-1}$)	K_L(L/mg)	K_F	n	R^2	RMSE
C6005	Langmuir	6.9582	0.0384			0.9928	0.2000
	Freundlich			0.7976	2.3743	0.9907	0.2069
C306005	Langmuir	21.9921	0.0272			0.8757	0.5903
	Freundlich			1.0603	1.5799	0.9887	0.4979

active sites with a pore-filling mechanism, while electrostatic and π–π interactions may also contribute.

The electrostatic attraction is the force of attraction or repulsion between two charged particles, which is also called Coulomb's force or Coulomb's interaction. According to Shao et al., 2017, the primary mechanisms for the adsorption of cationic dyes were complexation and electrostatic attractions between the oxygen-containing functional groups of the chemically modified adsorbent and the dye molecules. In the process of methylene blue (MB) adsorption onto biochar, MB is a well-known cationic and primary thiazine dye, while the biochar surface after KOH treatment is enriched with oxygen-containing functional groups (-OH, -COOH) and residual alkaline salts (K_2CO_3, KOH), which typically make the surface negatively charged in neutral to alkaline conditions and have a good adsorption performance for positive ions.

Methylene Blue (MB) is an aromatic heterocyclic basic dye enriched in π-electrons, whose conjugated aromatic rings enable π–π stacking interactions with the polyaromatic carbon structures of biochar formed during pyrolysis and exhibit increased aromaticity and graphitic content (Bollinger et al., 2025; Yu et al., 2024b; Chistie et al., 2025b). The biochar formed from lignocellulosic-rich feedstock has a stronger π–π stacking interaction with MB because its aromatic structure is more durable (Hu et al., 2024b; Hou et al., 2023). Experimental data indicating that biochar with more aromaticity could reach an MB adsorption capacity of more than 150 mg/g also supports the concept that π–π stacking is the main driving force for adsorption (Kataya et al., 2025).

Similarly, the cation-π interaction is a stabilizing electrostatic interaction of a cation with the polarizable π-electron cloud of an aromatic ring (Dougherty, 2025b), where positively charged MB^+ ions are attracted to π-electron-rich regions of aromatic carbon. It has also been acknowledged as a significant noncovalent force in the adsorption process. (Infield et al., 2021b; Kataya et al., 2025).

Compared to traditional methods of physical activation, activation based on KOH offers a unique advantage in terms of building pore structure as well as expanding available surface area, yielding better textural properties (Jedynak & Charmas, 2023). The development of many micropores and mesopores not only expands the available surface area but also makes it simpler for a network of interconnected pores to form. This structural enhancement directly improves the adsorption performance, making it possible for the material to effectively capture a wide range of contaminants such as heavy metals, organic dyes, and gases (e.g., CO_2, H_2, CH_4) (Jedynak & Charmas, 2023;

Zhao et al., 2020). Demonstrating that the treatment of biomass carbon with KOH enhances its specific surface area (SSA) with a large pore volume, multilevel porosity and enhances its performance in a variety of applications (Chang et al., 2025).

4. CONCLUSION

This study has demonstrated that durian husks can be effectively valorized into biochar through saponification pretreatment combined with pyrolysis. The results indicated that pyrolysis at 600 °C for 5 hours significantly enhanced the adsorption performance, particularly when coupled with KOH pretreatment, which exhibited notable adsorption capacity and methylene blue removal efficiency. Compared with the non-pretreated biochar, the treated material showed a larger surface area, higher CEC, and more abundant surface functional groups, all of which contributed to its improved adsorption behavior. Moreover, the adsorption kinetics were better described by the PFO model for the untreated biochar and by the pseudo-second-order model for the pretreated one, while the Freundlich isotherm provided the best fit for the equilibrium data, reflecting the heterogeneous surface characteristics. These findings highlight the dual benefits of converting agricultural residues into high-value adsorbents: addressing waste management challenges and providing a sustainable, low-cost, and environmentally friendly material for wastewater treatment. Future studies may extend this approach to other pollutants and investigate the regeneration and reuse of modified biochar to further assess its practical applicability.

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ASSESSMENT OF THE TROPHIC STATUS AND WATER QUALITY IN THE HINH RIVER BASIN, CENTRAL VIETNAM

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Abstract

This study aims to evaluate the eutrophication status and ecological conditions of the Hinh River basin underhydrological conditions. The Hinh River basin is essential for agriculture, hydroelectric power, and water supplies. Evaluating the trophic status and water quality is a supply-based science that is essential for environmental preservation and sustainable water resource usage. Surface water samples were collected from twenty-two sites in 2024-2025 during dry and rainy seasons. The result shows the parameters TSS, DO, COD, TN, and TP vary seasonally and are influenced by rainfall. The river is nitrogen-rich (TN exceeds standards by 2.7–3.8 times) and phosphorus-limited (N:P ratio > 20). The trophic index (TRIX) indicates the dominance of eutrophic conditions (TRIX > 6). Positive correlations between TRIX and TN, TP, and chlorophyll-a reveal nutrient enrichment mainly from agricultural, domestic, and industrial wastewater.

Keywords: *Eutrophication, nutrients, Hinh River basin, trophic state index, ecological.*

JEL Classification: *Q25, Q53, Q57.*

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1. INTRODUCTION

Surface run off from basins with diverse land use types flows into rivers, serving as a pathway for transporting nutrients in dissolved and suspended forms from the soil to receiving water bodies, which may include rivers, lakes, or oceans [1]. River, stream, lake, and reservoir systems are important aquatic ecosystems both ecologically and economically because of their high biodiversity and productivity. Therefore, for countries in tropical regions, when considering the current state of dammed rivers and future development projects, there is significant concern about the ecological conditions, nutrient status, and water quality of these systems.

The increase in the fertility of water bodies is a natural part of the developmental process of all aquatic systems. However, the accelerated eutrophication of these water bodies is more broadly recognized as a result of human activities. Changes in the state and quality of surface water are determined not only by the external input of nutrients but also by internal processes occurring within aquatic ecosystems [2]. Human activities alter the biogeochemical cycles of nutrients through processes such as changes in land use and land cover, as well as runoff from residential and agricultural areas, leading to a significant increase in nutrient loads within aquatic ecosystems [3]. Increased nutrient levels can disrupt the balanced nitrogen-to-phosphorus (N:P) ratio required for primary productivity. Excess nutrients can lead to blooms of certain microalgal species that may release toxins, thereby reducing natural biodiversity, degrading water quality, and causing nutrient imbalances [4].

The Hinh River basin is located in southwestern Phu Yen Province in central Vietnam. This basin's landscape is highly important, providing essential environmental services to downstream areas [5]. Located in the transition zone between the lowland plains and the Central Highlands, in the upper and middle reaches of major rivers and streams flowing through the southern part of Phu Yen Province, the Hinh River Basin holds significant value for watershed protection, water resource storage, and ecological conservation. The area has abundant and relatively rich surface water resources, but experiences water scarcity during certain periods. This reality has led to the construction of reservoirs that store water for human use. However, there have been only a few environmental studies related to this area, such as the use of the Water Quality Index (WQI) to assess river basin water quality [6].

Eutrophication is the process of enriching water with nutrients, primarily nitrogen and phosphorus, leading to an increase in the primary productivity of algae (in terms of chlorophyll-a) [7]. To assess river water quality, Dodds et al. (1998) proposed the use of values of TN, TP, and Chl-a to classify trophic status. However, using a univariate scale may not be sufficient to describe the nutrient status of rivers[8]. Therefore, a multivariate approach is needed to evaluate river water quality by using a trophic index (TRIX) [9, 10]. This index is a mathematical equation that integrates information from the most important parameters of the dataset, enabling it to describe the overall condition and reflect changes in a representative manner [11]. It is one of the main tools supporting decision-making related to water resources, contributing to the development of environmental policies at the local, regional, and national levels.

Access to safe water is essential for sustaining human life, ecosystems, and socioeconomic development. The objective of this study was to apply the Trophic State Index (TRIX) to assess the trophic status and ecological conditions of the Hinh River basin under the impact of anthropogenic pressures. The water quality in this river basin plays an important role in the socioeconomic development of Phu Yen Province and the Central Highlands region. The highlight points of the paper are: 1). Evaluated the water quality and eutrophication status of the Hinh River basin; 2). Identified nitrogen as a major pollutant, with concentrations exceeding standards.3). Determined anthropogenic inputs drive eutrophication and impact water quality.

The trophic status of aquatic ecosystems reflects the degree of nutrient enrichment and biological productivity, which directly influence water quality and ecological balance. Based on nutrient levels (TN, TP) and algal biomass (Chl-a), aquatic systems are generally classified as mesotrophic, meso-eutrophic, or eutrophic. Mesotrophic waters have moderate nutrient concentrations and primary productivity, indicating a balanced ecosystem with limited algal growth. Meso-eutrophic conditions represent a transitional stage between mesotrophic and eutrophic states, where nutrient enrichment and algal biomass increase noticeably, and water transparency begins to decline. Eutrophic waters are characterized by high nutrient concentrations, excessive algal blooms, and oxygen depletion, often resulting from anthropogenic nutrient loading. Understanding these trophic levels helps evaluate ecological conditions, diagnose eutrophication risks, and guide sustainable management of river basins such as the Song Hinh [8, 9, 23, 24].

2. MATERIALS AND METHODS

2.1. Study area

The Hinh River is one of the three largest tributaries of the Ba River. It originates from the Chu H'Mu peak at an elevation of approximately 2,051 m and converges with the Da Rang River in Duc Binh Tay commune of Song Hinh district after a course of approximately 88 km (Fig. 1).

The total area of the Hinh River basin is approximately 1,021 km², and its annual flow volume is approximately 1.7 billion m³ [12]. The climate of the Hinh River basin is a tropical monsoon climate, with an average annual temperature of 26°C, a minimum temperature of 22.1°C, and a maximum temperature of 28.7°C. The long-term average rainfall ranges from 2,200 to 2,400 mm, with an average of approximately 150–160 rainy days per year [5]. The main land use patterns in the basin include agricultural land and forestland, followed by water bodies and built-up areas. The main types of forests present in the area are evergreen broadleaf forests and plantation forests.

2.2. Sampling and analytical techniques

Surface water samples (n = 44) were collected in clean polyethylene bottles from twenty-two locations across the Hinh

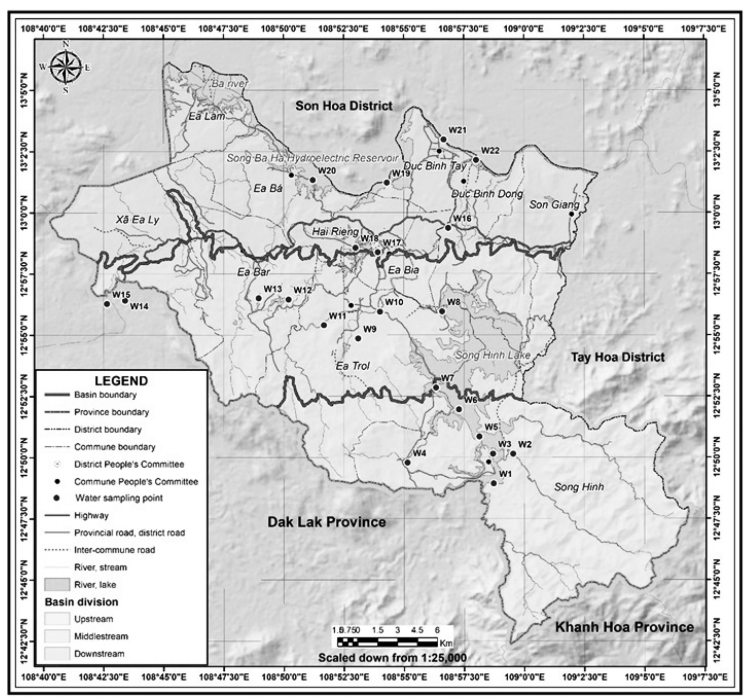

Figure 1. Study area diagram showing the sampling points in the Hinh River basin

River basin during the dry season (March 2024) and at the end of the rainy season (January 2025) (Figure 1). The sampling coordinates were determined via a Garmin 64S GPS device. All samples were collected to the standards TCVN 6663-1:2011, TCVN 6663-4:2020, and TCVN 6663-6:2018. After sampling, the water samples were pretreated and stored following TCVN 6663-3:2016 to prevent any changes in composition caused by chemical reactions, physical processes, or biological degradation. Water temperature (T), pH, and dissolved oxygen (DO) were measured directly in the field via a TOA WQC22A multiparameter meter. The samples were then transported in iceboxes to the laboratory. Analyses of total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and chlorophyll-a (Chl-a) were carried out following the standard methods outlined in the Vietnamese Technical Regulation (QCVN 08:2023) (Figure 1).

The selection of twenty-two sampling sites was based on the hydrological, geomorphological, and land-use characteristics of the Hinh River basin to ensure spatial representativeness of the entire watershed. The sites were distributed along the river's main course and its tributaries, covering upstream, midstream, and downstream sections with distinct topographic and land-use features. Upstream stations (W1–W6) represent forested headwaters with limited human influence; midstream stations (W7–W15) correspond to mixed agricultural and residential zones with moderate anthropogenic activities; and downstream stations (W16–W22) are influenced by intensive agriculture, aquaculture, and mining activities. This spatial framework captures the gradients of nutrient input and water quality variations across hydrological and land-use zones, thereby ensuring the representativeness of sampling points for the entire Hinh River basin [5, 15, 16].

2.3. Trophic status assessment

2.3.1. Nutrient stoichiometry (N:P)

The N:P mass ratio is considered an important factor for diagnosing trophic status and indicating nutrient limitation in aquatic systems [13]. An N:P ratio between 10 and 20 suggests balanced nutrient conditions in the water body, whereas a ratio below 10 indicates nitrogen limitation, and a ratio above 20 indicates phosphorus limitation [14]. The N:P ratio has been used to identify which nutrient has the greatest influence on primary productivity.

2.3.2. Trophic indices

In this study, the trophic status of the Hinh River basin was determined via the modified trophic index (TRIX) for river water, as proposed by Paula Filho et al. (2020) [10]. The multivariate TRIX index is calculated via Equation (1):

$$TRIX = [\log(Chl-a \times D\%O \times TN \times TP) - 3.7]/0.41 \quad (1)$$

Where TN, TP, and Chl-a are concentrations measured in μg/L, and D%O is the absolute deviation of dissolved oxygen from 100% oxygen saturation. The classification scale considers five trophic status categories as follows: TRIX < 2 (ultraoligotrophic/excellent); 2 < TRIX < 4 (oligotrophic/high); 4 ≤ TRIX < 5 (mesotrophic/good); 5 ≤ TRIX < 6 (mesotrophic to eutrophic/moderate); and TRIX > 6 (eutrophic/poor) [9].

2.4. Data analysis

Microsoft Excel 2016 and XLSTAT 2025 software were used for data processing. A t-test was applied to determine any statistically significant differences between the mean values of the hydrochemical variables ($p < 0.01$). Pearson correlation analysis was performed to identify linear relationships between variable pairs on the basis of correlation coefficient values ($p < 0.05$). Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were conducted to identify relationships among different physicochemical parameters and pollution sources. The correlation between the TRIX index and eutrophication parameters was analysed via a simple linear regression model. Maps were created viathe ArcGIS 9.0 software. The color distribution was implemented on the basis of values via a hierarchical color scheme. All maps were drawn via a geographic coordinate system with the WGS84 horizontal datum.

To demonstrate the effectiveness of Chl-a, TN, TP, and D%O parameters when applied to environmental research of the research area, the linear regression method was used to quantitatively test the relationship of the above environmental parameters.

3. RESULTS

3.1. Hydrochemical parameters and their variations

The data obtained from the analytical studies were subjected to descriptive statistics, including mean values and standard deviations. The water quality parameters and regulatory limits for the hydrochemical variables at the twenty-two sampling stations are summarized in Table 1. To assess the impact of anthropogenic activities within the basin, the water quality parameters were compared with the surface water quality standards for the best intended use (class A) set by Ministry of Agriculture and Environment (formerly Ministry of Natural Resources and Environment)-QCVN 08:2023/BTNMT. The t - test($p < 0.01$) revealed statistically significant differences in T, TSS, DO, COD, and TN between the dry and rainy season sampling periods. In contrast, pH, D%O, TP, and Chl-a were not significantly different. The Ave ± SD value represents the dispersion of the ambient values around the mean value (Table 1).

The pH measurements mostly fell within the regulatory range, with average recorded values of 7.5 (dry season) and 7.4 (rainy season). However, during the dry season, some pH measurement points are outside the level A threshold as prescribed in QCVN 08:2023, including points from 2 to 6. The TSS values were largely within the regulatory limits, ranging from 0.63 to 13.3 mg/L, with an average of 4.32 mg/L during the dry season, which was lower than the average during the rainy season (13.22 mg/L). In the rainy season, values exceeding the regulatory limit were observed at sites 17, 18, 20, and 21 (downstream area). Pearson's rank correlation test (Table 2) revealed a significant positive correlation between TSS and COD during the dry season ($r = 0.44$, $p < 0.05$). In terms of spatial distribution, the results indicated an increasing trend in the TSS values from the upstream to the downstream sections of the river in both seasons. The COD concentrations measured during the rainy season were higher than those measured during the dry season and exceeded regulatory limits, with an average of 30.0 mg/L (rainy season) compared with 13.82 mg/L (dry season). Like the TSS concentration, the COD concentration also tended to increase from the upstream area to the downstream area.

The DO concentration in the Hinh River basin ranged from 2.37 to 7.5 mg/L, with an average value of 5.9 mg/L (dry season). In the rainy season, the measured DO concentration was 1.1 times greater than that recorded in the dry season, with an average value of 6.66 mg/L. No significant positive correlations were found with the other studied water quality parameters, except for D%O ($r = 0.93$ and 0.97, $p < 0.05$). The negative correlation between DO and several other water quality parameters during the rainy season suggests the influence of rainfall patterns on water quality in the area, as well as the presence of organic pollution in the study region. This may be one of the main contributing factors to ecological and environmental degradation in the area.

According to Table 1, the SD values for the parameters TN, TP, COD, and Chl-aare relatively high. This is due to the unusually high actual measurements at sampling point W22, which is located at the intersection of Ba River and Hinh River. For example, during the dry season, the Chl-a level at point W22 is measured at 17.5 μg/L, which is over 8.5 times higher than the average value. The TP concentration at this location is 380 μg/L, approximately 7.5 times the average value. Similarly, both the TN and COD values at sampling point W22 are significantly higher than those recorded at other sampling locations. This area is characterised by a range of human activities, including agricultural cultivation and mineral extraction.

High TN concentrations dominated throughout the sampling period, ranging from 1120.0 to 5820.0 μg/L, with an average of 2275.45 (dry season), and from 670.0 to 2690.0 μg/L, with an average of 1395.45 μg/L in the rainy season. The values recorded during the rainy season were 1.6 times lower than those recorded during the dry season because of increased rainfall and water flow. However, all the sampling sites still had TN concentrations that exceeded the permissible limits. Strong positive correlations were detected between TN and Chl-a ($r = 0.81$ and 0.63, $p < 0.05$) and between TN and TP ($r = 0.83$ and 0.49, $p < 0.05$) in both seasons. The TP concentrations measured in different areas of the river basin were greater during the rainy season than during the dry season, with average values of 50.14 μg/L

Table 1. Changes in the water quality parameters of the Hinh River basin between the dry and rainy seasons

Parame-ters	Value	Dry season	Rainy season	P value	QCVN08:A
pH	Ave Min–Max	7.5 6.3 - 8.8	7.4 6.8 - 8.1	0.7093	6.5 - 8.5
TSS (mg/L)	Ave Min–Max	4.32 0.63 - 13.3	13.22 5.35 - 33.4	0.0000	≤ 25
DO (mg/L)	Ave Min–Max	5.9 2.37 - 7.5	6.66 4.8 - 7.4	0.009	≥ 6
T (oC)	Ave Min–Max	28.2 21.8 -32.8	23.1 21.1 - 25.2	0.0000	-
D%O	Ave Min–Max	76.75 30.6 - 106.4	78.57 56.5 - 86.9	0.6112	-
COD (mg/L)	Ave Min–Max	13.82 3.2 - 28.8	30.0 6.4 - 73.6	0.0001	≤ 10
TN (μg/L)	Ave Min–Max	2275.45 1120.0 - 5820.0	1395.45 670.0 - 2690.0	0.0007	≤ 600
TP (μg/L)	Ave Min–Max	48.18 10.0 - 380.0	50.14 19.0 - 91.0	0.9075	≤ 100
Chl-a (μg/L)	Ave Min–Max	2.03 0.11 - 17.50	1.79 0.28 - 4.53	0.7737	≤ 14

QCVN08:A = Vietnamese national technical regulation for surface water quality

Table 2. Correlation analysis of water quality parameters in the Hinh River basin between the dry and rainy seasons

	pH	TSS	DO	T	D%O	COD	TN	TP	Chl-a
Dry season									
pH	1								
TSS	0.10	1							
DO	**0.65**	0.18	1						
T(°C)	**-0.45**	-0.34	-0.19	1					
D%O	**0.49**	0.05	**0.93**	0.18	1				
COD	0.03	**0.44**	0.30	0.24	0.40	1			
TN	0.10	0.13	0.08	0.26	0.17	0.37	1		
TP	0.21	0.21	0.26	0.06	0.28	0.41	**0.83**	1	
Chl-a	0.34	0.29	0.29	-0.12	0.25	0.40	**0.81**	**0.93**	1
Rainy season									
pH	1								
TSS	0.35	1							
DO	0.11	-0.33	1						
T (°C)	-0.05	0.03	-0.08	1					
D%O	0.09	-0.32	**0.97**	0.15	1				
COD	-0.06	-0.03	-0.14	0.34	-0.06	1			
TN	0.41	0.43	-0.05	0.05	-0.04	0.03	1		
TP	0.36	0.42	-0.06	-0.04	-0.07	-0.17	**0.75**	1	
Chl-a	0.08	0.20	0.18	0.17	0.21	0.12	**0.63**	**0.49**	1

Coefficients in bold are significant at $P < 0.05$

and 48.18 μg/L, respectively. A strong positive correlation between TP and Chl-a was observed in both the dry and rainy seasons ($r = 0.93$ and 0.49, $p < 0.05$). The TP values tended to increase from the upstream areas to the downstream areas, and most values were within the regulatory limits, except for site 22 in the dry season, where the value was 3.8 times greater than the limit. The Chl-a concentration, an indicator of primary productivity, ranged from 0.11 to 17.50 μg/L (dry season) and from 0.28 to 4.53 μg/L (rainy season), with the highest concentration recorded at the downstream site (site 22) during the dry season. The spatial variation in the Chl-a concentration was similar to that observed for the other parameters, with higher average values recorded in the downstream section (Table 2).

Table 3. PCA of the environmental variables for the water quality data from the Hinh River basin

Parameters	Factor I	Factor II	Factor III	Factor IV	Factor V
pH	**0.521**	0.003	0.201	0.001	0.005
TSS	0.147	**0.285**	0.243	0.103	0.168
DO	0.241	**0.514**	0.213	0.000	0.009
T	0.123	**0.351**	0.300	0.000	0.204
D%O	0.145	**0.766**	0.077	0.000	0.003
COD	0.099	0.029	0.141	**0.705**	0.023
TN	**0.803**	0.035	0.084	0.027	0.002
TP	**0.737**	0.001	0.167	0.019	0.006
Chl-a	**0.814**	0.011	0.117	0.021	0.008
Eigenvalue	3.631	1.996	1.543	0.876	0.428
% Variance	40.35	22.18	17.14	9.73	4.75

Bold letter: The most significant factor loadings

3.2. Relationships among the ecological parameters of the Hinh River basin

Multivariate analysis techniques such as PCA and HCA have been proven to be highly important statistical tools for identifying the underlying relationships between various physicochemical parameters, detecting pollution sources, and grouping sites or parameters into similar clusters to gain a better understanding of water quality and the ecological status of the studied system [15]. In this study, PCA based on eigenvalues was used to determine the number of principal components needed to identify or confirm the key water quality variables (Table 3). Five principal components were extracted on the basis of the scree plot and eigenvalues. Factors I and II accounted for 62.53% of the total variance in the observed dataset for the Hinh River. The first factor mainly included pH, TN, TP, and Chl-a, indicating an increase in nutrients associated with eutrophication. The second factor suggested higher levels of suspended solids in the water body and a seasonal variation in the positive relationship between DO and temperature in the study area. Factor IV indicated that the COD levels in the surrounding watershed environment increased due to the presence of low-concentration industrial pollutants. These factors highlight the main variables affecting water quality in the study area, which include pH, TSS, DO, COD, and especially TN, TP, and Chl-a.

The dendrogram based on the HCA results reinforced the close relationships among the ecological parameters (Fig. 2) and supported the findings of the PCA. In Cluster I, TSS, pH, and DO were similar within a subcluster, indicating their collective influence on the system. Similarly, within the same cluster, TN, TP, and Chl-a also demonstrated a close association, suggesting an increase in anthropogenic activities in the watershed area and confirming

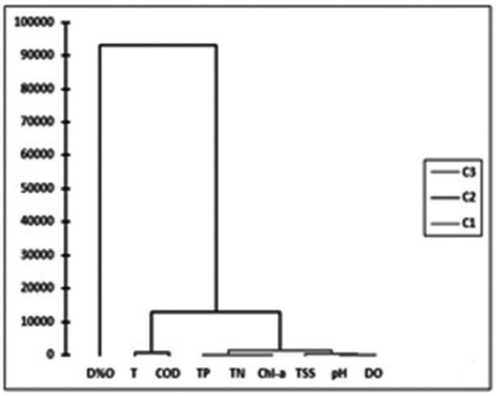

Figure 2. Dendrogram showing the cluster between the water quality ecological parameters of the Hinh River basin

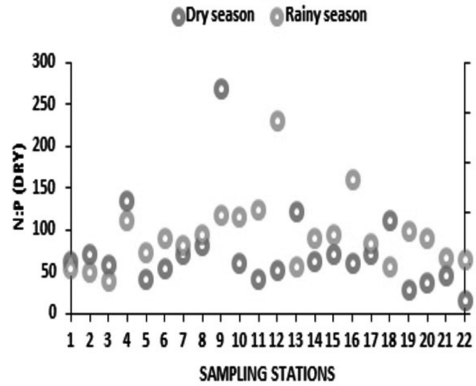

Figure 3. Spatial status of N:P ratio in surface water of the Hinh River basin in different hydrological periods

their importance as key variables in the TRIX index (Table 2). Temperature and COD were grouped into a separate cluster (Cluster II), indicating that COD may not be influenced by a single source but could result from anthropogenic, industrial, or agricultural origins.

3.3. Assessment of the trophic status of the Hinh River basin

The TN:TP ratio is closely related to land use activities that can directly impact the biological components of aquatic ecosystems[16]. In the Hinh River basin, the mass ratio of N:P (Fig. 3) during the dry season was greater (mean = 73.67) than the ratio recorded in the rainy season (mean = 30.98). In both seasons, we observed that the N:P ratio was greater in the midstream section than in the upstream and downstream areas. The results demonstrate that the Hinh River basin is a highly dynamic environment related to the availability of nutrients, as evidenced by seasonal changes in limiting nutrients. Although phosphorus is the limiting nutrient in both cases (N:P > 20), some river areas presented balanced ratios (10 < N:P < 20). This balanced ratio appeared in the dry season at site 22, where the Hinh River joins the Da Rang River, with TN and TP values recorded at 9.7 and 3.8 times above the permitted limits, respectively. During the rainy season, the upstream area (sampling sites 1–3), midstream area (site 13), and downstream area (site 18) were locations with balanced nutrient availability for primary productivity.

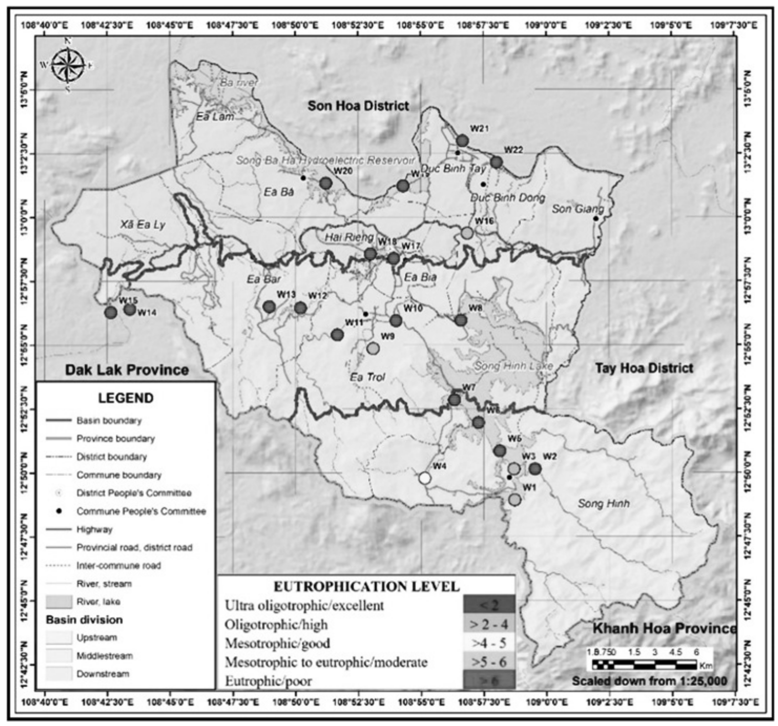

Figure 4. Spatial variation in the TRIX index along the sampling stations in the Hinh River basin in dry seasons

To determine the trophic status of the Hinh River basin, we used the TRIX index, which considers the sets of TN, TP, Chl-a, and D%O from two sampling campaigns. The average TRIX values were 7.31 and 7.5 for the dry and rainy seasons, respectively, indicating that eutrophic conditions prevailed in both seasons and across the spatial distribution of the river basin (Fig. 4). The results from the dry season revealed that 5% of the sampling sites were mesotrophic, 18% were meso-eutrophic, and 77% were eutrophic. During the rainy season, the proportion of mesotrophic conditions remained unchanged, whereas 13% were meso-eutrophic and 82% eutrophic (Figure 5,6).

This study revealed that the trophic status/water quality of the Hinh River basin is eutrophic/poor because of inputs from human activities, including agricultural, industrial, and domestic sources.

The correlations between the TRIX index and eutrophication-related parameters indicate a strong positive relationship between TRIX and the concentrations of TN, TP, and Chl-a (Fig. 5). In particular, the correlation was strongly demonstrated in the Chl-a and TP indices (R2 values were 0.7147 and 0.5736, respectively). These correlations clearly demonstrate that nutrient enrichment along the flow of the Hinh River significantly increases primary productivity (in terms of Chl-a) and eutrophication. Therefore, the TRIX index is highly sensitive in determining the trophic status of the Hinh River basin. The increase in eutrophication in parts of this river basin contributes to further nutrient enrichment, leading to more severe eutrophication in the downstream area of the Da Rang River before it flows into the sea.

The elevated TRIX values indicate eutrophic conditions mainly driven by human activities. Agricultural runoff is a major source of nutrients, as Phu Yen Province uses about 23,000–25,000 tons of chemical fertilizers annually, with urea and NPK accounting for over 80% of the total. Moreover, only ≈12% of rural and 40% of urban wastewater are treated before discharge. Combined with effluents from livestock and small industries, these sources increase nitrogen and phosphorus concentrations. The downstream rise in TRIX values thus reflects the cumulative effect of agricultural, domestic, and industrial inputs that accelerate eutrophication in the Hinh River basin [5, 16, 19, 22].

4. DISCUSSION

Assessment of the trophic status and water quality of river basins is of utmost importance for sustainable water resources management and ecosystem conservation[17, 18]. This study focused on the Hinh River basin, Phu Yen Province, an economically and ecologically significant area in Central Vietnam. The results showed that this river basin is significantly affected by human activities, leading to eutrophication, as shown by high TN concentrations and high TRIX index.

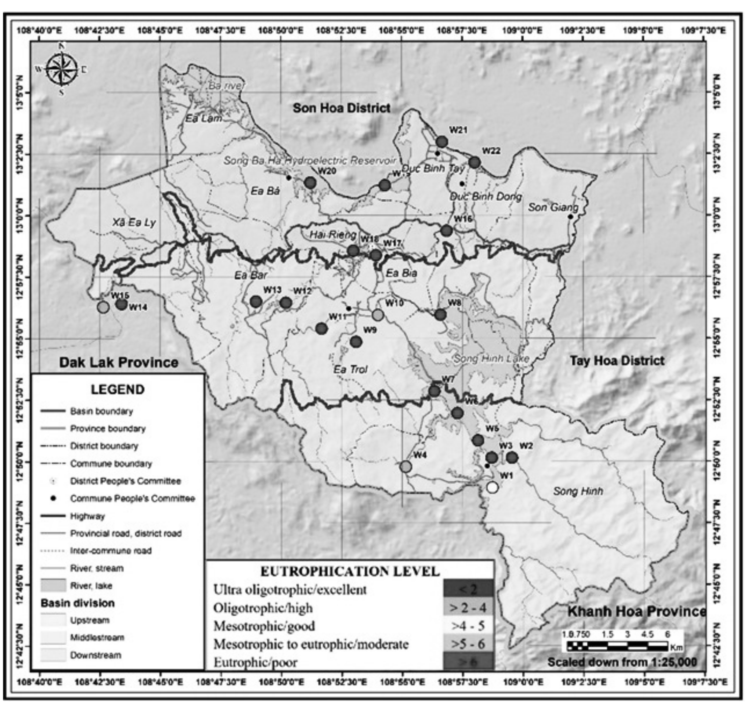

Figure 5. Spatial variation in the TRIX index along the sampling stations in the Hinh River basin in rainy seasons

Our results are consistent with previous studies showing that nutrient pollution is an increasing problem in river basins worldwide [19, 20]. Specifically, the high TN concentrations found in the Hinh River are similar to those in other rivers in Vietnam that are under pressure from agriculture and urbanisation[21, 22]. Eutrophication in the Hinh River can have negative impacts on aquatic ecosystems, including algal blooms, dissolved oxygen depletion, and biodiversity loss[23, 24]. These impacts can affect important ecosystem services provided by the Hinh River, such as water supply, aquaculture, and tourism.

The limited scope of the study, spanning only two seasons (dry and wet) over two years, presents a limitation. Therefore, the results may not be representative of long-term changes. In addition, this study focused on only a limited number of water quality parameters. Further research is needed to more fully assess the sources of pollution and their impacts on the ecosystem in the Hinh River basin.

Future studies should be conducted to accurately identify the specific sources of nutrient pollution in the Hinh River basin. This could include monitoring water quality at different points along the river and conducting surveys of farming, land use, and wastewater treatment practices in the area. In addition, we should evaluate the effectiveness of various management measures, such as best farming practices and upgrading wastewater treatment plants, in reducing nutrient pollution and improving water quality in the Hinh River basin.

Eutrophication in the Hinh River basin not only degrades aquatic ecosystems but also affects broader environmental and socioeconomic systems. Excessive nutrient loading promotes algal blooms, reduces water transparency, and causes oxygen depletion, threatening fishery resources and biodiversity. These impacts may reduce agricultural productivity in irrigated

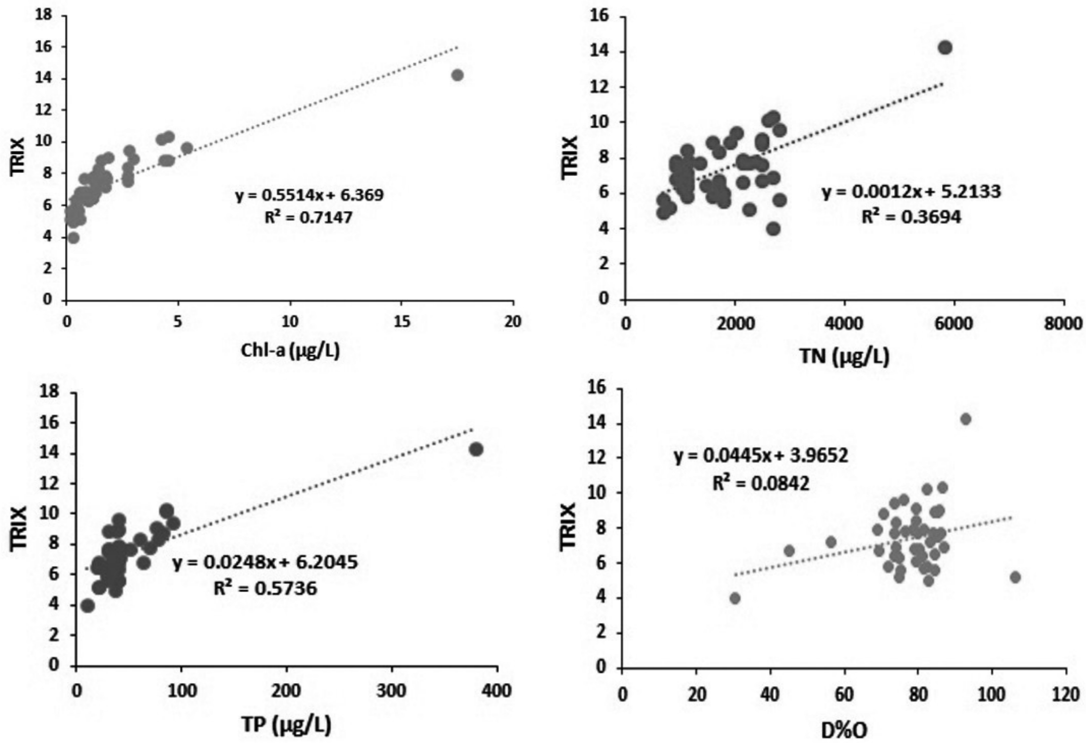

Figure 6. Correlations between TRIX and eutrophication parameters

areas, increase water treatment costs, and affect livelihoods dependent on river resources. To mitigate these effects, integrated river basin management is required, focusing on controlling nutrient inputs from agricultural and domestic sources. Priority actions should include expanding wastewater treatment coverage, promoting organic and low-emission agriculture, and strengthening riparian buffer zones to filter runoff. Implementing monitoring networks and community-based management would enhance long-term water quality control and support sustainable development in the Hinh River basin [17, 18, 19, 22].

5. CONCLUSION

In this study, hydrochemical and eutrophication parameters were identified to assess the water quality of the Hinh River basin. The results revealed that eutrophication-related parameters varied significantly across both space and time within the study area. High TN concentrations and seasonal increases in TP significantly enhanced primary productivity (in terms of Chl-a) and contributed to eutrophication. Accordingly, the water quality/trophic status of the Hinh River basin is classified as poor/eutrophic because of anthropogenic inputs from agricultural, industrial, and domestic discharges. The strong positive correlations between TRIX values and nutrient concentrations as well as Chl-a indicate that nutrient enrichment along the river's course contributes to increased eutrophication in the downstream section of the Da Rang River before it discharges into the sea. Therefore, measures are urgently needed to reduce the input of organic and inorganic substances into the Hinh River to sustainably manage eutrophication and ensure the ecological health of river systems in the region before they reach the marine environment.

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NATIONAL TECHNICAL REGULATION ON INDUSTRIAL EMISSIONS:
An important instrument in the Environmental Policy System

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1. INTRODUCTION

In recent years, air pollution in Vietnam has tended to increase and become increasingly complex, particularly in major urban areas such as Ha Noi, Ho Chi Minh City, and key industrial zones. The Air Quality Index (AQI) has, at times, exceeded permissible thresholds, while concentrations of fine particulate matter ($PM_{2.5}$, PM_{10}) frequently remain higher than the regulated limits, posing serious threats to public health, quality of life, and ecosystems. In this context, controlling emission sources - particularly industrial emissions, one of the main sources of pollution - has become an urgent task of decisive significance for air environment protection.

The National Technical Regulation (QCVN) on industrial emissions is an important instrument within the environmental policy system, stipulating limit values for pollutants in order to safeguard air quality. However, most current QCVNs on emissions were issued more than a decade ago, with approaches, limit values, and lists of parameters that are no longer suitable for the current pollution situation or new technological levels. This context requires a review, adjustment, integration, and modernization of the regulatory system to meet pollution management requirements in an effective, scientific, and internationally aligned manner.

This article aims to analyze the necessity and the key innovations in the process of revising the National Technical Regulation on industrial emissions. It clarifies the scientific basis, international experience, and policy approaches being applied in Vietnam, while also pointing out several challenges and making recommendations to enhance the effectiveness and feasibility of implementing the new QCVN in practice in the coming period.

The control of industrial emissions is an urgent and decisive requirement for air environment protection

2. CURRENT STATUS OF AIR POLLUTION AND INDUSTRIAL EMISSION MANAGEMENT IN VIETNAM

Air pollution in Vietnam has become a major concern in environmental management, with increasingly evident manifestations in large cities and concentrated industrial production areas. Between 2016 and 2020, $PM_{2.5}$ and PM_{10} concentrations in Ha Noi and Ho Chi Minh City frequently exceeded permissible limits set in QCVN 05:2013/BTNMT, at times reaching 1.5 - 2.2 times higher. Air quality deteriorated significantly during the winter and dry months, when unfavorable meteorological conditions combined with high emission density from transport, industry, construction, and open burning.

Major sources of pollution include: industrial zones (more than 290 currently operating), industrial clusters, traditional craft villages (over 4,500 villages, many facilities still lacking emission treatment infrastructure as required), thousands of boiler and incinerator facilities, along with the rapid development of construction, mining, and transport sectors (over 4 million cars and tens of millions of motorbikes). Waste burning, agricultural residue burning, and the use of honeycomb coal stoves in some localities are also significant contributors to increased particulate matter and pollutants such as CO, SO_2, and NO_2.

Although many national technical regulations on industrial emissions have been issued (including QCVN 19:2009/BTNMT, QCVN 20:2009/BTNMT, and several sector-specific QCVNs), most of these documents are outdated and have not been adjusted in time to respond to environmental changes and advances in production and treatment technologies. Fragmentation, lack of synchronization, and overlaps among existing QCVNs create difficulties in practical application, especially for enterprises with diverse business activities. In particular, the linkage between emission standards and ambient environmental quality objectives has not been fully established in the previous QCVN development process. This has resulted in many areas exceeding their capacity to absorb pollutants in the exhaust air, yet lack sufficient legal instruments to strictly control emissions based on environmental zoning - an important requirement outlined in the Law on Environmental Protection 2020.

Thus, improving the regulatory system on industrial emissions is not merely a technical step but a crucial condition to strengthen management effectiveness, prevent pollution at its source, and promote the adoption of clean technologies in production and business activities in Vietnam.

3. INTERNATIONAL EXPERIENCE AND NEW APPROACHES

International experience shows that effective emission standards must be based on the goals of protecting human living environment and ecosystems, while also aligning with technological reality and enforcement capacity. Most developed countries such as South Korea, Japan, the United States, and the European Union (EU) have adopted modern approaches to ensure effective control of air pollution while promoting clean technology transformation in industry.

***Ambient air quality objectives approach (ambient-based).** These countries determine emission limits based on protecting ambient air quality. This requires long-term environmental monitoring systems and health - ecological risk assessments as the basis for establishing permissible pollution thresholds. This forms the foundation for "upstream" emission standards that protect ambient air quality before defining acceptable emission levels.

***Technology-based approach.** In the United States and EU, emission limits are often set based on the treatment capacity of the best available techniques (BAT). BAT lists are updated periodically, making transparent the costs and environmental effectiveness of technologies, thereby enabling businesses and regulators to select feasible, effective, and fair emission thresholds. Linking emission standards to technological capacity serves as a powerful instrument to foster technological innovation in production.

***Strengthening the role of independent technical bodies**. In the EU, South Korea, and Japan, the process of developing and revising emission standards is often carried out by specialized research institutes - independent of administrative agencies. This ensures scientific rigor, transparency, and minimizes conflicts of interest in environmental policy-making.

***Differentiated standards by region and production type.** Some countries such as Japan and South Korea allow local authorities to set stricter standards than national ones, depending on the environmental carrying capacity. At the same time, each production type is required to control only a specific group of characteristic parameters, instead of applying a universal list as is the case in some current QCVNs in Vietnam.

Drawing from these advanced models, the process of revising QCVNs in Vietnam has applied two approaches simultaneously: (1) top-down - establishing air quality management objectives by region; and (2) bottom-up - based on the practical capacity of industries and actual monitoring results. In addition, the draft QCVN has drawn extensively on South Korea's experience - a country with many similarities in industrial development and enforcement capacity - as well as the EU's regulations on BAT and environmental zoning. These approaches not only ensure policy feasibility and effectiveness but also pave the way for Vietnam's deeper integration with national environmental standards in the region and globally, in the context of climate change and increasingly urgent sustainable development demands.

4. KEY INNOVATIONS OF THE NATIONAL TECHNICAL REGULATION ON INDUSTRIAL EMISSIONS

On December 30th, 2024, the Ministry of Natural Resources and Environment (now the Ministry of Agriculture and Environment) issued Circular No. 45/2024/TT-BTNMT on the national technical regulation on industrial emissions, QCVN 19:2024/BTNMT, effective from July 1st, 2025. The National Technical Regulation on Industrial Emissions (QCVN 19:2024/BTNMT) was promulgated with a spirit of comprehensive reform, ensuring consistency, modernization, feasibility, and alignment with the orientations of the 2020 Law on Environmental Protection. QCVN 19:2024/BTNMT introduces many notable innovations, representing a significant advancement in thinking and tools for industrial emissions management in Vietnam.

Consolidation and simplification of the regulatory system: QCVN 19:2024/BTNMT replaces seven existing regulations on industrial emissions (such as QCVN 19:2009/BTNMT, QCVN 20:2009/BTNMT, QCVN 21–23…) and partially revises provisions on emissions in other five regulations, merging them into a single standard applicable to all facilities that discharge industrial emissions. This unification helps reduce duplication, eliminate contradictions, enhance coherence, and facilitate practical application in management.

Environmental zoning-based management approach: Unlike the previous system that applied relatively complex Kp and Kv coefficients, QCVN 19:2024/BTNMT specifies emission limit values according to three environmental zones: Zone A (strict protection), Zone B (restricted emissions), and Zone C (other areas). This approach directly links discharge standards with the environmental carrying capacity of each specific area, while closely following the environmental zoning orientation in the 2020 Law on Environmental Protection and Decree No. 08/2022/ND-CP.

Review and optimization of control parameters: The total number of emission parameters has been reviewed and reduced to 66 characteristic indicators, including 54 gaseous pollutants and 12 particulate pollutants. Compared to the old system of 119 parameters (many of which were not suitable for specific industries), QCVN 19:2024/BTNMT classifies parameters according to the type of emission source, requiring monitoring only of those characteristic of each industrial sector, avoiding unnecessary burdens and impractical requirements for enterprises.

Tightening emission limits in line with new technological capacities: QCVN 19:2024/BTNMT adjusts the permissible limits of emission parameters to be stricter by 20 -30%, especially for SO_2, NO_x, CO, and particulate matter (PM). For particulates in particular, the new limits are two to three times stricter than existing standards. The adjustment is based on current technological capabilities, monitoring results from more than 300 facilities, and experiences from countries such as South Korea and the EU, where stringent emission standards have long been applied.

Establishments with high exhaust gas flow rates are required to conduct automatic and continuous monitoring of dust and gaseous emissions

Addition and clarification of technical terms and definitions: QCVN 19:2024/BTNMT updates and standardizes concepts such as “industrial emissions,” “dust,” “gaseous/particulate matter,” “emission equipment,” “emission zone,” and “reference oxygen content,” thereby increasing transparency and consistency in application. The standardization of terms also improves the capacity for inspection, supervision, and enforcement at different levels.

Linking technical requirements with measurement methods: All 66 parameters are accompanied by clearly defined methods of determination, limiting outdated and unstandardized approaches. QCVN 19:2024/BTNMT emphasizes referencing current international standards, thereby improving the reliability of measurement results and reducing disputes in emission verification between enterprises and regulatory authorities.

Thus, the innovations in QCVN 19:2024/BTNMT on industrial emissions reflect a shift from purely administrative management toward science- and risk-based management. At the same time, they create a legal framework to encourage enterprises to adopt cleaner technologies, reduce emissions, and strengthen transparency in air quality protection.

5. CHALLENGES AND RECOMMENDATIONS

The revision of the National Technical Regulation on Industrial Emissions marks an important step in improving the legal framework for air pollution control in Vietnam. However, implementation of the new QCVN will inevitably face challenges in terms of technology, institutions, and capacity. Identifying these difficulties is essential for proposing feasible solutions to ensure both effectiveness and consensus in application.

First, stricter emission limits mean higher requirements for treatment technologies, while many facilities - especially small and medium-sized enterprises still rely on outdated equipment and lack the capacity to comply. Financial constraints and limited access to clean technologies pose major obstacles in their compliance journey.

Second, emission monitoring, verification, and supervision systems in many localities remain fragmented, with staff capacity and equipment not yet meeting the new technical requirements. The application of environmental zoning (A, B, C zones) in emission control also raises higher demands on environmental planning and intersectoral coordination.

Third, businesses still express concerns about transparency in selecting characteristic parameters for monitoring and the risk of arbitrary application of technical requirements inconsistent with production specifics, if detailed and consistent guidance from central authorities is lacking.

Fourth, although QCVN 19:2024/BTNMT has introduced many innovations, the adoption of Best Available Techniques (BAT) is still at an early stage, requiring the establishment of mechanisms for evaluation, updating, and clearer guidance to ensure enterprises have an appropriate transition pathway.

Based on the above challenges, several recommendations are proposed to improve the effective implementation of QCVN 19:2024/BTNMT as follows:

- Strengthen technical and financial support, especially through environmental credit incentives, assistance for green technology innovation, and programs for BAT transfer to small and medium-sized enterprises.
- Develop independent monitoring and verification systems, invest in capacity-building for provincial environmental monitoring centers, and issue detailed, consistent technical guidelines for parameter selection, analysis methods, and zoning application.
- Establish consultation and intersectoral coordination mechanisms among environmental, industry, construction, and science-technology agencies to ensure coherence from planning to licensing, monitoring, and enforcement.
- Regularly review and update QCVN in line with actual environmental changes, technological progress, and international experiences, while aligning with Vietnam's environmental and climate commitments in the context of global integration.

6. CONCLUSION

Amid increasing air pollution and pressing demands for sustainable development, revising the National Technical Regulation on Industrial Emissions is a strategic move to enhance source-based pollution control, foster technological innovation, and improve the institutional framework for air quality management in Vietnam. QCVN 19:2024/BTNMT introduces significant reforms from unifying standards, adopting environmental zoning, identifying industry-specific parameters, to tightening emission limits in line with current technological capabilities. These changes not only enhance regulatory effectiveness but also motivate enterprises to invest in cleaner technologies and integrate more deeply with advanced environmental management practices worldwide.

It can be said that QCVN 19:2024/BTNMT is not merely a technical instrument but also a "policy safeguard" for air quality protection, ensuring the constitutional right to live in a healthy environment as stipulated in Article 43 of the 2013 Constitution and the 2020 Law on Environmental Protection. It also serves as a foundation for Vietnam to gradually align with international environmental standards, advancing toward green development, a circular economy, and long-term carbon neutrality■

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Strengthening state management of air quality

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In recent years, air quality in Vietnam, especially in major urban areas, has been under increasing pressure from urbanization, industrialization, and the growing number of vehicles. Air pollution not only directly affects public health but also poses considerable challenges to sustainable development goals.

Faced with this situation, improving institutions, policies, and strengthening state management capacity for air quality has become an urgent requirement. In recent times, the Ministry of Natural Resources and Environment (now the Ministry of Agriculture and Environment) has proactively implemented many comprehensive measures, from improving institutions and policies, developing monitoring systems, conducting emission inventories, to implementing forecasting, early warning, and emission source control programs.

This article focuses on analyzing and assessing the main achievements in state management of air quality, while also highlighting advantages, challenges, and proposing some solutions to improve the effectiveness and efficiency of management in the coming period.

1. STATE MANAGEMENT OF AIR QUALITY

Improvement of legal documents on air quality management

In recent years, the Ministry of Agriculture and Environment has taken an active and substantive role in formulating and refining the legal and policy framework for air pollution control and air quality management. To date, the legal framework for air quality management is basically complete, including: the Law on Environmental Protection 2020; the Law on Environmental Protection Tax 2010; Government Decree No. 08/2022/ND-CP dated January 10, 2022, detailing several articles of the Law on Environmental Protection, as amended and supplemented in Decree No. 05/2025/ND-CP dated January 6, 2025; Government Decree No. 153/2024/ND-CP dated November 21, 2024, on environmental protection fees for emissions; Circular No. 02/2022/TT-BTNMT dated January 10, 2022, of the Ministry of Natural Resources and Environment, detailing implementation of several articles of the Law on Environmental Protection, as amended and supplemented in Circular No. 05/2025/TT-BTNMT dated February 28, 2025; Circular No. 10/2021/TT-BTNMT dated June 30, 2021, of the Ministry of Natural Resources and Environment, on environmental monitoring techniques and management of environmental monitoring information and data, including air quality monitoring. These legal instruments form a synchronized basis and an important foundation for implementing effective air pollution control measures, aiming at sustainable development and protection of public health.

Along with improving the legal system, the Ministry has developed and submitted to the Prime Minister many important directives and decisions, including: Decision No. 1973/QD-TTg dated November 23, 2021, approving the National Plan on Air Quality Management for 2021–2025 (the Ministry is now drafting a new Prime Ministerial Decision on the National Action Plan on Air Pollution Remediation and Air Quality Management for 2025–2030); Decision No. 224/QD-TTg dated March 7, 2024, approving the Master Plan for the National Environmental Monitoring Network for 2021 - 2030, with a vision to 2050 (replacing Decision No. 90/QD-TTg dated January 12, 2016); and Directive No. 03/CT-TTg dated January 18, 2021, on strengthening air pollution control. These documents demonstrate the Government's strong commitment to controlling air pollution, providing unified and consistent guidance for air quality management nationwide.

Focus on developing and issuing the system of National Technical Regulations (QCVN) for air quality management

The Ministry has paid special attention to developing and issuing a system of QCVNs to support air quality management. For example, Circular No. 01/2023/TT-BTNMT dated March 13, 2023, promulgated QCVNs on ambient environmental quality, including soil, air, surface water, groundwater, and seawater. Subsequently, to unify the control of emissions from production, business, and service activities, the Ministry issued Circular No. 45/2024/TT-BTNMT dated December 30, 2024, promulgating QCVN on industrial emissions, replacing previous sector-based regulations. The new standard specifies pollutants by emission source type and sets stricter limit values, ensuring tighter control over industrial emission sources.

In the field of transport emissions management - a major source of air pollution - the Ministry has also developed and submitted QCVNs for motor vehicles in circulation. In particular, QCVN on emissions for automobiles in circulation in Vietnam was completed and promulgated under Circular No. 06/2025/TT-BNNMT dated June 16, 2025, of the Ministry of Agriculture and Environment, along with a draft roadmap for application submitted to the Prime Minister. At the same time, the Ministry is drafting QCVN on emissions for motorcycles and mopeds, ensuring compliance with the Law on Environmental Protection and the Law on Road Traffic Safety, together with an implementation roadmap to be submitted to the Prime Minister.

Strengthening the development and operation of the automatic, continuous ambient air quality monitoring system

The development and operation of the automatic, continuous air quality monitoring system has been promoted. At the central level, the Department of Environment has invested in and operated a total of 27 automatic, continuous monitoring stations meeting technical standards (Table 1). These stations are distributed across 22 provinces and centrally-run cities: 4 stations in Ha Noi, 2 in Ho Chi Minh City, 2 in Da Nang, and 1 in each of the remaining provinces/cities.

Amongthe 27 Stations, 7 Stations (Station 556 Nguyen Van Cu, Ho Chi Minh Mausoleum Station, Nha Trang - Khanh Hoa Station, Viet Tri - Phu Tho Station, Ha Long - Quang Ninh Station, Hue Station, Da Nang Station) were invested in during the period 2011-2013, while 18 stations were put into operation in 2024. In addition to these standard stations, the Department of Environment is currently managing 4 sensor-based stations in Ky Anh - Ha Tinh, serving scientific research purposes.

Automatic air quality monitoring stations shall be installed in urban areas of provinces and centrally governed cities

The monitored parameters include: particulate matter (PM_{10}, $PM_{2.5}$, PM_1), NO_x, SO_2, CO, O_3, benzene, toluene, xylene, total hydrocarbons, and meteorological parameters such as wind direction, wind speed, temperature, humidity, pressure, and solar radiation.

In addition, there are 10 air monitoring stations combined with hydrometeorological stations managed by the Department of Hydrometeorology with monitoring parameters including: SO_2, NO_x, CO, NH_3, TSP, PM_{10}, HC, O_3, some meteorological factors (wind direction and speed, temperature, humidity, atmospheric pressure, solar radiation, ultraviolet radiation).

Under Decision No. 224/QD-TTg dated March 7, 2024, approving the National Environmental Monitoring Network Plan 2021 - 2030, vision to 2050, the Ministry will continue to propose the construction of 16

Table 1. Number of Air Environment Monitoring Stations managed by the Department of Environment

No.	Locality	Number of Stations	No.	Locality	Number of Stations
1	Ha Noi	4	12	Quang Nam	1
2	Ho Chi Minh City	2	13	Quang Ngai	1
3	Quang Ninh	1	14	Binh Dinh	1
4	Phu Tho	1	15	Thua Thien Hue	1
5	Thai Binh	1	16	Da Nang	2
6	Hung Yen	1	17	Lam Dong	1
7	Bac Giang	1	18	Ninh Thuan	1
8	Hai Duong	1	19	Khanh Hoa	1
9	Ha Nam	1	20	Binh Duong	1
10	Ha Tinh	1	21	Ba Ria - Vung Tau	1
11	Quang Binh	1	22	Long An	1
Total					**27**

Table 2. Statistics on the current status of investment in automatic air environment monitoring stations of localities

No.	Locality	Number of Stations	No.	Locality	Number of Stations
1	Ha Noi	2	16	Binh Dinh	2
2	Hai Duong	10	17	Khanh Hoa	1
3	Hung Yen	2	18	Gia Lai	3
4	Nam Dinh	1	19	Dong Nai	2
5	Thai Binh	1	20	Ba Ria-Vung Tau	3
6	Bac Ninh	18	21	Binh Phuoc	3
7	Vinh Phuc	3	22	Tay Ninh	2
8	Thai Nguyen	2	23	Can Tho	1
9	Cao Bang	2	24	Long An	3
10	Lang Son	3	25	Vinh Long	3
11	Quang Ninh	11	26	Tra Vinh	2
12	Lao Cai	2	27	Kien Giang	4
13	Thanh Hoa	2	28	Hau Giang	1
14	Nghe An	1	29	Soc Trang	1
15	Da Nang	2	30	Bac Giang	2
Total					**95**

additional automatic air quality monitoring stations, bringing the total to 43 stations nationwide by 2030.

At the local level, 30 provinces currently operate 95 automatic monitoring stations (Table 2). Together with the central system, these contribute significantly to monitoring air quality, especially in urban areas, traffic corridors, and near industrial zones, providing data for pollution warnings to communities.

Along with the Central Air Environment Monitoring Station System, the local automatic continuous air environment monitoring stations are actively contributing to monitoring the current status and changes in ambient air quality, especially in urban areas, inner-city traffic routes, near industrial parks... contributing to comprehensively reflecting the current status of the air environment nationwide, providing data to support environmental pollution warnings to the community.

Enhancing forecasting and early warning capacity on air quality

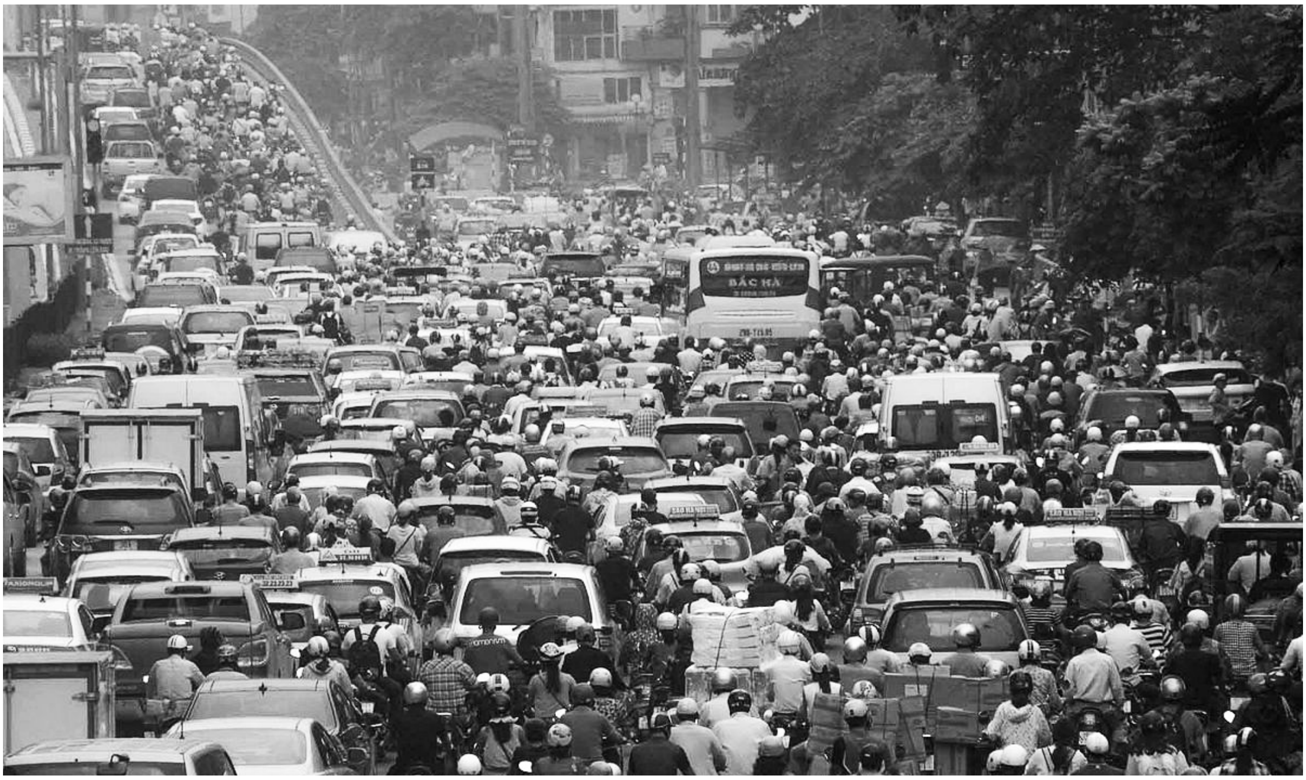
The Department of Environment has mobilized resources and accessed advanced air quality forecasting methods in the world, typically the CMAQ air quality forecasting model (USA), SILAM (Europe, Finland). Up to now, the Department of Environment has built and published the Internal Air Quality Forecast bulletin for short-term air quality for 24-48 hours nationwide and for 6 socio-economic regions; has built the Internal Air Quality Forecast bulletin for the next 2 days in 6 economic regions and for provinces and cities nationwide. In the future, the Department will integrate more data sources to improve forecasting accuracy and publish forecasts through the media.

Implementing effective emission inventory

Inventory of emission sources is one of the key contents serving the effective and scientifically based management of air quality. In the past period, the Department of Environment has advised the Ministry of Agriculture and Environment to issue a Technical Guide for Emission Inventory, as a basis for localities to develop a Provincial Air Environment Management Plan. On that basis, the inventory work is being implemented synchronously with many specialized activities such as: collecting information on emission sources, monitoring and analyzing $PM_{2.5}$ dust samples, determining the origin of PM2.5 dust, and measuring and inventorying emissions from road traffic sources, initially focusing on Ha Noi. It is expected that in 2025, the Department of Environment will complete the inventory of emissions in key economic regions in the North and South, thereby creating an important database serving the work of policy making, action plans and effective control of large emission sources on a regional and national scale.

Controlling major emission sources from industrial and service establishments

The Law on Environmental Protection 2020 stipulates that investment projects and facilities with large dust and gas emissions must conduct automatic, continuous and periodic monitoring. Decree No. 08/2022/ND-CP dated January 10, 2022 of the Government detailing a number of articles of the Law on Environmental Protection has detailed regulations on the subjects, types of works, dust and gas emission equipment and the flow rate or capacity of works, dust and gas emission treatment equipment that must conduct automatic,



Air quality in major cities is polluted by smoke and dust emissions from motor vehicles

continuous and periodic monitoring. Accordingly, strict control of emission quality is stipulated for a number of types of production, business and services with large scale and capacity of emission.

The Ministry of Agriculture and Environment has conducted research and reviewed the national environmental technical regulations system of Vietnam and issued Circular No. 45/2024/TT-BTNMT dated December 30, 2024 of the Ministry of Natural Resources and Environment promulgating national technical regulations on industrial emissions, effective from July 1, 2025, to control industrial emission sources in order to uniformly control industrial emissions arising from production, business and service activities. Accordingly, more specific regulations have been made on the control of pollution parameters according to the type of discharge equipment and the allowable limit values in emissions have been regulated in a more strict and tight direction.

In addition, to ensure consistency and compatibility between the law on environmental protection, environmental taxes and fees with the law on taxes and fees in general, ensuring the criterion of "polluters must pay", creating motivation for organizations and individuals engaged in production, business and service activities that discharge dust and emissions into the environment to improve production technology, invest in emission treatment technology to minimize emissions of pollutants into the environment, the Ministry of Agriculture and Environment has coordinated with the Ministry of Finance to develop and submit to the Government for promulgation Decree No. 153/2024/ND-CP dated November 21, 2024 regulating environmental protection fees for emissions. In particular, clearly defining the subjects subject to fees and the method of calculating fees, focusing on facilities that generate industrial emissions with large volumes, discharge a lot of dust and air pollutants, and also regulating preferential fees to encourage the application of advanced emission treatment technology.

2. ANALYSIS AND ASSESSMENT OF ADVANTAGES AND CHALLENGES IN AIR QUALITY MANAGEMENT

In recent times, air quality management has achieved important results, creating a favorable foundation for the implementation of air pollution control solutions nationwide. Accordingly, (i) the legal corridor system serving air environment management has been built relatively fully and synchronously, including legal documents from Laws, Decrees, Circulars to directives, administrative documents and technical instructions, in accordance with practical requirements; (ii) the issue of air pollution has increasingly received attention and close direction from the entire political system, with the active participation of all levels and sectors from the central to local levels; (iii) Environmental monitoring and emission source monitoring have also been promoted and invested in, contributing to improving the effectiveness of monitoring and warning as well as supporting the development of control policies suitable to the specific conditions of each locality; (iv) Localities have proactively developed and implemented the Provincial Air Quality Management Plan according to the guidance of the Ministry of Agriculture and Environment, while the remaining localities are actively completing it for implementation in the coming time.

In addition to the achieved results, the current air quality management work is still facing many major challenges such as (i) investment resources for air quality management are still really modest, while scientific and technological solutions have not been effective; (ii) the genuine engagement and determination of authorities and sectors from the central to the local levels remain insufficient; many localities have been slow in issuing documents, and numerous directives and administrative instructions have only recently been promulgated but have yet to be implemented; (iii) Controlling emission sources, especially dispersed emission sources, is still very difficult, both in terms of resources for implementation, assignment of responsibility for implementation and technical tools and measures for implementation; (iv) The monitoring, supervision, and forecasting of air quality have been implemented; however, the results remain limited. The number of monitoring points is still sparse, and the overall picture of pollution is neither characteristic nor representative. Remote sensing technologies have not yet been applied; monitoring results are insufficient to identify causes for control measures and, in particular, have not enabled the forecasting or early warning of pollution risks; (v) orientations and solutions in green transformation have just been formed and need to be strongly implemented and effectively promoted.

3. PROPOSING AND RECOMMENDING SOLUTIONS TO ENHANCE THE EFFECTIVENESS OF AIR QUALITY MANAGEMENT

In the face of increasingly complex developments in air pollution, especially in large cities and concentrated industrial areas, the requirement for air quality management is to have synchronous, fundamental and effective solutions. Air pollution control not only requires the efforts of state management agencies but also requires the active participation of localities, communities and businesses. In that context, proposing and implementing the specific solutions below is extremely necessary to enhance management effectiveness, protect public health and move towards sustainable development.

First, effectively implement the approved National Plan on Air Quality Management and Provincial Air Quality Management Plan.

Second, build and establish a network of automatic, continuous air monitoring stations that are large enough to ensure the monitoring, collection and transmission of data to help management agencies monitor, supervise, warn and forecast trends and changes in air quality, especially in large cities.

Third, promote investment and conversion from fossil fuels to renewable energy sources such as solar power, wind power and hydropower. Gradually limit the construction and use of coal-fired thermal power plants because they are a major source of emissions causing air pollution.

Fourth, develop "smart cities" with traffic systems and automation technology to better control the level of emissions from socio-economic activities.

Fifth, build and upgrade a high-quality public transport system that covers all urban areas, helping people easily choose public transport instead of using private vehicles. Establish areas that restrict personal vehicles during rush hours, especially in densely populated areas and city centers. Encourage the use of bicycles and public transport by building a wide-coverage, convenient support infrastructure for people.

Sixth, increase information and data sharing and have a mechanism for inter-sectoral, inter-regional and inter-provincial coordination in the work of controlling and reducing air pollution.

Seventh, review and strictly implement the provisions of urban planning, particularly the planning of green spaces and water bodies; invest in the development of additional green areas and public spaces, and increase tree planting in urban areas so as to ensure compliance with the per capita standards stipulated in the regulations.

4. CONCLUSION

Air quality management is one of the key tasks in national environmental protection. To achieve sustainable development goals, it is necessary to continue improving the legal framework, strictly control emission sources, increase investment in monitoring systems, and enhance forecasting and early warning capacities for air quality. At the same time, intersectoral coordination from the central to the local levels and raising public awareness will play a pivotal role in ensuring effective and long-term air pollution control■

A NEW STEP FORWARD IN ENVIRONMENTAL MANAGEMENT:

Three new National Technical Regulations on ambient environmental quality

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On May 15th, 2025, the Minister of Agriculture and Environment issued Circular No. 01/2025/TT-BNNMT - a key legal instrument officially promulgating three new National Technical Regulations (QCVN) on ambient environmental quality. These include QCVN 26:2025/BNNMT on noise, QCVN 27:2025/BNNMT on vibration, and QCVN 43:2025/BNNMT on sediment quality. This represents a significant step forward in state management of environmental protection, with the core objective of improving living environment quality, safeguarding public health, and promoting the sustainable development of the nation.

This Circular will officially take effect from November 14th, 2025, fully replacing previous regulations that had been applied for many years, including QCVN 26:2010/BTNMT, QCVN 27:2010/BTNMT, and QCVN 43:2017/BTNMT. Notably, the Circular also sets out a clear and flexible transitional roadmap. Facilities already in operation or investment projects approved before the effective date of the Circular are allowed to continue applying the old regulations (QCVN 26:2010/BTNMT, QCVN 27:2010/BTNMT) and relevant local government regulations until December 31st, 2026. Conversely, new investment projects or expansion projects must comply immediately with the provisions of QCVN 26:2025/BNNMT and QCVN 27:2025/BNNMT from the effective date of the Circular. This arrangement demonstrates that regulatory authorities have anticipated the challenges of adaptation for existing businesses and projects. Such an approach helps minimize conflicts between economic development objectives and environmental protection goals, creating favorable conditions for enterprises to transition while still ensuring the long-term objective of improving environmental quality.

1. THE NECESSITY OF ISSUING NEW QCVNS

The promulgation of new national technical regulations on noise, vibration, and sediment quality is not a sudden change but the outcome of a process of continuous review and updating, arising from the urgent needs of environmental management practice. Although previous QCVNs played an important role in establishing the initial legal framework for pollution control, after years of application their limitations became evident.

One of the most significant shortcomings of the old regulations was the lack of specificity and feasibility in implementation. Previous provisions did not provide clear guidance on identifying pollution sources, detailed classification of affected areas, or methods for handling violations. This created difficulties for regulatory authorities in law enforcement and for enterprises in compliance. In addition, emission thresholds were rather rigid, failing to take into account practical factors such as the duration of noise or vibration, or to provide baseline-adjusted limits.

Furthermore, the measurement methods referenced in the old regulations had become outdated or lacked sufficient detail. This posed challenges for monitoring agencies in implementation and undermined the reliability of environmental data.

The need for more detailed regulations that consider variable factors and provide clear methodological guidance has become an inevitable trend to enhance management effectiveness. This change reflects an environmental management system that continues to improve, learning from practical experience and moving toward the application of more modern, science-based management tools. Such an approach not only enables state authorities to enforce regulations more effectively but also creates a transparent and comprehensible legal environment for regulated entities.

The review and updating of technical regulations is mandated every five years or earlier if necessary under Article 35 of the Law on Standards and Technical Regulations, ensuring that regulations remain aligned with practical realities and scientific advances.

2. QCVN 26:2025/BNNMT AND QCVN 27:2025/BNNMT – MORE COMPREHENSIVE CONTROL FOR QUALITY OF LIFE

QCVN 26:2025/BNNMT and QCVN 27:2025/BNNMT are national technical regulations on noise and vibration, prescribing maximum permissible noise levels in areas where people live, work, and conduct activities. These regulations cover noise and vibration generated from production, business, and service facilities, construction sites under operation, transportation activities, and daily life activities. However, they do not apply to occupational noise exposure in workplaces.

The new and notable features of QCVN 26:2025/BNNMT and QCVN 27:2025/BNNMT, compared with QCVN 26:2010/BTNMT and QCVN 27:2010/BTNMT, represent a significant advancement in noise management:

More detailed classification of affected areas: Instead of the previous two categories, "special areas" and "ordinary areas," the new QCVNs classify into specific zones (A, B, C, D, E) based on the type of construction and sensitivity to noise.

Threshold adjustments by noise/vibration duration: The new QCVNs allow threshold limits to be adjusted according to the duration of noise and vibration emissions. This provides a degree of flexibility, accepting high-intensity noise or vibration for short periods while maintaining strict control over continuous emissions. Such flexibility reduces unnecessary compliance burdens for enterprises in certain cases while ensuring overall environmental protection. It encourages activities that generate short-term loud noise to have clear mitigation plans to minimize cumulative impacts.

Inclusion of noise and vibration limits from transportation: For the first time, QCVN 26:2025/BNNMT and QCVN 27:2025/BNNMT introduce specific limits for noise from road and rail traffic, differentiated by area classification (A, B, C, D, E) and by time (day/night). Transportation noise and vibration are among the most common and significant sources of urban pollution, but had not previously been regulated separately.

Adjustment based on background noise/vibration levels: The new QCVNs provide clear guidance on measuring background levels and adjusting results when differences between emitted noise/vibration and background levels occur (with reductions of 1–3 dB depending on deviation). This ensures accuracy and fairness in assessment, particularly where background levels are close to emission levels but within a 10 dB difference. In real environments, there is always some background noise and vibration. The new rules ensure that only the incremental impact from the source is assessed. This enhances objectivity and scientific rigor, reduces disputes between regulators and regulated entities, and encourages stakeholders to focus only on controlling noise they themselves generate.

Updated and detailed measurement methods: The new QCVNs provide clearer requirements on measurement locations, equipment, conditions (avoiding rain, winds stronger than level 4), measurement duration, and calculation methods for each type of noise and vibration. This technical detailing ensures consistency, accuracy, and reliability of monitoring data. Reliable monitoring data form the foundation for regulatory decision-making and enforcement. Enhanced measurement standards also strengthen the evidentiary basis for law enforcement while encouraging monitoring units to upgrade technical capacity and equipment.

3. QCVN 43:2025/BNNMT – SEDIMENT QUALITY: A FOUNDATION FOR PROTECTING AQUATIC LIFE

QCVN 43:2025/BNNMT is the national technical regulation on sediment quality, prescribing threshold values for surface water and marine sediment quality parameters. This regulation applies to the assessment and control of sediment quality for the purpose of protecting aquatic life. It is applicable to state environmental management agencies as well as organizations and individuals conducting environmental monitoring and sediment quality assessment on land and in Vietnam's marine areas.

Compared to QCVN 43:2017/BTNMT, QCVN 43:2025/BNNMT largely retains the same definitions, number of parameters, and threshold values. However, the new regulation focuses on standardization and updates to improve feasibility and effectiveness in implementation:

Standardization of nomenclature and chemical formulas: The new QCVN adopts the nomenclature of substances in accordance with TCVN 5530:2010 - Chemical Terminology – Nomenclature of Elements and Compounds, and supplements specific chemical formulas. This is particularly important as sediment quality QCVNs aim to control cumulative pollutants in the environment, mainly organic parameters. Clear chemical definitions provide monitoring and management units with a more solid basis for identifying and controlling pollutants.

Updated measurement methods: The measurement methods referenced in QCVN 43:2017/BTNMT have been updated or replaced. QCVN 43:2025/BNNMT incorporates new methods consistent with national standards (TCVN) and equivalent or higher-precision international standards. This ensures that sediment monitoring and analysis use advanced techniques, yielding more accurate and reliable environmental data.

Additional management provisions: The new QCVN introduces specific management requirements, including mandatory periodic sediment quality monitoring and the use of monitoring results to directly provide and disclose environmental quality information to the public. Such activities must be conducted by organizations that meet the legal capacity requirements for environmental monitoring. Moreover, it emphasizes that periodic sediment monitoring must be aligned with monitoring objectives to select appropriate parameters. These additions enhance the legal validity and usability of monitoring results to support state environmental management objectives, enabling timely reflection of pollution accumulation trends in sediments.

4. EXPECTATIONS FOR IMPROVEMENTS IN STATE ENVIRONMENTAL MANAGEMENT

The promulgation of three new National Technical Regulations on noise, vibration, and sediment quality brings high expectations for national environmental management, aiming toward a better living environment for the people and the sustainable development of the nation.

First, the new regulations will enhance feasibility and effectiveness in law enforcement. With more detailed classifications of affected areas, clearer provisions on pollution sources (including annexes listing specific equipment), and specific guidance on determining and calculating measurement results, state management agencies will have a stronger legal basis to identify pollution sources, assess violations, and apply appropriate corrective measures. This will minimize disputes and difficulties in handling administrative violations while strengthening the accountability of organizations and individuals causing pollution.

Second, the new provisions will ensure greater accuracy and fairness in environmental quality assessments. The inclusion of threshold adjustments based on emission duration and baseline correction rules in the noise and vibration QCVNs represents an important step forward. This allows for the assessment of the actual impacts of pollution sources, eliminating interference from surrounding environments or intermittent activities. Such flexibility not only provides enterprises with a clear basis for managing their operations but also establishes a fair legal environment that encourages more effective pollution reduction measures.

Third, monitoring capacity and the quality of environmental data will be significantly improved. Detailed regulations on measurement locations, equipment, conditions, and calculation methods for each type of pollution (continuous, impulsive, or intermittent noise and vibration) will standardize monitoring procedures nationwide. Updating national and international measurement standards also ensures that collected data are accurate, reliable, and comparable. High-quality data provide a solid foundation for policymaking, environmental planning, and timely management decisions.

Fourth, the new regulations reflect a more comprehensive approach to environmental protection, particularly with the addition of threshold limits for noise and vibration from transportation. These are common and highly impactful sources of urban pollution that had not previously been specifically regulated. Controlling such sources will contribute significantly to reducing overall pollution, improving air quality, and enhancing living conditions in residential and urban areas.

Fifth, these improvements will effectively support planning and sustainable development. With clearer and more detailed standards on noise and vibration, urban planners and investors will have better tools to assess the environmental impacts of projects, thereby incorporating environmentally friendly design, construction, and operational solutions from the outset. This not only prevents pollution but also promotes harmonious development between the economy and the environment.

It can be said that the Ministry of Agriculture and Environment's issuance of Circular No. 01/2025/TT-BNNMT, along with the three new National Technical Regulations on ambient environmental quality, marks an important milestone, reflecting progress in Vietnam's environmental management. These new provisions not only address shortcomings of the previous system but also demonstrate a strategic vision, aiming to protect public health and comprehensively improve quality of life in a sustainable manner.

For the QCVNs to be effectively implemented, there must be close coordination and strong commitment from all stakeholders: state management agencies in disseminating, guiding, and supervising implementation; organizations, individuals, and enterprises in proactively studying, complying with, and investing in environmentally friendly technologies; and the wider community in raising awareness and jointly protecting the living environment. Only then can we build a greener, cleaner, and more livable Vietnam for both present and future generations■

Science and technology,innovation and digital transformation in the field of environment and water resources

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In 1998, the first Law on Water Resources was promulgated, by 2023 the Law was amended and supplemented, marking a turning point in management, protection and development of water resources. In particular, the State's policy on water resources clearly states: Modernize and professionalize water resources management towards national governance of water resources on a digital technology platform through the National information system and database on water resources, and decision support tool system, ensuring efficient use of resources in water resources management [1]. Since the Law on Water Resources 2023 took effect, the Ministry of Natural Resources and Environment (now the Ministry of Agriculture and Environment) has directed the application of scientific and technological achievements in water resources management to use resources effectively and efficiently, especially in supervisingwater resources, operating inter-reservoirs, forecasting drought & water shortage and water resources scenarios, building the National database on water resources to ensure that it is "Correct, sufficient, clean, and alive". The article focuses on results: (i) Supervising water resources on the IoT platform; (ii) Implementing the inter-reservoir operation process on the digital technology and IoT platform; (iii) Real-time drought map on the basis of digital technology; (iv) Organizations and individuals exploiting and using water, conducting baseline surveys of water resources, must update information and data into the National information system and database on water resources for management, implementation of policies promptly and effectively [2].

1. SUPERVISING WATER RESOURCES ON THE IOT PLATFORM

1.1. Model of supervising water resources

Realizing that promoting the application of advanced solutions and technologies to effectively manage water resources, focusing on the application of information technology in water resources management is an urgent requirement, since 2018 the Department of Water Resources Management has coordinated with the Department of Digital Transformation and Environmental Resources Data Information to develop a Supervision system on exploitation and use of water resources (https://iot.monre.gov.vn/tnn/).With set objectives, including: Online tracking and supervising surface water exploitation and use

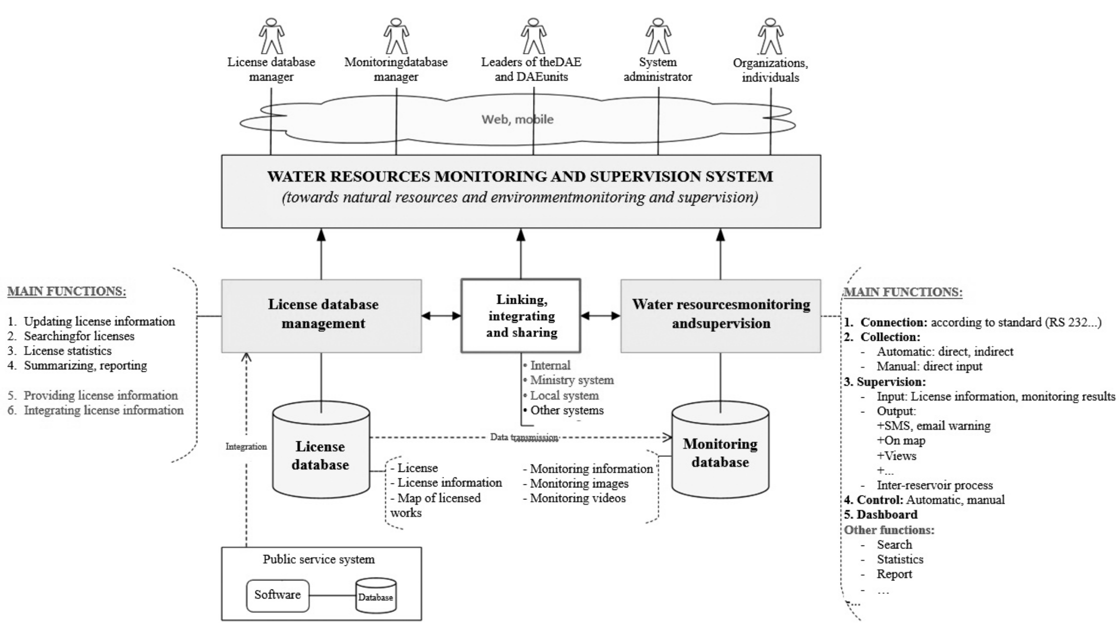


Figure 1. General model of the water resources monitoring and supervision system

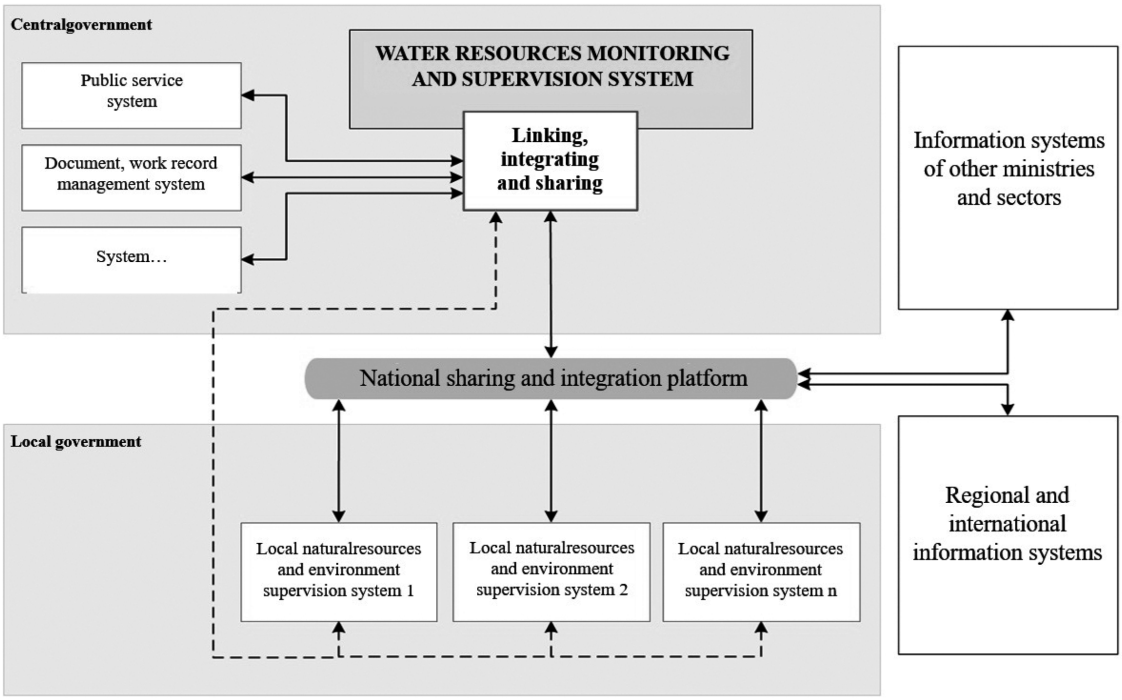


Figure 2. Integrated, shared linkage model

works; underground water exploitation and use works licensed by the Ministry of Natural Resources and Environment (now the Ministry of Agriculture and Environment) (supervision according to license), the design is based on open standards to ensure connection, communication, integration and sharing of information and data with systems of 63 provinces/cities nationwide; connection, communication with existing systems for monitoring water flowrate, level and quality of irrigation and hydropower reservoirs under the issued inter-reservoir operation process; automatic or manual information update (water flowrate, level, quality and images) into the system for supervising and warning.

Water resources supervision is implemented according to two models: General model of water resources monitoring and supervision system; Integrated and shared linkage model (Figures 1,2). Following is a description of model components.

Direct and continuous data sources: Information is directly collected from measuring equipment located at facilities with water resources exploitation and use works; Monitoring equipment: Sensors, Protocols send data from monitoring stations, Data sending/receiving devices at the station have IP addresses and can be connected to the Internet.

The frequency of sending information from the device depends on the type of water resources exploitation and use works as prescribed in Circular No. 17/2021/TT-BTNMT dated 14 October 2021 of the Ministry of Natural Resources and Environment on supervision of water resources exploitation and use; Decree No. 53/2024/ND-CP dated 16 May 2024 of the Government detailing the implementation of a number of articles of the Law on Water Resources.

Camera supports H264 or H265 image compression standard; supports remote control standards (taking pictures, recording videos) according to OnVif standard.

Other data sources: Data is connected and shared from database systems of local Departments of Agriculture and Environment; from database systems of the Vietnam Meteorological and Hydrological Administration, the National Center for Water Resources Planning and Investigation; Data is linked and shared from relevant ministries and sectors; Data is connected, synchronized and shared from the national database system on natural resources and environment monitoring.

Technological solutions: Collect data, receive information and data from monitoring stations and real-time surveillance cameras at water resources exploitation and use works; Connect, link, and share data from database systems of units under the Ministry (Vietnam Meteorological and Hydrological Administration, National Center for Water Resources Planning and Investigation, etc.), ministries, sectors, and local authorities; Support for additional input and conversion of data on water resources licensing of the Ministry of Agriculture and Environment into the system; Manage, organize, operate the database, build a software group to manage and operate the database.

Exploiting and sharing information and data: Support data analysis and processing for warning and forecasting; publish and share information; build a software group to support data analysis and processing, publish and share information.

Deployment plan: The system is deployed centrally at the Data Center of the Ministry of Agriculture and Environment on the WAN/Internet environment.

1.2. Results of implementing the water resources supervision system

As of the end of April 2025, the system had updated a total of 13,507 water resources licenses of all types to the system, including 2,270 ministerial-level licenses and 11,237 provincial-level licenses.

In addition, implementing Circular No. 17/2021/TT-BTNMT dated 14 October 2021 stipulating the supervision of water resources exploitation and use and Decree No. 53/2024/ND-CP dated 16 May 2024 detailing the implementation of a number of articles of the Law on Water Resources, by the end of April 2025, 58 Departments of Agriculture and Environment had updated and connected information of local water resources licenses to the central database of shared information of water resources licenses; 5 Departments of Agriculture and Environment (Hoa Binh, Dong Nai, Vinh Long, Bac Lieu, Ca Mau) had not updated. As of April 2025, 11,237 water resources licenses of all types issued by provincial-level People's Committees had been entered into the water resources supervision system.

Implementing provisions of the Law on Water Resources 2023 and Decree No. 53/2024/ND-CP of the Government on guiding the implementation of the Law on Water Resources, in April 2025, a number of Departments of Agriculture and Environment contacted to test and connect works licensed by local authorities to the system (Departments of Agriculture and Environment: Ho Chi Minh City; Nghe An, Quang Ninh, Ninh Thuan, Thai Nguyen).

Along with that, as of April 2025, the water resources supervision system had 831 water resources exploitation works subject to licensing by the Ministry of Agriculture and Environment registered and connected to transmit data to the system. Of which, the Department of Water Resources Management successfully approved the connection to transmit data to the system for 810 works (surface water works: 697; underground water works: 111; seawater works: 2).

The water resources supervision system has been built, put into operation and has brought initial results, actively supporting the management work at the Central level and local levels. From the data of connected works, transmitted to the Central water resources supervision system, it has effectively contributed to the management and operation work, making decisions for the state management of water resources of the Department of Water Resources Management such as: Collecting and storing data from monitoring stations of organizations and individuals exploiting and using water resources to ensure convenience, efficiency and speed; Synthesizing, analysing and building related charts and graphs; Providing statistical data by time, type, by administrative unit, river basin; Searching and managing information; Displaying monitoring stations on the map; Giving warnings and notifications when there are signs about to exceed the threshold or when the prescribed threshold has been exceeded; Extracting data, making reports on the list and information about connected works.

2. IMPLEMENTING THE INTER-RESERVOIR OPERATION PROCESS ON THE DIGITAL TECHNOLOGY AND IoT PLATFORM

According to Point a, Clause 5, Article 60 of the Law on Water Resources 2012 and Clause 7, Article 38 of the Law on Water Resources 2023: the Ministry of Natural Resources and Environment (now the Ministry of Agriculture and Environment) shall develop and adjust the inter-reservoir operation process on river basins and submit it to the Prime Minister for approval.

In order to carry out assigned tasks, in the past time, the Ministry of Agriculture and Environment has developed and completed 11 inter-reservoir operation processes on 11 large and important river basins (processes are reviewed and updated regularly). After having issued, the Ministry has directed competent authorities to regularly supervise and examine the operation of reservoirs according to provisions of inter-reservoir operation processes on 11 river basins issued by the Prime Minister. With a total of about 134 reservoirs and dams on 11 river basins regulated and operated according to the inter-reservoir mechanism with the principle of top priority during the flood season being to ensure the safety of works, cut and reduce floods for downstream areas, prioritize maintaining minimum flow, and supply water to downstream for production and people's lives in the dry season. Of which, there are 37 reservoirs having regulations on flood prevention capacity with a total flood prevention capacity of about 12 billion m^3 (about 22% of the total capacity of all reservoirs) and in case of flood, this capacity can reach a maximum of 13 billion m^3 (about 24% of the total capacity of all reservoirs).

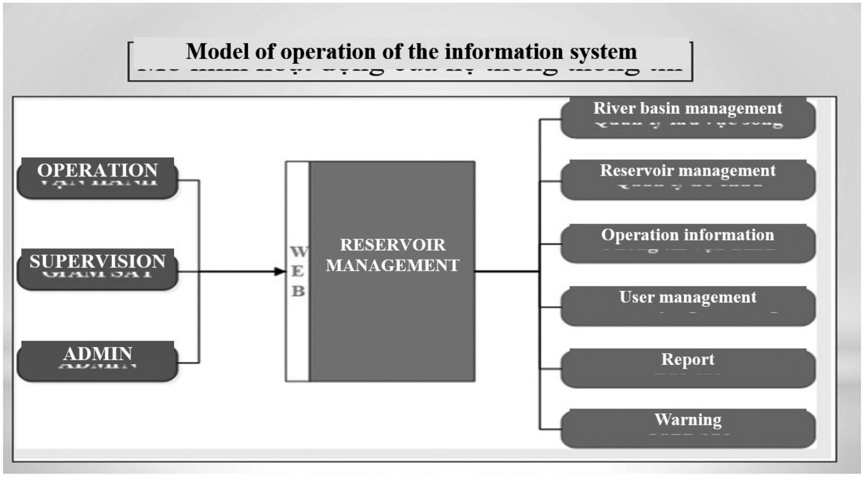


Figure 3. Model of operation of the information system for reservoir operation for the direction and operation

Based on provisions in inter-reservoir operation processes, the Ministry of Agriculture and Environment is responsible for directing the Department of Water Resources Management and relevant agencies to inspect, examine and supervise the operation of reservoirs according to these processes and organize the development of supervision and calculation tools to support for advising for directing the operation of reservoirs according to its authority.

To fulfil tasks under the responsibility of the Ministry of Agriculture and Environment, the Department of Water Resources Management is currently using the reservoir operation data information system for the direction and operation work, built since 2015 (https://quanly.dwrm.gov.vn/hochua). The current system has received operation data of more than 134 reservoirs applying inter-reservoir operation processes on 11 river basins (including rivers: Red; Ma; Ca; Huong; Vu Gia - Thu Bon; Tra Khuc; Kon - Ha Thanh; Ba; Se San, Srepok; Dong Nai). Necessary information for the process of supervising and examining the operation of reservoirs according to provisions of inter-reservoir operation processes, as a basis for directing the operation of reservoirs, includes: (1) Monitoring data on water level of reservoirs, inflow to reservoirs, discharge through dams, discharge through power generation; (2) Monitoring data on water flowrate and level, time when water level at hydrological stations reaches water level value according to alarm levels and provisions in inter-reservoir operation processes; forecast and warning bulletins...

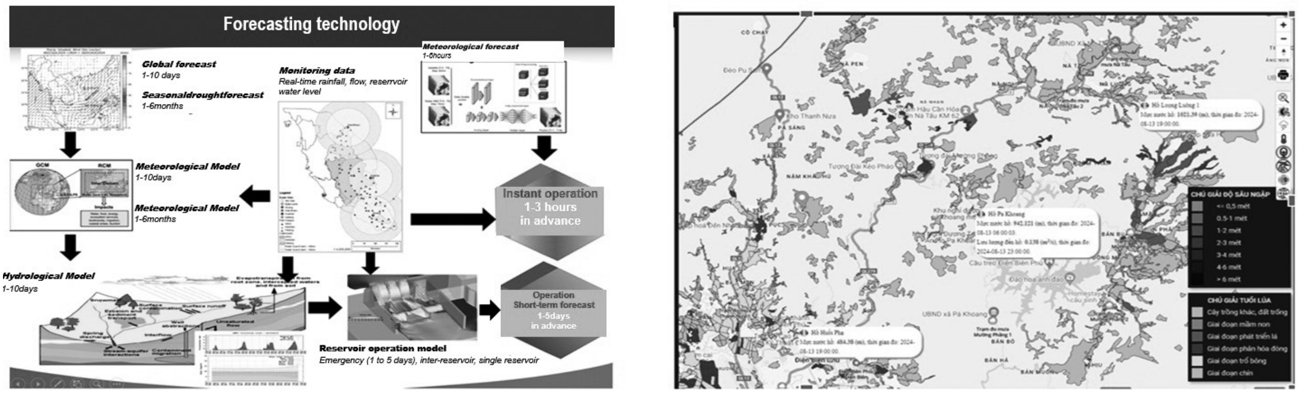
The operation information and data that the reservoir management unit updates to the system is an important basis for analysing and evaluating the compliance with provisions of inter-reservoir operation processes on 11 river basins and is the basis for the Department of Water Resources Management to promptly urge and guide reservoir owners to strictly implement the operation to ensure cutting and reducing floods for downstream areas and coordinate the operation and regulation of reservoirs to ensure supplying water to downstream areas during the dry season, periods of drought and water shortage on river basins and according to provisions of inter-reservoir operation processes on 11 river basins through the form of documents, telephone, email... (Every year, over 100 documents are sent to reservoir owners and local authorities to urge, guide and direct the operation).

In addition, direct specialized agencies to regularly provide timely forecasts and warnings to local authorities and reservoir owners; urge for the strict implementation of provisions of inter-reservoir operation processes. Send working groups to conduct field surveys in flooded areas in some provinces and cities such as Da Nang City, Quang Nam, Hue City... and reservoirs; work, exchange; support the direction and operation; answer, guide, and remove obstacles in the operation of reservoirs according to processes. For the dry season, send working groups to work with local authorities to unify plans to direct and regulate water in reservoirs, especially during times of drought and water shortage to ensure the operation of reservoirs to supply enough water to downstream areas of river basins (Figure 3).

3. REAL-TIME DROUGHT MAP ON THE DIGITAL TECHNOLOGY PLATFORM

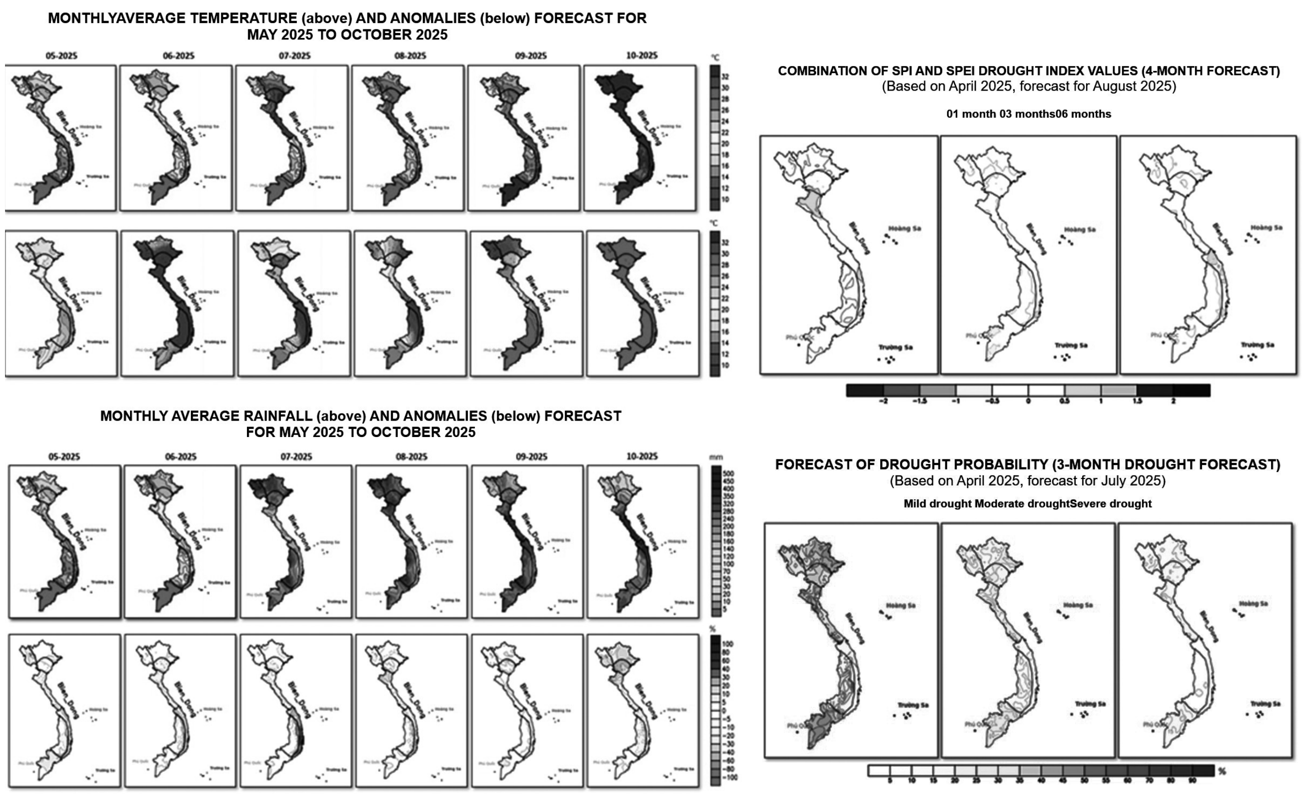
Vietnam is one of countries heavily affected by climate change, having extreme weather and climate phenomena occurring with increasing frequency such as unusual floods, prolonged droughts, and saltwater intrusion. River basins, especially downstream areas such as Red - Thai Binh, Dong Nai - Sai Gon, are key socio-economic areas, ensuring food security and water security. However, in the context of increasingly complex climate change, along with the rapidly increasing demand for water exploitation and use, water sources in river basins are facing many serious challenges.

Faced with this situation, the proactive development of water sources scenarios is an urgent requirement, as a basis for ministries, sectors and provincial-



Real-time drought mapping technology based on forecasting technology, integrated modeling and big data

Seasonal drought/rain forecast map: Updated monthly, providing information on rainfall trends



Real-time drought severity and drought probability forecast map products updated monthly

level People's Committees in river basins, within the scope of their tasks and powers, to direct the planning for appropriate exploitation and use of water resources. This is also one of key tasks to implement Resolution No. 57-NQ/TW dated 22 December 2024 of the Politburo on breakthroughs in the development of science, technology, innovation and national digital transformation. Water sources scenarios (for example, drought scenarios in the Red - Thai Binh river basin) not only provide information to forecast and warn of drought risks but also support the regulation and distribution of water resources in river basins, contributing to ensuring water security, food security, energy security and other essential needs of the people.

Methods for developing drought scenarios: The process of developing drought maps and water sources scenarios synchronously applies modern digital transformation technologies, specifically according to following steps:

Collecting and processing big data: The process of developing drought maps and drought scenarios is based on the collection, synthesis and analysis of continuously updated big data sources, including: data on rainfall, flow, reservoir water volume, groundwater level and water demand...

Applying digital models: All data are integrated into a centralized management system, allowing quick update, synchronization and retrieval; Build and apply a combination of digital models for forecasting seasonal rainfall to forecast rainfall for next 6 months to provide information to scenarios; Apply hydrological models to forecast water flow and level variations at reservoirs; Use methods/algorithms to analyse drought trends and assess water shortage risks by region and sub-region.

Zoning drought areas and building digital maps: Based on simulation results, areas are divided according to the level of water shortage: mild, moderate, severe; Build drought maps on the GIS platform: Drought zones are visually represented on digital maps, helping users easily identify affected areas, severity and developments over time.

Developing water sources scenarios: Establish water sources development scenarios based on rainfall trends, water flow trends, total water storage in hydroelectric reservoirs, water levels in underground aquifers and exploitation and usage needs of sectors. From there, analyse the impact of each scenario on water supply to domestic, agricultural and hydropower activities.

Outstanding products of the digital transformation process: The monthly drought/rain forecast bulletin/map is updated periodically, providing information on rainfall trends, thereby providing warnings about lack of rainfall; The forecast bulletin/map of river flows and reservoirs based on rainfall trends provides the flow trends of major rivers and the amount of water stored in large reservoirs to provide early warnings to local authorities and production sectors to proactively respond to water shortages; Drought map by region and time displays areas with water shortages.

4. ORGANIZATIONS AND INDIVIDUALS EXPLOITING AND USING WATER, CONDUCTING BASELINE SURVEYS OF WATER RESOURCES, MUST UPDATE INFORMATION AND DATA INTO THE NATIONAL INFORMATION SYSTEM AND DATABASE ON WATER RESOURCES

This is a big step forward in development of a database on water resources specifically stipulated in the Law on Water Resources, including: The Ministry of Agriculture and Environment organizes the development, management, operation, and maintenance of the national information system and database on water resources; updating information and data on water resources [3]; Organizations and individuals conducting baseline surveys of water resources using the state budget must update information and results of baseline surveys of water resources into the National information system and database on water resources [4]; The Ministry of Agriculture and Environment organizes the implementation of inter-provincial river basin master plan; updating information and data on inter-provincial river basin master plan records into the National information system and database [5]; Provincial-level People's Committees shall consider and decide on the conversion of purposes of use of mineral, soil and building material mining pits after the mining has stopped to form reservoirs for water regulation, storage, supply and landscape creation when meeting all requirements prescribed by this Law, legislation on investment, land, environmental protection, minerals and update and supplement the list of intra-provincial surface water sources and the list of reservoirs, ponds, lagoons and estuaries that must not be filled [6]; Results of monitoring water resources, hydrometeorology and water environment quality must be updated and shared to the National information system and database on water resources [7]; Organizations and individuals exploiting water resources are responsible for updating, connecting, and transmitting monitoring data to the National information system and database on water resources for supervision of water resources exploitation [8]; Underground water exploitation works of households specified in Clause 4, Article 52 of the Law on Water Resources must be declared [9]; Cases of works exploiting and using water resources must be registered [10]; Declaration and registration are carried out on the application for declaration and registration of exploitation and use of water resources [11]; District-level People's Committees and Communal-level People's Committees organize for updating of data on underground water exploitation registration in the area into the National information system and database on water resources [12]■

REFERENCES

1. Article 4 of the Law on Water Resources.
2. Article 7 of the Law on Water Resources.
3. Clause 5, Article 7 of the Law on Water Resources.
4. Clause 5, Article 10 of the Law on Water Resources.
5. Clause 4, Article 18 of the Law on Water Resources.
6. Clause 5, Article 27 of the Law on Water Resources.
7. Point đ, Clause 1, Article 51 of the Law on Water Resources.
8. Point b, Clause 2, Article 51 of the Law on Water Resources.
9. Clause 1, Article 8 of Decree No. 54/2024/ND-CP stipulating the practice of underground water drilling, declaration, registration, licensing, services of water resources and fees for granting the right to exploit water resources.
10. Clause 2, Article 8 of Decree No. 54/2024/ND-CP.
11. Point a, Clause 1, Article 25, Decree No. 54/2024/ND-CP.
12. Clause 4, Article 57, Decree No. 54/2024/ND-CP.

Strong decentralization, delegation of power and determination of authority in the field of sea and islands

PHẠM THỊ GẤM
Vietnam Agency of Seas and Island

Implementing the Party and State's policy in Conclusion No. 127-KL/TW dated 28th February 2025 of the Politburo and the Secretariat on studying and proposing to continue to reorganize the apparatus of the political system; Resolution No. 190/2025/QH15 dated 19th February 2025 of the National Assembly on handling a number of issues related to the reorganization of the state apparatus; Decision No. 759/QD-TTg dated 14th April 2025 of the Prime Minister approving the Scheme on rearranging and reorganizing administrative units at all levels and building a model of organizing 2-tier local government dated 12th March 2025,the Government has issued Decree No. 131/2025/ND-CP stipulating the determination of authority of two-tier local government in the field of state management of the Ministry of Agriculture and Environment (MAE); Decree No. 136/ND-CP stipulating the decentralization and delegation of power in the field of agriculture and environment. These Decrees have adjusted current regulations to ensure the implementation of two-tier local government, while strongly decentralizing authority of the Government, the Prime Minister and the Minister of MAE to the local government, improving administrative procedures.

(1) Regarding the determination of authority to the two-tier local government, the authority of district-level government to assign sea areas has been fully determined to communal-level government. According to Article 35, Decree No. 131/2025/ND-CP, the Chairman of the communal-level People's Committee has the authority to assign sea areas, amend, supplement, recognize, and extend the decision on assigning sea areas, allow the return of certain sea areas for Vietnamese individuals with registration dossiers when such individuals must switch from coastal fishing to aquaculture according to the decision of a competent state agency or permanently residing in the area whose main source of income depends on income from aquaculture within the scope of assigned sea areas for aquaculture calculated from the lowest average sea level edge over many years to 3 nautical miles within the scope of management.

(2) Many tasks of the Prime Minister stipulated in the Law on Marine and Island Resources and Environment have been decentralized and delegated to the Minister of MAE, the provincial-level People's Committee and the Chairman of the provincial-level People's Committee. Accordingly, the Prime Minister has delegated power to the Minister of MAE to approve key programs for basic survey of marine and island resources and environment; approve, adjust the program for integrated management of coastal resources with inter-provincial scope; approve the map of zoning of marine and island environmental pollution risks; and approve the system for integrated monitoring and supervision of marine and island resources and environment. Articles 51, 52, 54 of

Nhon Hai fishing village is located along the coast of Quy Nhon (currently Quy Nhon Dong Ward, Gia Lai Province)

Decree No. 136/ND-CP stipulate the authority of the Prime Minister in the field of integrated management of marine and island resources and environmental protection: (i) Delegating power to the provincial-level People's Committee to approve mineral exploitation activities in prohibited areas of the coastal protection corridor; approve other cases permitted to be carried out in archipelagos, islands that must be protected, conserved, and shallow and submerged banks; (ii) Decentralizing to the Chairman of the provincial-level People's Committee to approve land reclamation, sea encroachment, mineral and oil & gas exploration in restricted areas of the coastal protection corridor.

(3) Duties and powers of the Minister of MAE stipulated in the Law on Marine and Island Resources and Environment are strongly decentralized, delegated to the Chairman of the provincial-level People's Committee. Specifically, the authority of the Minister of MAE to grant, extend, amend, supplement, return, and regrant the dumping permit has been decentralized to the Chairman of the provincial-level People's Committee from sea areas outside 6-nautical mile sea areas (calculated from the lowest average sea level edge over many years of the mainland and the largest island of special zones) to the end of the provincial-level administrative management boundary at sea and even in some cases outside the provincial-level administrative management boundary at sea, including projects with investment policy approved and accepted by the National Assembly and the Prime Minister, assigned to the provincial level for management, and projects with investment policy approved and accepted by the provincial-level People's Committee. However, at present, because the administrative management boundary at sea has not been announced, this authority of the Chairman of the provincial-level People's Committee is still within 6-nautical mile sea areas (Clause 1, Article 53, Decree No. 136/ND-CP).

In addition, the authority of the Minister of MAE to grant, re-grant, extend, amend, supplement, suspend, and revoke decisions on granting scientific research licenses to foreign organizations and individuals to conduct in Vietnamese sea areas under the management of the local government is also delegated to the Chairman of the provincial-level People's Committee. This is a very strongly decentralized authority, because according to current regulations, all authority to grant, re-grant, extend, amend, supplement, suspend, and revoke decisions on granting scientific research licenses to foreign organizations and individuals to conduct in Vietnamese sea areas belongs to the Minister of MAE (Clause 2, Article 53, Decree No. 136/ND-CP).

In addition, the authority to assign, recognize, and permit the return of sea areas; extend, amend, and supplement decisions on assigning sea areas has been strongly decentralized in Decree No. 65/2025/ND-CP, but continues to be decentralized. Accordingly, Article 55 of Decree No. 136/ND-CP stipulates that the Minister of MAE to decentralize to the Chairman of the provincial-level People's Committee to assign, recognize, and permit the return of sea areas; extend, amend, and supplement decisions on assigning sea areas from sea areas outside 6-nautical mile sea areas to the administrative management boundary at sea of the provincial level and even some cases outside the administrative management boundary at sea of the provincial level, including projects with investment policy approved and accepted by the National Assembly and the Prime Minister assigned to the provincial level for management, and projects with investment policy approved and accepted by the provincial-level People's Committee. In particular, in the case of assigning sea areas for scientific research, measurement, monitoring, exploration and survey at sea, only decentralize the administrative management boundary at sea of the provincial level. However, at present, because the administrative management boundary at sea has not been announced, this authority of the Chairman of the provincial-level People's Committee is still within 6-nautical mile sea areas. In addition, the entire authority of the Minister of MAE to reclaim sea areas has been decentralized to the provincial-level People's Committee.

(4) The requirement to consult with superior agencies has been removed when authority has been decentralized and delegated to the local government. This provision is to enhance the responsibility of the local government assigned authority when performing their tasks. Specifically, for tasks that have been decentralized and delegated to the provincial-level government with regulations requiring consultation with the Government, the Prime Minister or the MAE (including units under the MAE) before making a decision, from the effective date of Decree No. 136/2025/ND-CP (1st July 2025), the provincial-level government does not have to consult but decide on its own and is responsible for its own decisions (Clause 5, Article 62, Decree No. 136/ND-CP).

Thus, to ensure that the two-tier local government is carried out immediately after the reorganization of the apparatus, regulations related to the authority of the two-tier local government in the field of sea and islands have been fully promulgated. At the same time, decentralization, delegation of power, especially decentralization, delegation of power to the local government in the field of sea and islands has been thoroughly implemented, creating favourable conditions for the local government to be proactive in implementing within the scope of management■

AUTHORITY OF THE COMMUNAL-LEVEL PEOPLE'S COMMITTEE AND THE CHAIRMAN OF THE COMMUNAL-LEVEL PEOPLE'S COMMITTEE IN THE FIELD OF SEA AND ISLANDS

COMMUNAL-LEVEL PEOPLE'S COMMITTEE

1. Participate in responding to and remedying oil and toxic chemical spills at sea; monitor, detect and participate in resolving incidents causing marine environmental pollution and coastal erosion as prescribed in Point d, Clause 2, Article 74 of the Law on Marine and Island Resources and Environment.

2. Manage and protect coastal protection corridors as prescribed in Clause 2, Article 43 of Decree No. 40/2016/ND-CP dated 15th May 2016 of the Government detailing the implementation of a number of articles of the Law on Marine and Island Resources and Environment.

3. Determine the location, boundary, and area of sea areas for cases under the authority of assignment as prescribed in Point e, Clause 4, Article 5 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government.

4. Manage activities of using sea areas for aquaculture as prescribed in Article 41 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government.

CHAIRMAN OF THE COMMUNAL-LEVEL PEOPLE'S COMMITTEE

1. Be a member of the Council for appraisal of the program for integrated management of coastal resources within a province or centrally-run city as prescribed in Point b, Clause 3, Article 16 of Decree No. 40/2016/ND-CP dated 15th May 2016 of the Government detailing the implementation of a number of articles of the Law on Marine and Island Resources and Environment.

2. Decide on assignment of sea areas to Vietnamese individuals for aquaculture as prescribed in Clause 4, Article 8 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government.

3. Recognize sea areas for Vietnamese individuals for aquaculture as prescribed in Clause 5, Article 8 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government.

4. Extend the term of use of sea areas for Vietnamese individuals for aquaculture as prescribed in Clause 5, Article 8 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government.

5. Allow the return of sea areas (in whole or in part) for Vietnamese individuals for aquaculture as prescribed in the Clause 5, Article 8 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government.

6. Amend and supplement the Decision on the assignment of certain sea areas to Vietnamese individuals for aquaculture as prescribed in Clause 5, Article 8 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government.

7. Reclaim sea areas for Vietnamese individuals for aquaculture as prescribed in the Clause 5, Article 8 of Decree No. 11/2021/ND-CP dated 10th February 2021 of the Government stipulating the assignment of certain sea areas to organizations and individuals with the need to exploit and use marine resources, as amended and supplemented by a number of articles in Decree No. 65/2025/ND-CP dated 12th March 2025 of the Government■

Some regulations on decentralization, delegation of power and determination of authority in the field of environment, nature and biodiversity conservation

1. INTRODUCTION

In the context of strong reform of the state administrative apparatus towards streamlining, effectiveness and efficiency, clear determination of authority and responsibility between levels of government, especially at the local level, has become an urgent requirement. Resolution No. 60-NQ/TW dated 12th April 2025 of the 11th Conference of the 13th Party Central Committee clearly defined the policy of building a two-tier local government model (provincial level and communal level), and at the same time ending the operation of district-level administrative units from 1st July 2025. On that basis, ministries and sectors are assigned the task of reviewing and adjusting the legal system to suit the new organizational model, ensuring that state management activities are not interrupted, especially in interdisciplinary and far-reaching areas such as environmental protection and biodiversity conservation.

To implement this policy, the Ministry of Agriculture and Environment (MAE) has submitted to the Government two important draft Decrees: (i) Draft Decree stipulating decentralization and delegation of power in the field of agriculture and environment, in which the key content is to transfer part of the authority from the Government, the Prime Minister and the Minister to the local government, in accordance with practical capacity and management requirements at the grassroots level; (ii) Draft Decree stipulating determination of authority of the two-tier local government in the field of state management of the Ministry to specify the two-tier government model and promptly handle legal gaps arising when abolishing the district level.

On that basis, on 12th June 2025, the Government issued Decree No. 136/2025/ND-CP stipulating decentralization and delegation of power in the field of agriculture and environment (Decree No. 136/2025/ND-CP) and Decree No. 131/2025/ND-CP stipulating determination of authority of the two-tier local government in the field of state management of the MAE (Decree No. 131/2025/ND-CP) creating a legal foundation for decentralization, delegation of power and determination of authority in accordance with the new government model, ensuring unified management from the Central Government and promoting the proactive role of the local government. This article will analyse the core content of the two documents above in the field of environmental protection, nature and biodiversity conservation, clarify the legal basis and new regulations for effective implementation in the coming time.

2. LEGAL AND POLITICAL FOUNDATION OF DECENTRALIZATION, DELEGATION OF POWER

Decentralization, delegation of power and determination of authority in the field of agriculture and environment are not only technical management requirements, but first of all the result of a strategic, comprehensive and consistent policy-making process from the Central Government. Since 2017, Resolution No. 18-NQ/TW of the 6th Conference of the 12th Party Central Committee has laid the foundation for new thinking in organizing the apparatus, emphasizing requirements for innovation, streamlining and efficiency in the operation of the political system. By 2025, Central Government's documents continue to specify that policy in new conditions, especially the requirement to reorganize the local government in a two-tier direction (provincial level and communal level), in accordance with modern governance trends and practical conditions in Vietnam.

Environment, nature and biodiversity conservation are directly affected by socio-economic activities, highly dependent on geographical and ecological conditions and have specific inter-regional and inter-sectoral management characteristics, so delegation of power to the local government is a breakthrough step. The local government is the place that directly receives and handles environmental issues, as well as manages and protects indigenous ecosystems. Therefore, decentralization and delegation of power not only help improve operational efficiency but also ensure timely and flexible responses to risks of environmental degradation and biodiversity loss.

The legal basis for this is clearly established in legal documents and implementation plans. The Law on Government Organization and the Law on Local Government Organization 2025 stipulated the principle of determination of authority between the Central level and the local level in the direction of "strong and reasonable delegation of power, linking

The environment is a sector directly affected by socio-economic development activities

power with responsibility", especially from Article 6 to 9 and from Article 11 to 14. Resolution No. 60-NQ/TW dated 12th April 2025 of the 13th Central Executive Committee emphasized the requirement to organize the two-tier local government, in which maximum power is delegated to the grassroots level, with people at the center. Conclusion No. 155-KL/TW dated 17th May 2025 of the Politburo clearly states principles: Central management is at the macro level, local government is responsible for implementation; decentralization and delegation of power are clear and non-overlapping; promote administrative procedure reform; specifically define between the general authority of the People's Committee and the specific authority of the Chairman of the People's Committee. Plan No. 447/KH-CP dated 17 May 2025 and Decision No. 758/QD-TTg dated 14th April 2025 of the Government assigned the MAE to preside over the development of two Decrees related to decentralization, delegation of power and determination of authority within the scope of its management.

Thus, the promulgation of Decree No. 136/2025/ND-CP on decentralization and delegation of power from the Central government to the local government and Decree No. 131/2025/ND-CP on determination of authority between the two levels of government - not only has a practical basis but also a high consensus from high-level political decisions. This is the step to synchronously institutionalize policies of the Party and the State, laying a clear and transparent legal foundation to reorganize state management in key areas, in which environmental protection and biodiversity conservation are top priorities.

3. CONTENTS OF DECENTRALIZATION, DELEGATION OF POWER IN THE FIELD OF ENVIRONMENT, NATURE AND BIODIVERSITY CONSERVATION

Decree No. 136/2025/ND-CP was issued to decentralize and delegate power of the Government and the Prime Minister to the Minister of MAE and the local government or power of the Minister to the local government according to the Party's policy, ensuring the principles of determination of authority stipulated in the Law on Government Organization 2025, the Law on Local Government Organization 2025, ensuring the initiative of the local government in deciding on their local issues. According to Decree No. 136/2025/ND-CP, contents related to environmental protection, nature and biodiversity conservation are clearly stated in Chapter XI and Chapter XIII, with many new breakthroughs in the approach to local governance.

3.1. Contents of decentralization, delegation of power in the field of environment

According to Decree No. 136/2025/ND-CP, the Prime Minister decentralized and delegated power to the Minister of MAE with following outstanding tasks and powers: Issuing criteria on environmental protection in rural building and development; approving the National environmental monitoring master plan; issuing environmental criteria and certifying projects granted green credit, issuing green bonds according to regulations.

For the local government, the Prime Minister delegated power to the provincial-level People's Committee to issue plans to handle, remediate and restore particularly serious soil contamination in cases specified in Clause 3, Article 15 and in Point c, Clause 1, Article 19 of the Law on Environmental Protection (LEP) and Clause 1, Article 18 of Decree No. 08/2022/ND-CP.

In addition, the Minister of MAE delegated power to the local government to perform a number of notable tasks, powers including: Developing plans to handle, remediate and restore particularly serious soil contamination; directing, organizing the management of dredged mud from canals, ditches and irrigation works under the local management authority to meet environmental protection requirements; stipulating economic and technical norms for the collection, transportation and treatment of domestic solid waste in the province; appraising environmental impact assessment reports, granting environmental licenses (if subject to environmental licensing) for investment projects under the authority of the MAE to appraise environmental impact assessment reports as specified in Clause 1, Article 35 of the LEP. However, this licensing power does not apply to following cases: Investment projects that have investment policy decided and approved by the National Assembly or the Prime Minister; investment projects under the authority of the MAE to grant mineral exploitation licenses, water resource exploitation and use licenses, sea dumping licenses, and decide on assignment of sea areas; investment projects to build and operate infrastructure of concentrated production, business and service areas; investment projects with large land use scale, land with large water surface (excluding hydropower projects, projects with only one or more objectives: planting annual crops, planting perennial crops, propagating and caring for agricultural seedlings)...

3.2. Contents of decentralization, delegation of power in the field of nature and biodiversity conservation

Decree No. 136/2025/ND-CP clearly stipulates decentralization, delegation of power between management levels from the central level to local level.

Fordelegation of power

The Government assigned the Minister of MAE to perform many important tasks such as: Specifying criteria for determining species and management and protection regimes for species in the List of endangered, precious and rare species prioritized for protection; promulgating the List of endangered, precious and rare species prioritized for protection; specifying the order and procedures for appraising dossiers of proposals for inclusion or removal from the List of endangered, precious and rare species prioritized for protection; deciding on species to be included or removed from the List of endangered, precious and rare species prioritized for protection; specifying the authority, order and procedures for bringing species in the List of endangered, precious and rare species prioritized for protection into biodiversity conservation facilities or releasing them into their natural habitats; specifying the authority, order and procedures for granting licenses to access genetic resources; providing information on genetic resources... In addition, the Prime Minister also delegated power to the Minister to decide to establish a national conservation reserve with the entire area located in two or more provinces or centrally run cities and promulgate regulations on the management of conservation reserves and buffer zones.

The Prime Minister delegated power to the Chairman of the provincial-level People's Committee to decide to establish a national conservation reserve with the entire area located in a province with following procedures: Surveying, assessing the current status of biodiversity where the conservation reserve is expected to be established and establishing a project for the national conservation reserve with the entire area under their management; organizing public consultation with the community of residents legally living in or adjacent to the area; establishing an interdisciplinary appraisal council and appraising the project for the national conservation reserve with the entire area under their management...

Fordecentralization

The Prime Minister decentralized to the Minister of MAE following tasks and powers: Approving the conservation program for wild animals and wild plants in the List of species prioritized for protection; approving the conservation program for plant varieties, livestock breeds, microorganisms and fungi in the List of species prioritized for protection; deciding to establish a national wetland conservation reserve with the entire area located in two or more provinces or centrally run cities; recognizing a national natural

The Prime Minister delegates authority to the Chairmans of provincial People's Committees to decide on the establishment of national-level wetland reserves entirely located within their respective localities

heritage located in two or more provinces or centrally run cities or in sea areas where the administrative management responsibility of the provincial-level People's Committee has not been determined; approving the policy of nominating international organizations to recognize international titles for natural heritages.

The Prime Minister decentralized to the Chairman of the provincial-level People's Committee to decide to establish a national wetland reserve having the entire area under their management with following procedures: Organizing survey and assessment of the current status of biodiversity, environment, economy, culture and society of the wetland area where the national wetland reserve is expected to be established; establishing a project for the national wetland reserve; organizing public consultation with the community of residents legally living in or adjacent to the area; establishing an interdisciplinary council and organizing appraisal of the project dossier to establish the national wetland reserve...

In addition, the Chairman of the provincial-level People's Committee also has the authority to recognize a national natural heritage if the entire area is located within the locality with the following procedures: Organizing survey and assessment of the area expected to establish the natural heritage; developing a project for the natural heritage; organizing public consultation on the project to establish the natural heritage; establishing an appraisal council and organizing appraisal of the project dossier to establish the natural heritage...

Finally, the Minister ofMAE also decentralized to the Chairman of the provincial-level People's Committee a number of specific tasks such as granting, extending and revoking licenses to access genetic resources; registering access to genetic resources and allowing the transfer of genetic resources abroad for study and research purposes only, not for commercial purposes; stipulating the organization and operation of the council for appraisal of licenses to access genetic resources; establishing the council for appraisal and conducting appraisal of dossiers for licenses to exploit wild animals and wild plants in the List of species prioritized for protection; granting licenses to exploit wild animals and wild plants in the List of species prioritized for protection...

4. DETERMINATION OF AUTHORITY OF TWO-TIER LOCAL GOVERNMENT IN THE FIELD OF STATE MANAGEMENT OF THE MINISTRY OF AGRICULTURE AND ENVIRONMENT

In the context of reorganizing the local government apparatus according to a model without the district level, clear determination of authority between the provincial level and the communal level is of decisive significance for the effectiveness of state management at the local level. Decree No. 131/2025/ND-CP was issued to ensure the legal basis for the normal, continuous and smooth operation of agencies; to avoid work interruptions, overlaps, duplications or omissions of functions, tasks, fields, areas, etc.

4.1. Determination of authority in the field of environment

The provincial-level People's Committee has the authority to invest in the construction of environmental protection infrastructure works for industrial clusters in cases where there is no investor in the construction and business of industrial cluster infrastructure. The provincial-level People's Committee also has the right to request compensation for damages and organize the collection and appraisal of data and evidence to determine environmental damage caused by pollution and degradation in the area of 02 or more communal-level administrative units; organize the collection and appraisal of data and evidence to determine environmental damage caused by pollution and degradation at the request of the communal-level People's Committee according to regulations. In addition, the provincial-level People's Committee also receives reports on craft villages, approves the environmental protection plan for craft villages of the communal-level People's Committee according to regulations.

The Chairman of the provincial-level People's Committee has the responsibility to grant environmental licenses according to provisions of Clause 4, Article 41 of the LEP for investment projects and establishments belonging to groups I, II, III specified in Appendices III, IV and V issued together with Decree No. 08/2022/ND-CP dated 10 January 2022 of the Government detailing a number of articles of the LEP, as amended and supplemented by Decree No. 05/2025/ND-CP dated 6th January 2025 of the Government, that must prepare a dossier applying for environmental license according to provisions of Article 39 of the LEP when falling into one of following cases: Having domestic wastewater discharged into the environment that must be treated with a total flow rate of 50 m^3/day or more; having industrial wastewater discharged into the environment that must be treated for projects and establishments that pose a risk of causing environmental pollution; having industrial wastewater discharged into the environment that must be treated with a total flow rate of 10 m^3/day or more; having domestic wastewater and industrial wastewater discharged into the environment that must be treated with a total flow rate of 50 m^3/day or more... In addition, the Chairman of the provincial-level People's Committee also has the responsibility to grant, adjust, re-grant, and revoke environmental licenses according to provisions of Point b, Clause 2, Article 168 of the LEP.

The communal-level People's Council has the responsibility to arrange funds to carry out environmental protection tasks according to the current budget decentralization prescribed in Point h, Clause 2, Article 168 of the LEP.

The communal-level People's Committee has the responsibility to make a list of industrial clusters without centralized wastewater collection, drainage and treatment systems in the area and report to the provincial-level People's Committee; synthesize budget needs for environmental protection activities in craft villages according to regulations; direct and implement environmental protection models in craft villages; invest in the construction and organize the operation of solid waste collection and treatment models, on-site wastewater treatment systems that meet environmental protection requirements invested by the State from construction investment funds, environmental expenditure sources and contributions from organizations and individuals according to regulations; manage production, business and service activities to ensure compliance with environmental protection regulations according to approved planning; manage waste collection and treatment at the communal level; invest in and upgrade waste water drainage and treatment systems, collect and treat solid waste in rural areas...

The Chairman of the communal-level People's Committee has the authority to receive environmental registration for projects and establishments subject to regulations; direct incident response, mobilize forces, equipment, and means to respond to environmental incidents, and appoint a commander and a spokesperson for communal-level environmental incidents occurring in the area; establish an unannounced inspection team according to regulations; identify waste incidents, direct response to waste incidents; establish a working group to determine the cause of waste incidents at the communal level immediately after the incident occurs according to regulations

4.2. Determination of authority in the field of nature and biodiversity conservation

The communal-level People's Committee has the authority to send representatives to participate as members of the council for appraisal of projects for provincial-level wetland reserves; send representatives to participate as members of the council for appraisal of projects for provincial-level natural heritages according to regulations.

The Chairman of the communal-level People's Committee has the authority to decide on self-defence plans to protect people's lives and limit damage to wild animals according to regulations.

5. CONCLUSION

In short, the simultaneous development and promulgation of two Decrees on decentralization, delegation of power and determination of authority is a necessary and timely step in the context of Vietnam's transition to a two-tier local government model. This is not only a technical adjustment in administrative management but also demonstrates a profound institutional reform mindset, aiming to build a service-oriented administration, focusing on governance efficiency as the center, and placing people and communities in the position of participating subjects.

Provisions in the two Decrees show a significant change in the way state power is organized at the local level, shifting from formal decentralization to substantive decentralization, from a centralized management model to a multi-center governance model. In which, the highlight is the individualization of the responsibility of the head, clearly defining roles between the provincial level and the communal level, and at the same time creating favourable conditions for the local government to be more proactive, flexible and connected to the socio-ecological realities of each region.

For the field of environment, nature and biodiversity conservation, that requires quick, practical responses and is directly affected by the community - decentralization, delegation of power and determination of authority clearly can bring about strong changes, from reforming administrative procedures to increasing the effectiveness of monitoring, management and conservation. However, for these regulations to be effective, synchronous support in terms of legislation, human resources, finance and technology is needed, along with the involvement of the entire political system and the active participation of the people.

In the international context of increasing pressure on countries on environmental protection and biodiversity conservation, improving national institutions through above Decrees is a prerequisite for Vietnam to affirm its role and responsibility as a developing country with strong determination for the global sustainable development program■

NGUYỄN HẰNG

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State management of land needed to be innovated at the two-tier local government

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Implementing the Party and State's policy on innovation and reorganization of the political system to be streamlined and operate effectively and efficiently, from 1st July 2025 the two-tier local government has officially come into operation. The legal system in general and legislation on land in particular have had renewed regulations, relatively timely supplementing to suit the two-tier local government organization. However, there needs to be additional regulations and instructions in organizing the implementation of state management of land at the local level...

Summarizing the implementation of Resolution No.18-NQ/TW dated 25th October 2017 of the 6th Plenum of the 12th Central Executive Committee, the whole country has been implementing the Party and State's policy on innovation and reorganization of the political system to be streamlined and operate effectively and efficiently. Along with the reorganization and rearrangement of ministries and sectors at the Central level, the reorganization and rearrangement of administrative units at all levels nationwide into the two-tier local government (provincial and communal levels) has officially come into operation since 1st July 2025.

The reorganization and rearrangement of ministries and sectors at the Central level and local administrative levels have a great impact on the legal system and the organization for implementation of legislation in general. Most Laws are affected by the rearrangement and streamlining of the apparatus organization; many socio-economic activities need to be adjusted in the organization for implementation...

After the arrangement of the two-tier local government on 1st July 2025, the number of communal-level administrative units has changed significantly, from a total of 10,035 communal-level administrative units, this number has decreased to 3,321 units, including 2,621 communes, 687 wards and 13 special zones. Thus, there have been 6,714 communal-level administrative units reduced, equivalent to a reduction rate of 66.91%. Like other socio-economic fields, state management of land at the communal level will have to undergo many changes, in which it will both perform functions and tasks of the old communal level and perform new functions and tasks transferred from the old district level.

Right before the two-tier local government officially came into operation, the Government issued 28 decrees on decentralization, delegation of power, and determination of authority when organizing the two-tier local government for socio-economic fields, in order to ensure the legal basis for the two-tier local government to operate smoothly and effectively. In particular, the Government issued Decree No. 151/2025/ND-CP dated 12th June 2025, stipulating the determination of authority of the two-tier local government, decentralization and delegation of power in the field of land. Decree No. 151/2025/ND-CP stipulates the authority, order, procedures for performing tasks and powers of competent agencies and individuals in the field of state management of land as prescribed in laws, resolutions of the National Assembly, ordinances, resolutions of the National Assembly Standing Committee, decrees of the Government, and decisions of the Prime Minister that need to be adjusted to implement the determination of authority, decentralization and delegation of power in the field of land.

On 20th June 2025, the Minister of Agriculture and Environment issued Circular No. 23/2025/TT-BNNMT stipulating the decentralization and determination of authority of state management in the field of land, including:

- Detailing a number of contents in Decree No. 151/2025/ND-CP of the Government stipulating the determination of authority of the two-tier local government, decentralization and delegation of power in the field of land.

- Amending and supplementing a number of articles of legal documents under the authority of the Minister of Agriculture and Environment to implement decentralization and determination of authority in the field of land.

Similar to other fields, land management is affected by the organization of the two-tier local government, requiring many contents related to administrative levels to be renewed, from amending

From July 1st, 2025, land statistics and inventory activities at the local level shall be implemented at the commune and provincial levels

and supplementing relevant regulations to guiding and directing the organization for implementation. Some areas of work that require relatively large changes in state management activities on land include:

- Land use planning and plans;
- Land measuring and cadastral mapping; land registering, preparing and managing cadastral records, issuing certificates of land use right and ownership of assets attached to land; building land database;
- Land statistics and inventories.

To clarify contents that need to be renewed, here are some specific issues:

1. FOR LAND USE PLANNING AND PLANS

The Land Law 2024 stipulates the system of land use planning and plans, including: National land use planning and plans; Provincial land use planning and plans; District land use planning and annual district land use plans; National defence land use planning; Security land use planning. According to provisions of the Land Law 2024, land use planning at all administrative levels includes following levels: national, provincial, and district. When organizing the two-tier local government, there will no longer be a district level, which means there will be no district-level land use planning and plans. The provincial and communal levels will both expand in terms of area, population, etc. due to the merger and consolidation of existing units. Issues raised for the system of local land use planning and plans include: (i) whether or not there are communal-level land use planning and plans to replace district-level land use planning and plans, and how to organize for preparation and implementation of communal-level land use planning and plans? (ii) how to prepare and adjust land use planning and plans for new administrative units?

To address above practical needs, Decree No. 151/2025/ND-CP dated 12th June 2025 on the determination of authority of the two-tier local government, decentralization and delegation of power in the field of land has stipulated land use planning with following main contents:

- Article 14 of the Decree stipulates the responsibility of the communal-level People's Committee, including contents of land use planning and plans such as: Giving opinions on provincial-level land use planning prescribed in Point a, Clause 2, Article 70 of the Land Law; Organizing the preparation and adjustment of communal-level land use planning and 5-year communal-level land use plans prescribed in Articles 19 and 20 of this Decree; Publicly announcing the communal-level land use planning and the 5-year communal-level land use plan prescribed in Articles 19 and 20 of this Decree; Organizing the implementation of local land use planning and plans prescribed in Clause 3, Article 76 of the Land Law; Reporting results of implementation of land use planning and plans to the provincial-level People's Committee before 15 October every year prescribed in Clause 1, Article 77 of the Land Law.

- Article 19 of the Decree stipulates contents of communal-level land use planning and plans, including main contents: Basis for preparing communal-level land use planning; Contents of preparing communal-level land use planning; Mapping, building and updating communal-level land use planning data into the national land database; Provisions for localities, that already have urban planning or zoning planning prepared in accordance with legislation on urban and rural planning, are not required to prepare land use planning; Provisions on public announcement of communal-level land use planning; Adjustment of communal-level land use planning.

- Article 20 of the Decree stipulates contents of communal-level land use plans, including: Basis for preparing communal-level land use plans; Criteria for determining works and projects in communal-level land use plans; Gathering land use needs in preparing communal-level land use plans; Contents of communal-level land use plans; Mapping for communal-level land use plans; Provisions on public announcement of communal-level land use plans; Provisions on adjusting communal-level land use plans; Provisions on continuing to implement unfulfilled land use targets until the next land use plan decided and approved by a competent state agency; The period of the communal-level land use plan is 5 years.

Circular No. 23/2025/TT-BNNMT of the Ministry of Agriculture and Environment on the decentralization and determination of authority of state management in the field of land also stipulates amendments and supplements to a number of articles of Circular No. 29/2024/TT-BTNMT dated 12th December 2024 of the Minister of Natural Resources and Environment stipulating technical requirements on the preparation and adjustment of land use planning and plans including provisions guiding basic contents of communal-level land use planning and plans: Survey, collection of information and documents; Analysis and assessment of natural and socio-economic conditions, state of environment and climate change, assessment of resources directly affecting land use at the communal level; Analysis and evaluation of the current status of land use, land use changes in the past 10 years, and results of implementing the previous land use planning period; Determination of viewpoints, goals, and forecast of trends in land use structure changes; Orientation of land use during the planning period; Development of land use planning options; Contents of the 5-year communal-level land use plan in the communal-level land use planning; Development of reports on communal-level land use planning and 5-year communal-level land use plans; Techniques for preparing communal-level land use plans in cases where communal-level land use planning is not required.

Although the Government and the Ministry of Agriculture and Environment have promptly issued regulations on land use planning and plans when the two-tier local government comes into operation, there are still some issues on organization for implementation that have not been specifically guided, which may lead to inconsistent implementation in localities. Specifically:

- For newly established provinces and cities due to the merger or consolidation of old provinces and cities, should land use planning and plans of new provinces and cities be adjusted and consolidated by "addition" from approved land use planning and plans of old provinces and cities or should new land use planning and plans be re-prepared? This issue requires specific study by scientists and managers to have appropriate regulations, guidelines and solutions, both meeting immediate requirements of planning management and meeting long-term requirements.

On the other hand, the land use planning period is stipulated as 10 years, the land use plan period is 5 years. Currently, it is the middle of the land use planning period (2021-2030), the end of the first period of the 5-year land use plan. Is there a need for guidance on organization for implementation for provinces and cities to prepare an additional (or adjusted) provincial-level land use planning or only prepare a land use plan for 5 years of 2026-2030?

- For communal level: Each new commune needs to prepare land use planning and plan to meet immediate and long-term needs. Therefore, it is necessary to issue specific regulations and instructions for preparing and adjusting communal-level land use planning and plans for new communes; especially for the current planning period (2021-2030), there needs to be specific instructions on following contents: whether to prepare a land use planning for new communes or only prepare a 5-year land use plan (2026-2030) and prepare an annual land use plan; specific requirements on contents of land use planning and plans for the (new) communal level, how to inherit contents from approved district-level land use planning, etc.

2. FOR MEASURING FOR PREPARING CADASTRAL MAPS; REGISTERING, PREPARING AND MANAGING CADASTRAL RECORDS, ISSUING CERTIFICATES OF LAND USE RIGHT AND OWNERSHIP OF ASSETS ATTACHED TO LAND; BUILDING LAND DATABASE

According to provisions of the Land Law 2024 and related legislation, most of state management of land is carried out at administrative levels; many of which are carried out at communal-level administrative units, some local contents are carried out at 3 administrative levels: province, district, commune, and now are decentralized and determined authority at 2 levels: province and commune.

Commune is the basic administrative unit to carry out the state management of land: Measuring for preparing and adjusting cadastral maps; land registering, preparing and managing cadastral records; issuing certificates of land use right and ownership of assets attached to land; building cadastral database, land database. From 1st July 2025, most of new communes and wards are merged from old communes, wards and towns (on average, in the whole country 3 units merge into 1 new unit). New communes and wards have larger areas, leading to following basic impacts on land management contents:

2.1. For measuring for preparing cadastral maps

a. Boundaries of administrative units

Article 49 of the Land Law 2024 stipulates: "Boundaries of administrative units are established according to administrative units at communal, district and provincial levels. Administrative unit boundary records show information on the establishment, merger, division and adjustment of boundaries of administrative units and boundary markers, boundary lines of that administrative unit" and "The People's Committee at the higher level directly directs and guides relevant People's Committees at the lower level to determine boundaries of administrative units in the field and prepare records on boundaries of administrative units within the locality".

The merger of communal-level administrative units changes administrative boundaries, giving rise to following tasks:

- Re-define administrative boundaries of new communes and wards, especially in cases where administrative boundaries of old units are not fully merged.
- Determine the total natural area of new communes and wards.
- Re-prepare administrative boundary maps and records for management.

Thus, there should be regulations and instructions to direct the implementation of above-mentioned tasks to manage administrative boundaries at the communal level.

b. Measuring, preparing and adjusting cadastral maps

Article 50 of the Land Law 2024 stipulates:

1. Cadastral maps are the basis for state management of land and building national land database. Measuring for cadastral mapping is carried out in detail for each land plot according to communal-level administrative units; where communal-level administrative units are not established, cadastral maps are prepared according to district-level administrative units.

2. Cadastral maps must be adjusted when there are changes in the shape, size, area of land plots and other elements related to contents of cadastral maps and at the same time updated in the national land database.

According to current regulations, cadastral maps are prepared for each communal-level administrative unit within the administrative boundary; showing details for each land plot regarding following contents: plot number, land area, purpose of use (land type), land users and some other geographical elements. The cadastral map of each commune may consist of many adjacent cadastral maps at one or more different scales (numbered from 1 to the end for each commune) depending on the density of elements and the accuracy requirements to be shown. Land management based on cadastral maps is management of each land plot. The serial number of land plots (plot numbers) on the cadastral map is numbered in Arabic numerals according to the plot code principle:

< plot code > = < province >< district >< commune >< map sheet >< plot number >

Thus, each land plot has a plot code and address that is unique in the cadastral map system; there are no two duplicate land plots.

When merging communal-level administrative units, the prepared cadastral map used for the new commune may cause problems:

- The map sheet number system is duplicated (if 2 old communes are merged, the new commune will have 2 map sheets number 1; 2 map sheets number 2...) and the address of each land plot is no longer unique, so it does not meet management requirements.
- It is necessary to combine adjacent map sheets of 2 old communes with administrative boundary lines passing through, so it is necessary to handle duplicate plot numbers; in this case, there may be overlaps or gaps when connecting the map border between 2 adjacent map sheets of 2 old communes; or when the map sheets have different scales.

To address above issues, there are currently not enough necessary regulations. The Ministry of Agriculture and Environment only stipulates in principle that the local government organizes implementation in accordance with provisions of the

Law and its guiding documents. In Article 8 of Circular No. 23/2025/TT-BNNMT, the Ministry of Agriculture and Environment has stipulated "Amending and supplementing a number of contents of Circular No. 26/2024/TT-BTNMT dated 26th November 2024 of the Minister of Natural Resources and Environment stipulating technical requirements on measuring and preparing cadastral maps". However, amended and supplemented regulations only include main contents: Provisions on measurement excerpts, presentation and editing of measurement excerpts, and confirmation signatures in measurement excerpt cases; Provisions on central meridians of cadastral maps, and measurement excerpts of cadastral maps when merging administrative units.

Thus, to have a set of cadastral maps for the new commune for long-term land management, there needs to be unified regulations and instructions to implement following contents:

- For communes that have been measured and mapped for the entire commune: Edit and re-prepare cadastral maps: change the name of the province (if any), remove the name of the district, change the name to the new commune; merge, process and edit map sheets with administrative boundary lines running through two old communes; re-number map sheets; re-number plots; update information and other necessary elements.

- For communes that have not been fully measured and mapped according to administrative boundaries or have many changes: It is necessary to conduct additional measurements of missing areas, measure and adjust changes; edit and re-prepare cadastral maps similar to cases where the entire commune has been measured.

The system of cadastral maps of the commune is a very important initial document for next steps: Preparing and managing cadastral records, issuing certificates, and building database. Therefore, the preparation of cadastral maps for new communes must comply with common and unified regulations, avoiding inconsistencies between localities.

2.2. For registering, preparing cadastral records, issuing certificates of land use right and ownership of assets attached to land

a. Re-preparing land records

Article 129 of the Land Law 2024 stipulates: Cadastral records include documents showing detailed information about each land plot, the person assigned to manage the land, the land user, the owner of assets attached to land, the legal status of the land plot and assets attached to land, fully reflecting the current status of land management and use in the area. Cadastral records are prepared in digital format, including following documents: Cadastral maps; Land inventory books; Cadastral books; Copies of various types of certificates.

Article 128 of the Land Law 2024 also stipulates: Cadastral records are prepared for each land plot, ensuring scientific and consistent information in the records with the current status of land management and use; collected according to communal-level administrative units or according to district-level administrative units where no communal-level administrative units are established.

Cadastral records must be fully and promptly adjusted and updated when land users carry out land-related administrative procedures or at the request of competent state agencies, ensuring full reflection of the current status of land management and use in the area.

According to regulations, information in documents of the basic cadastral records must be consistent with each other: Between the cadastral map and the inventory book, the cadastral book, and various certificates. Therefore, when a commune re-prepares its cadastral maps, it must also re-prepare its cadastral records.

To re-prepare the new commune's land records for uniformity, in addition to having to re-arrange the numbering of books (of all types), arrange information and documents, it is also necessary to follow the newly edited system of cadastral maps with new sheet and plot numbers.

Similar to cadastral maps, Article 5 of Circular No. 23/2025/TT-BNNMT on "Amending and supplementing a number of contents of Circular No. 10/2024/TT-BTNMT dated 31st July 2024 of the Minister of Natural Resources and Environment stipulating cadastral records, certificates of land use right and ownership of assets attached to land" also only stipulates a number of contents on amending and supplementing a number of technical operations, on the handover of records and documents, but does not have provisions and instructions on how to prepare, consolidate cadastral records, and adjust cadastral records for new communal-level administrative units. Therefore, there needs to be specific guidance for the local government to implement consistently, ensuring that each new commune and ward has a set of land records in accordance with regulations for long-term land management.

b. Issuing and exchanging certificates

Information on certificates of land use right and ownership of assets attached to land must be consistent with the system of cadastral maps and records used for land management. Therefore, the issuance and exchange of certificates of land use right and ownership of assets attached to land must be carried out in principle for long-term land management. However, this is a large-scale task that affects land users, so there must be specific regulations and implementation plans to ensure limited impact on the people and stability in state management activities on land.

2.3. For building cadastral database, land database

Article 165 of the Land Law 2024 stipulates that the national land database includes following components: Database of legal documents on land; Cadastral database; Database of land survey, assessment, protection, improvement and restoration; Database of land use planning and plans; Database of land prices; Database of land statistics and inventories; Database of inspection, examination, citizen reception, settlement of disputes, complaints and denunciations on land; Other databases related to land.

In which, the cadastral database is the core and most important component, built from the system of cadastral maps and records, so it is also built according to the communal-level administrative units. Other local land databases can also be built according to communal, district and provincial administrative units. Therefore, when new communes and wards come into operation, the structure of the cadastral database and land database must also change for the management and exploitation of the database according to administrative units.

When re-preparing cadastral maps and records due to the formation of new communes, it is mandatory to adjust and update the cadastral database according to the new system of cadastral maps and records (according to map sheet numbers, new plot numbers, etc.) to ensure consistency in management, exploitation and updating of changes in cadastral maps, records and databases.

Due to the absence of district level, changes in provincial and city scale, and changes in communal scale, it is necessary to adjust the structure of local land database from 3 levels (commune, district, province) to 2 levels (province, commune) for components such as Database of land use planning and plans; Database of land prices; Database of land statistics and inventories.

To implement above contents, it is necessary to issue full regulations and instructions for unified implementation by the local government.

3. FOR LAND STATISTICS AND INVENTORIES

Article 57 of the Land Law 2024 stipulates that land statistics and inventories are conducted within the scope of administrative units at communal, district, provincial levels and nationwide. Land statistics are conducted annually, up to 31st December of the statistical year, except for the year in which land inventories are conducted; Land inventories are conducted every 5 years, up to 31st December of the year with the last digit being 4 or 9. People's Committees at all levels organize the implementation of and approve local land statistics and inventories; People's Committees at communal and district levels report to People's Committees at the next higher level on results of land statistics and inventories.

From 1st July 2025, land statistics and inventories at the local level will be carried out at communal and provincial levels. There should be specific regulations on contents, implementation time, and implementation responsibilities in accordance with current requirements at local levels.

The current arrangement and operation of two-tier local government has a great influence and impact on state management of land, requiring a huge amount of work to be done for land management in new conditions, meeting the needs of land management in particular and socio-economic development in general. To effectively carry out the above workload, it is necessary to focus on following contents: (i) Effectively organize the implementation of decrees and circulars stipulating decentralization and determination of state management authority in the field of land; (ii) Continue to study and issue additional regulations and instructions for the local government to implement consistently and effectively; (iii) The local government has specific implementation plans and pays attention to investing resources in organizing the implementation■

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AMBIENT AIR QUALITY LEGISLATION: A comprehensive approach and recommendations for Vietnam

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Air quality deterioration is becoming a global concern due to its serious impacts on human health and the ecological environment. In order to support countries in developing and improving their legal system on air quality, the United Nations Environment Programme (UNEP) has published the Guide on Ambient Air Quality Legislation, 2023 [1]. This document has high orientation value and suggests principles and elements to consider in the process of developing or amending air quality legislation. This article introduces and analyses important contents of the above Guide, thereby providing some recommendations suitable to the context of Vietnam.

1. GLOBAL CONTEXT OF AIR QUALITY LEGISLATION

Air pollution is a transboundary and global issue, but there is currently no comprehensive international treaty that mandates ambient air quality standards (AAQS). However, many regions and nations have enacted regional or national legislation to control and improve air quality.

In Europe, the European Union (EU) is one of pioneers in developing a legal system on air quality with a tight legal framework, typically the Cleaner Air For Europe (CAFE) Directive 2008/50/EC[3]. This Directive not only specifies the AAQS but also establishes a mechanism for monitoring, reporting, public consultation and access to justice, creating a strong legal foundation for member countries to fulfil their obligations to protect the air environment.

In developing regions, soft law agreements play an important role in coordinating regional cooperation. For example, in Africa, regional policy frameworks such as the Lusaka Agreement (South), the Nairobi Agreement (East), and the Abidjan Agreement (Central-West) promote harmonization of AAQS and sharing of monitoring data. In Latin America and the Caribbean, the Regional Action Plan on Air Quality (2022) is also being implemented. In Asia, the Acid Deposition Monitoring Network in East Asia (EANET) has been expanded to include transboundary air pollution.

Another important pillar of global air quality governance is the WHO Global Air Quality Guidelines (WHO AQGs) updated in 2021. Although not legally binding, the AQGs provide a valuable scientific basis for countries to internalize or refer to in the process of developing national standards. Threshold values in the AQGs are based on medical and epidemiological evidence, aiming to protect public health at the optimal level. The AQGs 2021specifically emphasize key pollutants such as $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3- and recommend their gradual application according to practical conditions of each country [2].

In addition, many countries have enacted separate laws or integrated regulations on air pollution into environmental laws, demonstrating the trend of considering clean air as a human right. The historic decision of the United Nations General Assembly (UNGA) in July 2022 officially recognized the human right to a clean, healthy and sustainable environment [5]. This decision not only enhances the political and legal status of the air pollution issue but also creates a basis for individuals and organizations to request the State to fulfil its obligations to protect the air environment.

The COVID-19 pandemic has further highlighted the link between air quality and public health. Several studies have shown that areas with high air pollution have higher COVID-19 mortality rates due to prolonged exposure that weakens the respiratory system. In addition, the lockdown measures during the pandemic have demonstrated that improving air quality is possible with coordinated policy and strong political will.

In general, the current global context is opening up favourable opportunities for countries, including Vietnam, to build a strong legal framework, based on principles of the rule of law, science and environmental justice. The Guide of the UNEP 2023 isdeveloped in that context, as a strategic document to support the process of transforming awareness into specific legislative action [1].

2. NATIONAL LEGISLATIVE FOUNDATION: CORE ELEMENTS

An effective legal system on ambient air quality (AAQ) cannot stop at setting technical parameters, but needs to be structured on a comprehensive legislative foundation, including clear objectives, solid scientific basis, effective promulgation and enforcement mechanisms, as well as ensuring full participation of stakeholders. Accordingly, six core elements are necessary to develop and operate an effective legal system in this field.

First, laws or national policies on air quality should clearly define directional goals, not only limited to reducing pollution concentrations, but also aiming at protecting public health, ensuring environmental justice and realizing the human right to clean air. These goals should be specified through quantitative commitments or implementation roadmaps. International experience shows that the Clean Air Conservation Act 2022 of South Koreatargets a 30% reduction in transport emissions by 2030, while the EU Directive 2008/50/EC sets both mandatory legal values and recommended target values. In Vietnam, the Law on Environmental Protection 2020 has mentioned air quality as a state management content, but still lacks specific quantitative commitments, making implementation unoriented and difficult to quantify effectiveness.

In addition, a mandatory requirement in the process of developing air quality standards is the use of reliable scientific evidence and epidemiological data. WHO has published the global Air Quality Guidelines 2021 (AQGs), which update the safety thresholds for six major pollutants such as $PM_{2.5}$, NO_2, SO_2, O_3, CO and PM_{10}. Countries are recommended to internalize them according to a roadmap appropriate to national conditions. Referencing these recommendations should become a legal obligation in the process of establishing or amending national technical regulations. In Vietnam, current thresholds specified in QCVN 05:2013/BTNMT on PM2.5 are still 5 times higher than WHO recommendations [7], indicating a significant gap between the current legal framework and international scientific standards.

In terms of legal form, AAQ standards should be issued through documents with high legal value such as laws, decrees instead of existing only in non-binding technical regulations or action plans. This is to ensure enforcement, as a basis for sanctioning violations and create a foundation for judicial or administrative tools. Many countries such as South Africa, Israel and Mexico have enacted specific laws on clean air, which clearly stipulate the scope of application, mandatory parameters, and enforcement mechanisms [4]. Vietnam currently mainly regulates pollution thresholds through the technical regulations system (QCVN), which is not legally effective enough to prosecute violations. Therefore, integrating AAQ standards into the main legal system or developing a separate law on clean air is a necessary direction.

Along with that, defining responsibilities among levels of authority and functional agencies is also a core element. Countries need to clearly define the authority to issue standards, the agency responsible for monitoring, and the forms of inter-sectoral coordination. The US model with the Clean Air Act, which gives the authority to set standards to the federal Environmental Protection Agency (EPA), but allows states to apply more stringent regulations, is a typical example [4]. In Vietnam, the responsibility for managing air quality is still dispersed: the Ministry of Agriculture and Environment plays a focal role, but monitoring capacity depends largely on local authorities and data is not effectively shared among sectors such as transportation, industry and trade, and health.

An important and indispensable principle is transparency and public participation. The Aarhus Convention has established three basic rights of people in the environmental field: right of access to information, right of consultation and right of access to justice[4]. The legal system on AAQ needs to ensure the publication of real-time air quality data, organize public consultations during the policy making process, and create favourable conditions for people and civil society to file lawsuits or report if the air quality is violated. Although some platforms providing AQI have appeared in Vietnam, the data system is still inconsistent, incomplete and the ability of people to independently monitor is limited.

Finally, legislation needs to demonstrate a clear commitment to protecting vulnerable populations such as children, the elderly, pregnant women, and those living in areas of chronic high pollution. This requires a legal system that is not only universal, but also incorporates elements of environmental justice, through provisions that prioritize actions, require social impact assessments in environmental policies, and collect data disaggregated by gender, age, and geographic location. This is an important step in ensuring that no one is left behind in the governance of air quality.

In summary, six elements mentioned above are the basic legal foundation that every country needs to consider when developing a legal system on ambient air quality. Designing policies based on these elements will contribute to improving enforcement, enhancing accountability and realizing the right to live in a clean environment for all citizens.

3. MONITORING, ENFORCEMENT AND COMPLIANCE

Establishing air quality standards is only one part of the legal framework for protecting the air environment. A legal system that is to be effective in practice needs to have reliable monitoring mechanisms, effective sanctions and strong enforcement capabilities, while also creating favourable conditions for citizens and civil society to participate in monitoring the implementation process.

Monitoring - the foundation of law enforcement: The air quality monitoring system is the first and most important element in assessing the level of compliance with the established standards. Monitoring must be designed in a scientific, transparent and early warning manner, including continuous measurements at fixed stations and instant measurement methods (mobile, satellite, low-cost sensors). Measurement data must cover key areas such as densely populated urban areas, industrial zones, and pollution “hotspots” and must be frequent enough to reflect real-time developments. The monitoring system serves not only a technical purpose but also has legal value, as a basis for identifying violations, assessing results of action plans, and establishing obligations for polluters.

Air quality zoning and improvement plans: An important mechanism for ensuring legal compliance is air quality zoning - identifying areas that exceed pollution thresholds and where specific management measures can be applied. The legal system should clearly define the responsibility for developing and implementing air quality improvement plans for each classified area.

Sanctions and enforcement mechanisms: One of the biggest weaknesses in enforcement of environmental legislation in many countries is the lack of strong sanctions and the lack of practical enforcement capabilities. In some countries, serious air polluting activities such as open burning of waste, operating industrial equipment without dust collection systems, or vehicles with excessive emissions are often handled only with administrative fines, which are not enough of a deterrent. Currently, laws of many countries are expanding sanctions by allowing civil or environmental lawsuits against public authorities when they fail to protect air quality; Establishing criminal liability for persistent excess emissions (Germany, Japan); Applying economic sanctions such as pollution taxes, emission pricing, or closing facilities if they do not meet technical standards [4,9].

Rights of citizens and the role of civil society: A core element of clean air governance is ensuring the role of social monitoring and criticism. Legal mechanisms should affirm rights of citizens to access real-time air quality data; to receive early warnings when pollution exceeds thresholds; to comment to draft policies and action plans; and to file complaints, lawsuits or compensation claims when directly affected by air pollution.

4. SOME RECOMMENDATIONS FOR VIETNAM

Air quality is the result of a combination of many factors from traffic, industrial, construction, agricultural emissions to natural conditions such as climate and terrain. Therefore, air quality management cannot be placed solely on the shoulders of a specialized environmental agency, but requires multi-sectoral, inter-regional and inter-level coordination, with clear responsibilities and unified management mechanisms.

One of the biggest challenges today is the phenomenon of “institutional fragmentation” when each sector, each local authority implements individual policies without coordination, leading to overlap, gaps or even policy conflicts. Many countries have established national or metropolitan-level interdisciplinary councils to coordinate clean air policies. For example, Mexico established a National Air Policy Coordination Committee with the participation of ministries and sectors such as environment, energy, transport, health and finance.In India, a new Air Quality Management in National Capital Region and Adjoining Areas Act (2021) has established an intergovernmental body with monitoring, coordination, and enforcement powers for neighbouring states. These models show that coordination is not just an administrative process, but also requires a clear legal framework to define responsibilities, financial mechanisms, data sharing, and conflict resolution.

In Vietnam, the Law on Environmental Protection 2020 has made progress in clearly defining responsibilities between central and local authorities in air protection, requiring pollution control planning, and encouraging the use of economic instruments. However, the current coordination mechanism is still limited, mainly voluntary, lacking mandatory regulations on information sharing, and specific assignment of responsibilities among ministries and sectors, as well as local authorities with sources and impacts of transboundary pollution. The lack of a coordinating agency with independent legal authority makes it difficult for clean air policies to achieve consistency and synchronization across the system.

Based on analysis from the Guide of the UNEP and management practices in Vietnam, this article proposes some key recommendations to improve ambient air qualitylegislation and institutions:

Firstly, Vietnam needs to soon internalize WHO recommendations on air quality standards, especially for PM2.5, according to a roadmap suitable to economic and technical conditions of each region [2,7]. Adjustments to QCVNs need to be made publicly, with independent scientific consultation and linked to policy impact assessments, in order to create a solid legal basis for pollution control plans and sanctions for violations.

Secondly, it is necessary to upgrade the legal status of AAQ standards from the level of technical regulations to binding regulations in higher-level legal documents such as decrees, specialized laws or integrate into the Law on Environmental Protection. This will ensure enforcement and create a foundation for determining legal obligations of the State, enterprises and other emission entities [6].

Thirdly, establish a modern, synchronous and open national air quality monitoring network. Data should be collected according to unified technical standards, updated in real time, made public on digital platforms, and interconnected among sectors, local authorities and communities. In addition to the fixed station system, it is necessary to encourage the deployment of mobile sensors, citizen science and digital platforms for people to participate in monitoring [8].

Fourthly, establish a central-level inter-sectoral clean air policy coordination agency, with representatives from the Ministry of Agriculture and Environment, the Ministry of Health, the Ministry of Construction, etc., and key provinces and cities [6]. This agency should be empowered to propose, monitor, and evaluate the implementation of clean air plans at the local level, and have an independent budget to implement cross-sectoral initiatives.

Fifthly, need to enhance the role of the public and civil society in enforcing the air quality legislation. Legislation needs to clearly stipulate the right to access real-time environmental information, the right to participate in giving opinions on policies and action plans, as well as the right to sue or request compensation if affected by air pollution. The environmental complaint-denunciation-mediation mechanism also needs to be designed in accordance with characteristics of the air sector which is pervasive, has unclear sources, but has far-reaching and long-lasting impacts.

Finally, the development of air quality legislation needs to incorporate the principle of environmental justice protecting vulnerable groups, ensuring fair distribution of benefits and costs in pollution management, and encouraging the development of market-based policy instruments (environmental taxes, emission credits, clean air funds, etc.) to create long-term motivation for changing emission behaviour.

Institutional coordination and regulatory improvement are prerequisites for translating technical standards into tangible results: cleaner air, improved public health, and a transparent and efficient regulatory ecosystem. As a developing country heavily impacted by air pollution, Vietnam should consider this a policy priority in the coming period■

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Transboundary haze pollution problem in Southeast Asia

Transboundary haze is a recurring air pollution issue in Southeast Asia caused mainly by slash-and-burn agriculture and peatland fires, particularly in Indonesia, that drifts across national borders, leading to severe health, environmental, and economic impacts. ASEAN has experienced periodic episodes of transboundary haze pollution resulting from land and forest fires caused by seasonal burning to clear vegetation on the ground for various purposes. Despite more than a decade since the ASEAN Haze Agreement came into force, the problem still recurs and sometimes with serious consequences to health, transportation, tourism, and other activities. What is urgently needed is a reframing of the way the issue is being currently addressed, i.e. mostly tackling at the tail-end of the problem of putting out the fires after they have been lit rather than preventing or curbing the illegal burning practices at source. It also represents balancing economic development initiatives with environmental protection and international relations concerns.

ROOT CAUSES OF TRANSBOUNDARY HAZE

One of the main causes of smoke haze is the result of uncontrolled burning to clear the land for other development purposes such as for growing agricultural crops like corn and plantation trees such as pulpwood, rubber or oil palm. Where legal restrictions are absent due to the lack of appropriate rules prohibiting the use of fires for land clearance or otherwise where enforcement of such regulations is weak, then burning becomes the economically cheapest way to clear land without incurring heavy penalties and thus further encouraging such environmentally and socially unsound practices. Moreover, the draining of peatlands found in many parts of Southeast Asia and especially on the Indonesian islands of Sumatra and Kalimantan for development greatly increases the risk of fire and haze due to peat's smoke generating characteristics when burnt and the fact that it can burn through the peat seam layers underground which are out of sight and thus become difficult to control. Other factors which could also contribute to the problem include overlapping rules and regulations among the concerned government agencies thus creating gridlock and/or loopholes in the process, the lack of adequate information and/or awareness, limited resources (capital, equipment, personnel, amongst others) as well as the lack of political will to tackle the problem, the strong patronage and/or special links between the main perpetrators and the relevant authorities and therefore overriding the rule of law and good governance, and the associated private and/or individual profit motives including corruption practices such as bribery at the expense of social and/or environmental costs and public goods at large. In brief, the basic issue could be summed up as lax compliance by land developers and poor enforcement and the lack of capacity on the part of concerned authorities including having weak judicial systems. It also reflects the need to balance economic development initiatives with appropriate environmental protection concerns as well as maintaining good international relations and image including corporate social responsibility and/or socially responsible investing. The impacts resulting from fires and transboundary haze, however, could be significant and include: Losses to property and/or degradation of natural resources, forest, biodiversity, and ecosystem including damage to agricultural production. Increase in emissions of greenhouse gases and other hazardous pollutants. Harmful effects on health including injuries and fatalities to humans and animals leading to untimely ailments and even early deaths. Adversely affecting various modes of transport operations due to safety concerns including accidents arising from poor visibility. Negative impact on tourism and business. Rights to clean air, good health, and quality livelihoods being denied to numerous affected communities and ordinary citizens. Strained neighbourly relations amongst ASEAN member countries, if not others. Seriously dent the image of ASEAN solidarity and effectiveness.

THE IMPACTS OF TRANSBOUNDARY HAZE

Transboundary haze is a recurring environmental disaster in Southeast Asia, primarily caused by land and forest fires, particularly in Indonesia and Malaysia, for agricultural purposes. It has severe impacts on health, the environment, and the economy.

Health impacts: Transboundary haze is a major public health crisis. The smoke contains high levels of fine particulate matter ($PM_{2.5}$), which can penetrate deep into the lungs and cause significant health problems.

Respiratory and cardiovascular illnesses: Exposure to haze is directly linked to a sharp increase in respiratory ailments like asthma, bronchitis, and acute respiratory infections. It also exacerbates cardiovascular conditions, leading to an increased risk of heart attacks and strokes.

Premature deaths: Severe haze events have been associated with a rise in premature deaths, with some studies estimating tens of thousands of deaths across the region from conditions related to the poor air quality.

Other symptoms: Haze also causes immediate physical symptoms, including eye and skin irritation, sore throat, and headaches, and can lead to psychological stress among the affected population.

Environmental Impacts: The fires that cause the haze are a major source of environmental degradation, harming ecosystems and contributing to climate change.

Deforestation and Biodiversity Loss: The "slash-and-burn" clearing method destroys vast areas of forests and peatlands, which are critical habitats for many endangered species, including the orangutan. This leads to a severe loss of biodiversity.

Increased greenhouse gas emissions: The burning of carbon-rich peatlands releases enormous amounts of carbon dioxide (CO_2) and other greenhouse gases into the atmosphere. The 2015 haze crisis in Indonesia alone was estimated to release more daily emissions than the entire U.S. economy.

Soil degradation: Fires can sterilize and degrade soil quality, making it less fertile and more vulnerable to erosion.

Economic impacts: The economic costs of transboundary haze are staggering, causing billions of dollars in losses across the region.

Disruption of business and tourism: Haze severely disrupts daily life and economic activity. Airports often face flight delays and cancellations due to poor visibility, impacting tourism and logistics. Tourism, a vital sector for many Southeast Asian economies, sees a sharp decline during haze seasons.

Productivity and healthcare costs: The rise in haze-related illnesses leads to increased healthcare costs and a loss of productivity as workers stay home or work less efficiently. Schools are often forced to close for days or weeks, disrupting education.

Agricultural damage: The fires and smoke can damage crops and reduce agricultural yields, directly affecting the livelihoods of local farmers. The fires themselves destroy valuable plantations and agricultural land.

Political and social impacts: Transboundary haze is a significant source of diplomatic tension and social strife in the region.

Strained international relations: The recurring nature of the haze has often strained diplomatic ties between affected countries, particularly between Indonesia and its neighbors, Malaysia and Singapore. The ASEAN Agreement on Transboundary Haze Pollution was signed in 2002 to foster regional cooperation, but its effectiveness has been limited.

Social disruption: The persistent haze creates a sense of helplessness and frustration among the public, who feel that their right to clean air and a healthy life is being denied.

POTENTIAL SOLUTIONS

Transboundary cooperation is important when natural resources and environmental spaces are shared. It helps promote better understanding and exchange of knowledge and concerns between neighbouring countries and leads to collective responses to shared problems such as transboundary haze pollution, allowing new opportunities and ways of overcoming these common threats. The ASEAN Agreement on Transboundary Haze Pollution (AATHP) which came into force in 2003 received a boost when Indonesia submitted its instruments of ratification to the ASEAN Secretary General on 20th January 2015, thus completing the ratification process of this Agreement by all 10 ASEAN member countries. With Indonesia finally coming on board, more concerted and cooperative actions should hopefully follow to address the problem. However, one major shortcoming of the AATHP is that there is no sanction clause for failure to meet the stipulated obligations, it is after all the ASEAN Way of resolving disputes diplomatically, through consultation and negotiation. Perhaps that is one reason why Singapore enacted its own Transboundary Haze Pollution Law in 2014 which seeks to take civil and criminal liability actions against entities responsible for causing or contributing to transboundary haze pollution in Singapore. Effective implementation of this measure is likely to be problematic due to the extra-juridical, territorial, and national sovereignty issues involved coupled with the difficulty of making irrefutable attribution or correlation between cause and effect of the problem. However, it could readily serve as a 'warning shot' to highlight the urgency of tackling the issue in a more serious and timely manner. Just like merely institutionalising a zero burning policy across the board, while desirable, is probably not going to be a fully effective solution by itself but can help direct appropriate attention and response pertaining to the matter.

Nevertheless, further actions in areas such as the following are required: More efficient and timely sharing of information, especially identifying specific locations on land clearance, hotspots, and actual burning areas as well as haze movement among ASEAN member countries which would facilitate early detection and enhance quick response and thereby help address the problems instantly rather than causing them to get out of control. One major constraint in this connection is the release of such vital information in a timely and responsive manner. A clear example of this is an earlier decision to pursue setting up the ASEAN Subregional Haze Monitoring System (HMS) for the above-stated purpose. However, and concerns over sharing of information on sensitive matters pertaining to territorial integrity and sovereignty and extra juridical issues has slowed the process. So although the concept of having the HMS was discussed before, its operationalisation has been stalled. Strictly enforcing relevant laws and policies pertaining to the fire and/or haze problem, streamlining institutional capacity, and introducing more simplified procedures that enhance the cost effectiveness of implementation. It would also be worth considering having some kind of sanction provision for noncompliance.

ASEAN member states do have laws governing prohibition and/or limitation on burning vegetation especially during certain restrictive conditions and/or time periods. However, the problem is they are not always strictly enforced often due to dereliction of duty by the concerned authorities and/or overlapping jurisdiction by agencies pertaining to the issues at hand. In some cases, there may be a lack of capacity to adequately cover the areas in question coupled with meagre resources available to track developments and make appropriate interventions. One bottleneck that has occurred especially in the rapid deployment of needed resources is the amount of bureaucratic red tape that is encountered in obtaining the necessary clearances. So much time is lost in the approval process, thus delaying the implementation of the required urgent actions.

Finally, for the rules and regulations to be meaningful and enforceable, strict compliance and enforcement coupled with appropriate sanctions and/or penalty provisions are necessary. However, this is an area where many ASEAN countries are lacking and weak at both the national level as well as at the regional level including in the ASEAN Haze Agreement. Vigorous promotion in conjunction with the provision of incentives for encouraging non-burning alternatives for clearing land, particularly in the sustainable management of peatlands and raising awareness of the potential cobenefits that could be derived through such practices which would be for mutual interest and bring about collective gain. Attempts have been made in both ASEAN subregional frameworks for fighting the fire and/or haze problem to engage the concerned private sector more pro-actively and vigorously in finding solutions which could yield win–win results. Properly internalising the externalities and costs of burning in the business models of the relevant corporate sector through a suitable combination of rewards and punishment would encourage a shift towards adopting less damaging methods of land clearing from economic, environmental, and social points of view.

Governments of ASEAN countries should also institutionalise policies and legislation that would provide suitable incentives and/or disincentives to move in a more desirable and sustainable path of development. Improving coordination to develop good understanding, close rapport, and active cooperation including enhancing capacity and awareness between all relevant stakeholders such as government agencies, private developers, small farmers, civil society groups, and local communities on the fire and haze issue, including the possible causes and the potential solutions. It goes without saying that to successfully address the fire and haze issue in ASEAN requires a multistakeholder approach and framework involving all relevant parties and on an equitable footing or representation. A constructive enabling environment needs to be created so that all concerned entities feel they are properly informed and have a meaningful stake in solving the problem. Having appropriate corporate social responsibility initiatives and/or socially responsible investing could also help in the process and support moving in the right direction. Educating ASEAN and other consumers about the causes and effects in the chain of events or complete life cycle analysis of the entire production systems from agricultural and/or forestry land with links to the fire and/or haze problem and its corresponding consequences leading to more active consumer understanding, engagement, and action for adopting more environmentally and socially sound solutions. Building up such like-minded coalitions of the willing is essential if there is any hope of combating the fire and haze problems in the Southeast Asian region. Adopting eco-labelling standards for encouraging more sustainable consumption and production processes by the public at large would go a long way in sending the right signals to the producers of agricultural and forestry land to implement more environmentally friendly non-burning methods of cultivation.

ASEAN REAFFIRMS COMMITMENT TO TACKLE TRANSBOUNDARY HAZE WITH FINANCIAL FRAMEWORK

The ASEAN Investment Framework for Haze-Free Sustainable Land Management (AIF) aims to mobilise an estimated of USD 1.5 billion by 2030 to address the root causes of the transboundary haze across sub-region. Complimenting these efforts, the ASEAN Secretariat with Global Environment Centre (GEC) under IFAD-financed Measurable Action for Haze-Free Sustainable Land Management in Southeast Asia (MAHFSA) Programme has identified a total of USD 1,231,000 million from the 39 ongoing projects and 23 identified pipeline projects aligned with the AIF objectives. This highlights the need for coordinated efforts and resource mobilisation following the endorsement of AIF in August 2023.

The Partners Dialogue on AIF-HFSLM – Sustainable Investment in Tackling Haze for Better Living took place on 13th August 2024, held in parallel with the 9th ASEAN Task Force on Peatlands (ATFP) in Bangkok, Thailand. This Dialogue served as a platform to engage stakeholders, share inputs and explore potential strategies to support the development of the Implementation Plan for the AIF, as well as to highlight ASEAN commitment to enhance investment in sustainable practices. Marking the first event for the AIF since its endorsement, this Dialogue signifies a crucial step toward realising the shared vision of a haze-free and sustainable ASEAN by 2030.

ASEAN reaffirmed their commitment to supporting the partners of AIF to ensure the smooth coordination from ASEAN perspective. ASEAN Secretariat's Head of Environment, Dr. Vong Sok reiterate the framework's 5 broad objectives designed to address peatland and haze-related matter, offering various opportunities for partners to participate according to their interests and priorities. He also expressed his appreciation for the active participation of partners in joining the initiative. AIF aligns with other ASEAN frameworks such as the Second ASEAN Peatland Management Strategy (APMS 2023-2030), the Second ASEAN Cooperation on Transboundary Haze Pollution Control with Means of Implementation (ASEAN Haze-Free Roadmap 2023-2030) and the ASEAN Sustainable Finance Taxonomy. It emphasises sustainable financing, community empowerment and integrated land management.

The Dialogue's discussion session was preceded by six presentations from Global Green Growth Institute (GGGI), IFAD, Asian Development Bank (ADB), Sustainable Rice Platform (SRP), USAID Partnerships for Green Investment (PAGI), and The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ-Thailand) presented their ongoing and pipeline projects, highlighting their potential alignment with the AIF.

A total of 35 representatives from 17 international stakeholders and funding partners participated in the Partners Dialogue on AIF – Sustainable Investment in Tackling Haze for Better Living. Some of the key suggestions and recommendations raised by the participants focused on the importance of linking sustainable land management initiatives to prevent duplication and enhance synergy among projects. Participants urged the mobilisation of donor forums and national investment agencies to better coordinate efforts and maximize the impact of available resources. Other points highlighted are challenges in peatland carbon projects and critical role of the ASEAN Secretariat in guiding the AIF initiatives. Another key suggestion included establishing a directory of partners and a registry of projects to ensure transparency and collaboration, as well as strategic use of existing ASEAN mechanisms.

Participants also highlighted the need for additional funding, proposing innovative approach such as utilising the ASEAN Regional Clean Air Fund and establishing a sustainable rice financing facility. Participants also suggested linking the AIF to Partnerships for Green Investment (PAGI), a new USAID-funded project aimed at supporting sustainable land use practices in Southeast Asia, focusing on emissions reductions, climate resilience, biodiversity protection, inclusiveness, and benefit sharing. The participants stressed the importance of engaging a broader range of stakeholders, including urban dwellers in funding mechanisms, which is crucial for the success of these initiatives.

The Dialogue marks a significant milestone in the collaborative efforts to tackle the transboundary haze issue in ASEAN. As the region moves toward a haze-free future by 2030, the commitments made by stakeholders and the active participation of diverse partners demonstrate the importance of unified action. With continued engagement, resource mobilization, and strategic alignment of projects through frameworks like AIF, ASEAN is ready to strengthen its sustainable land management practices and ensure a healthier, haze-free environment for its people. The road ahead requires collective action, innovative solutions, and long-term funding to address the root causes of haze, however this Dialogue has set a promising foundation for transformative impact■

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HIỀN NHÂM

THE WEF GLOBAL RISKS REPORT 2025: Increasingly fragmented global landscape

The Global Risks Report 2025, the 20th edition from the World Economic Forum, reveals an increasingly fragmented global landscape. It highlights a decline in optimism and a growing sense of instability due to a combination of geopolitical, environmental, societal, and technological challenges. The report, based on a survey of over 900 global experts and leaders, highlights a sharp decline in optimism and a growing sense of instability across geopolitical, environmental, societal, and technological domains. The report categorizes risks by two time horizons: immediate (over the next two years) and long-term (over the next ten years).

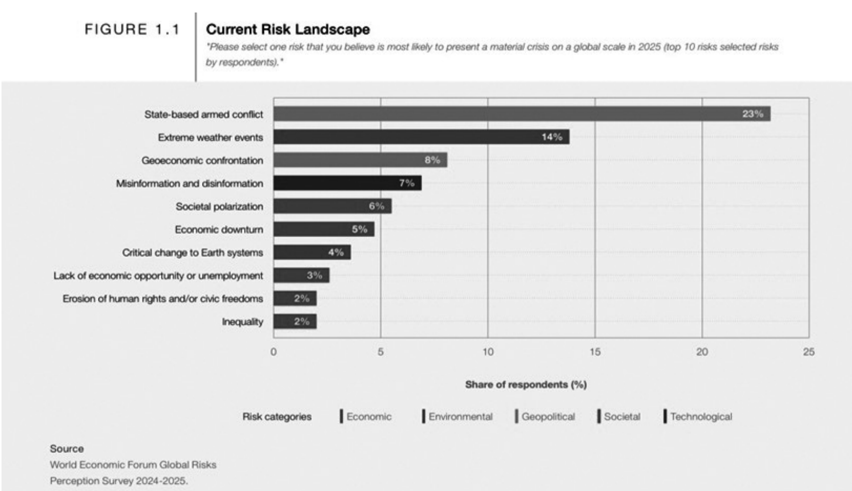


Figure 1. Current Rick Lanscape

The Global Risks Report 2025 presents the findings of the Global Risks Perception Survey 2024 - 2025 (GRPS). The report analyses global risks through three timeframes to support decision makers in balancing current crises and longer-term priorities. Chapter 1 explores current or immediate term (in 2025) and short-to medium-term (to 2027) risks, and Chapter 2 focuses on the risks emerging in the long term (to 2035). The report considers not only the survey findings and the range of implications, but also provides six in-depth analyses of selected risk themes.

The 20th Global Risks Report continues to shine a light on globally relevant risks that are often complex and sometimes alarming. Yet, in examining the trajectory of the risks foreseen over the last two decades, it is clear that there is no viable alternative to multilateral solutions going forward. Leaders across the public and private sectors, civil society, international organizations and academia must seize the baton to work openly and constructively with each other. By deepening honest dialogue and acting urgently to mitigate the risks that lie ahead, we can rebuild trust and together create stronger, more resilient economies and societies.

1. GLOBAL RISK PERCEPTIONS OVER THE SHORT TERM (2 YEARS)

As we enter 2025, the global outlook is increasingly fractured across geopolitical, environmental, societal, economic and technological domains. Over the last year we have witnessed the expansion and escalation of conflicts, a multitude of extreme weather events amplified by climate change, widespread societal and political polarization, and continued technological advancements accelerating the spread of false or misleading information. Optimism is limited as the danger of miscalculation or misjudgment by political and military actors is high. We seem to be living in one of the most divided times since the Cold War, and this is reflected in the results of the GRPS, which reveal a bleak outlook across all three time horizons – current, short-term and long-term.

State-based armed conflict: This is identified as the most pressing immediate concern, reflecting escalating geopolitical tensions and a fractured international order. Nearly a quarter of respondents cited it as the top threat. The current geopolitical climate, following Russia's invasion of Ukraine and with wars raging in the Middle East and in Sudan, makes it nearly impossible not to think about such events when assessing the one global risk expected to present a material crisis in 2025: close to one-quarter of survey respondents (23%) selected State based armed conflict (proxy wars, civil wars, coups, terrorism, etc.) as the top risk for 2025. Compared with last year, this risk has climbed

Figure 2. Change in short-term (2 year)

from #8 to #1 in the rankings. Geopolitical tensions are also associated with the rising risk of Geoeconomic confrontation (sanctions, tariffs, investment screening), ranking #3, which is also driven by inequality, societal polarization and other factors.

Misinformation and disinformation: This risk remains a leading short-term concern. It is seen as a key driver of instability, eroding public trust and exacerbating societal divisions, especially with the rise of sophisticated AI-generated content. The advent of new technologies and the increase in user-generated content platforms is leading to a corresponding rise in the volume of content online. Flows of misinformation and disinformation from those creating it are becoming more challenging to detect and remove in an increasingly fragmented media landscape. Differentiating between AI- and human-generated false or misleading content in the form of video, images, voice or text can be difficult. Gen AI lowers the barriers for content production and distribution, and some of that content is inaccurate. Threat actors, state agencies in some countries, activist groups, and individuals who may or may not have criminal intentions can automate and expand disinformation campaigns, greatly increasing their reach and impact. Misinformation and disinformation can also be the result of AI-hallucinated content or human error, and these too are likely to rise amid the growing volume of content. The upshot is that it is becoming increasingly hard to know where to turn for true information. Both political and societal polarization skew narratives and distort facts, contributing to low and declining trust in media. Across a sample of 47 countries, only 40% of respondents said that they trusted most news. According to the EOS, respondents in high-income countries are generally more likely to express concern about the risk of misinformation and disinformation over the next two years than respondents in lower-income countries, with some exceptions.

Extreme weather events: The increasing frequency and severity of extreme weather events are a significant immediate threat, causing widespread disruption and economic damage. The risks associated with extreme weather events also is a key concern for the year ahead, with 14% of respondents selecting it. The burden of climate change is becoming more evident every year, as pollution from continued use of fossil fuels such as coal, oil and gas leads to more frequent and severe extreme weather events. Heat waves across parts of Asia; flooding in Brazil, Indonesia and parts of Europe; wildfires in Canada; and hurricanes Helene and Milton in the United States are just some recent examples of such events.

Societal polarization: Deepening social and political divides, both within and between nations, are seen as a major risk, complicating collective action and undermining global stability. Respondents identifying this risk often also highlight societal polarization as one of the most severe risks in the same timeframe. Poor quality content and lack of trust in information sources continue to present a threat to societies. Algorithms, especially complex machine learning models, can also be an entry point for cyber attacks that use disinformation. An example of this would be a structured query language injection attack, in which inputs are manipulated to generate incorrect outcomes or to compromise training data sets. As many models lack transparency, either by intention, by accident, or because of intrinsic opacity, it is difficult to identify vulnerabilities and mitigate potential threats. In addition, given the reliance of algorithms on third-party data sources, software libraries and network infrastructures, threat actors can compromise the supply chain to manipulate algorithms and cause widespread damage. Further, as algorithms come to govern or influence more aspects of society, the potential for coordinated cyber attacks using automated systems grows.

Cyber threats: The report highlights the growing risks from cyber espionage and warfare, which can disrupt critical infrastructure and destabilize governments. The global outlook for 2027 is one of increased cynicism among survey respondents, with a high proportion of respondents to the GRPS 2024-25 anticipating turbulence (31%), a four percentage point increase since last year's edition. There is also a two percentage-point year-on-year increase to 5% in the number of respondents who are anticipating a stormy outlook, the most alarming of the five categories respondents were asked to select from over the next two years. The top risk for 2027 according to survey respondents is misinformation and disinformation for the second year in a row, since it was introduced into the GRPS risk list in 2022-2023. Respondent concern has remained high following a year of "super elections", with this risk also a top concern across a majority of age categories and stakeholder groups. Moreover, it is becoming more difficult to differentiate between AI- and human generated misinformation and disinformation. AI tools are enabling a proliferation in such information in the form of video, images, voice or text. Leading creators of false or misleading content include state actors in some countries. In a year that has seen the mass rollout of developments in AI and considerable experimentation with AI tools by companies and individuals, concerns about adverse outcomes of AI technologies is low in the risk ranking.

Respondents also express unease over cyber espionage and warfare, which is #5 in the two-year ranking, echoing concerns outlined in the World Economic Forum's 2024 Chief Risk Officers Outlook, where 71% of Chief Risk Officers expressed concern about the impact of Cyber risk and criminal activity (money laundering, cybercrime etc.) severely impacting their organizations. The rising likelihood of threat actor activity and more sophisticated technological disruption were noted as particular concerns. Elevated cyber risk perceptions are one aspect of a broader environment of heightened geopolitical and geoeconomic tensions, which is reflected in the two-year ranking of State-based armed conflict moving up from #5 in last year's report to #3 now.

2. GLOBAL RISKS OVER THE LONG TERM (10 YEARS)

The current and short-term risks landscape described in Chapter 1 may be exacerbated in terms of severity as the world moves towards 2035, unless we collectively act on such foresight today and work collaboratively across all stakeholder groups towards a more promising future. This chapter focuses on the longer-term horizon, outlining survey results for the likely impact of risks in the next 10 years and providing in-depth assessments of three risk themes: pollution, biotech and super-ageing societies. The chapter concludes with a retrospective analysis of findings from the last two decades of Global Risks Reports. The GRPS suggests that the road to 2035 will be challenging to navigate.

Figure 2. Global ricks over the long term (10 years)

Extreme weather events: This risk dominates the long-term outlook, with experts anticipating that extreme weather will become even more severe in the coming decade.

As the effects of climate change-induced events and developments have become more visible over time, and public awareness of their implications has risen, the rankings of environmental risks have continued to rise. The ranking of extreme weather events has tended to rise as such events have worsened in intensity and frequency. Extreme weather events are becoming more common and expensive, with the cost per event having increased nearly 77%, inflation-adjusted, over the last five decades. The effects of climate change-driven extreme weather events are being felt across the world and often hit the poorest communities the hardest. Global heat records continue to be broken. The pollution risk demonstrates shifting prominence over time in the 10-year risk outlook. First introduced in 2009, Pollution risk initially encompassed air pollution and nanoparticles pollution (paint, cosmetics, healthcare). Over the subsequent 10 years, the risk evolved in concept and rose in perceived importance.

Biodiversity loss and ecosystem collapse: This is ranked as a top long-term threat, reflecting concerns about the irreversible damage being done to natural systems that underpin human life and the global economy. Technological risks fare little better than environmental risks over the next 10 years. Adverse outcomes of AI technologies follows biodiversity loss and ecosystem collapse as one of the risks expected to increase in severity the most from the two-year to the 10-year timeframe, ranking #6 on the 10-year risk outlook compared to #31 on the two-year risk outlook. Pollution at a crossroads explores under-appreciated pollutant risks that are likely to become more top of mind by 2035, given their significant impacts on health and ecosystems. Unless concrete action is taken today to address polluting activities, these impacts will only worsen.

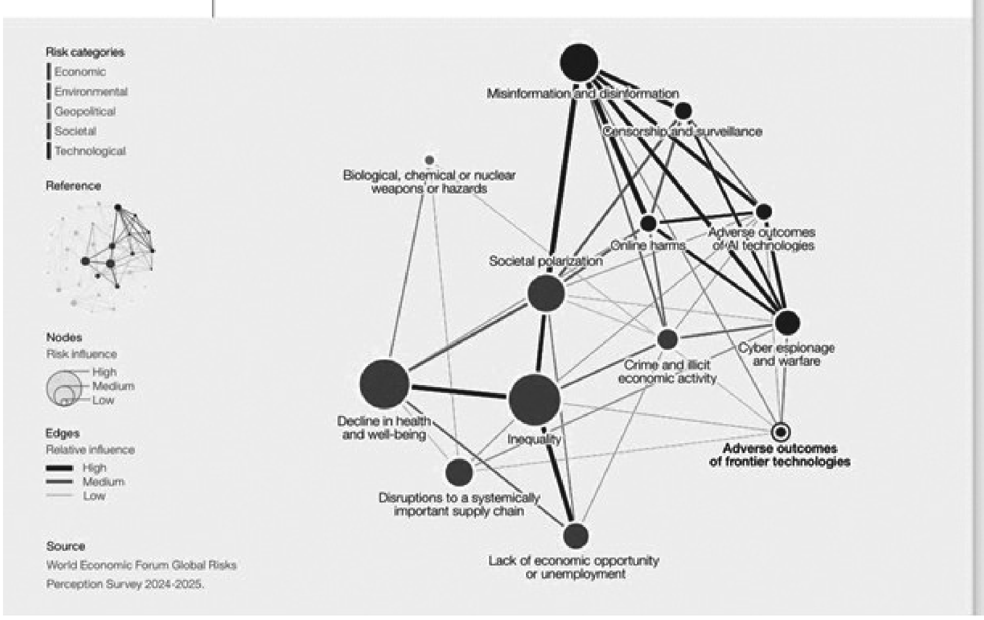
Critical change to earth systems: This includes risks such as permafrost melt, large-scale deforestation, and other tipping points that could lead to catastrophic environmental shifts.

Natural resource shortages: The report highlights the long-term threat of shortages in critical resources like water and food, which could lead to conflicts and mass migration.

Misinformation and Disinformation: While an immediate risk, its long-term impact is also seen as severe, as it can permanently undermine trust and hinder efforts to address other global challenges.

Pollution ranks #10 in the GRPS 10-year risk ranking, with 23% of respondents expressing maximal concern. Moreover, it is noticeable that younger survey respondents are especially alarmed, with the under 30s age group ranking it at #3 in the 10-year risk ranking. By 2035, the compounded effects of pollution threaten to erode ecosystem resilience, diminishing its ability to sustain life and deliver essential services. Decline in health and well-being is increasingly associated with pollutant exposure, including the rising incidences of cardiovascular diseases, respiratory conditions, infertility rates and cancer. Anthropogenic activities are

FIGURE 2.11 Risk interconnections: Adverse outcomes of frontier technologies



key drivers of all types of pollution. These activities are expected to increase further over the next decade unless a different course of action is taken. Some polluting activities and pollutants are addressed under climate adaptation and mitigation efforts, including the drive towards net-zero greenhouse gas (GHG) emissions. However, there is a concerning common denominator of many countries' green transition pathways: explicit, comprehensive plans for tackling the mounting health and ecosystem impacts of pollution are missing.

Pollution poses greater risks in specific geographies and disproportionately affects vulnerable groups of the population that are exposed to higher levels of pollution. Marginalized communities, urban areas and industrial zones bear the large brunt of its impacts due to proximity to sources of emissions, including waste disposal sites, and often limited green spaces. These disparities create further inequities in healthcare access and burden, as well as in economic costs.

Super-ageing societies: By 2035, populations in super-ageing societies could be experiencing a set of interconnected and cascading risks that underscore the GRPS finding that the severity – albeit not the ranking – of the risk of Insufficient public infrastructure and social protections is expected to rise from the two-year to the 10-year time horizon. An ongoing concern is that government funding for public infrastructure and social protections gets diverted during short-term crises. Some super-ageing societies could be facing crises in their state pensions systems as well as in employer and private pensions, leading to more financial insecurity in old age and exacerbated pressure on the labour force, which includes a growing number of unpaid caregivers. Indeed, super-ageing societies by 2035 are likely to face labour shortages.

Global economic growth over the next decade is likely to be constrained by demographics in superageing societies, many of which are among the world's largest economies. In addition, there are likely to be direct knock-on impacts from today's super-ageing societies. Despite policy pushback on immigration in the short-medium term, in the longer term the need to fill labour shortages could be decisive in shaping policy. As a consequence, countries with more youthful populations will face the risk of depletion of their own future workforces as many more young, working-age people migrate to super-ageing societies to help fill labour shortages there. Working-age people who remain in the superageing societies of the future could be left hardpressed to sustain the rest of the populations there.

Economic instability: The report points to mounting debt burdens, high inflation, and illicit economic activity as key factors contributing to global fragility. Economic risks fall mostly in the bottom half of the 10-year risk ranking and have remained relatively stable compared to last year's survey. The Global Risks Report shows, economic risks tend to be volatile over time – meaning that an economic crisis should not be ruled out over the next 10 years. One significant area of concern is crime and illicit economic opportunity, which has increased 16 positions year-on-year to #15 in the 10-year ranking.

Economies already experiencing this challenge are resorting to stop-gap measures, including attracting migrant care workers from other economies. But if this turns into a talent drain from countries with more youthful societies, those countries may then struggle to reap the benefits of their demographic dividend and will, several decades from now, run into super-ageing society challenges of their own. There will be no easy solutions to this problem set, given the sustained strength to 2035 of the two underlying trends generating higher average dependency ratios, not only across super-ageing societies, but at the global level: declining fertility rates and rising life expectancy, though not necessarily in better health.

Declining cooperation: A central theme is the decline in international cooperation. The report warns that the mechanisms for multilateral collaboration are buckling at a time when they are most needed. The report emphasizes that international cooperation is weakening, which complicates efforts to address these interconnected global crises. It urges leaders to prioritize dialogue and rebuild trust to work toward a sustainable and inclusive future.

Societal vulnerabilities: The report discusses how risks like inequality and population aging are contributing to a more fragile world. The report notes that rising inequality, societal polarization, and economic instability including mounting debt burdens and illicit activity are contributing to global fragility.

In conclusion, the Global Risks Report 2025 paints a sobering picture of a world facing a "turbulent or stormy" decade ahead. It underscores the urgency of global collaboration to address these interconnected crises and calls on leaders to rebuild trust to ensure a more sustainable and inclusive future.

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XUÂN THẮNG

APPLICATION OF AI AND BIG DATA TO AIR POLLUTION MONITORING AND FORECASTING:

Experiences of some countries around the world and proposed solutions for Vietnam

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Air pollution (AP) is currently considered one of the most serious threats to public health and the path to realizing the global Sustainable Development Goals (SDGs). Faced with this reality, more and more countries around the world are prioritizing the choice of modern technology, considering this as the main solution in the fight against AP, in which, artificial intelligence (AI) and big data (Big Data) are emerging as breakthrough tools, helping to analyze complex environmental data from many different sources. Thanks to their fast and accurate processing, these systems can identify pollution "hot spots" in real time; simulating the trend of dispersing hazardous substances, and at the same time providing a scientific foundation to develop effective and timely response policies. The article introduces a number of typical countries in the world that have successfully applied AI and Big Data to AP monitoring and forecasting, thereby proposing an appropriate direction for Vietnam.

1. SOME TYPICAL COUNTRIES HAVE SUCCESSFULLY APPLIED AI AND BIG DATA TO AIR POLLUTION MONITORING AND FORECASTING

In recent years, AI and Big Data have emerged as a widely used technological tool to control and minimize the harm of toxic substances that cause ethanol [7]. The development of the internet in the 21st century has allowed AI to reach its full potential and apply this technology to model complex environmental problems, especially air quality (AQ) regulation. To diagnose, monitor, and cure a number of diseases related to AP, many researchers around the world have used AI approaches in healthcare decision-making tools [8]. For example, Heuvelmans et al., have developed a deep learning-based approach to simulate the progression of cancer cells in the lungs using CT scan image datasets [9]. Polezer et al., again, used artificial neural networks (Multilayer Perceptron (MLP), Echo State Networks (ESN), and Extreme Learning Machines (ELM) to assess the negative effects of atmospheric AP on individual health [10].

This article mentions the US, China, Singapore... are proofs that the application of advanced technology in AP monitoring can bring positive results in both accuracy and coverage. Notably, more and more people around the world are actively using AI-integrated devices and applications to monitor AQ. This not only raises public awareness of environmental issues, but also plays an important role in supplementing practical data, contributing to the improvement of effective pollution warning and management systems.

1.1. The United States - A pioneer in applying AI and Big Data to air quality management

The US has built many modern monitoring systems that effectively support urban pollution control, including the AirNow System operated by the US Environmental Protection Agency (EPA). This system collects data from more than 4,000 monitoring stations nationwide, combines AI algorithms to analyze and provide real-time AQ information. Each year, more than 100 million people in the U.S. access AirNow through websites, mobile apps, and public electronic boards. According to statistics from the EPA, thanks to the application of this technology, the number of days with high pollution levels in big cities has decreased by 8 - 10% in just 5 years [1].

In addition, the TEMPO Sensor System, a spectrophotometer mounted on a geostationary orbit satellite, developed by the US National Aeronautics and Space Administration (NASA), capable of tracking AQ variants on a suburban scale, marks an important step forward in large-scale AP monitoring. This device allows the data collection of several contaminants such as nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2) and formaldehyde (CH_2O) with high resolution, hourly frequency. As a result, scientists can continuously monitor changes in the AQ and trace emissions in urban areas along the stretch from Canada to Mexico. TEMPO is a clear demonstration that AI and Big Data are being applied more and more extensively in an effort to control AP.

In addition, many major cities in the US such as New York, Los Angeles, Chicago... are also deploying mobile sensor systems mounted on buses, drones, and public bicycles to enhance air monitoring capabilities at the micro level. According to the Massachusetts Institute of Technology (MIT) Senseable City Lab, these sensors can detect localized pollution points smaller than 100 meters - areas that are often missed by traditional fixed surveillance systems. In particular, air data coverage in the inner city area has increased from less than 40% to more than 85% [1]. On the other hand, from 2021, AI will be used in smart grid systems, helping to optimize energy consumption, reducing greenhouse gas emissions by 15 - 20% in US states.

1.2. China: Monitoring and controlling air pollution through AI and Big Data China is focusing on investing in the application of AI and Big Data to manage environmental protection, through the deployment of the "Skynet" system of more than 20 million surveillance cameras, combined with data from environmental sensors to monitor and control environmental and water pollution. At the same time, the country has also implemented strong AI in its monitoring program, with a notable step being the automation of environmental monitoring stations, a combination of AI, drone equipment, and automated laboratories [1]. In the field of monitoring water and water, the upgrading and digitization of national monitoring stations will help automate the monitoring process without the need for operating personnel, thereby reducing the frequency of maintenance and processing time by more than 70%. Sampling and analysis are also made easier with drone sampling technology and automatic laboratory sample analysis, helping to save more than 50% of time, manpower, and transportation costs [2]. In addition, China also uses AI to predict dense fog, thereby providing early warning measures for citizens.

Currently, many major Chinese cities such as Beijing, Shanghai, Shenzhen, and Guangzhou have implemented smart city models, AI applications, the internet of things (IoT), Big Data and environmental sensors to monitor AQ, pollution control, power consumption forecasting and waste management, etc wastewater. Digital technology also supports optimal traffic regulation, public lighting, early warning of the environment and improving the efficiency of urban governance. A 2022 study by Tsinghua University showed that the application of AI helped reduce the level of COVID-19 in Beijing by 12% during the winter. China is also promoting the development of green e-commerce, digital finance for green projects, blockchain application in traceability, and agricultural supply chain transparency. The models of "digital carbon credit" and "digital carbon bank" have been tested in many localities, helping businesses and people participate in the carbon market more transparently and effectively. In particular, China is a pioneer in integrating digital solutions into green manufacturing, smart agriculture and renewable energy. Many smart factories apply AI, robots, and IoT to help optimize production processes, reduce resource waste and greenhouse gas emissions. In agriculture, automatic irrigation systems, environmental sensors, and product traceability contribute to saving resources, limiting emissions, improving product quality, and achieving sustainable development goals [3].

Not only that, China is also known as a leading country in monitoring biodiversity and environmental noise with smart sensor equipment, thereby being able to detect ecological abnormalities early and improve the accuracy of monitoring. Smart devices such as infrared cameras, bird voice recorders, amphibian and reptile monitoring radars, butterfly monitoring devices, etc. have helped automate the monitoring process, achieving an accuracy of over 85%. In the future, China's Ministry of Ecology and Environment will continue to promote the application of digital technology to manage discharge points according to the "one point per code" model, in order to ensure that data can be connected, retrieved and monitored closely. Some technologies such as satellite remote sensing, automatic monitoring will also be applied to detect and promptly handle illegal discharges that cause environmental pollution [2]. These achievements demonstrate the central role of digital technology in green economic development, contributing to pollution control, emission reduction, and improving the quality of life, while strengthening China's international integration capacity.

1.3. Singapore: Technology is the foundation for environmental strategy and smart cities

As a small country with a high population density and commercial activity, Singapore is under great pressure to control the AP, so from a very early age, the Singapore Government has been deeply aware of the key role of digital technology and AI in the future of the country's development; identifying this as an important foundation for green urban development, helping the city effectively adapt to all environmental challenges, towards the goal of sustainable development.

As early as the 2010s, Singapore has begun to implement the vision of a "smart nation", integrating Big Data, AI, IoT into all socio-economic fields to improve the quality of life of its citizens. One of the typical initiatives is the MAREMIS Project, in cooperation with the Port of Hamburg (Germany), which uses AI to monitor and regulate emissions from ships. The system analyzes transportation data, wind speed, and humidity to predict NO_x and SO_x emissions, thereby supporting accurate decision-making. According to the Singapore National Environment Agency (NEA), MAREMIS has helped reduce NO_x emissions in the port area by an average of 18% after 3 years of implementation [1]. In addition, the "OneMap", "Smart Water" projects

The American AirNow system collects data from more than 4.000 monitoring stations nationwide, combining AI algorithms to analyze and provide real-time AQ information

and environmental sensor systems help monitor and forecast water and water conditions; optimizing water supply and drainage operations, contributing to saving resources and preventing flooding. Lighting systems, public transportation are automated, reducing energy consumption, greenhouse gas emissions and promoting green transportation. Smart residential areas also connect data between electricity, water, transportation, and health to optimize operation and control emissions at the source.

Singapore is also a country that stands out for its comprehensive smart management solutions for infrastructure and public services, such as environmentally friendly air, water, lighting, waste and transportation control. The "Virtual Singapore" model - 3D Virtual City is a revolutionary creation. The system integrates a wide range of data sources from environmental sensors, traffic systems, security cameras, and weather maps. As a result, managers can simulate policies, test solutions, and predict effectiveness before implementing them in practice. According to the NEA, the use of Virtual Singapore in the simulation of inner-city traffic adjustments has helped reduce CO_2 emissions from private vehicles by more than 10% after just two years of testing in the Tengah district. GS. Michael Batty, University College London commented, "Virtual Singapore is a prime example of the city of the future, where every decision on environmental planning and infrastructure is based on real-time data and advanced predictive modeling" [1].

2. PROPOSE SOME SOLUTIONS FOR VIETNAM

2.1. Advances in the application of AI and Big Data to air pollution monitoring and forecasting

Fi-Mi: A mobile system for monitoring and predicting air quality with AI application

In Vietnam, in recent years, the application of AI and Big Data in the field of environment and pollution reduction has made significant progress. Specifically, in order to increase the accuracy of low-cost monitoring devices and minimize the number of devices used, a Vietnamese research team from Hanoi University of Science and Technology, Chiba University (Japan) and Toshiba Corporation has successfully coordinated to implement the project "Fi-Mi: Mobile system for monitoring and predicting AQ with AI application" under the sponsorship of Vingroup Innovation Fund (VinIF). With the Fi-Mi system, the research team has built a system to monitor AP parameters and emission sources affecting human health, contributing to solving two main problems: (i) Automatically calibrate the data collected by low-cost monitoring equipment, in order to increase accuracy; (ii) Prediction of monitoring data in space and time, in order to build a high-resolution AQ map, while not needing to deploy too many instruments [4].

The Fi-Mi system consists of three layers (sensors, information, applications), in which, the sensor layer consists of air monitoring devices, which are placed on vehicles (buses), continuously collect AQ indicators and send them to the server system. The information layer consists of communication protocols, which take care of the transmission and receipt of data between the sensor layer and the application layer. The application layer includes a server system, which is responsible for processing, storing, and displaying visualized data for users; use machine learning models to predict AQ in space and time. With a compact structure and low price, Fi-Mi monitoring devices are suitable for installation on buses and cars moving around the city, helping to collect temperature, humidity, $PM_{2.5}$, SO_2, NO_2, CO indicators. real-time data on the server system. In addition to information about air and weather monitoring, the devices also send to the server signal strength/weakness information (RSSI) and the location of the device collected through the GPS module. The entire operation of each Fi-Mi monitoring device is controlled by the MCU central controller programmed by the research team at Hanoi University of Science and Technology [5].

Not only stopping at the problem of predicting AQ over time, one of the outstanding applications of Fi-Mi is to study methods to estimate the distribution of AQ, that is, using AQ data obtained from the locations of monitoring equipment to estimate AQ in places where there is no monitoring equipment. On the other hand, the Fi-Mi Project builds a deep learning model, using graph neural networks to represent the spatial relationship between observation stations. This is also the first project to use deep learning in PM2.5 prediction, implemented on Vietnam's dataset. The results of the evaluation on the AQ dataset collected in Hanoi showed that the Encoder-Decoder model reduced the prediction error by 53.7% compared to the solution of some other studies. Furthermore, the use of an input feature auto-selection algorithm can help reduce prediction error by 13.7% compared to other algorithms. In addition, the combination of meteorological information, especially wind, to increase the accuracy of predictions is also a strength of Fi-Mi. Results from several experimental studies show that Fi-Mi's solution has helped reduce the prediction error from 4.93% to 34.88% compared to current methods [6].

After the project ends and is accepted in 2023, the team of scientists at Ha Noi University of Science and Technology together with researchers in the field of AI and the environment continue to pursue related research, aiming to build a complete system, which will not only help track AP parameters but also the source of emissions as well as the impact of AP on human health.

Application of Big Data in remote sensing to monitor and reduce air quality from waste treatment sites

From July 2020 to December 2022, scientists from the National Remote Sensing Agency, Ministry of Agriculture and Environment implemented the project "Research on the application of Big Data - Remote sensing in monitoring AP from waste treatment (WT) areas" through the use of data from the Sentinel-5P satellite and ground monitoring to build AQ maps; determine the dispersal of some pollutants such as SO_2, NO_2, CH_4, etc. As a result, the research team has built a scientific basis and methodology for the application of Big Data - Remote sensing to monitor AP from waste treatment zones; the application combines specialized remote sensing data Sentinel-5P, specialized UAV flight data and ground observation data for regular and high-granular monitoring of the AQ around the WT area. At the same time, it is possible to build a technological process for applying Big Data - Remote sensing to monitor the status of AP from waste treatment sites; propose steps, from remote sensing data processing, remote sensing and monitoring data integration, and modeling of AQ propagation; identified the spread of a number of toxic chemical components that cause NOKK from concentrated wastewater treatment areas such as SO_2, NO_2, CH_4. In addition, the research team collected and processed Sentinel-2 remote sensing data; Sentinel-5P, Landsat-8/9; data collected from UAVs; monitoring data to calculate a number of AQ components such as $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, CH_4; collect ozone data as a basis for building the AQI24h map.

After publication, the research results are transferred to the agencies tasked with monitoring and supervising the waste management in general, the pollution caused by the operation of concentrated landfills in particular by the method of direct transfer accompanied by training and user manuals.

The system of monitoring, forecasting and warning of air quality on the basis of collecting and integrating multi-source data

In order to build a real-time monitoring, forecasting and warning system for AQ applications of IoT technology, cloud computing (Cloud), AI and numerical modeling, Assoc. Prof. TS. Pham Tran Vu, University of Science and Technology, Vietnam National University of Ho Chi Minh City and his colleagues have successfully implemented the project "Building a system of monitoring, forecasting and warning of AQ on the basis of collecting and integrating multi-source data, piloting for a large city", under the National Key Program for the period to 2025 "Supporting research, development and application of technology of industry 4.0", code KC-4.0/19-25.

Implementing the project, the research team integrated AI with the most advanced 3-layer model and machine learning to forecast short-term AP for Ho Chi Minh City in 24 hours, helping to provide early warning of AP to protect people's health as well as reduce economic losses. Specifically, the research team has studied the real-time monitoring, forecasting and warning system of AQ in the world and Vietnam, thereby building wireless communication sensor clusters; the AQ estimation model from satellite imagery and auxiliary data for the Ho Chi Minh City area; the AQ forecasting model using AI; monitoring network, simulation model system for forecasting and warning of AQ on the mobile application platform and website. As a result, a model of real-time air environment monitoring stations has been built connected according to IoT standards: SO_2, CO, NO_2, NO, O_3, PM_{10}, $PM2_{.5}$; monitoring and forecasting system for AQ for pilot application in Ho Chi Minh City. At the same time, the research team has completed the design of the sensor node, serving data collection activities for testing and evaluation; testing AI models and CMAQ models to forecast and warn AQ; completed the model of estimating $PM_{2.5}$ dust concentration from remote sensing images.

The advantage of the system is that when installing the application or accessing the website, people can know the current AQ in an area, and at the same time, be forecasted for the next 1 - 2 days to promptly have a plan to protect their health against the impact of AP. In particular, the application will send a direct message to users when AP shows signs of increase, thereby making appropriate recommendations depending on the level of pollution.

2.2. Challenges, barriers and solution proposals

Challenges and barriers

Despite the initial success, Vietnam still faces many barriers in the application of AI and Big Data in forecasting and warning of environmental pollution in general and AP in particular, specifically: (i) Lack of synchronous and high-quality data platform: Environmental data in Vietnam is still scattered, lack of standardization, difficult to integrate, and not ready for AI analysis. Many localities still collect data manually, lack sensor equipment, and do not have an effective sharing mechanism between levels and sectors; (ii) Limited analysis and implementation capacity: The number of AI and data science experts in Vietnam is still low; current AI models are only small experiments, and there is no ecosystem strong enough to be applied on a large scale. The ability to apply AI to public decision-making is still limited, due to the lack of coordination between engineering and management; (iii) Mechanisms and policies have not really created encouragement: Investment in AI and Big Data in the field of environment has not been considered a national priority. Vietnam does not have a clear legal mechanism for data use, privacy protection, information security as well as effective budget allocation for digital technology in the natural resources and environment sector; (iv) Lack of public-private partnership (PPP): The participation of businesses, startups and research institutes in this field is still fragmented, and there is no strong enough incentive mechanism to promote public-private cooperation. Technology projects are often limited by budget or do not have the right testing corridors; (v) Lack of connection with international trends: Vietnam has not participated deeply in global initiatives on environmental technology such as the global atmospheric data network, the AI platform for the environment of the United Nations Environment Programme, or open projects on Earth data, etc. This deprives us of access to advanced technology and large-scale data.

Solution-oriented in the coming time

Firstly, Vietnam needs to establish a comprehensive national environmental data system, connecting data from monitoring stations, IoT sensors, satellite imagery and local reports. Data must be standardized, expanding the ability to be shared and used by state agencies, research institutes, and businesses. This requires the Government to play a central role in the design of the legal framework and technical infrastructure.

Secondly, the development of AI testing models in the field of AP monitoring in large cities in the form of PPP should be encouraged to take advantage of the strengths of the private sector. At the same time, AI and Big Data need to be integrated into decision-making support tools in developing pollution forecasting policies for urban planning, environmental impact analysis (EIA), etc. On the other hand, it is necessary to soon include contents related to the application of AI and Big Data in monitoring and forecasting in undergraduate and postgraduate training programs, professional training to increase the number as well as improve the capacity of a team of experts who are strong enough in data science. AI and environmental management.

Thirdly, it is possible to participate in international programs related to the development and implementation of environmental policies, especially the reduction of AP, such as Copernicus - the European Union's Earth Observation Program, which provides free satellite data on the environment, thereby supporting member states in monitoring and managing natural resources; initiatives from the United Nations Environment Program, the World Bank on environmental technology, etc. in order to learn from experience, access to global data, open source technology and financial and technical support to implement a number of pilot projects with high pervasiveness.

Fourthly, it is necessary to soon complete the National Action Plan to overcome pollution and manage pollution, with specific goals for 2025 and the period 2026 - 2030, focusing on main groups of solutions such as energy, waste sources, transportation, and construction; strengthen the application of AI and Big Data to analyze and forecast AQ; integrate automatic monitoring systems and national databases, helping localities periodically inventory emissions and publicize information transparently.

Fifthly, AI and Big Data bring transformative power in efforts to solve the problem of urban climate change, this tool helps improve the capacity to measure, forecast, optimize and act, thereby supporting the construction of smarter, cleaner, fairer and more livable cities. In order for digital technology to truly be a force for the common good, it is necessary to ensure 3 criteria: (i) Inclusivity, in which, all people can access benefits, not only those who own smartphones or wearable devices; (ii) Equity (The system must be designed not to transfer pollution to communities that are already environmentally burdened); (iii) Transparency and ethics (Community trust requires clear governance, open access, and substantive citizen participation). Therefore, AI and Big Data should not be something that is "imposed on humans", but must be tools built "with humans". That means opening up access to data, encouraging open-source development, and incorporating local voices into the design and deployment of tools. At the same time, AI and Big Data must be key tools if we want to achieve global goals - as announced by the World Health Organization at the Global Conference on AP and health, to reduce the health impact of AP by 50% by 2040. To realize the above goal, Vietnam cannot rely on algorithms alone, but needs intentional coordination between the Government, researchers, startups, urban planners and the whole community.

3. CONCLUSION

AI and Big Data are being applied more and more extensively in an effort to control AP. Practical experiences from the United States, China, and Singapore show that technology is no longer just a technical tool but has become a solid foundation in environmental and health policymaking. Like many countries around the world, with the strong development of AI and Big Data, AP monitoring and forecasting in Vietnam is becoming more accurate, faster and more effective, helping to minimize negative impacts on the environment as well as human health, towards the goal of sustainable development■

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Potential of using oyster shells in seafood processing wastewater treatment

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In Vietnam, the aquaculture and seafood processing industry plays a vital role in economic growth and exports but also generates large amounts of solid waste and wastewater, putting pressure on coastal environments. Oysters and other mollusks are increasingly farmed, producing substantial shell waste each year. While part of this is reused in animal feed or as artificial reefs, most oyster shells are directly discarded, causing pollution and resource waste. In the context of a shift toward sustainable and environmentally friendly consumption, recycling oyster shells is highly practical, helping to reduce pollution while adding economic value. With calcium carbonate ($CaCO_3$) as their main component, oyster shells hold strong potential for application in seafood processing wastewater treatment. This contributes to mitigating coastal environmental pollution while also promoting a sustainable pathway for the fisheries industry.

1. INTRODUCTION

The aquaculture and seafood processing industry makes a significant contribution to the national economy and foreign exchange earnings; however, it also generates environmental pollution due to the large volumes of solid waste and wastewater released during production. According to the Vietnam Environment Administration (2011), the processing of catfish produces 5 - 7 m^3 of wastewater per ton of product, with pollutant concentrations exceeding permissible standards. If left untreated, these discharges can exert adverse impacts on the environment (Nguyen Vo Chau Ngan et al., 2015).

The degree of pollution in wastewater generated from seafood processing varies considerably, depending on the type of raw materials (e.g., shrimp, fish, squid, octopus, crab, clams, mussels), as well as seasonal fluctuations and even daily production activities. In particular, processing lines are often characterized by high concentrations of pollutants, with pH ranging from 6.5 to 7.0, suspended solids (SS) from 500 to 1,200 mg/L, chemical oxygen demand (COD) from 800 to 2,500 mgO_2/L, biochemical oxygen demand over 5 days (BOD_5) from 500 to 1,500 mgO_2/L, total nitrogen from 100 to 300 mg/L, total phosphorus from 50 to 100 mg/L, and oil and grease from 250 to 830 mg/L (Le Hoang Viet et al., 2014). These values indicate that seafood processing wastewater is rich in organic matter and highly biodegradable, as reflected by the BOD/COD ratio, which ranges from 0.6 to 0.9 (Nguyen Trung Viet et al., 2011; Pham Thi Phuong Trinh et al., 2016). Conventional wastewater treatment methods, such as aerobic and anaerobic processes, microbial applications, or chemical treatments, typically require high capital and operational costs, while also generating secondary sludge that poses additional challenges for environmental management.

Oysters in particular, and mollusks in general, are widely farmed in coastal regions. Globally, hundreds of tons of shell waste from mollusks, including oyster shells, are generated annually, posing a significant environmental burden (W.H. Park et al., 2008). In Vietnam, the average oyster production in three coastal provinces - Quang Ninh, Hai Phong, and Thanh Hoa - reaches approximately 10,000 - 12,000 tons per year. Estimated production in other provinces is as follows: Nghe An, 2,000 tons/year; Thua Thien - Hue, 2,500 tons/year; Phu Yen, 1,800 tons/year; and Ba Ria - Vung Tau, 2,000 tons/year, while most remaining coastal provinces produce 500 - 1,500 tons annually. Overall, Vietnam's oyster production amounts to 30,000 - 35,000 tons per year, corresponding to an estimated 25,500 - 29,700 tons of oyster shell waste (Nguyen Xuan Thi et al., 2011; Fisheries Encyclopedia, 2007; Nguyen Xuan Thi, 2019).

Oyster shells represent an abundant waste source from aquaculture and seafood processing. Their reuse not only reduces the burden of solid waste management but also offers potential as an effective adsorbent material. Numerous studies have demonstrated the capacity of oyster shells to remove heavy metals; however, applications for treating organic matter, nutrients, and microorganisms in seafood processing wastewater remain limited. Compared with other mollusks, oysters are produced in large quantities, and their shells consist primarily of $CaCO_3$, which can be readily transformed into CaO and other active derivatives, highlighting their potential for the remediation of diverse pollutants. Recycling oyster shells could therefore mitigate coastal environmental pollution while providing a sustainable pathway for the aquaculture industry. At present, however, their utilization has mainly been restricted to animal feed additives and artificial reef construction, with limited effectiveness. Consequently, research on oyster shell recycling - particularly the transformation mechanisms of $CaCO_3$ under different conditions for wastewater treatment in seafood processing - holds significant practical value and promising prospects in Vietnam.

2. LITERATURE REVIEW

2.1. International Research

Worldwide, several studies have investigated the reuse of oyster shell powder as an adsorbent material for environmental pollution control (Nguyen Xuan Thai, 2019). This potential is attributed to the high $CaCO_3$ content in oyster shells, which can be converted into CaO after thermal treatment, enabling effective wastewater treatment. A study by Darioush Alidoust and colleagues in Japan reported that the chemical composition of oyster shells consisted of 97.21% CaO, 0.80% Na_2O, 0.61% SO_3, 0.35% MgO, 0.39% SiO_2, 0.24% SrO, 0.11% P_2O_5, 0.07% K_2O, 0.11% Al_2O_3, 0.09% Fe_2O_3, 0.01% TiO_2, and 0.01% MnO (Darioush Alidoust, 2015).

In the study conducted by Asaad F. Hassan and Radim Hrdina, oyster shells were calcined at 900^{0}C to convert $CaCO_3$ into CaO. The resulting CaO was finely ground and reacted with HNO_3 to synthesize $Ca(NO_3)_2$, while a 0.5 M H_2PO_4 solution was added to maintain the pH within the range of 10 - 11. The mixture was then dried at 110^{0}C and subsequently treated in a microwave furnace at 800^{0}C, yielding nano - sized $Ca(NO_3)_2$. This nanomaterial was applied for mercury ion adsorption, and the results demonstrated high adsorption efficiency as well as desorption capacity, confirming its potential for heavy metal pollution treatment (AsaadF. Hassana et al., 2018; Nguyen Xuan Thai, 2019).

Darioush Alidoust and colleagues treated oyster shells collected from restaurants in Japan by first brushing off the attached algae, followed by crushing and calcination at different temperatures (450^{0}C, 650^{0}C, 750^{0}C, 800^{0}C, 900^{0}C) for 2 hours. The calcined materials were then evaluated for their cadmium ion (Cd^{2+}) adsorption capacity. The results indicated that thermally treated oyster shells exhibited significantly enhanced Cd^{2+} adsorption efficiency and capacity compared to the raw material (Darioush Alidoust, 2015; Nguyen Xuan Thai, 2019).

In the study by Hsing Yuan Yen and colleagues, calcined oyster shells demonstrated a strong ability to adsorb nickel ions (Ni2+). Oyster shells calcined at 900^{0}C exhibited a porous structure with numerous micropores on the surface. The adsorption efficiency of Ni2+ using shells calcined at 900^{0}C was significantly higher than that of shells calcined at 600^{0}C. Specifically, the adsorption efficiency at 600^{0}C was 48.3%, while at 900^{0}C it reached 99.9% under conditions of pH 10 and an adsorption temperature of 60^{0}C (Hsing Yuan Yen et al., 2015). Similarly, Liwei Fan and colleagues developed a composite material from oyster shells and nanoscale iron for arsenic (As^{3+}) adsorption. The material achieved an adsorption efficiency of 96.5% under conditions of pH 6.8, temperature 20^{0}C, an initial As^{3+} concentration of 1.8 ppm, and an adsorption time of 24 hours (Liwei Fan et al., 2015).

Based on the analysis of the adsorption properties of oyster shells, Huang, Mian-Li and colleagues investigated the treatment of phosphorus-containing wastewater using oyster shells and examined the effect of temperature on phosphorus removal efficiency. X-ray diffraction (XRD) analysis was employed to identify crystalline phases, revealing that $CaCO_3$ was the principal component of oyster shells. At a pretreatment temperature of 800^{0}C, part of the $CaCO_3$ was decomposed into CaO, and the amount of CaO increased with higher temperatures. This thermal pretreatment activated calcium species, thereby significantly enhancing phosphorus adsorption from wastewater (Huang et al., 2010).

In South Korea, Jae-Hoon Huh and colleagues investigated the use of oyster shell powder to improve the water quality of lakes by controlling algal blooms. Waste oyster shells were calcined at 1000^{0}C for 1 hour in air, converting raw oyster shell powder into calcium oxide powder, which effectively reacted with phosphorus and nitrogen to remove algal blooms from eutrophic wastewater. The application of oyster shell powder resulted in reductions of 97% in total phosphorus, 91% in total nitrogen, and up to 51% in chemical oxygen demand (COD), compared with the total pollutant load of untreated algal solutions (Jae-Hoon Huh et al., 2016).

The antibacterial potential of nano- and micro-sized thermally treated oyster shell powders was investigated by Watanabe and colleagues using two bacterial strains:

E. coli and B. subtilis. Nano-sized particles derived from oyster shells were prepared using a wet milling method followed by heat treatment (HSS), and their antibacterial activity was compared with that of micro-sized particles against both bacterial cells and spores. The sporicidal activity of the nano-sized particles was markedly higher than that of the micro-sized particles, with HSS-derived nanoparticles demonstrating the ability to inactivate Bacillus subtilis spores. Specifically, the number of B. subtilis spores decreased nearly threefold after 30 minutes of exposure to HSS nanoparticles at a concentration of 5 mg/mL and 60^{0}C (Watanabe T. et al., 2014; Nguyen Xuan Thi, 2019).

The study by Zheng Liu et al. employed pyrolyzed oyster shell (POS) to remove Cu(II) from aqueous solution. The Taguchi method was applied to optimize process conditions and identify the key influencing factors. Results indicated that pyrolysis temperature and reaction time were the two determining factors, with Cu(II) removal efficiency reaching 99.82% at 25^{0}C, 900^{0}C, 100 mg/L, 0.2 g POS, and 30 minutes. Adsorption kinetics followed the pseudo-second-order model, while the Langmuir isotherm accurately described the experimental data, with a maximum adsorption capacity of 1093 mg/g at 900^{0}C (Zheng Liu et al., 2024).

Oyster shell (OS) is commonly used to mitigate acidification during methane production but is limited by its low electron transfer efficiency. This study developed a magnetite - oyster shell composite (MOC) with different Fe_3O_4 contents to simultaneously buffer pH and enhance electron transfer. The results showed that MOC exhibited superior redox activity, conductivity, and pH buffering capacity compared to OS and Fe_3O_4 alone. MOC15% (10 g/L) achieved the best performance, increasing methane yield by 9.7 times and improving pH by 44% compared to the control. The enhanced efficiency was attributed to its dual role in mitigating acid stress and promoting direct interspecies electron transfer (DIET), as well as enriching microorganisms such as Methanothrix and Geobacter. This provides a sustainable and cost-effective solution to enhance biomethane recovery from high-COD, carbohydrate-rich wastewater (Fangyuan Feng et al., 2025).

Studies by Kikuo et al. (2000), Achanai Buasri et al. (2013), Jingyu et al. (2018), and Ramakrishna Chilakala et al. (2019) also demonstrated that treated oyster shells can adsorb or remove various wastewater contaminants such as coliform, E. coli, and phosphates.

Thus, worldwide, numerous studies have focused on the use of oyster shells for the removal of heavy metals from wastewater. However, research on their application for the treatment of organic matter, nutrients, and coliforms remains limited.

2.2. In Vietnam

In relation to the present research topic, several studies have been conducted in Vietnam as follows:

Nguyen Xuan Thai successfully treated and modified oyster shell powder samples collected from the two coastal provinces of Quang Ninh and Phu Yen. The adsorption capacity of these treated samples for the heavy metal ion Cr^{6+} was subsequently evaluated. The results indicated that the morphology and structure of the treated oyster shells differed significantly from those of the untreated samples, with the treated shells exhibiting a porous structure and numerous micropores on their surfaces (Nguyen Xuan Thai, 2019).

Ngo Thuy Diem Trang and colleagues investigated the effect of calcination temperature on the phosphorus adsorption capacity of blood cockle (Anadara granosa) shell powder. The study evaluated three temperature levels (550^{0}C, 750^{0}C, and 950^{0}C) using shell particles of ≤2.0 mm. Phosphorus adsorption experiments were conducted over 24 hours at an initial concentration of 20 mg PO_4^{3-}/L. The results demonstrated that thermally treated shells exhibited a higher phosphorus adsorption capacity compared with untreated shells; however, effective performance required calcination above 750^{0}C. At 950^{0}C, the phosphorus adsorption efficiency reached 99.2% (Ngo Thuy Diem Trang et al., 2017).

Tran Do Mai Trang investigated the treatment of freshwater mussel shell powder and evaluated its adsorption capacity for methylene blue dye in aqueous solution. The results showed that pretreated mussel shell powder (referred to as "initial shell powder") exhibited good adsorption capacity for methylene blue, with an efficiency of approximately 80%. The initial shell powder also demonstrated moderate adsorption capacity for Cr(VI) ions, with an efficiency of around 50%. The optimal conditions for Cr(VI) adsorption in aqueous solution were identified as 0.5 g of adsorbent, pH 7, temperature 30^{0}C, an initial methylene blue concentration of 10 ppm, and a contact time of 70 minutes (Tran Do Mai Trang, 2022).

Nguyen Xuan Thi and colleagues optimized the calcination process of oyster shells. The optimization results identified the suitable conditions for shell calcination as a temperature of 850^{0}C, a duration of 92 minutes, and shell lengths of 4.0 - 7.0 cm, yielding a CaO recovery rate of 55.75% relative to the raw shells. X-ray diffraction analysis revealed that under these optimized conditions, $CaCO_3$ crystals were no longer present; instead, characteristic peaks of CaO appeared, while no peaks of $CaCO_3$ were detected. This confirmed that $CaCO_3$ in the oyster shells was completely decomposed during calcination (Nguyen Xuan Thi et al., 2018).

Duong Thi Minh Hoa and colleagues investigated the modification of clam shells for the removal of Pb from contaminated water. The study prepared two types of materials: cleaned clam shell powder dried for 12 hours (control) and thermally modified clam shell powders calcined at 400⁰C, 500⁰C, 600⁰C, 700⁰C, 800⁰C, 900⁰C, and 1000⁰C, each exhibiting distinct properties. At 1000⁰C, $CaCO_3$ was completely decomposed into CaO, resulting in the highest adsorption performance. The modified clam shell at 1000⁰C achieved a removal efficiency of 99.67% with an adsorption capacity of 2.990 (Duong Thi Minh Hoa et al., 2022).

Thus, in Vietnam, studies on the application of oyster shells for wastewater pollution treatment remain limited and have primarily focused on individual pollutants. The treatment capacity of oyster shell powder for specific types of industrial wastewater, as well as the optimal experimental conditions required to achieve maximum efficiency, has not yet been comprehensively evaluated.

3. PROPOSED RESEARCH CONTENT

3.1. Research Objectives

To evaluate the removal capacity of treated oyster shell powder for organic matter, nutrients, and coliforms from seafood processing wastewater.

3.2. Investigation of modified oyster shells for the treatment of pollutants (organic matter, nutrients, and coliforms) in wastewater from the seafood processing industry

Collection and preliminary treatment of discarded oyster shells.

Calcination of oyster shells at different temperatures: 750⁰C, 800⁰C, 850⁰C, 900⁰C, 1000⁰C.

Grinding of calcined oyster shells to obtain powder, followed by storage in separate containers for experimental preparation.

3.3. Experimental study on the pollutant removal capacity (organic matter, nutrients, and coliforms) of oyster shell powder in seafood processing wastewater

Evaluation of the treatment efficiency of oyster shell powder under different experimental conditions. If the removal efficiency is satisfactory, the experiments may be repeated with a lower dosage of powder; conversely, the dosage may be increased if the efficiency remains low.

4. PROPOSED RESEARCH METHODS AND TECHNIQUES

4.1. Research methodology

a) Literature review methodology: Collection and utilization of existing materials from research subjects or relevant articles and reports published in specialized journals.

b) Survey and sampling method for seafood processing wastewater: Sampling is conducted in accordance with Circular No. 10/2021/TT-BTNMT on environmental monitoring techniques and the management of environmental quality monitoring information and data. After sampling, the handling and preservation of samples for laboratory analysis are carried out following the guidelines of Standard Methods for the Examination of Water and Wastewater, 24th edition (APHA, 2023).

c) Procedure for the treatment and modification of oyster shells (Nguyen Xuan Thai, 2019)

Oyster shells were collected, washed, and air-dried, then soaked in a NaClO (Javel water) solution for 24 hours to remove algae, sand, impurities, and residual organic matter. Afterward, the shells were rinsed with distilled water and dried to constant weight before being ball-milled with a NaOH/NaClO solution (shells/solution ratio of 8/40 g/mL, NaOH/NaClO ratio of 80/20) for 24 hours. The resulting oyster shell powder was again washed with distilled water and oven-dried in a natural convection air oven at 100⁰C until constant weight. Calcination was then carried out at different temperatures (750⁰C, 800⁰C, 850⁰C, 900⁰C, and 1000⁰C) for 2 hours. After cooling, the calcined oyster shell powder was stored in sealed polyethylene (PE) bags.

Modification of pretreated oyster shell powder with EDTA was performed as follows: 0.3 g of EDTA was accurately weighed and dissolved in 50 mL of distilled water using a magnetic stirrer at 60⁰C. Subsequently, 3 g of oyster shell powder was added to the solution and stirring was continued for 2 hours. Finally, the oyster shell powder was washed with distilled water, and the solid fraction was collected by filtration. The powder was then oven-dried at 100⁰C until constant weight.

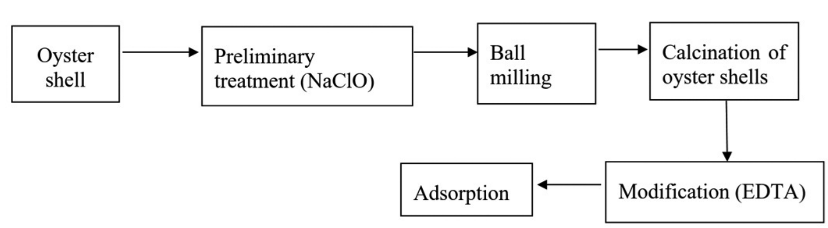

Figure 1. Process of treatment and modification of oyster shells

d) Experimental design for evaluating the pollutant removal capacity (organic matter, nutrients, and coliforms) of oyster shell powder in seafood processing wastewater.

- Collection of seafood processing wastewater samples and analysis of pollutant concentrations (BOD_5, COD, TSS, NH^{4+}, PO_4^{3-}, coliform) in the initial wastewater.

- Division of wastewater into separate containers (V liters) with the addition of treated oyster shell powder, followed by experiments under different conditions:

+ Different dosages of oyster shell powder used in the experiments, for example: 20 g/L; 50g/L; 100 g/L.

+ Different experimental durations: 1 day, 2 days, and 5 days.

- Collection of wastewater samples after the experiments and evaluation of pollutant concentrations (BOD_5, COD, TSS, NH^{4+}, PO_4^{3-}, coliform) in the effluent.

Note: Measure the pH of the influent and effluent wastewater in the experiments. All experiments are conducted using a magnetic stirrer to homogenize the test samples.

4.2. Analytical techniques employed

a) Techniques for measuring parameters in the field and in the laboratory

The pH of the wastewater is measured using a pH meter with an accuracy of 0.01 pH units. The wastewater temperature is displayed on the pH meters equipped with a temperature probe.

b) Techniques for analyzing wastewater samples in the laboratory

TSS analysis method: The TSS content in wastewater is determined by filtering an accurately measured volume of the sample through a filter membrane. The membrane containing the retained solids is rinsed with distilled water to remove salts, oven-dried at 105^0C to constant weight, cooled, and weighed.

BOD_5 analysis method: The sample is incubated at 20^0C for a fixed period of five days in the dark, in completely filled and tightly sealed bottles. The dissolved oxygen concentration is measured before and after incubation, and the amount of oxygen consumed per liter of sample is calculated.

COD analysis method: Potassium permanganate ($KMnO_4$) is used to oxidize organic compounds in an alkaline medium. The amount of potassium permanganate consumed in the reaction is expressed as mg O_2 per liter.

Phosphate (PO_4^{3-}) analysis method: The determination of phosphate ions in water is based on their reaction with ammonium molybdate reagent in an acidic medium to form a yellow phosphomolybdate complex, H7[P(Mo_2O7)6]. This complex, when reduced with stannous chloride (SnCl2), produces a molybdenum blue complex. The absorbance of the solution is then measured at a wavelength of 690 nm using a UV-VIS spectrophotometer.

Ammonium (NH^{4+}) analysis method: Ammonium is determined according to SMEWW 4500-NH3 F using the colorimetric method on a DR/3900 spectrophotometer (HACH, USA).

Coliform analysis method: The determination of coliform density in wastewater is carried out in accordance with TCVN 6187-2:1996 (Detection and enumeration of coliform bacteria, thermotolerant coliform bacteria, and presumptive Escherichia coli).

c, Data processing method

- Adsorbed mass and percentage of adsorbed substance (Tran Do Mai Trang, 2022).

The mass of substance adsorbed per gram of adsorbent, Q (mg/g), is calculated using the following formula:

$$Q = \frac{(C_0 - C_e).V}{\mathrm{W}} \qquad (1)$$

Where Q is the amount of substance adsorbed per gram of adsorbent at equilibrium (mg/g); C_0 and C_e are the initial and equilibrium concentrations of the adsorbate in solution (mg/L), respectively; V is the solution volume (L); and W is the mass of the adsorbent (g).

The percentage of substance adsorbed is calculated as follows:

$$H(\%) = \frac{(C_0 - C_e).100}{C_0} \qquad (2)$$

- Investigation and development of adsorption isotherm equations (Tran Do Mai Trang, 2022).

In this study, the Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich isotherm models were selected to investigate the adsorption process in the solid–liquid system (oyster shell powder - wastewater samples containing BOD_5, COD, TSS, NH^{4+}, PO_4^{3-}, and coliform). The Langmuir isotherm equation describes the adsorption process in solution by a solid adsorbent as follows:

$$Q_e = \frac{Q_0.k_L.C_e}{1 + k_L.C_e} \qquad (3)$$

Where Q_e is the amount of substance adsorbed per gram of adsorbent at equilibrium (mol/g), C_e is the equilibrium concentration of the solute (mol/L), and Q_0 and kL are Langmuir constants, with Q_0 representing the maximum monolayer adsorption capacity and kL representing the binding energy or affinity parameter of the adsorption system.

The Freundlich isotherm equation for the above system is expressed as follows:

$$Q_e = k_F.C_e^{1/nF} \qquad (4)$$

Where k_F is the Freundlich isotherm constant (L1/n mg(1−1⁄n) g-1) and $1/n_F$ is the Freundlich exponent.

The Temkin isotherm equation for the above system is expressed as follows:

$$Q_e = B.\ln A_T + B.\ln.C_e \quad \text{với } B = RT/b_T \qquad (5)$$

Where A_T is the Temkin isotherm equilibrium binding constant (L/g), b_T is the Temkin isotherm constant, R is the gas constant (R = 8.314 J/mol/K), and T = 298K.

The Dubinin - Radushkevich (D - R) isotherm equation for the above system is expressed as follows:

$$\ln Q_e = \ln Q_s - K_{ad}.\varepsilon^2$$
$$\varepsilon = R.T.\ln(1+\frac{1}{C_e}) \qquad (6)$$

Where Qs is the theoretical saturation capacity of the isotherm (mg/g) and K_{ad} is the Dubinin - Radushkevich isotherm constant (mol^2/kJ^2).

- Investigation of adsorption kinetics (Tran Do Mai Trang, 2022).

In this study, the first - order, pseudo - first - order, second - order, and pseudo - second - order adsorption kinetic models were selected to investigate the adsorption kinetics of wastewater samples (BOD_5, COD, TSS, NH^{4+}, PO_4^{3-}, coliform) using oyster shell powder.

First-order adsorption kinetic model:

$$\ln C_t = \ln C_0 - k1_t \qquad (7)$$

Pseudo-first-order adsorption kinetic model:

$$\ln (Q_0 - Q_t) = \ln Q_0 - k_{s1}t \qquad (8)$$

Second-order adsorption kinetic model:

$$\frac{1}{C_t} = \frac{1}{C_0} + k_2.t \qquad (9)$$

Pseudo-second-order adsorption kinetic model:

$$\frac{1}{Q_e - Q_t} = \frac{1}{Q_e} + kt \Rightarrow \frac{t}{Q_t} = \frac{1}{h} + \frac{1}{Q_e}.t$$
$$h = k.Q_e^2 \qquad (10)$$

Where C_0 and C_t are the solute concentrations at the initial time and at time t (mg/L); Q_0 is the maximum monolayer adsorption capacity (mg/g); Q_t and Q_e are the amounts of substance adsorbed per gram of adsorbent at time t and at equilibrium (mg/g); and K_1, K_{S1}, K_2, and k are the rate constants for the first-order, pseudo-first-order, second-order, and pseudo-second-order kinetic models, respectively.

5. CONCLUSION

The overview indicates that, globally, numerous studies have focused on using oyster shells for the removal of heavy metals from wastewater, whereas research on the treatment of organic matter, nutrients, or microorganisms remains limited. In Vietnam, this research area is still at an early stage, primarily addressing the removal of individual pollutants, without a comprehensive assessment of the potential application of oyster shells for various types of industrial wastewater or the optimization of experimental conditions. Given that seafood processing wastewater is generated in large volumes with high pollutant concentrations (COD, BOD, nitrogen, phosphorus, oils and fats, etc.), posing significant treatment challenges due to high investment and operational costs, the utilization of waste oyster shells as a recycled material for wastewater treatment offers both environmental benefits and practical prospects. Therefore, in-depth studies are needed to explore the potential of oyster shells in treating seafood processing wastewater.

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CLIMATE CHANGE AND GREENHOUSE GAS EMISSIONS: Causes, Impacts, and Solutions for Vietnam

Climate change and the resulting increase in greenhouse gas (GHG) emissions are among the most pressing global challenges. These issues have profound implications for all countries, and Vietnam, with its vulnerable geography and reliance on agriculture, faces a particularly urgent need to address them. Greenhouse gas (GHG) emissions are the release of heat-trapping gases into Earth's atmosphere. These gases form a natural blanket around the planet, allowing sunlight to pass through but trapping some of the heat that radiates back from the surface. This process, known as the greenhouse effect, is essential for life, keeping the planet warm enough to support ecosystems. However, human activities have dramatically increased the concentration of these gases, intensifying this effect and leading to global warming and climate change.

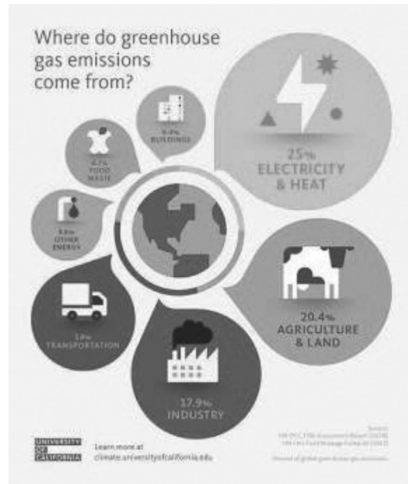
1. CAUSES AND IMPACTS OF GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions are a phenomenon where gases in the atmosphere absorb the infrared radiation and heat from Earth. Then, they will radiate them in many directions. In fact, this natural phenomenon is beneficial for our planet because it can maintain a warm temperature. However, with the utilization of non-renewable energy and other human activities, the production of gases in the atmosphere is getting out of control. As a result, greenhouse gas emissions hold too much heat and infrared in the atmosphere, making the Earth scorching. This causes climate change and global warming.

In general, the gases in the atmosphere are called greenhouse gases. They act like the glass in a greenhouse, retaining heat to keep the temperature warm. Some examples of greenhouse gases are methane, nitrous oxide, fluorinated gases, and carbon dioxide. Those gases create an insulating layer that prevents the Earth's heat from escaping into space. However, impulsive human activity produces more gases in the atmosphere, trapping more of the Earth's heat, making the temperature hotter, and leading to global warming.

Greenhouse gas emissions come from various sources, either naturally or due to human activity. Here are some greenhouse gas emission causes you should know:

Agricultural activity, particularly livestock farming and rice cultivation, are major sources of methane and nitrous oxide. Methane is produced by livestock digestion and the decomposition of organic matter in flooded rice paddies. Nitrous oxide is released from the use of nitrogen-based fertilizers.



Fossil combustion activity: Fossil combustion is one of the main causes of greenhouse gas emissions. Fossil energy, such as coal and natural gas, is the source for power plants, industry, and transportation. The process of fossil combustion can emit carbon dioxide into the atmosphere. Moreover, other gases, like nitrogen dioxide and sulfur dioxide, also cause air pollution. The combustion process occurs not only in the industrial sector but also in transportation, where vehicles powered by gasoline also produce carbon dioxide and other pollutants. In addition, cultivated rice fields also produce methane, especially if the rice fields are flooded, allowing anaerobic processes to occur and release more methane into the atmosphere.

Deforestation: Deforestation contributes to greenhouse gas emissions because carbon dioxide-absorbing trees are cut down. This results in the loss of carbon sinks as well as the production of carbon through land burning. Forests act as vital carbon sinks, absorbing CO_2 from the atmosphere. When forests are cleared, not only is this carbon-absorbing capacity lost, but the stored carbon is also released back into the atmosphere.

Industrial processes: Many industrial activities, such as cement and chemical production, release GHGs as a byproduct.

Waste management: Landfills and waste treatment facilities produce methane as organic waste decomposes.

Greenhouse gas emissions have existed for hundreds of years and play a crucial role in maintaining Earth's warm temperature. However, with the uncontrolled emissions recently, we might see these impacts:

Global warming: Greenhouse gas emissions are the main cause of global warming, as gases in the atmosphere hold more heat and radiate it back to the Earth. As a result, temperatures continue to rise and cause extreme weather changes, such as droughts, storms, and heat waves.

Environmental damage: This emission affects the environment significantly, as it can increase sea warming and ocean acidification. Additionally, coral reef life is also under threat, even though coral reefs serve as a habitat for various types of marine life.

Economic impact: Excessive greenhouse gas emissions affect the environment and the economy. This phenomenon damages the agricultural field and infrastructure, halting the economic cycle.

The main causes of greenhouse gas (GHG) emissions are human activities, primarily the burning of fossil fuels for electricity, heat, and transportation, followed by agriculture, deforestation, industrial processes, and waste management. These activities release significant amounts of gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere, trapping heat and increasing global temperatures.

2. IMPACTS OF CLIMATE CHANGE TO SECTORS

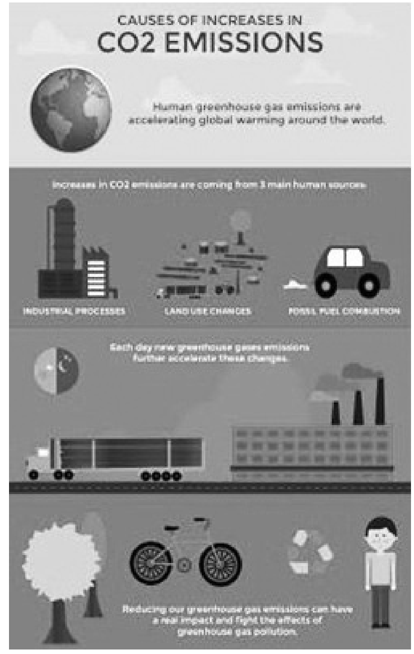
Natural resources and environment

Water resources: In recent years, water flows of main river basins have been lower than the average for many years. Water flows in the dry season decrease, the water levels reach historic lows in many places, droughts and water shortages happen more frequently, and saline intrusion extends further into the mainland. Under climate change scenarios, in most river basins, flows during the flood season tend to increase; high and extreme floods occur with higher frequency and severity.

Land resources: Prolonged heat and droughts increase the risk of arid soil, reducing soil quality. Increased droughts during the dry season and increased rainfall during the rainy season cause a rise in erosion and landslides in riverside and upland areas. Flooding due to sea level rise is one of the major threats to land resources of the delta and coastal areas.

Forest resources: Increased heat will increase the risk of forest fires. Rising temperature, high humidity, heavy rain, strong wind, degraded land, and other factors create favorable conditions for pests and insects to grow and spread, severely affecting the conservation and development of forest ecosystems. Reduced area due to forest fires, pests and diseases, as well as changes in the growth and development of forest ecosystems will affect the output and value of forest products.

Sea and island resources: Rising sea temperature changes the growing season, increasing the outbreak of phytoplankton, which is detrimental to the growth of seagrasses. Climate change increases ocean acidification; strong storms destroy coral reefs, grasslands, give rise to species modification, and decrease marine fish resources. The islands and island groups will bear the brunt of climate change impact.



Mineral resources: Rising sea level may cause soil, rock and ore to be inundated, contaminated with salt and alum, increasing mining and processing costs. Climate change may also facilitate the formation of new ore bodies. Some types of heavy minerals found in solid rocks (gemstones, gold, titanium, etc.) can easily accumulate over time and form placer deposits and weathered mines.

Biodiversity: Climate change and sea level rise can change the structure and distribution of species and biodiversity of ecosystems. Rising temperature will change the distribution and structure of biomes. Sea level rise and increased storm intensity change the composition of sediments, salinity, and pollute water, degrade and threaten mangroves and species.

Agriculture and rural development

Cultivation: Vietnam's rice and corn yields could decline by 8.8% and 18.7% in 2030, and 15.1% and 32.9% in 2050 respectively. If the sea level rises by 100cm, 32.2% of agricultural land is at risk of flooding. Under the climate change scenario, if rice yield and cultivation area remain unchanged with no adaptation measures, Vietnam will run the risk of losing 21.4% of rice production by 2100.

Husbandry: Impacts of climate change on husbandry include changes in the production and quality of animal feed, and increase in disease outbreaks. Pig farming is expected to decrease by about 8.2% in terms of headcount.

Forestry: Climate change and extreme weather events will increase the risk of forest fires, especially in the Northwest, North Central and Central Highlands; affect the distribution of biodiversity in sensitive forests such as dipterocarp forests, mangroves, evergreen broadleaf forests; increase the risk of developing forest pests and diseases; affect the productivity and suitability of planted forests; change the distribution and risk of biodiversity loss, especially for species with narrow ecological distribution.

Aquaculture: Saline intrusion will significantly reduce areas of freshwater aquaculture, affecting the ecological environment, and changing biodiversity.

Transportation infrastructure

Storms and heavy rains cause flooding and erosion, damaging traffic works and equipment in ports and wharves; sea level rise and spring tide may cause flooding of roads, coastal stations, port and wharves infrastructure; storms, fog and heavy rain affect aviation activities; saline intrusion causes structural corrosion and damage equipment. The roadways sector is heavily affected by climate change, followed by railways and inland waterways. The maritime and aviation sectors are insignificantly affected. Mountainous areas in the North, Central Coast and Central Highlands are at risk of erosion and landslides. The Red River Delta and the Mekong River Delta regions are at risk of flooding due to sea level rise. Central coastal provinces face risks of inundation and erosion caused by rain and floods. All of these risks have an impact on transport infrastructure.

Urban development and housing

Sea level rise may cause the inundation of metropolises such as Ho Chi Minh City as well as cities in the Mekong River Delta and along the Central Coastal regions. Municipalities in the Northern mountainous, hilly region and the Central regions are often affected by extreme rain and post-storm circulation, causing floods, flash floods and landslides. Climate change also affects water resources and water supply systems.

Tourism

Climate change has direct impacts on tourism resources, infrastructure and travel activities. Tourism service facilities, accommodations and entertainment facilities are damaged or degraded under the impact of typhoons and floods. Climate change also indirectly affects tourism activities through its effects on other sectors, such as transport, energy, water management, and land-use, etc.

Public health

Climate change will adversely affect human health, especially that of the elderly, women, children, and people with chronic illnesses. According to statistics, an average temperature increase of 1°C results in a 3.8% increase of hospitalisation rate for children aged under 5 due to respiratory infections. Climate change facilitates the development of vector-borne diseases, increasing the likelihood of outbreaks and spread of diseases, such as influenza A, diarrhea, cholera, dysentery, malaria, dengue fever, yellow fever, typhoid, viral encephalitis, severe acute respiratory syndrome, plague, and zika.

Industry and trade

Industry: Rising temperatures lead to increases in energy consumption in industries as well as costs of ventilation and cooling for mines and reduce the efficiency and output of power plants. Rain, storms and sea level rise will affect the operating process, increasing the cost of maintenance and repair works; affect the supply and consumption of energy; increase the risk of inundation in industrial zones. If the sea level rises by about 100 cm, most coastal industrial zones will suffer from flooding of between 10% and 67% of their total areas.

Energy: Increased temperatures increase the energy demand due to the use of cooling equipment. Unusual rainfall and water flows affect the supply capacity and production plan of hydroelectricity, damage the electricity supply infrastructure, increase the cost of new investment, renovation, repair and upgrading of equipment and electricity distribution network. Sea level rise has negative impacts on power plants, power transmission systems, substations, fuel systems, mines, coal yards and other energy-related facilities in coastal areas.

Trade: Climate change can affect commercial infrastructure through local flooding, impacting the storage and circulation of goods. Sea level rise will affect seaports, river ports as well as trade and logistics centres in coastal areas. Different climate change responses in different countries could also affect global, regional and domestic trade.

Impacts of climate change to delta, coastal and mountainous areas

- *Delta areas:* The delta areas will face risks of inundation due to sea level rise. Increased saline intrusion and droughts bear serious impacts on freshwater supply, reducing water quality; rice yield may decrease between 8% and 15% by 2030, and possibly 30% by 2050. Other threats are also on the rise, such as lack of water for domestic use, negative effects on the aquaculture and fishing environments, increased crop diseases, degradation of soil, and the loss of biodiversity and rare genetic resources.

- *Coastal areas:* Coastal areas of Vietnam are severely affected by sea level rise and such climate-related hazards as typhoons and tropical depressions, floods, and landslides. Sea level rise will increase the risk of inundation in coastal areas. Climate change accelerates soil degradation processes, increases saline intrusion area, reduces rice production and creates many other environmental consequences; degrades biodiversity in coastal areas, changes the ecosystems of lowland areas; shrinks the area of forests and natural vegetation.

- *Mountainous areas:* Rising temperatures will affect agriculture, biodiversity, energy production and consumption, and public health. Floods will affect agriculture, water resources, transportation, people's health and lives. The heavily affected groups are mainly people in mountainous areas, especially ethnic minorities and the elderly, women and children. Under the impact of heavy rains caused climate change, the intensity of flash floods tends to increase, causing greater impacts on people's lives.

3. EFFORTS IN CLIMATE CHANGE ADAPTATION

Vietnam has implemented many programs and projects to adapt to climate change.

Climate monitoring, early warning of natural disasters

The monitoring system for climate change and sea level rise has been developed and operated. Developing hydrometeorological forecasting technology; enhancing the accuracy in typhoon and tropical depression forecasts. Establishing the earthquake and tsunami warning system, warning of geological hazards and natural environmental disasters; establishing a set of zoning maps to provide warnings for different natural disasters.

Natural disaster response, flood prevention for major cities, reinforcement of river dikes, sea dikes, and the safety of reservoirs

- Consolidating irrigation infrastructure; developing and expanding clean water supply systems in rural areas; supporting residents in areas that are prone to floods and landslides; formulating plans to relocate and resettle residents in areas frequently hit by floods, typhoons, flash floods and landslides; adjusting production plans and infrastructure to adapt to and limit the negative impacts of climate change;

- Proactively undertaking natural disaster prevention, focusing on areas vulnerable to natural disasters; improving the capacity of search, rescue and disease prevention; implementing flood prevention planning in the Day and Red - Thai Binh River systems; protecting flood drainage spaces in the river basins like the Red - Thai Binh River, Mekong, Cau, Nhue - Day, Dong Nai, and Saigon Rivers and other major rivers; constructing drainage works;

- Repairing and improving dam safety in the North, Central Coastal regions and Central Highlands; building new large reservoirs in the Central Northern, Central Southern Coastal regions and Central Highlands; building new small reservoirs and spillway clusters in the Northern mountainous regions; repairing and upgrading irrigation systems in the Red River Delta; completing and finalizing the irrigation systems, expanding flood drainage canals and regulating sewers in the Mekong River Delta; continuing the investment program to reinforce, protect and upgrade sea dikes from Quang Ninh to Quang Nam and from Quang Ngai to Kien Giang provinces;

- Promoting measures to prevent and mitigate impacts of high tides, inundation, and saline intrusion; developing flood risk maps based on sea level rise scenarios at the commune level; implementing flood prevention schemes for Ho Chi Minh City, Can Tho, Ca Mau and other coastal cities, especially those in the Mekong River Delta;

Ensuring food security

Transforming crop structure, developing large-scale agricultural production; researching, selecting, creating and applying new plant and animal species adaptable to climate change; constructing irrigation works for production restructuring; restructuring public investment, significantly directing investment capital into irrigation to serve multiple purposes; prioritizing capital for implementation of irrigation for upland crops, high-value industrial plants and for aquaculture; facilitating and ensuring the interests of the parties involved in agricultural insurance and risk-sharing.

Ensuring water security

Formulating and implementing the national master plan on water resources and the consolidated master plan for river basins, integrated with climate change; implementing solutions to ensure water security in the context of climate change; determining the minimum flow on rivers, streams and downstream of reservoirs and dams; promulgating legal documents on incentives for thrifty use of water and restriction of underground water exploitation; developing criteria for products, equipment and technologies for economical use of water.

Building climate-resilient communities

Enhancing community capability and participation in climate change response; focusing on local response experiences and the role of governments at all levels and community organisations; developing sustainable livelihood; improving public health and access to basic healthcare and education services; promoting the use of local knowledge in responding to climate change

Protecting and sustainably developing forests and preservation of biodiversities

Conserving and improving forest carbon stocks; protecting and restoring forests, planting mangroves and coastal protection forests; protection of ecosystems and conservation of biodiversity achieved a number of important results.

4. SOLUTIONS AND LESSONS FOR VIETNAM

Many climate change solutions can deliver economic benefits while improving our lives and protecting the environment. We also have global frameworks and agreements to guide progress, such as the Sustainable Development Goals, the UN Framework Convention on Climate Change and the Paris Agreement. Three broad categories of action are: cutting emissions, adapting to climate impacts and financing required adjustments.

Switching energy systems from fossil fuels to renewables like solar or wind will reduce the emissions driving climate change. But we have to start right now. While a growing coalition of countries is committing to net zero emissions by 2050, about half of emissions cuts must be in place by 2030 to keep warming below 1.5°C. Fossil fuel production must decline by roughly 6 per cent per year between 2020 and 2030.

Adapting to climate consequences protects people, homes, businesses, livelihoods, infrastructure and natural ecosystems. It covers current impacts and those likely in the future. Adaptation will be required everywhere, but must be prioritized now for the most vulnerable people with the fewest resources to cope with climate hazards. The rate of return can be high. Early warning systems for disasters, for instance, save lives and property, and can deliver benefits up to 10 times the initial cost.

Vietnam has adopted the National Climate Change Strategy for 2050, which guides action, including during the 2021-2025 period, by enhancing climate resilience and adaptation across natural, economic, and social systems. Key strategies include building resilient agriculture, strengthening forest protection, developing adaptive infrastructure, and improving disaster preparedness through modern monitoring and forecasting systems. The nation is also working on reducing methane emissions and managing greenhouse gases, with a specific action plan targeting a 30% reduction by 2030 compared to 2020 levels.

Vietnam is one of the countries most vulnerable to the impacts of climate change, particularly sea-level rise and extreme weather. To mitigate these risks, the country must implement a comprehensive strategy that includes both global cooperation and domestic action.

Transition to renewable energy: Vietnam should accelerate its shift from fossil fuels to renewable energy sources like solar, wind, and hydropower. The country has significant potential for solar and wind energy, especially in its coastal and central regions. Investing in smart grid technology and energy storage will be crucial for this transition.

Promote sustainable agriculture: The agricultural sector is a major source of emissions. Solutions include: Adopting climate-smart farming techniques that reduce methane emissions from rice paddies; improving livestock management to capture and utilize methane; promoting efficient use of fertilizers to cut nitrous oxide emissions.

Coastal and urban adaptation: With a long coastline, Vietnam is highly susceptible to sea-level rise. The country must invest in building resilient coastal infrastructure, restoring mangrove forests, and developing urban planning strategies that account for rising sea levels and increased flood risks.

International cooperation: Vietnam must actively participate in global climate initiatives, such as the Paris Agreement. By collaborating with international partners, Vietnam can gain access to crucial funding, technology, and expertise to support its green transition.

Education and awareness: A national effort to educate the public and policymakers about the urgency of climate change is essential. This can drive behavioral changes and build public support for green policies.

In conclusion, addressing climate change and GHG emissions requires a multifaceted approach that combines technological innovation, policy reform, and international collaboration. For Vietnam, the path forward involves a strategic shift toward a sustainable, low-carbon economy to protect its people, environment, and long-term economic prosperity■

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NHÂM HIỀN

THE GLOBAL IMPERATIVE: Embracing Climate-Smart Agriculture

The global food system stands at a critical juncture. It must not only feed a growing population - projected to reach 9.7 billion by 2050 but also do so in the face of escalating climate change. Traditional agricultural practices, which are major contributors to greenhouse gas (GHG) emissions and land degradation, are no longer viable. The solution lies in a transformative approach: Climate-Smart Agriculture (CSA).

Developed by the Food and Agriculture Organization (FAO) of the United Nations, CSA is an approach that helps manage agricultural landscapes to address three interconnected goals: sustainably increasing productivity and incomes, adapting and building resilience to climate change, and reducing and/or removing GHG emissions. It isn't a single technology or practice, but rather a flexible framework that's tailored to specific local conditions and challenges.

THE THREE PILLARS OF CLIMATE-SMART AGRICULTURE

The core of the CSA concept is its three-pronged approach.

Sustainably increasing agricultural productivity and incomes

This pillar focuses on boosting food security through more efficient and resilient production. CSA practices aim to maximize yields while minimizing resource use, such as water and nutrients. For instance, precision agriculture uses GPS, sensors, and drones to apply the exact amount of water, fertilizer, and pesticides needed, reducing waste and boosting output. Similarly, improved seed varieties that are more productive or resistant to drought and heat can significantly increase crop yields. These innovations help farmers produce more food on less land, improving their livelihoods and ensuring a stable food supply.

Adapting and building resilience to climate change

The second pillar recognizes that agriculture is among the sectors most vulnerable to climate change. CSA emphasizes building resilience into farming systems to withstand shocks like floods, droughts, and extreme temperatures. Agroforestry, the practice of integrating trees and shrubs into crop and animal farming systems, is a prime example. Trees can provide shade, reduce soil erosion, improve water retention, and offer additional income streams. Another key strategy is crop diversification, which involves planting a variety of crops instead of relying on a single one, thereby spreading risk and enhancing the farm's ability to cope with unpredictable weather patterns.

Reducing and/or removing greenhouse gas emissions

The final pillar tackles agriculture's role as a major emitter of GHGs. CSA seeks to lower the carbon footprint of food production by promoting practices that either reduce emissions or sequester carbon in the soil. For example, improved manure management in livestock farming can capture methane, a potent GHG, for use as an energy source. The practice of no-till farming, where soil is left undisturbed, can significantly reduce carbon emissions and build up organic matter in the soil, effectively turning farmland into a carbon sink. This "carbon farming" not only mitigates climate change but also improves soil health and fertility.

Challenges and the path forward

Despite its clear benefits, the widespread adoption of CSA faces several hurdles. A major challenge is the initial cost of implementing new technologies and practices, which can be prohibitive for smallholder farmers in developing countries. There's also a need for stronger policy frameworks, financial incentives, and

But achieving these interconnected goals is a growing challenge, particularly in the face of a changing climate and pressure from growing global food and agriculture demand.

knowledge-sharing platforms to support farmers in making this transition.

However, the momentum is building. International organizations, national governments, and private sectors are collaborating to scale up CSA through investment, research, and policy reform. The future of global food security and environmental sustainability hinges on our ability to transform our agricultural systems. Embracing Climate-Smart Agriculture is not just an option—it is a global necessity.

The global adoption of CSA faces several challenges. These include lack of knowledge of CSA technologies and limited access to resources by smallholder farmers, as well as a lack of adequate policies. There are also financial barriers to introducing CSA techniques due to high initial building costs.

Overcoming these barriers requires investments in education programmes, stronger institutional support and better access to CSA technologies. Organizations like CABI provide farmers with easy access to information on science-based solutions and training resources. These programmes empower farmers with the tools and knowledge needed to implement climate-smart practices, improving resilience and sustainability in agriculture.

PREPARING FARMERS FOR THE FUTURE OF CLIMATE-SMART AGRICULTURE

As climate change reshapes agricultural systems, preparing farmers for climate-smart practices is essential. This requires a coordinated effort in training, education, and policy support.

Training and education

Education plays a vital role in helping farmers transition to CSA. Through training programs, farmers can learn about sustainable techniques like conservation farming and water management and how to maintain the efficiency of crop production. They can also learn about the tools and technologies available to help them in their transition to CSA.

For example, CABI offers valuable free courses on topics such as sustainable soil management practices and water management, empowering farmers to adopt efficient techniques that enhance productivity in their agricultural system, while protecting natural resources.

Policy support and government role

Governments play a pivotal role in supporting farmers to adapt to climate change by providing the necessary tools, resources, and policy frameworks. Governments can help by funding research projects and providing farmers with adaptive tools and evidence-based information to face climate challenges, safeguarding food security and biodiversity.

For instance, the USDA and its Natural Resources Conservation Service (NRCS) have developed projects that address soil health, water conservation, and pest management. This USDA service provides farmers with technical assistance and financial incentives to adopt sustainable practices that protect both agricultural productivity and natural resources.

THE GLOBAL IMPERATIVE FOR A HEALTHY SUSTAINABLE PLANET

The United Nations Sustainable Development Goals (SDGs) establish targets for achieving inclusive economic growth, social development and natural resource conservation and biodiversity by 2030.

Sustainable agriculture practices and technologies contribute to many of the 17 SDGs by helping to end hunger and malnutrition, reducing post-harvest loss and food waste, mitigating climate change, providing clean energy, preserving biodiversity and promoting good health and gender equality.

Sustainable agriculture must satisfy human needs; enhance environmental quality and the natural resource base; sustain the economic vitality of food and agriculture systems and improve the quality of life for farmers, ranchers, forest managers, fishers, agricultural workers and society as a whole. But achieving these interconnected goals is a growing challenge, particularly in the face

See and Spray technology, developed by John Deere and Blue River Technology, uses machine learning to identify weeds and spray chemicals only where needed.

of a changing climate and pressure from growing global food and agriculture demand.

Agri-food production systems impact the natural resource base and are the source of nearly one quarter of global greenhouse gas (GHG) emissions. The majority of agricultural emissions are from deforestation and land use change (the conversion of forest to croplands or livestock grazing lands), and from methane emitted from livestock, along with poor soil management.

Agriculture is also impacted by climate change. Recent models show that with a 2° Celsius increase in global mean temperature (the temperature ceiling for a climate-safe planet), yields are expected to decrease, on average, 14 percent for maize, 12 percent for wheat, 6.4 percent for rice and 6.2 percent for soybeans.

Climate change also brings rising threats from the growing assault on crops by insect pests. When average global surface temperatures increase by 2° Celsius, models indicate the median increase in yield losses due to pest pressure is 46 percent for wheat, 19 percent for rice and 31 percent for maize. The Inter-Governmental Panel on Climate Change's (IPCC) fifth assessment report confirms this strong linkage between warming and increased threats to agriculture from pests and disease.

Degraded soils, lack of clean water for agriculture and human consumption, failing crops and livestock and rising temperatures lay the groundwork for food crises and economic and political instability. Conflict, migration and drought are tightly interwoven and must be viewed through the lens of sustainability.

Agricultural production in the United States continues to evolve as consumers, investors, farmers and agribusinesses seek lower-carbon operations and better soil and water quality on farms and in watersheds.

By setting goals for reductions in greenhouse gas emissions, water use, soil erosion, land and energy use, and by entering into conservation partnerships, rice and pork farmers are making continuous improvements in stewardship and sustainability.

Precision agriculture is the use of data and technology to increase the productivity and profitability of agricultural operations, including crops, livestock, aquaculture, dairy forests and orchards. Precision agriculture is also a powerful tool that helps producers shift to precision conservation and reduce greenhouse gas emissions.

Farmers use tractors, combines and sprayers with global positioning system (GPS) devices and precision guidance satellite receivers that enable them to navigate for sub-inch accuracy in the field. Using equipment such as in-field monitors and sensors, farmers and farm service providers can record data on temperature, rainfall, soil conditions and plant growth, capturing information for analysis and to generate models that help them make good decisions about operations and investments.

Integrated software that contains data about their operations helps farmers precisely apply crop nutrients, control weeds and pests and add water only where it is needed for maximum yield and at lowest cost.

Remote sensing is widely used along with satellite imagery to collect data; unmanned aerial vehicles (drones) also collect data and are used to generate maps and assess crop health.

Precision systems enable each farmer to manage and track, year after year, progress towards maximizing the productivity of each field, while placing less productive areas into conservation or creating refuges for pollinators and wildlife.

For livestock operations, sensors on the animals can alert ranchers to the presence of a disease before it spreads throughout an entire herd. Livestock monitors check animals for breeding cycles and disease and track the amount of food and water consumed. Using their own data, precision systems help farmers raise healthier animals and manage grazing lands for sustainability goals. Farmers also invest in automated and computer-controlled barns that provide consistent temperatures and readily available feed and water.

In forest operations, remote sensing images can measure tree height and canopy information, as well as tree diameter and biomass as part of a carbon sequestration strategy. Estimating timber volume allows forest managers to make better decisions about where and when to harvest trees.

As a whole, precision systems can monitor, manage and optimize irrigation, farm vehicles, livestock, greenhouses and stables, aquaculture, forests and storage of crop and livestock products; such integrated systems can reduce energy, labor, and make the best use of scarce natural resources■

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SUSTAINABLE BIOSENSING FOR WATER SECURITY: A review of technologies for heavy metal detection in wastewater

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Increased industrialization has led to the widespread contamination of wastewater with toxic heavy metals, creating significant risks for public health and environmental stability and directly challenging the achievement of the United Nations' Sustainable Development Goal (SDG) 6 (Clean Water and Sanitation). While precise, conventional laboratory-based methods for detecting these pollutants are often too costly, slow, and complex for the rapid, on-site monitoring required for effective environmental management. This technological gap hinders timely progress toward global water safety targets. This paper provides a comprehensive review of recent advancements in biosensor technologies, aiming to highlight their potential as a sustainable and cost-effective tool to support the achievement of water- and environment-related SDGs. The research method involves a systematic review of current scientific literature, examining the fundamental principles, classifications, and components of various biosensor systems. The analysis focuses on case studies that utilize novel biorecognition elements and nanomaterials to improve performance and sustainability. The principal findings indicate that biosensor technology has advanced significantly, achieving high sensitivity for detecting key heavy metals. The development of eco-biosensors using biodegradable components aligns with SDG 12 (Responsible Consumption and Production) by minimizing waste. These technologies also support SDG 13 (Climate Action) by reducing the energy consumption of traditional analyses and contribute to protecting ecosystems as targeted by SDG 14 (Life Below Wate) and SDG 15 (Life on Land). In conclusion, biosensors offer a transformative approach to environmental monitoring that directly supports the broader goals of sustainable development. Although challenges in mass production, long-term stability, and regulatory validation persist, overcoming these hurdles will enable the widespread deployment of biosensor systems as a critical tool for achieving global clean water and sustainability goals.

1. INTRODUCTION

Water is integral to the achievement of the United Nations' SDGs, serving as a critical resource that underpins societal progress [1]. Over the years, escalating urbanization and industrialization have led to an increasing demand for water, consequently resulting in substantial wastewater discharge into the environment. In 2022, roughly 42 % of global domestic wastewater was released without adequate treatment, amounting to 113 billion m3/year [2]. In low-income countries only 8 % of wastewater receives treatment, compared with 70 % in high-income countries. Wastewater sources are broadly categorized into point and non-point sources. Sources of wastewater are typically classified as either point sources, which are specific, identifiable locations like industrial outlets or sewage plants, or non-point sources, such as diffuse agricultural and urban runoff, the latter being more difficult to manage. The complex composition of wastewater, laden with inorganic and organic compounds, HMs, and emerging pollutants like microplastics, antibiotics, endocrine disruptors, and perfluoroalkyl and polyfluoroalkyl substances (PFAS), exacerbates freshwater scarcity by degrading both its quantity and quality [3, 4]. Industrial effluents frequently contain elevated levels of HMs pollutants [5]. Exceeding these limits causes neurotoxicity, kidney damage and cancer in humans as well as reproductive and growth impairments in aquatic species. Addressing the issue of wastewater is imperative, as it directly influences public health and mitigates the prevalence of waterborne diseases. Therefore, creating swift, accurate, and field-deployable detection systems for environmental pollutants becomes crucial for facilitating preventative public health surveillance [6]. Industrial activities cause significant annual global releases of HMs, estimated at around 22,000 metric tons of cadmium, 939,000 tons of copper, 783,000 tons of lead, and 1,350,000 tons of zinc [7]. This underscores the essential requirement for efficient treatment of industrial wastewater prior to its discharge into the environment.

Even trace amounts of pollutants in wastewater can have profound environmental impacts, necessitating the creation of highly sensitive detection techniques [8]. Although sophisticated analytical tools like HPLC, GC, and diverse spectroscopic methods yield precise detection of contaminants, their high cost, time requirements, and need for trained personnel restrict their use for real-time, on-location monitoring [6]. Since the advent of the first biosensor in 1962, significant advancements have been made in biosensor technology, resulting in innovative designs and enhanced functionality [9]. Biosensors, analytical devices engineered to detect and quantify pollutants by transducing biological signals into optical or electrical outputs, provide rapid, precise, and reliable real-time data on analytes. The high specificity inherent to biosensors reduces signal interference from non-target substances, rendering them highly valuable tools for environmental surveillance. The effectiveness of biosensors in continuous or single-point detection and measurement is contingent on the biological elements employed. Utilizing organisms to predict chemical pollution exposure further enhances the predictive power of these devices, enabling exact assessment of environmental pollutants' detrimental effects.

More than just a detection tool, advanced biosensor technology offers a pathway to broader sustainable development. While previous reviews have covered biosensor fundamentals, this paper uniquely bridges these technological advancements with their direct, quantifiable impacts on achieving the UN's SDGs [6, 9, 10]. This paper reviews current biosensor technologies and highlights recent advances in their use for environmental monitoring, with a focus on improved detection of HMs in wastewater. This paper highlights how innovations in biorecognition elements and nanomaterials are creating sustainable, cost-effective tools.

2. PRINCIPLES OF BIOSENSORS

Functionally, a biosensor operates as a self-contained, integrated system that yields precise quantitative or semi-quantitative analytical results by employing a biological sensing element in direct physical contact with a signal transducer [11]. The components of a biosensor are divided into three segments including (1) the biological recognition elements, such as enzymes, antibodies, and DNA, play a crucial role in biosensors. The device incorporates: (2) a signal transducer to transform the biological interaction into a quantifiable and readily interpretable output, and (3) a signal processor designed to present this converted signal clearly and efficiently. A common approach categorizes biosensors according to either their method of signal transduction (e.g., optical, electrochemical, piezoelectric) or the nature of their biorecognition component (including elements like antibodies, aptamers, cells, enzymes, receptors, or neurons). Aptamer-based electrochemical sensors achieve LOD 60.7 nM for Pb^{2+} in lake water via G-quadruplex folding (FAM-Pb-14S) [12]. Co-ions like Cu^{2+} can induce 15 % false responses unless blocked by e.g. 6-mercaptohexanol monolayers.

2.1. Classifications of biosensor

Electrochemical biosensors see extensive application partly because their design centers on electrodes suitable for immobilizing biomolecules; these electrodes facilitate the detection of biochemical occurrences by translating them into quantifiable electrical signals [11, 13]. This conversion enables the investigation of diverse biochemical reactions and molecular interactions within biosensing applications. A significant advantage of electrochemical biosensors lies in their straightforward integration with existing electronics manufacturing processes, facilitating their suitability for mass production [14]. The adaptability of biosensors has led to their widespread use across varied fields, including ensuring food safety, performing medical diagnostics, and conducting environmental surveillance [9]. Their small footprint and economic advantages position biosensors as strong contenders for environmental monitoring roles, particularly for the early detection of toxic agents like HMs, viruses, or organic pollutants. Despite some limitations, such as a limited operating temperature range, a brief shelf life, and the potential for cross-sensitivity, their cost-effectiveness ensures they are readily available to many. For instance, the hybrid Pt NPs/SiO_2-DNAzyme electrochemical biosensor reported by Skotadis et al. achieves ultralow limits of detection (LODs) of 0.8 nM for $Pb2^+$, 1 nM for $Cd2^+$, and 10 nM for $Cr3^+$, with rapid response times of 7 - 19 s [15]. Calibration was performed using six concentrations (1, 2, 5, 10, 20, 50 nM), yielding a linear range of approximately 1 - 50 nM for $Pb2^+$ and $Cd2^+$, and 10 - 100 nM for $Cr3^+$ [15]. The biosensor also proved excellent precision, with standard deviations ranging from 0.28 - 1.2% across ten independent sensor replicates per ion. In recent work on optical-plasmonic sensing, nanocrystalline cellulose/PEDOT (NCC/PEDOT) thin films have been shown to enhance surface-plasmon-resonance (SPR) sensitivity for mercury ions, achieving a limit of detection as low as 2 ppb (≈10 nM) within 30 min while maintaining selectivity against common co-ions [16]. Similarly, piezoelectric quartz-crystal-microbalance (QCM) platforms functionalized with homocysteine and nanoparticle coatings detect Hg2+ down to 0.1 ppb (0.498 nM) over a vast dynamic range (0.1 ppb to 1 355 ppm) in under 30 min; their portability, milliliter-scale sample requirement, and excellent repeatability make them ideal early-warning systems for on-site mercury monitoring [17].

The basis of optical biosensor operation lies in utilizing the interplay between an optical field and the biorecognition element [18]. This sensing modality proves especially helpful for analyzing colored or turbid samples, encompassing various biomolecules or microorganisms like viruses, bacteria, and other pathogens. Optical biosensors operate using one of two primary detection strategies: label-based or label-free. The label-based detection employs a labeling molecule, with the optical signal generated via colorimetric, fluorescent, or luminescent methods. Label-based detection involves labeling the bioanalyte to generate an optical response, commonly used in environmental monitoring of pathogens like Escherichia coli and Salmonella typhimurium in water and food through techniques such as fluorescence and colorimetry [9]. However, label-based methods have certain drawbacks, including the potential for the labeling process to alter the bioanalyte's activity and introduce quantification errors. This has sparked increased interest in label-free methods, particularly SPR, which relies solely on bioanalyte-transducer interactions. In the label-free mode, the detection signal arises directly from the interaction between the analyte and the transducer. Despite its advantages, optical biosensing, particularly label-free methods related to SPR, faces challenges in terms of miniaturization, portability, and sustainability for broader application.

The fundamental operation of mass-based biosensors centers on finding changes in mass that take place when the target analyte attaches to the biorecognition element fixed on the sensor's surface. This mass change is typically measured using transducers like piezoelectric devices, which convert mechanical stress into an electrical signal correlated with the analyte concentration [19]. An illustrative case is the quartz crystal microbalance (QCM) biosensor, which has found extensive application in both research and environmental monitoring. In the context of biological studies, QCM sensors offer notable advantages including heightened sensitivity, ease of use, and cost-efficiency, showing them as useful tools within analytical chemistry. Their versatility enables the detection of various molecules, chemicals, polymers, and biological samples. However, a key challenge is still in optimizing the crystal coating process to ensure uniform and cohesive deposition layers. Addressing this challenge, with a focus on sustainability, could unlock the full potential of QCM sensors for broader applications.

Progress in biosensor technology owes much to nanoscience and nanotechnology, clearly demonstrated by the emergence of nanobiosensors and devices capable of single-molecule detection [20, 21]. Integrating nanomaterials like functionalized nanoparticles, nanowires, or nanotubes into sensor designs has led to considerable gains in sensitivity, selectivity, and overall performance characteristics. These advancements arise from the distinct qualities of nanomaterials, such as their shape and size-dependent properties, extensive surface area, and cost-efficiency. Practical challenges persist, however, encompassing issues like detecting analytes present at extremely low levels, addressing potential target sequence mutations or evolution (particularly for oligonucleotides and proteins), and achieving an optimal trade-off between fabrication cost and operational effectiveness across diverse sensor types.

2.2 Key performance characteristics of biosensors in heavy metal detection

To be effective for environmental monitoring, biosensors are evaluated based on several key performance characteristics. These metrics determine their suitability for rapid, on-site analysis and their advantage over traditional laboratory methods.

- *Selectivity:* This is the sensor's ability to detect a specific target heavy metal (e.g., Pb^{2+}) without generating a false signal from other, similar ions (e.g., Cu^{2+}, Cd^{2+}) that may be present in the same sample.

- *Limit of detection (LOD):* This represents the minimum concentration of a heavy metal that the sensor can reliably distinguish from a blank sample. Low LODs (in the nM or ppb range) are essential, as many metals are toxic even at trace concentrations.

- *Response time:* This is the time required for the sensor to provide a stable measurement after the sample is introduced. A rapid response (from seconds to minutes) is a primary advantage for real-time monitoring and immediate intervention.

- *Linear range:* this is the concentration range where the sensor's output signal is directly proportional to the analyte concentration. A wide linear range allows the sensor to accurately quantify both low and high levels of contamination.

- *Stability and shelf-life:* this refers to the sensor's ability to maintain its performance over time. Operational stability is its ability to function in field conditions, while shelf-life is how long it can be stored.

This is a significant challenge, as biological components can be sensitive to temperature or environmental conditions.

3. HEAVY METALS MONITORING BY BIOSENSORS

Heavy metals (HMs) contamination is commonly released due to human activities and industrial processes, including refineries, metal processing, mining, cement production, and smelting operations [22]. This form of contamination presents considerable dangers to human well-being and ecological systems. HMs pose substantial health risks to ecosystems even at minimal concentrations, primarily because they resist biological breakdown, are not easily chemically degraded, and tend to bioaccumulate within organisms [23, 24]. Additionally, water, soil, and living beings are known to accumulate these metals, underscoring the need of environmental monitoring to prevent contamination and illness [6]. Various methods, including chromatography (gas chromatography, high-performance liquid chromatography), inductively coupled plasma mass spectrometry, or atomic absorption spectroscopy, can be employed at laboratory for qualitative and quantitative HMs analysis [8]. Nevertheless, real-time detection, excessive costs, and by-product release pose significant challenges for environmental monitoring by these techniques. Through biosensors, a method offering high sensitivity for deciding HMs concentrations is available, thereby aiding efforts to manage water safety and quality.

Detection of HMs can be achieved using DNA probes, which function as recognition elements working via several distinct mechanisms. Among these mechanisms is the specific interaction between DNA bases and target metal ions, leading to the creation of a stable duplex DNA structure [11]. Additionally, HMs can break DNAzymes, and a guanine-rich probe can undergo a transition to a stable G-quadruplex structure [25]. Whole-cell microbial biosensors offer a means to detect HMs through the use of genetic components engineered to react to designated chemical substances [26]. The performance characteristics of such biosensors depend on the interplay between regulatory proteins associated with promoters and the specific reporter genes chosen to signal the presence of pollutants. Within microorganisms engineered for biosensing, reporter genes act as indicators, converting specific biological responses to pollutants into quantifiable physicochemical signals [27]. Table 1 presents typical biosensors for HMs monitoring.

Table 1 illustrates that various platforms, including whole-cell and electrochemical methods, are attaining

Table 1. Typical biosensors for HMs monitoring

Type of biosensor	Material/ Bacteria	Wastewater	Detection limits	Time	Remarks	Reference
Biosensor cell	A luminescent bacterium *Vibrio* sp. MM1	Synthetic water	Zn^{2+} (0.97 mg/L), Ni^{2+} (3.0 mg/L), Cu^{2+} (3.62 mg/L), Pb^{2+} (5.75 mg/L), Co^{2+} (6.16 mg/L, and Cd^{2+} (14.54 mg/L)	15 min	high sensitivity in detecting HMs	[28]
Light-up biosensor	FAM-Pb-14S	Lake water and serum samples	60.7 nM	1 h	Simple, rapid and reliable,	[29]
Molecular biosensors	*Acinetobacter baylyi* ADP1 Tox2	River water	-	30 min	Detect and manage pollution in urban river systems	[30]
A protein biosensor	mApple-D6A3 protein	Tap water	Cu^{2+} (18.7 μM), Ni^{2+} (21.4 μM), and Cd^{2+} (19.3 μM)	20 min	Detection accuracy exceeds 80%	[31]
Electrochemical biosensor	Oxygen-type electrochemical biosensor by a packed-bed bioreactor	Synthetic water	Cr^{6+} (0.0762 mg/L)	5 min	Cost-effective, accurate	[8]

Electrochemical biosensor	Cu-TCPP/Au/Pb^{2+}-G4-hemin	Synthetic water	1.7 nM	–	High sensitivity and high selective	[32]
Electrochemical biosensor	Hybrid nanoparticle (Pt NPs/SiO_2)/DNAzyme	Synthetic water	Pb^{2+} (0.8 nM), Cd^{2+} (1 nM) and Cr^{3+} (10 nM)	–	Good sensitivity, precision, and sufficient dynamic range	[15]
A dual-colored bacterial biosensor	A CadR-regulated vioABE expression module and a MerR-regulated VioC expression module	Sea water	Cd2+ (4.9 nM), Pb2+ (24.4 nM, and Hg2+ (0.5 nM)	4 h	High sensitivity and selectivity	[33]

impressive nanomolar (nM) detection limits for essential metals such as Hg^{2+} (0.5 nM), Pb^{2+} (0.8 nM), and Cd^{2+} (4.9 nM). Electrochemical sensors demonstrate rapid response times, detecting Cr^{6+} in 5 minutes, while whole-cell systems may necessitate incubation periods of up to 4 hours. The table highlights a validation gap: many top-performing sensors were tested solely in synthetic water. The use of lake or sea water in some tests highlights the significant gap in data regarding complex industrial wastewater, which poses a major challenge for practical field deployment.

4. BIOSENSOR APPLICATIONS AS A PATHWAY TO THE SDGS

Biosensors provide rapid, accurate monitoring, shifting environmental management from reactive remediation to proactive prevention [9, 10]. This strategy of real-time, source-level detection allows for immediate intervention, which is more cost-effective and successful at preventing widespread ecological and human harm than subsequent cleanup.

4.1 SDG 3: Good health and well-being

Biosensors for HMs detection play an essential role in advancing SDG 3, especially Target 3.9, which specifically aims to "substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination". The primary approach for this contribution is prevention. Biosensors facilitate the swift and regular assessment of drinking water, food sources, and residential soil for hazardous metals such as lead, mercury, and cadmium, serving as a crucial initial barrier to avert human exposure and potential harm [5, 26]. This work is particularly important for safeguarding at risk groups, like children, whose cognitive growth can suffer irreversible damage due to lead exposure [9]. Implementing affordable biosensors within communities enables the detection of contamination sources, like aging lead pipes or industrial emissions, thereby supporting focused public health initiatives and ultimately preserving lives while alleviating the impact of chronic diseases.

4.2. SDG 6: Clean water and sanitation

Access to clean water is essential for health, dignity, and economic progress, positioning SDG 6 as a fundamental element of the 2030 Agenda for Sustainable Development. Biosensors play a crucial role in fulfilling Target 6.1, which aims for universal and equitable access to safe and affordable drinking water, along with Target 6.3, focused on enhancing water quality through pollution reduction. Their portability and real-time capabilities render them exceptionally suited for the continuous monitoring of water quality across the entire water cycle [7]. These systems can be utilized at water treatment plant intakes to monitor upstream contamination, within distribution networks to pinpoint issues such as pipe leaching, and at the tap in homes and schools to verify that water is safe for consumption. Biosensors play a crucial role in wastewater management by allowing treatment facility operators to continuously monitor effluent, ensuring that the discharged water complies with regulatory standards and does not contaminate receiving water bodies [34]. This swift feedback mechanism facilitates prompt modifications to processes, thereby averting the discharge of pollutants and safeguarding downstream ecosystems and water consumers.

4.3. SDG 14: Life Below Water

Marine ecosystems serve as a crucial repository for numerous pollutants originating from land, such as heavy metals. SDG 14, particularly Target 14.1, seeks to "prevent and significantly reduce marine pollution of all kinds, especially from land-based activities". Biosensors serve as an essential early warning mechanism to accomplish this objective. Implementing sensor networks in rivers, estuaries, and channels that handle industrial or agricultural runoff in coastal areas allows for real-time monitoring of heavy metal flow from land to sea [28]. An alert from a biosensor can initiate a prompt examination to identify and stop the source of pollution before it inflicts considerable damage on vulnerable marine ecosystems such as coral reefs and mangrove forests [28]. This proactive strategy is essential for preserving marine biodiversity, ensuring the sustainability of fisheries that are important for coastal communities, and mitigating the bioaccumulation of harmful substances such as mercury within the marine food web [35].

4.4. SDG 15: Life on Land

The well-being of terrestrial ecosystems is central to SDG 15, which encompasses Target 15.3, an initiative aimed at "combating desertification, halting and reversing land degradation, and preventing biodiversity loss". Heavy metal contamination significantly contributes to soil degradation, leading to infertility, detrimental effects on vital soil microorganisms, and risks to the safety of agricultural products for consumption [26]. Biosensors serve as an efficient and economical method for assessing soil contamination over extensive regions. This data is crucial for land-use planning, enabling authorities to pinpoint high-risk areas and execute focused remediation strategies. On-site soil testing using biosensors provides farmers with critical insights for making informed decisions regarding crop selection and necessary soil amendments, ultimately supporting land productivity and the enduring sustainability of agricultural practices [6]. Protecting soil health through biosensors is crucial for preserving biodiversity and the essential ecosystem services that terrestrial life offers.

5. KEY CHALLENGES AND FUTURE PERSPECTIVES

5.1 Key challenges in field deployment

The design possibilities for environmental biosensor applications have been significantly broadened by recent progress in nanomaterial and molecular recognition elements. Nevertheless, increasing attention is being directed towards technologies allowing the direct, real-time monitoring of pollutants at the sampling location. Drones have become valuable tools for environmental monitoring. With the help of advanced technology, drones are now being utilized for a wide range of purposes, including assessing water and air quality, monitoring agricultural activities, and measuring volcano gas emissions [36]. A noteworthy instance involves the incorporation of a whole-cell biosensor into drones to monitor air and water quality in distant regions. This system showcases the capabilities of combining biosensors with drones for cost-effective and efficient environmental monitoring [36, 37].

Within environmental monitoring, electrochemical and enzymatic biosensors find significant use, with acetylcholinesterase-based systems being prime examples frequently employed for pesticide detection [26, 38]. Such biosensing systems gain appreciation due to their user-friendliness, dependable accuracy, and relatively low cost. Broader adoption of certain biosensors faces hurdles such as the significant expense of enzyme purification, insufficient thermal stability, and limitations in their effective operating conditions. On the other hand, aptamers offer a hopeful alternative because of their capacity to rehybridize, identify a wide range of targets, and endure different environmental conditions. Immunosensors, employed for the monitoring of organic molecules like toxins and endocrine-disrupting chemicals, offer an impressive degree of specificity [19]. Nonetheless, they face specific hurdles related to the regeneration of antibodies, their immobilization, and the optimization of their activity. These challenges pose significant obstacles to the development of immunosensors, requiring added research to improve their practical applications.

A primary limitation hindering the deployment of many current environmental biosensors is the insufficient validation using authentic environmental matrices. This validation gap is demonstrated clearly in Table 1; the majority of the high-performance sensors listed were tested in synthetic water, lake water, or tap water, not in the complex, high-interference industrial wastewater or agricultural runoff where they are most needed. Testing is often confined to simplified samples, which restricts a true assessment of their real-world performance. The lack of commercial biosensors for environmental monitoring is primarily due to this gap, which stands in stark contrast to their extensive use in clinical settings. The diverse aspects of biosensor development, along with the difficulties in achieving consistent results and on-site functionality, contribute to this discrepancy. Notwithstanding the existing challenges, considerable progress has occurred on the deployment of biosensors in actual environmental contexts. Recent research has proved the effective use of biosensors in various environments, such as lakes, rivers, seawater, soil, and wastewater. Such research initiatives reflect a committed focus on tackling the difficulties associated with environmental biosensors and expanding their practical, field-based applications. In summary, while the field of environmental biosensors has seen noteworthy progress, several hurdles stay that require solutions.

5.2. Future perspective: advanced biorecognition

To meet the high selectivity and low detection limits required for environmental monitoring, sensors must move beyond traditional bioreceptors and employ advanced molecular tools coupled with powerful signal amplification strategies. Replace protein-based antibodies with aptamers—short, single-stranded DNA or RNA molecules. Aptamers are chemically synthesized, making them cheaper, more consistent batch-to-batch, and far more resistant to the thermal and chemical denaturation that plagues antibodies in environmental samples. Crucially, they can be selected to bind with high affinity and specificity to non-immunogenic targets like heavy metal ions, for which developing high-quality antibodies is difficult. Additionally, implement CRISPR-Cas systems as the ultimate tool for programmable biorecognition. While not used for direct metal detection, they can be programmed to identify highly specific secondary indicators of contamination. For example, a sensor could be designed to detect the unique DNA sequence of a microorganism that only thrives in the presence of mercury or to recognize specific nucleic acid biomarkers of metal-induced cellular stress. This programmability allows for the rapid development of assays for new contaminants. Furthermore, use nanomaterials like gold nanoparticles, graphene, and carbon nanotubes to amplify the signal from these specific binding events. The high surface-area-to-volume ratio of these materials allows for a much denser loading of aptamers or probes on the sensor surface, increasing the probability of a binding event. Their unique electronic properties also act as catalysts and conductive bridges in electrochemical sensors, dramatically enhancing the electrical signal and pushing detection limits down to the parts-per-trillion levels required by environmental regulations.

5.3. Future perspective: integrated smart systems

The end goal is not a perfect standalone sensor, but a smart, networked system that provides actionable intelligence. This requires a paradigm shift from component-level work to system-level integration, leveraging IoT and AI to transform raw data into predictive insights. Deploy arrays of multiplexed biosensors at key nodes within a watershed or municipal water system. By connecting these sensors using low-power, long-range communication protocols (e.g., LoRaWAN), a continuous, high-resolution spatiotemporal map of water quality can be generated. This moves monitoring from infrequent, single-point measurements to a dynamic, system-wide view, allowing for the precise identification of pollution sources in real-time. Additionally, use AI/ML to process the vast datasets from these sensor networks. At the device level, ML algorithms can perform real-time fault diagnosis and self-calibration, correcting for signal drift caused by biofouling and extending the sensor's operational life in the field [39]. At the network level, ML can analyze complex data streams to identify the unique chemical fingerprints of specific pollution sources and, most powerfully, train predictive models. By learning from historical data, these systems can accurately forecast contamination events up to 48 hours in advance, allowing authorities to shift from a reactive cleanup strategy to a proactive, preventative management model.

Continuous improvements in designing biosensors, particularly focusing on boosting enzyme stability, broadening the applicability of aptamers, and refining immunosensor performance, are vital for the field's advancement. Successfully translating laboratory-validated performance into reliable, practical field use is essential to foster wider adoption and deployment of biosensors specifically for environmental monitoring purposes. The worldwide market for biosensors is projected to experience substantial growth, increasing from USD 30.6 billion in 2024 to USD 49.6 billion by 2030. This represents a compound annual growth rate of 8.4%, with environmental applications poised to emerge as a significant sub-segment [40]. The integration of artificial intelligence and data analytics, particularly through the combination of multiplex sensor arrays with machine learning algorithms, has improved the ability to deconvolute analyte signals and can predict pollution events up to 48 h in advance [41]. As the field evolves, the development of ISO standards for biosensor calibration and data formatting will play a critical role in ensuring interoperability, consistency, and regulatory acceptance across international markets.

6. CONCLUSION

Employing biosensor technology to detect HMs in wastewater provides fundamental benefits compared to traditional analytical methods, chiefly through enabling swift, portable, and economical measurements. Innovations in nanomaterial design and ecofriendly biorecognition elements have produced sensors that detect trace concentrations of lead cadmium mercury and arsenic with high precision. Feasibility studies have confirmed their applicability in matrices such as industrial discharge, municipal wastewater, and agricultural runoff. Combining these sensors with internet-connected monitoring grids and compact chip-based platforms promises to enable ongoing, real-time surveillance and provide timely alerts for pollution incidents. Key barriers remain in mass production of consistent sensors validation in complex sample matrices and compliance with evolving environmental regulations. Addressing these issues through standardized manufacturing protocols robust material functionalization and comprehensive field trials will be critical. Successfully bridging these gaps will empower practitioners to implement biosensor systems at scale thereby supporting sustainable water management initiatives and advancing public health protection goals■

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