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Finite Element Strength Assessment of a Crane Foundation Deck in a Multi-Cat Fish Farm Support Vessel

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Abstract This study evaluates the structural strength of the forecastle deck in the crane foundation area of a Multi-Cat vessel using the finite element method. A three-dimensional finite element model was established to simulate the deck structure under crane operating loads. The analysis considered the most critical lifting condition and included eight crane rotation angles. Stress results were assessed according to the allowable stress requirements of the ABS Rules for Building and Classing Steel Vessels under 90 Meters. The results show that the maximum Von Mises stress occurs at a rotation angle of 180°, with a value of 160.4 MPa, which is lower than the allowable limit of 165 MPa. Therefore, the deck structure in the crane foundation region satisfies the strength requirement under the examined operating conditions. The study confirms that finite element analysis is an effective tool for verifying the structural safety of crane-supported deck structures.

Keywords FEM; Crane; Forecastle; Deck; ABAQUS; Foundation

1 Introduction

The structural integrity of ship decks subjected to concentrated loads is a key issue in marine structural design, especially in regions supporting crane foundations. During lifting operations, crane loads generate significant local stresses and deformation in the deck plating, stiffeners, girders, and supporting substructure. If these effects are not properly evaluated at the design stage, they may lead to excessive deformation, local yielding, fatigue damage, or even structural failure in service. Therefore, local strength assessment of deck structures under crane loading is an essential part of structural verification for crane-mounted marine vessels.

Recent studies have shown that finite element analysis has become an effective approach for evaluating local reinforcement schemes and structural responses in crane-supported marine structures. For example, Dragatogiannis et al. (2024) analyzed deck reinforcement arrangements for crane installation on a composite yacht and showed that local strengthening has a significant influence on stress distribution and structural safety. Hernández-Ménez et al. (2023) proposed a structural assessment methodology for an FPSO main deck supporting an offshore crane and demonstrated that different crane operating conditions may substantially affect deck behavior. In addition, Abdullah et al. (2023) carried out a finite element strength analysis of a deck crane barge and confirmed that numerical simulation is a practical tool for identifying critical stress locations in crane-bearing deck structures. These studies indicate that finite element-based assessment has become an important method for evaluating the structural adequacy of crane foundation regions in marine applications.

With the development of computational mechanics, the finite element method (FEM) has been widely adopted to simulate complex structural responses under localized marine loading conditions with high accuracy. Compared with simplified analytical approaches, FEM can represent the interaction between deck plating, stiffeners, girders, supporting bulkheads, and pillars more realistically, making it particularly suitable for crane foundation regions where load transfer is highly localized and structurally discontinuous. In practical ship design, classification society rules provide the basis for determining whether the calculated stresses are acceptable. Consequently, combining finite element analysis with rule-based acceptance criteria offers a rational and reliable framework for assessing deck strength in crane installation areas.

This study investigates the structural behavior of the forecastle deck in the crane installation area of a Multi-Cat vessel by means of finite element analysis in accordance with ABS requirements. The analysis focuses on the stress distribution and structural response of the deck and its supporting members under crane loading, with particular attention to the influence of crane slewing position on the critical stress state. The results are intended to support structural verification of the crane foundation region and to provide a practical reference for deck reinforcement design in similar working vessels.

The contribution of this work can be summarized as follows. First, a three-dimensional finite element model is established for the forecastle deck together with its surrounding supporting structure, so that the local load transfer mechanism in the crane foundation region can be evaluated in detail. Second, the crane loading is examined under a series of slewing angles, which makes it possible to identify the most unfavorable operating position rather than relying on a single loading direction. Third, the calculated stresses are assessed against an ABS-based allowable stress criterion, allowing the numerical results to be directly linked to practical structural acceptance in ship design.

2 Research Methods

2.1 Vessel particulars

The vessel analyzed in this study is a Multi-Cat boat classified by ACS and operating under the Iranian flag, with an overall length of 19 m, a moulded breadth of 7.20 m, a moulded depth of 2.20 m, a displacement of 160 tonnes, and a midship draft of 1.70 m (Table 1).

Table 1 Principal particulars of the multi-cat vessel

Ships Name	MULTI CAT BOAT
Classification	ACS
Flag	Iran
GROSS/NET Tonnage	---
Length overall	19 m
Length Between Perpendiculars	18 m
Breadth (moulded)	7.20 m
Depth @ MID (moulded)	2.20 m
DISPLACEMENT	160 tonnes
Draft (mid)	1.70 m
Class Notation	SPECIAL SERVICE, FISH FARM SUPPORT CRAFT
Navigation area	INTERNAL & TERRITORIAL WATERS

2.2 Abaqus software

The software used in this study is SIMULIA Abaqus FEA, which provides comprehensive capabilities for modeling, analysis, and simulation based on the Finite Element Method (FEM).

2.3 System of units

A consistent unit system was adopted throughout the numerical analysis, including millimeters for length, tons for mass, ton/mm^3 for density, newtons for force, and MPa (N/mm^2) for stress and pressure (Table 2).

Table 2 System of units used in the analysis

Unit	Parameter
mm	Length
Ton	Mass
ton/mm3	Density
N	Force
MPa (N/mm2)	Tension (Pressure)

2.4 Analysis type

The deck structure has been analyzed using the linear static analysis method. The fundamental assumptions for employing linear static analysis are as follows:

The material behavior is linear, and stress is directly proportional to strain according to Hooke's law. The applied loads on the structure are static and constant. The relationship between applied loads and structural displacements is linear (Figure 1).

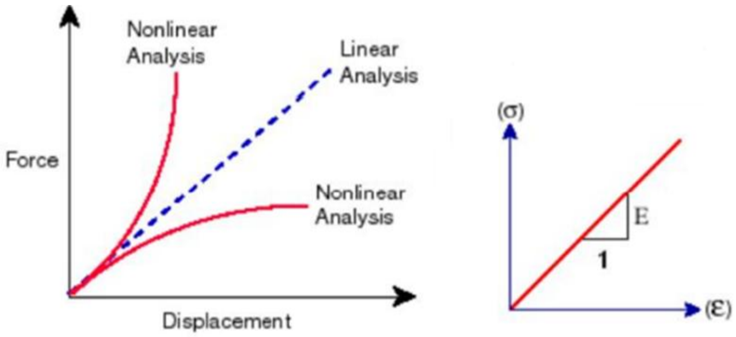

Figure 1 Assumptions of linear static analysis

2.5 Coordinate system

A right-handed Cartesian coordinate system was adopted for structural modeling and analysis. The longitudinal direction was defined as the X-axis and taken as positive toward the bow, the transverse direction was defined as the Y-axis and taken as positive toward port, and the vertical direction was defined as the Z-axis and taken as positive upward toward the deck (Table 3). The origin of the coordinate system was located at the intersection of the ship centerline (CL) and the baseline (BL) (Figure 2).

Table 3 Coordinate system (KR for Steel Ships, Part 3, Annex 3-2, Page 139)

Axis	Direction	Positive orientation
X	Longitudinal	Forward (toward the bow)
Y	Transverse	Port (toward the left)
Z	Vertical	Deck (upwards)

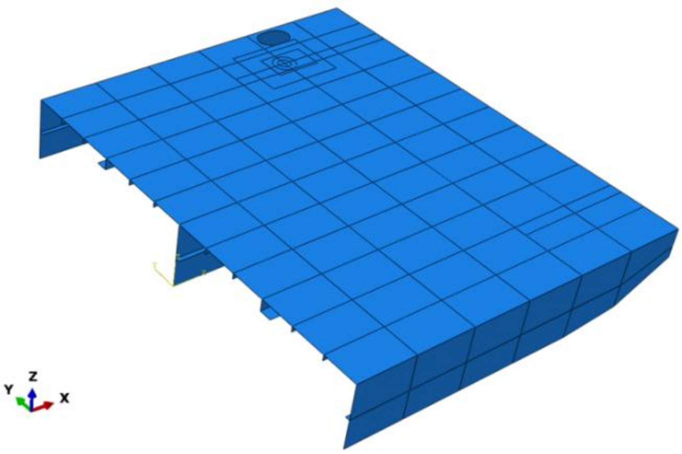

Figure 2 Assumptions of linear static analysis

2.6 Geometric properties of the model

The structural model extends from aft bulkhead 12 to the forecastle region, covering three compartments. The modeled deck region has dimensions of 6 000 mm in the longitudinal direction, 7 200 mm in the transverse direction over the full ship breadth, and 1 100 mm in the vertical direction below the deck (Figure 3).

The hull lines and all structural members in the modeled region were represented using shell elements based on the midship section drawing. The arrangement of frames, bulkheads, and other structural components was defined according to the structural drawings, including the sectional configurations from Frame 13 to Frame 18 and the bulkhead layout in the analyzed region (Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10).

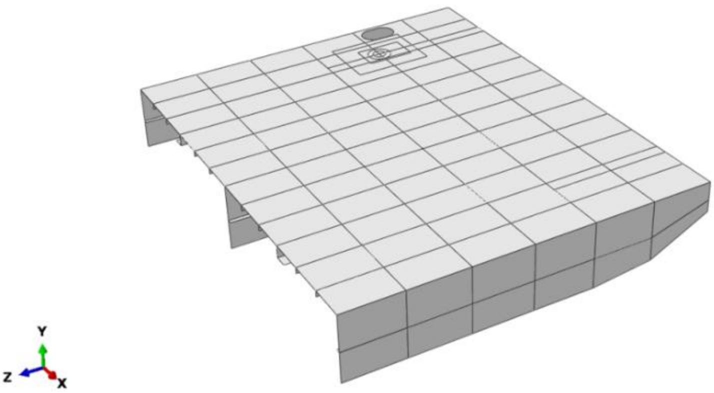

Figure 3 The model represents a length of three compartments in the Abaqus software

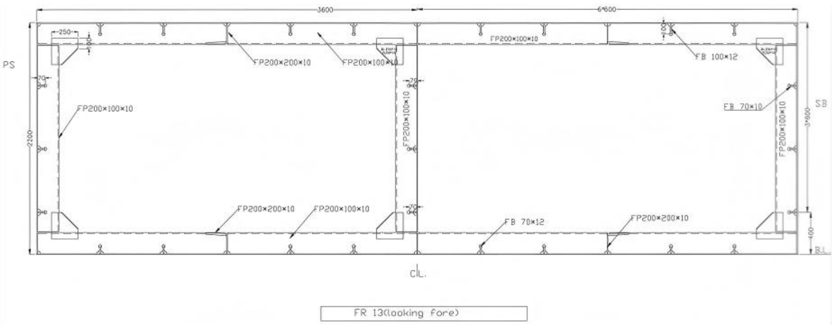

Figure 4 Frame 13 structure

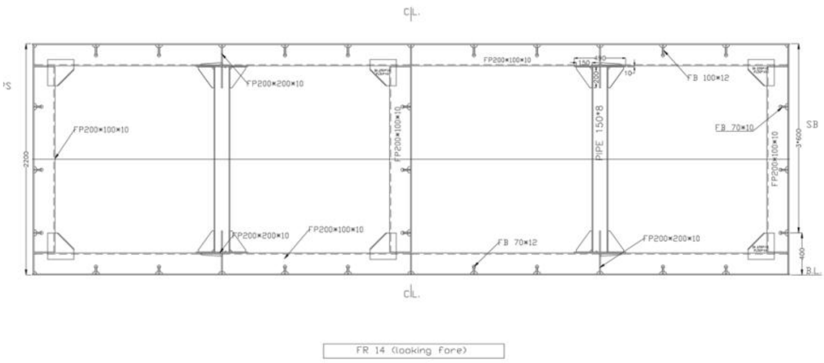

Figure 5 Frame 14 structure

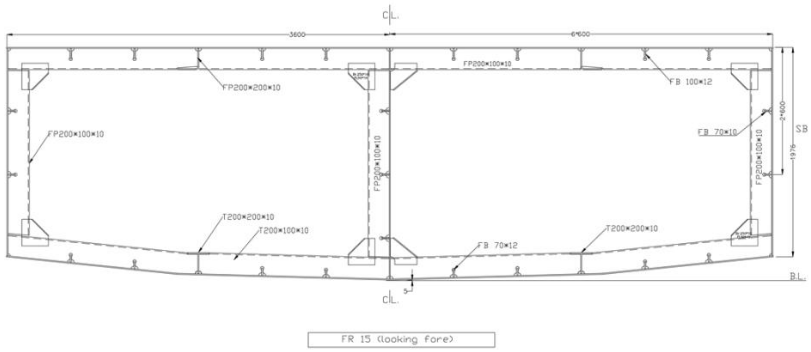

Figure 6 Frame 15 structure

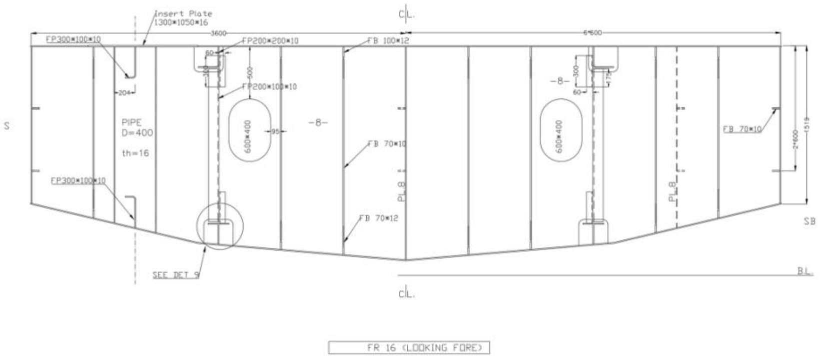

Figure 7 Frame 16 structure

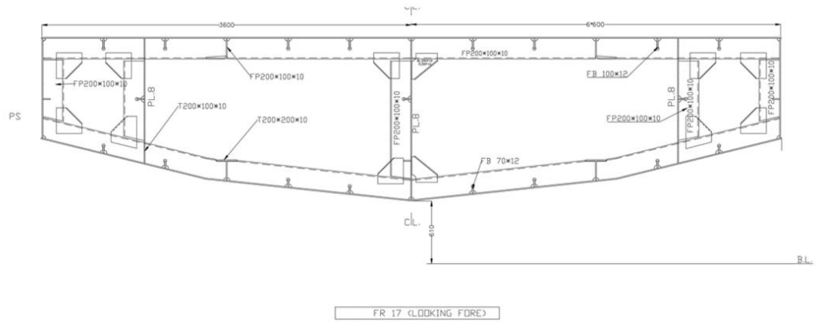

Figure 8 Frame 17 structure

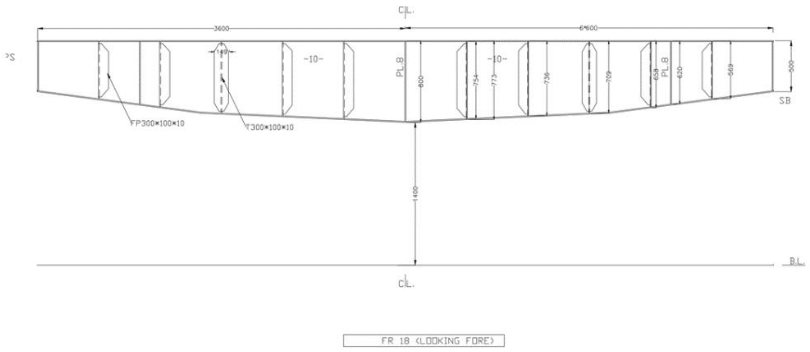

Figure 9 Frame 18 structure

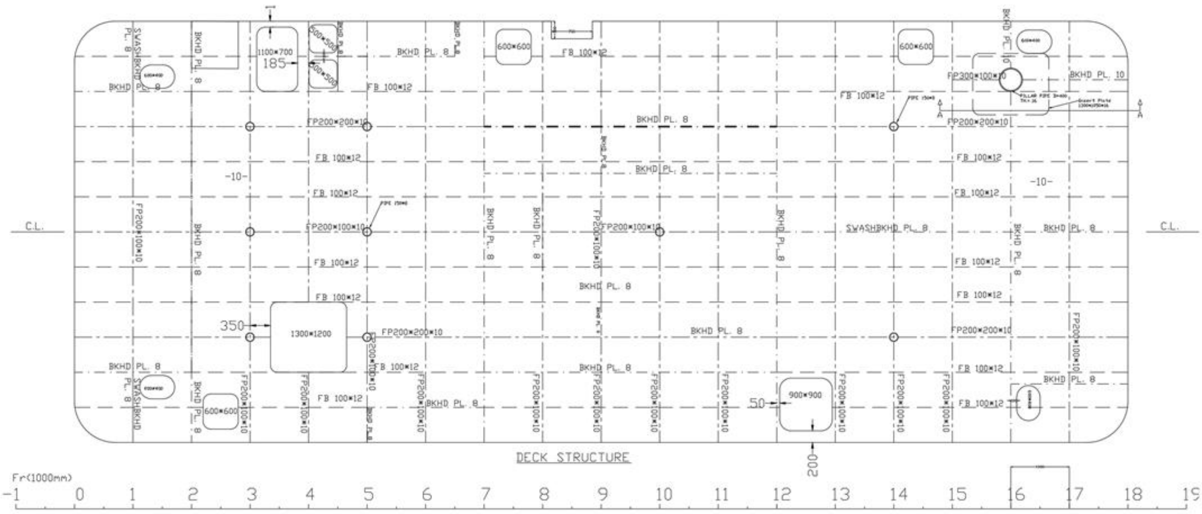

Figure 10 Layout of bulkheads in the modeled region

The dimensions of all structural elements have been modeled as shell elements in Abaqus, as specified in Table 4. The thickness of each element has been defined in the Property Section Manager module.

Table 4 Geometric properties of structural elements in the model

DECK CEN. GIRDER	L200×100×10 mm
DECK SIDE GIRDERS	L200×200×10 mm
DECK TR	L200×100×10 mm
DECK PLATE	10 mm
DECK BEAMs	FB 100×12 mm
SIDE PLATE	10 mm
SIDE TR	L200×100×10 mm
PILLAR	PIPE400×16 & PIPE150×8 mm

To simplify the finite element model, small local features such as cutouts, lugs, scallops, air holes, and snipes were not included in the analysis (Figure 11).

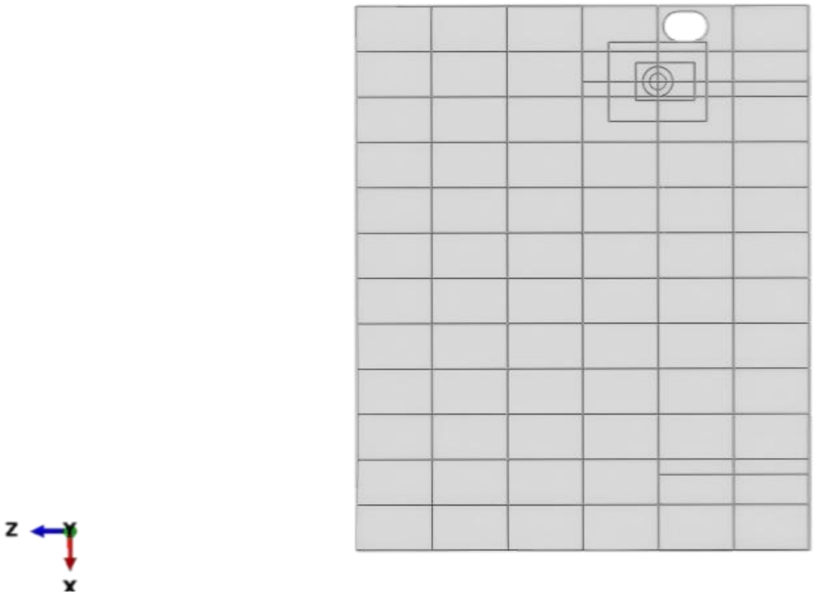

Figure 11 Deck plan showing the layout of longitudinal and transverse reinforcements and columns in Abaqus

2.7 Geometric Properties of the Model

The finite element mesh was generated using free meshing with the medial axis algorithm. The mesh consists of both quadrilateral and triangular shell elements, with a global element size of 40 mm. The final model contains 71 996 nodes and 72 259 elements, including 71 822 quadrilateral elements of type S4R and 437 triangular elements of type S3 (Table 5).

Table 5 Mesh properties of the finite element model

Parameter	Specification
Element Shape	Triangular and Quadrilateral
Meshing Algorithm	Medial Axis
Meshing Technique	Free
Global Element Size (mm)	40
Number of Nodes	71,996
Number of Elements	72,259
Number of Quadrilateral Elements (S4R)	71,822
Number of Triangular Elements (S3)	437

2.8 Material mechanical properties

Marine steel Grade A was selected as the material for the deck structure. The mechanical and physical properties used in the analysis include a Poisson's ratio of 0.28, a Young's modulus of 2.10×10^5 N/mm², a density of 7.8×10^{-9} ton/mm³, and a gravitational acceleration of 9.81×10^3 mm/s² (Table 6).

Table 6 Mechanical properties of marine steel grade A

Parameter	Value	Unit
Poisson's Ratio (ν)	0.28	-
Young's Modulus (E)	2.10×10^5	N/mm²
Density (ρ)	7.8×10^{-9}	ton/mm³
Gravity (g)	9.81×10^3	mm/s²

2.9 Boundary conditions

A simply supported boundary condition was applied to the modeled deck structure. The displacements at both ends and along the side boundaries of the modeled region were restrained in the X-, Y-, and Z-directions, while rotational degrees of freedom were left unconstrained (Figure 12). In addition, displacement in the Z-direction was constrained along the outer boundary lines at the free ends of the columns and walls in order to represent the structural support conditions more realistically (Figure 13, Figure 14).

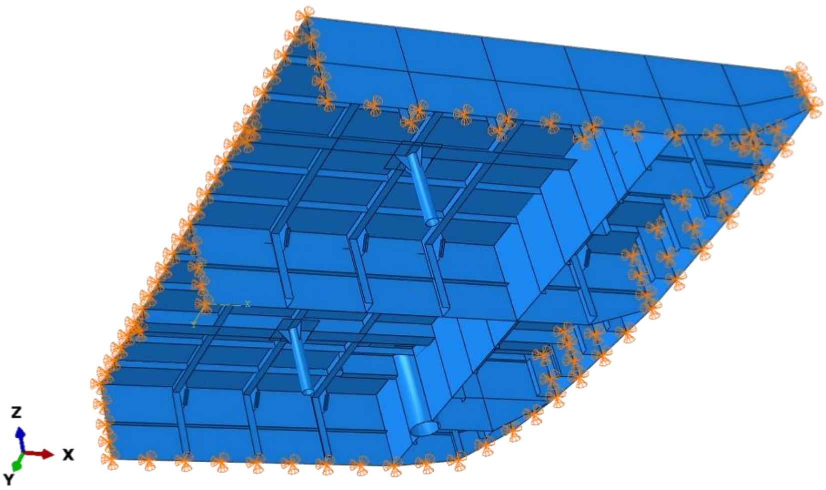

Figure 12 Representation of the simple support boundary condition in the cross-section view

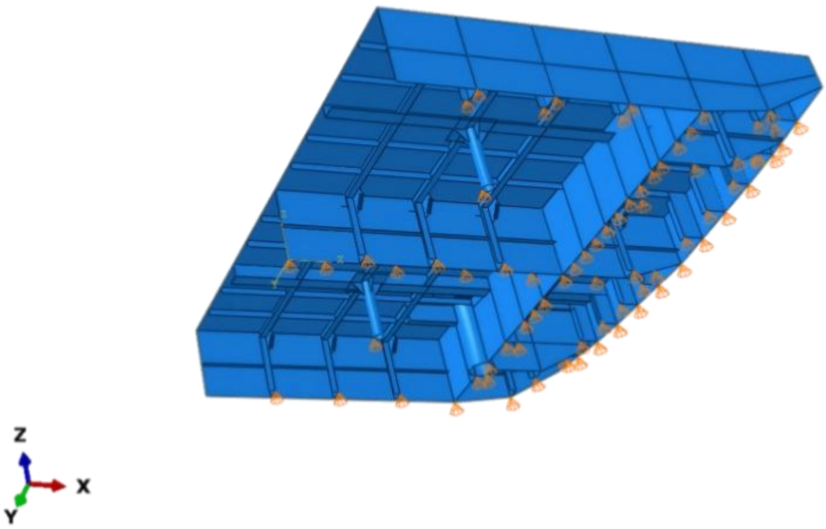

Figure 13 Illustration of Z-direction displacement constraint in 3D view

3 Results and Discussions

3.1 Loading conditions

The deck structure was evaluated under a series of crane loading cases corresponding to different slewing positions. The critical lifting condition considered in this study was defined by a boom length of 2 100 mm and a crane load of 6 300 kg. After applying a safety factor of 1.3, the effective lifting load increased from 61 803 N to 80 344 N. In addition, the boom self-weight of 12 753 N was applied at the boom center of gravity for each slewing position, and a uniformly distributed load of 0.3355 N/mm² representing the crane self-weight was also applied to the deck surface. The crane loading was examined from 0° to 315° at intervals of 45°, with clockwise rotation taken as the positive direction (Figure 14, Figure 15). The loading analysis was conducted under calm sea conditions in order to isolate the local structural response of the crane foundation region from wave-induced global effects.

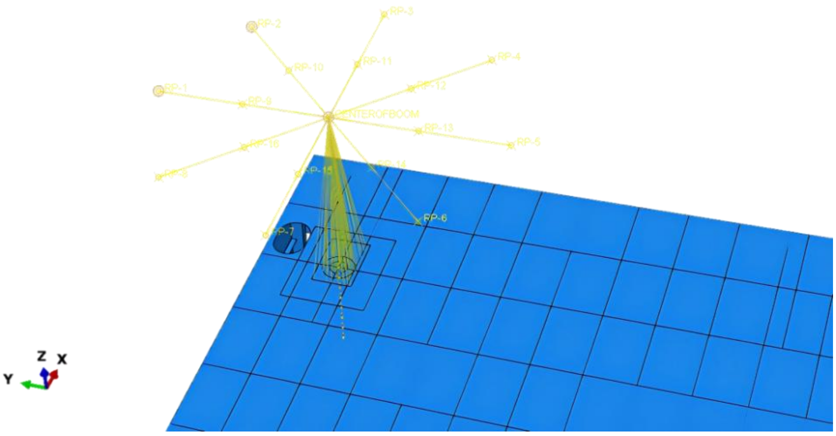

Figure 14 Crane loading cases

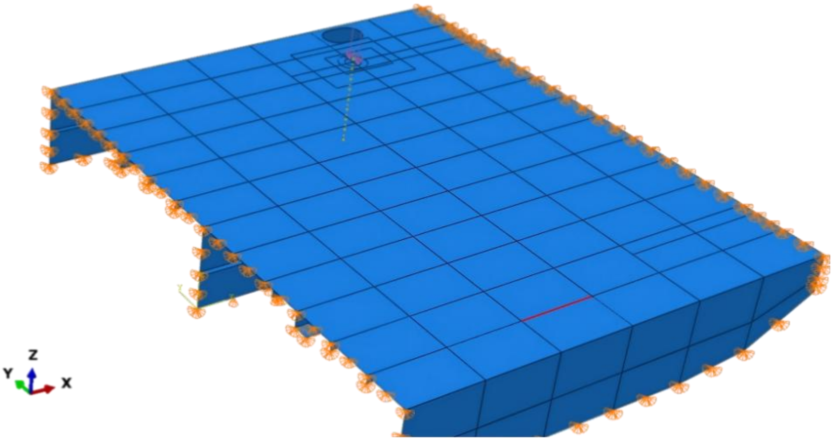

Figure 15 Application of crane self-weight as a static load

3.2 Control criteria

The structural assessment was carried out using the allowable stress criterion specified in the ABS Rules for Building and Classing Steel Vessels under 90 Meters. For conventional steel, the allowable stress is defined as:

σ_{allow}=0.78 Sm Fy

Where Sm=1 for conventional steel and Fy is the stress modification factor, which equals 1 for conventional steel, is the yield strength of the material. Because hull girder strength effects were not included in the present local model, the allowable stress was further reduced by 10% in accordance with the ABS requirement. As a result, the limiting stress adopted for the deck structure was 165 MPa (Figure 16). This criterion was used as the primary basis for evaluating the structural adequacy of the crane foundation region under all investigated loading angles.

Mesh Size	Stress Limit	
	Static + Dynamic	Static
1 × stiffener spacing (*SS*)	0.90 S_mF_y	0.63 S_mF_y
$^1/_2$ × *SS*	0.95 S_mF_y	0.67 S_mF_y
$^1/_3$ × *SS*	1.00 S_mF_y	0.70 S_mF_y
$^1/_4$ × *SS* (1)	1.06 S_mF_y	0.74 S_mF_y
$^1/_5$ × *SS* ~ $^1/_{10}$ × *SS* (1)	1.12 S_mF_y	0.78 S_mF_y

Figure 16 Mesh size and stress limits (American Bureau of Shipping (ABS), 2019)

Since the forces due to hull girder strength were not applied in the model, and in accordance with the aforementioned ABS rules, the allowable stress has been reduced by 10%. Consequently, the maximum permissible stress for the deck structure is considered to be 165 MPa.

4 Conclusion

4.1 Simulation results

The finite element results demonstrate that the forecastle deck structure in the crane foundation region satisfies the ABS allowable stress requirement under all investigated crane loading conditions. Tthe maximum Von Mises stress among the eight slewing cases occurs at a crane rotation angle of 180°, where the stress reaches 160.4 MPa, while the second highest value is obtained at 0° with 154.3 MPa. By contrast, the lowest stress is recorded at 315°, with a value of 105.6 MPa (Table 7). Since all calculated stresses remain below the allowable limit of 165 MPa, the deck structure can be regarded as structurally adequate for the considered static operating conditions. At the same time, the 180° case leaves only a limited safety margin of about 4.6 MPa, indicating that this loading direction governs the strength assessment of the crane foundation region.

Table 7 Maximum von mises stress under different crane loading angles

No.	Angle Relative to Bow (°)	Von Mises Stress (MPa)	Figure No.
1	0	154.3	15
2	45	111.0	16
3	90	139.3	17
4	135	112.8	18
5	180	160.4	19
6	225	117.0	20
7	270	137.6	21
8	315	105.6	22

The stress contour plots shown in Figures 17-24 further clarify the structural behavior behind the values listed in Table 7. In particular, the stress cloud corresponding to the 180° slewing condition (Figure 21) identifies the most critical stress concentration in the crane-supporting region, whereas the contours for 0° (Figure 17) and 270° (Figure 23) also show relatively high stress levels compared with the other loading cases. By comparison, the stress distributions for 45°, 135°, 225°, and 315° (Figure 18, Figure 20, Figure 22, Figure 24) are more moderate, indicating that these slewing directions produce a more favorable load-transfer path through the deck structure. Taken together, Table 7 and Figure 17, Figure 18, Figure 19, Figure 20, Figure 21, Figure 22, Figure 23, Figure 24 show that the structural response is strongly dependent on crane orientation and that a single loading direction would not be sufficient to identify the governing condition.

Similar orientation-dependent stress redistribution has also been reported in crane-supporting marine structures, where different crane positions lead to different load-transfer paths and local reinforcement demands (Hernández-Ménez et al., 2023; Dragatogiannis et al., 2024). From the engineering point of view, these results indicate that the deck plating, girders, stiffeners, and supporting pillars are able to work together to transfer the crane load effectively into the surrounding structure. The highest stresses appear only in specific orientations, which suggests that the local arrangement of supporting members plays a key role in controlling the load path and the resulting stress concentration. Therefore, although the current reinforcement scheme is sufficient for the investigated loading envelope, the regions associated with the 180° and 0° cases should be regarded as critical hot-spot zones for inspection and maintenance (Abdullah et al., 2023; Dragatogiannis et al., 2024).

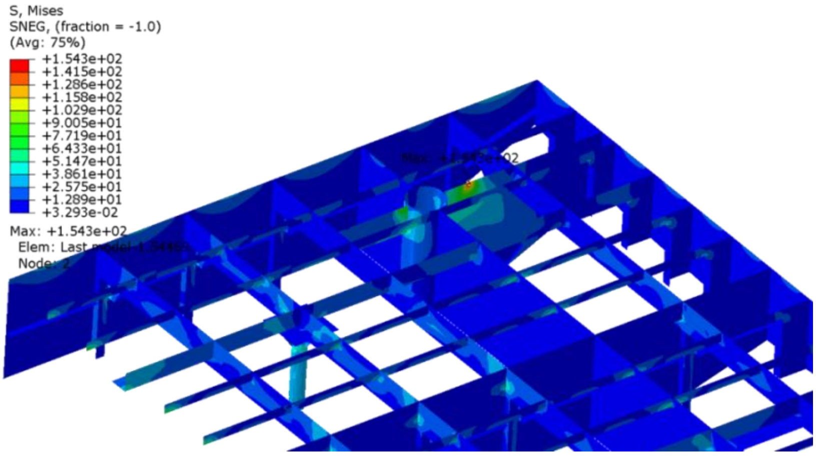

Figure 17 Von mises stress results at 0° crane rotation

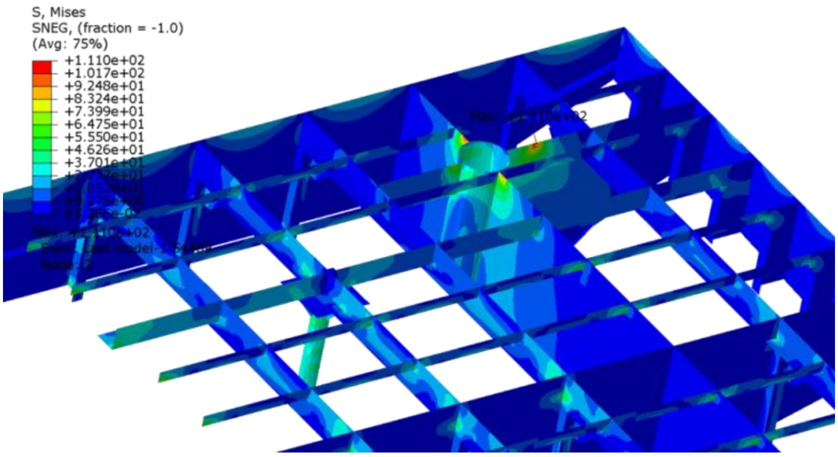

Figure 18 Von mises stress results at 45° crane rotation

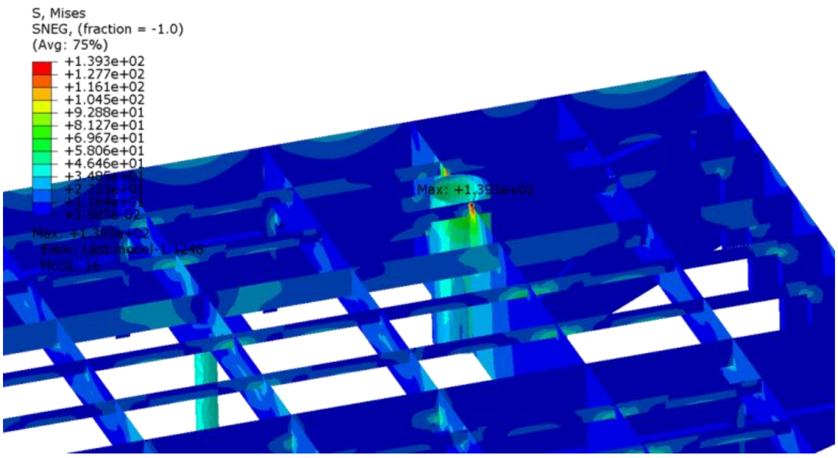

Figure 19 Von mises stress results at 90° crane rotation

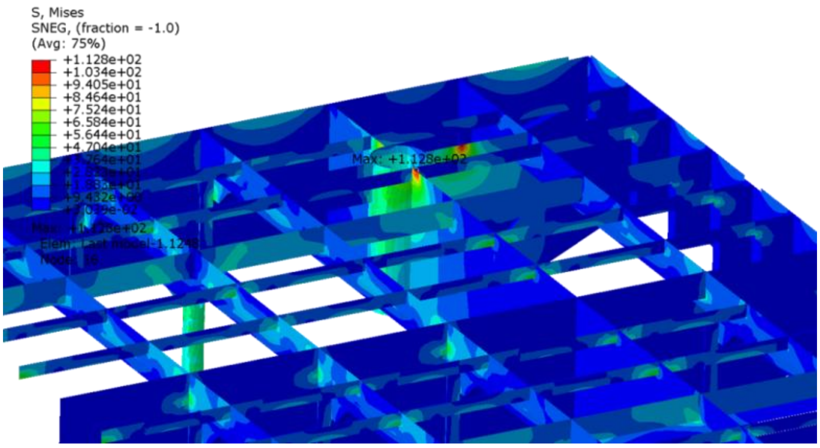

Figure 20 Von mises stress results at 135° crane rotation

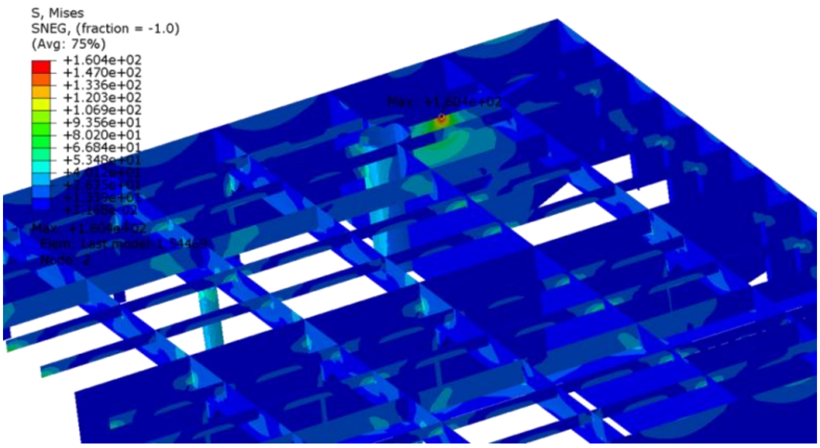

Figure 21 Von mises stress results at 180° crane rotation

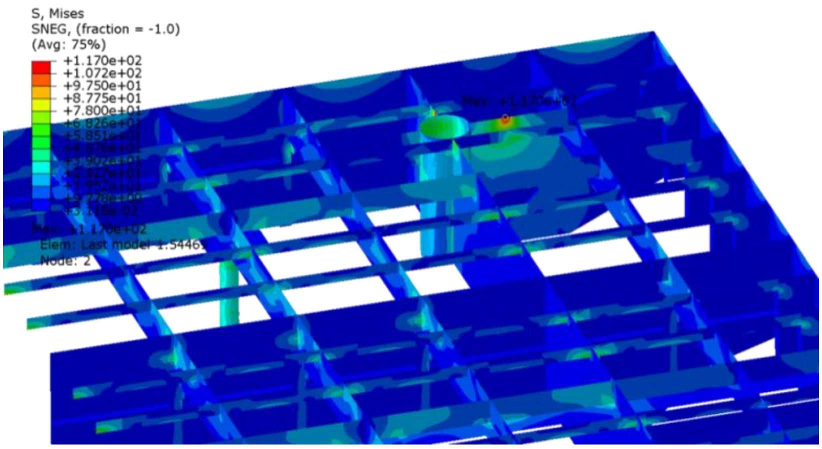

Figure 22 Von mises stress results at 225° Crane Rotation

Repeated crane operation in these unfavorable directions may increase the risk of fatigue damage in welded joints, girder intersections, and pillar-to-deck connections, even if the static stress remains below the allowable limit. This load-sharing mechanism agrees with previous marine structural studies showing that deck plating, longitudinal/transverse stiffeners, and supporting members jointly govern the local stiffness and stress response around crane foundations and similar equipment-support regions. Recent reviews further indicate that repeated loading/unloading, transient operational loading, and welded-detail geometry are among the key factors governing fatigue resistance in ship and offshore structures (Dong et al., 2022).

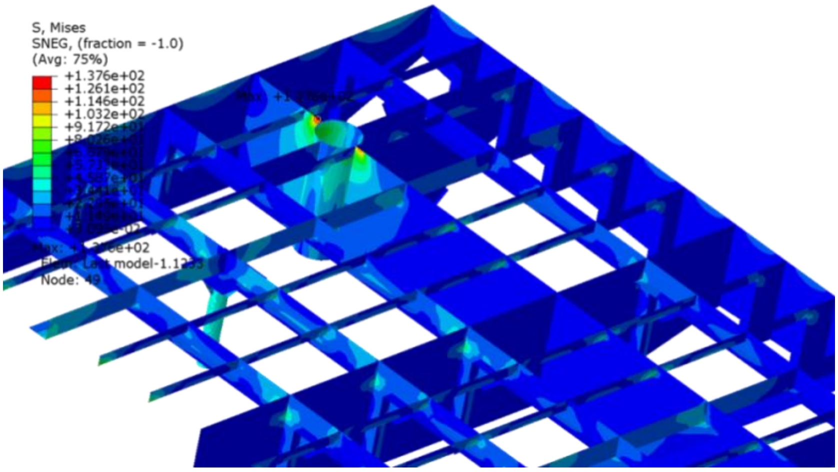

Figure 23 Von mises stress results at 270° crane rotation

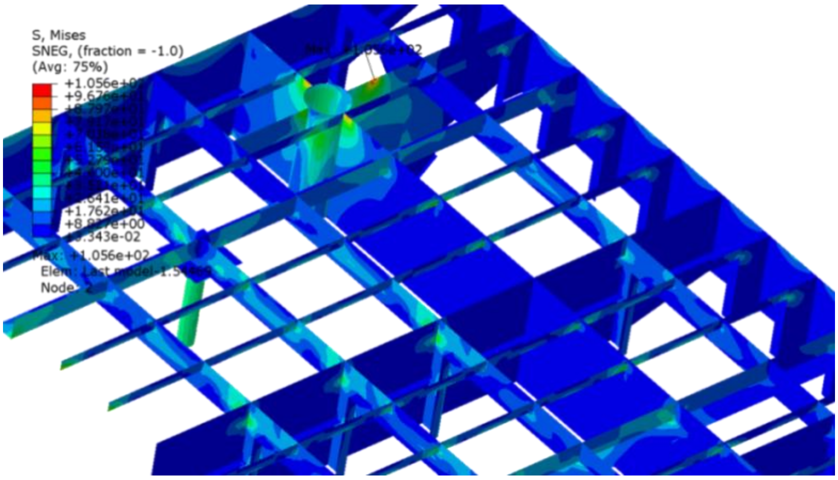

Figure 24 Von mises stress results at 315° crane rotation

Several limitations of the present study should also be acknowledged. First, the analysis was based on a simplified geometric model in which local details such as cutouts, scallops, snipes, and other small discontinuities were not included, although such features may affect local stress concentration in practice. Second, the present assessment was limited to linear static analysis under calm sea conditions, and therefore did not consider dynamic effects associated with vessel motions, impact loading, or oscillation of the lifted load. Third, the study focused on rule-based strength verification and did not include a detailed fatigue assessment of the identified hot-spot regions. For these reasons, the present conclusions are suitable for preliminary structural verification, but they do not fully represent the complete long-term service behavior of the crane foundation structure.

Future work should therefore extend the present analysis in several directions. A fatigue assessment should be performed for the most highly stressed regions identified in Figure 21 and the other critical contour plots. Dynamic loading conditions caused by vessel motion and crane operation in realistic sea states should also be considered in order to provide a more complete structural evaluation. In addition, local sub-modeling of the hot-spot regions would help capture stress concentration more accurately than the current global shell model. If higher lifting loads or more demanding operating conditions are expected in future service, structural optimization measures such as local plate thickening, bracket addition, or improved stiffener continuity may be investigated to increase the available safety margin and improve fatigue resistance. Moreover, refined local stress assessment methods should be considered for welded joints around the crane foundation, since hot-spot stress prediction can vary with the adopted finite element formulation and extraction technique (Li and Choung, 2021). Overall, by combining the numerical comparison in Table 7 with the stress contour interpretation in Figure 17, Figure 18,

Figure 19, Figure 20, Figure 21, Figure 22, Figure 23, Figure 24, this study confirms that the deck structure in the crane foundation area is structurally acceptable under the considered crane loading cases, while also identifying the 180° slewing condition as the governing design case and the most important target for future fatigue assessment, maintenance planning, and possible structural refinement.

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Conflict of interest
The authors declare that they have no conflict of interest.

Authors' contributions
Farzad Tahmasebi (100% of contributions) including: conceived and designed study, collected and analyzed the data and writing conclusions.

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Phytochemical Characterization and Anaesthetic Efficacy of Citrus Leaf Extracts for Sedation and Handling of Nile tilapia (*Oreochromis niloticus*) and African Catfish (*Clarias gariepinus*)

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Abstract This study investigated the anesthetic efficacy and safety of aqueous leaf extracts of *Citrus sinensis*, *Citrus aurantium*, and *Citrus limon* in Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*) under controlled immersion conditions. Qualitative phytochemical screening revealed distinct variation in bioactive constituents among the extracts. Experimental exposure was conducted at concentrations ranging from 1 000 to 4 000 mg L^{-1}, and responses were evaluated using induction time, recovery time, survival, behavioural indicators, and flesh quality parameters. Anesthetic effects were concentration dependent in both species. *Citrus sinensis* produced mild to moderate sedation across all tested concentrations, with no mortality recorded even at 4 000 mg L^{-1}, indicating a wide safety margin, and 3 000 mg L^{-1} was identified as the highest effective concentration for routine handling. In contrast, *Citrus aurantium* and *Citrus limon* induced deeper anesthetic states at lower concentrations but resulted in 100 percent mortality at 4000 mg L^{-1} in both species**.** Fish exposed to *Citrus sinensis* exhibited more favourable post exposure welfare indicators, including faster recovery and earlier resumption of feeding, whereas the other extracts were associated with delayed recovery and behavioural impairment. These findings indicate that *Citrus sinensis* appears more compatible with short term handling welfare and represents a practical and cost effective botanical anesthetic for freshwater aquaculture.
Keywords Fish anesthesia; Citrus leaf extracts; *Clarias gariepinus*; *Oreochromis niloticus*; Handling stress; Aquaculture welfare

1 Introduction

Aquaculture has become an essential component of global food systems, contributing significantly to animal protein supply and economic development, particularly in developing regions. Species such as Clarias gariepinus and *Oreochromis niloticus* are widely cultivated due to their adaptability, rapid growth, and high market acceptance (Klimuk et al., 2024; Webster and Lim, 2024). However, routine aquaculture practices such as handling, grading, transport, and sampling expose fish to stress, which can negatively affect physiological stability, immune function, and overall productivity (Martos Sitcha et al., 2020; Dawood et al., 2022). The use of anesthetic agents is therefore essential to reduce stress, improve handling efficiency, and enhance fish welfare during aquaculture operations (Neiffer, 2021; Brønstad, 2022).

Conventional fish anesthetics, including synthetic compounds, have been widely used due to their effectiveness in inducing rapid sedation and recovery. However, concerns have been raised regarding their cost, regulatory restrictions, potential toxicity, and residue accumulation in fish tissues (Vergneau Grosset and Benedetti, 2022; Sedyaaw and Bhatkar, 2024). These limitations have prompted increasing interest in the development of alternative anesthetic agents derived from natural sources. In particular, plant based anesthetics have gained attention due to their accessibility, lower environmental impact, and perceived safety in aquaculture systems (Yaşar and Yardımcı, 2022; Haihambo et al., 2023).

Recent studies have demonstrated that plant derived compounds, especially those obtained from essential oils, can effectively induce anesthesia in fish. For example, eugenol based extracts and other bioactive plant oils have been shown to produce rapid induction and acceptable recovery profiles in several aquaculture species (Ventura et al., 2020; Zahran et al., 2021). Similarly, essential oil extracts such as chamomile oil and citronellal have been reported to exhibit anesthetic efficacy in fish, influencing behavioural and physiological responses during exposure (Ak et al., 2022; Hoseini et al., 2022). Reviews have further highlighted the growing application of essential oils as sedatives and anesthetics in aquaculture, with evidence supporting their role in improving fish handling and reducing stress (Rodrigues Brandão et al., 2022; Minaz et al., 2025). These findings indicate that plant based anesthetics represent a viable alternative to conventional synthetic agents.

Despite these advances, several limitations remain in current knowledge. Most studies have focused on a limited number of plant species, particularly those rich in essential oils, while comparatively less attention has been given to aqueous leaf extracts from widely available tropical plants. In addition, there is limited comparative research evaluating multiple plant species under similar experimental conditions, especially with respect to induction time, recovery dynamics, survival outcomes, and post exposure welfare indicators (Haihambo et al., 2023; Mphande et al., 2023). Furthermore, the relationship between phytochemical composition and anesthetic performance is not consistently established, as many studies do not integrate chemical profiling with functional assessment of anesthetic effects.

Citrus species represent a promising but underexplored source of bioactive compounds with potential anesthetic properties. Citrus leaves and by products are known to contain a wide range of phytochemicals, including flavonoids, limonoids, terpenoids, carotenoids, and phenolic compounds, many of which exhibit biological activity (Addi et al., 2021; Saini et al., 2022; Lu et al., 2023). Flavonoids and related compounds have been associated with antioxidant, antimicrobial, and physiological regulatory effects, which may influence stress response and metabolic processes in aquatic organisms (Barreca et al., 2020; Bhowal et al., 2022). In addition, citrus leaf extracts and essential oils have demonstrated bioactive properties, including antimicrobial and antiproliferative activities, indicating their potential for broader biological applications (Asker et al., 2020; Othman et al., 2022). The availability of citrus waste and leaf biomass further enhances their relevance as cost effective and sustainable resources for aquaculture applications (Russo et al., 2021; Maqbool et al., 2023; Šafranko et al., 2023).

However, despite the documented phytochemical richness of citrus species, their anesthetic potential in fish has not been systematically evaluated. Existing studies have largely focused on nutritional, antimicrobial, or pharmaceutical properties, with limited attention to their functional role as anesthetic agents in aquaculture systems (Leporini et al., 2020; Zahr et al., 2023). Moreover, comparative assessments of different citrus species under controlled experimental conditions remain scarce, particularly in relation to key performance indicators such as induction efficiency, recovery time, survival rate, and post exposure behavioural responses.

In this context, the present study aims to address these gaps by evaluating the anesthetic efficacy of aqueous leaf extracts of *Citrus sinensis*, *Citrus aurantium*, and *Citrus limon* in Clarias gariepinus and *Oreochromis niloticus*. Specifically, the study integrates phytochemical screening with functional assessment of induction time, recovery patterns, mortality outcomes, and welfare related behavioural responses. By providing a comparative analysis across multiple citrus species and linking phytochemical composition to anesthetic performance, this study contributes new evidence toward the development of plant based anesthetic alternatives for sustainable aquaculture practices. This study represents one of the first comparative evaluations of aqueous citrus leaf extracts as anesthetic agents in tropical aquaculture species.

2 Materials and Methods

2.1 Study location and experimental fish

The experiment was conducted at the aquaculture research facilities of the Department of Fisheries and Aquaculture, Delta State University, Abraka, Nigeria. Nile tilapia (*Oreochromis niloticus*) and African catfish

(*Clarias gariepinus*) were selected because they dominate aquaculture production in sub Saharan Africa and exhibit distinct physiological and behavioural responses to handling stress, making them appropriate models for anesthetic evaluation (Musa et al., 2021; Klimuk et al., 2024).

A total of 180 healthy adult fish comprising 90 Nile tilapia and 90 African catfish were obtained from a commercial aquaculture facility in Warri, Delta State. The fish were size matched to ensure experimental consistency, with Nile tilapia having a mean body weight of 130 ± 10 g and total length of 16 ± 2 cm, while African catfish had a mean body weight of 200 ± 20 g and total length of 22 ± 3 cm. Fish were transported in aerated containers and acclimated for three weeks in 1 000 L circular tanks under continuous aeration. Stocking density was regulated to minimise crowding stress, and fish were fed once daily with a commercial extruded diet. Water quality parameters were monitored throughout acclimation and maintained within recommended ranges for tropical freshwater species to ensure that observed responses were attributable to treatment effects rather than environmental variation (Shaw et al., 2022; Zidan et al., 2022).

Treatments that resulted in complete mortality were excluded from inferential statistical analysis because their inclusion would have introduced perfect separation of outcomes and artificially inflated variance, thereby violating the assumptions of parametric testing. Under such conditions, descriptive reporting is considered more appropriate and is widely adopted in fish anesthesia research where lethal thresholds produce non-variable outcomes (Neiffer, 2021; Soldatov, 2021)

2.2 Plant material collection and extract preparation

Fresh leaves of *Citrus sinensis*, *Citrus aurantium*, and *Citrus limon* were collected from the university botanical garden, washed with distilled water, and air dried under shade at ambient temperature to preserve heat sensitive phytochemicals, as recommended for maintaining the integrity of plant secondary metabolites (Asker et al., 2020; Leporini et al., 2020).

For phytochemical screening, dried leaves were milled into powder. Thirty grams of each sample were macerated in 120 mL of solvent for 12 h at 25 °C, followed by filtration, concentration using rotary evaporation, and drying in a water bath. The extraction procedure yielded approximately 8 to 12 percent of dry extract relative to initial plant mass, which is consistent with reported recovery ranges for citrus leaf phytochemicals (Cebadera Miranda et al., 2020). The dried extracts were reconstituted to 1 mg mL^{-1} for qualitative analysis (Cebadera Miranda et al., 2020; Othman et al., 2022).

For anesthetic trials, fresh leaves were homogenized in sterile distilled water and filtered through muslin cloth to obtain crude aqueous extracts. Filtration effectively removed coarse particulate material, although fine suspended particles remained, reflecting the use of minimally processed extracts. The reported concentrations therefore represent the mass of fresh plant material per unit volume of water rather than purified extract mass. Phytochemical screening was conducted using dried extracts to provide general chemical characterization, whereas fresh aqueous homogenates were used in exposure trials to simulate preparation methods applicable under practical aquaculture conditions. This dual approach ensured alignment between laboratory based analysis and field relevant application (Indriyani et al., 2023; Maqbool et al., 2023).

2.3 Phytochemical screening

Qualitative screening was conducted to detect flavonoids, limonoids, terpenoids, phenolic acids, carotenoids, coumarins, essential oils, and alkaloids. These compound classes were selected based on documented associations with sedative activity, antioxidant function, and modulation of physiological responses in fish (Barreca et al., 2020; Bhowal et al., 2022; Šafranko et al., 2023).

2.4 Experimental design and anesthetic exposure

Fish of each species were randomly assigned to four extract concentrations of 1 000, 2 000, 3 000, and 4 000 mg L^{-1}. Each treatment was replicated three times with ten fish per replicate, resulting in thirty fish per treatment per species.

The selected concentration range was informed by preliminary range finding observations, which identified the lower threshold for observable behavioural response and the upper threshold associated with toxicity, and this range is consistent with dose selection strategies used in studies of plant derived anesthetics in fish (Ventura et al., 2020; Hoseini et al., 2022).

Fish were fasted for 24 h prior to exposure to reduce metabolic variability and minimise the influence of feeding related physiological processes on anesthetic response (Martos Sitcha et al., 2020; Dawood et al., 2022). During exposure, aeration was suspended to facilitate uptake of anesthetic compounds across the gill surface, a procedure that has been shown to enhance immersion anesthesia efficiency (Brønstad, 2022).

Anesthetic induction was assessed using behavioural criteria including reduced responsiveness, loss of equilibrium, and complete immobility. Following exposure, fish were transferred to clean aerated water, and recovery time was recorded as the time required to regain normal swimming behaviour. Mortality was assessed 24 h after exposure to determine safety margins (Neiffer, 2021; Soldatov, 2021).

The level of replication employed is consistent with established experimental designs in fish anesthesia research, where the tank is treated as the experimental unit because fish within a tank experience identical exposure conditions and are not statistically independent (Neiffer, 2021; Vergneau Grosset and Benedetti, 2022).

2.5 Statistical analysis and welfare assessment

Induction and recovery time data were analysed separately for each fish species. One way analysis of variance was applied within each extract type to evaluate the effect of concentration on induction and recovery time. Only treatments in which recovery occurred were included in the inferential analysis, as the inclusion of treatments with complete mortality can violate the assumptions of normality and homogeneity of variance and may lead to biased statistical outcomes (Neiffer, 2021; Vergneau Grosset and Benedetti, 2022).

Prior to inferential analysis, all datasets were assessed for compliance with parametric assumptions. Normality of data distribution was evaluated using the Shapiro-Wilk test, while homogeneity of variance was examined using Levene's test. These procedures confirmed that the data satisfied the assumptions required for parametric analysis, thereby justifying the application of one way analysis of variance. The use of these diagnostic tests is consistent with established statistical practice in experimental aquaculture research, where verification of distributional properties and variance structure is essential for ensuring the validity of statistical inference (Rodrigues Brandão et al., 2022; Minaz et al., 2025). Where significant differences were detected, mean values were separated using Tukey multiple comparison test, and statistical significance was accepted at p less than 0.05. All statistical analyses were performed using IBM SPSS Statistics software version 26.0.

Although the experimental design incorporated multiple extract types and concentration levels, a factorial analysis of variance was not applied due to the occurrence of complete mortality in some treatment combinations. This resulted in an unbalanced dataset and violated the assumptions required for two way analysis of variance. Consequently, statistical analysis was restricted to biologically recoverable treatments, and one way analysis of variance was applied within these subsets to ensure valid estimation of treatment effects and to avoid distortion of variance structure, in line with recommended analytical approaches in fish anesthesia studies.

Post exposure welfare was assessed through systematic observation of behavioural recovery after transfer to clean water. Observations were conducted at predetermined intervals during the recovery period, with frequent assessments within the first thirty minutes, followed by additional evaluations at one hour and twenty four hours, in order to capture both immediate and delayed behavioural responses. Behavioural criteria included opercular movement, swimming stability, restoration of equilibrium, and time to resumption of feeding. These indicators are widely recognised as reliable measures of post anaesthetic recovery and physiological status in fish (Martos Sitcha et al., 2020; Vergneau Grosset and Benedetti, 2022). Behavioural responses were documented using standardised descriptive criteria to ensure comparability across treatments (Neiffer, 2021).

2.6 Flesh quality assessment

Flesh quality evaluation was undertaken on fish exposed to citrus leaf extracts at a concentration of 3 000 mg L^{-1}, which elicited clear anesthetic responses without causing immediate mortality in the treatments considered. After complete behavioural recovery, fish were humanely euthanised in line with established practices for aquaculture research. Dorsal muscle tissues were excised immediately after euthanasia, placed on ice, and analysed within six hours in order to minimise post mortem biochemical changes that could influence flesh quality parameters (Shadieva et al., 2020; Ventura et al., 2020).

Muscle pH was determined using a calibrated digital pH meter inserted into homogenised muscle tissue, a method routinely employed to assess post exposure metabolic condition and flesh stability in cultured fish species (Shadieva et al., 2020; Zahran et al., 2021). Crude protein content was analysed using standard wet chemistry procedures widely applied in fish nutrition and flesh composition research, while lipid content was quantified through solvent extraction techniques appropriate for detecting variations in muscle lipid reserves associated with handling stress and anesthetic exposure (Fawole et al., 2020; Shadieva et al., 2020). All biochemical determinations were conducted in triplicate, and results were expressed on a wet weight basis to ensure consistency with established reporting practices in aquaculture studies.

Organoleptic assessment was performed to examine potential post anesthetic effects on flesh characteristics relevant to consumer acceptance. Evaluated attributes included flesh odour, texture, colour, and the presence or absence of off flavour characteristics. Sensory evaluation was conducted by a trained panel using established descriptive criteria commonly adopted in studies assessing the influence of handling stress and anesthetic agents on fish flesh quality (Ventura et al., 2020; Russo et al., 2021). These evaluations were qualitative in nature and intended to identify pronounced alterations in sensory attributes rather than to provide detailed quantitative sensory profiling, in line with the applied objectives of fisheries and aquaculture research (Zahran et al., 2021).

2.7 Ethical consideration

All experimental procedures involving fish were carried out in compliance with internationally recognised guidelines governing the care and use of aquatic animals in research. Handling time and exposure duration were kept to the minimum necessary to limit stress, and any fish showing signs of severe distress were promptly removed from the experimental tanks. Throughout the study, established institutional best practices for ethical research involving live aquatic organisms were strictly observed.

3 Results

All tables and figures are explicitly referenced within the text. Phytochemical variation among the citrus extracts is presented (Table 1), behavioural responses are summarised (Table 2 and Tables 3), mortality outcomes are shown (Table 4), and recovery dynamics are quantitatively illustrated (Figure 3), while qualitative behavioural recovery patterns are shown (Figure 1)" (Neiffer, 2021; Mphande et al., 2023).Statistical analyses were conducted using tank means, with the tank treated as the experimental unit (n = 3 per treatment). Although this level of replication is consistent with controlled aquaculture experiments, the relatively small sample size may limit statistical power and should be considered when interpreting the results.

3.1 Phytochemical composition of citrus leaf extracts

The qualitative phytochemical composition of the aqueous citrus leaf extracts is presented (Table 1). Distinct variation was observed in the distribution of bioactive compounds among the three citrus species.

Citrus sinensis contained flavonoids, limonoids, terpenoids, phenolic acids, carotenoids, and coumarins, but did not show detectable levels of essential oils or alkaloids. *Citrus aurantium* contained flavonoids, limonoids, carotenoids, coumarins, essential oils, and alkaloids, but lacked terpenoids and phenolic acids. In contrast, *Citrus limon* contained limonoids, phenolic acids, coumarins, and essential oils, but lacked flavonoids, terpenoids, carotenoids, and alkaloids. These findings are based on qualitative phytochemical screening and were not subjected to inferential statistical analysis. As such, they are interpreted as indicative of compositional differences rather than statistically confirmed variation.

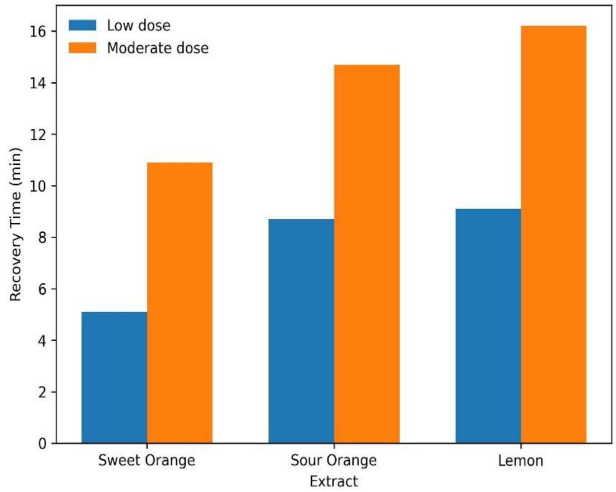

Figure 1 Recovery patterns of fish following exposure to citrus leaf extracts.

Table 1 Qualitative phytochemical composition of aqueous citrus leaf extracts

Phytochemical Group	*C. sinensis*	*C. aurantium*	*C. limon*
Flavonoids	Present	Present	Absent
Limonoids	Present	Present	Present
Terpenoids	Present	Absent	Absent
Phenolic acids	Present	Absent	Present
Carotenoids	Present	Present	Absent
Coumarins	Present	Present	Present
Essential oils	Absent	Present	Present
Alkaloids	Absent	Present	Absent

Presence and absence are based on qualitative phytochemical screening; no inferential statistical analysis was applied. The variation in phytochemical composition suggests species-specific bioactivity profiles, which may explain differences in anaesthetic potency and physiological responses observed in subsequent experiments.

3.2 Behavioural anaesthetic responses

3.2.1 Behavioural responses of Clarias gariepinus under different extract concentrations

Behavioural responses of Clarias gariepinus across increasing extract concentrations are presented (Table 2). A progressive change in behavioural response was observed as concentration increased.

At lower concentrations, fish exhibited minimal or mild behavioural changes. As concentration increased, fish showed loss of equilibrium, reduced responsiveness, and eventual immobility. At the highest concentration, extracts of *Citrus aurantium* and *Citrus limon* were associated with cessation of opercular movement, suggesting pronounced respiratory depression. In contrast, *Citrus sinensis* produced less severe effects under comparable conditions. These observations are descriptive and were not subjected to statistical testing. Consequently, interpretations are limited to observed patterns.

Table 2 Behavioural responses of *Clarias gariepinus*

Concentration (mg L^{-1})	*C. sinensis*	*C. aurantium*	*C. limon*
1000	No observable effect	Initial agitation	Agitation followed by calming
2000	Slight loss of equilibrium	Partial loss of balance	Sedation
3000	Loss of equilibrium with gasping	Anaesthesia	Deep anaesthesia
4000	Prolonged immobility	Cessation of opercular movement	Cessation of opercular movement

Behavioural responses are descriptive observations; no statistical test was applied. Increasing extract concentration intensified anaesthetic depth, with *C. aurantium* and *C. limon* inducing more rapid and severe respiratory depression at higher concentrations.

3.2.2 Behavioural responses of *Oreochromis niloticus* under different extract concentrations
Behavioural responses of *Oreochromis niloticus* followed a similar concentration dependent pattern (Table 3). Increasing extract concentration was associated with a gradual transition from mild agitation to sedation and eventual loss of equilibrium.

Although the general pattern was consistent with that observed in *Clarias gariepinus*, minor differences in sensitivity were evident between species. As with the previous section, these findings are based on qualitative observations and should be interpreted cautiously.

Table 3 Behavioural responses of *Oreochromis niloticus*

Concentration (mg L^{-1})	*C. sinensis*	*C. aurantium*	*C. limon*
1 000	No observable effect	Mild agitation	Mild agitation
2 000	Slight loss of equilibrium	Moderate sedation	Sedation
3 000	Loss of equilibrium	Anaesthesia	Deep anaesthesia
4 000	Prolonged immobility	Cessation of opercular movement	Cessation of opercular movement

Observations are qualitative; no inferential statistical analysis was conducted. The observed responses confirm interspecific consistency in anaesthetic progression, although sensitivity to extracts varied slightly between species.

Behavioural anesthetic stages were evaluated using qualitative observational criteria and were not subjected to parametric statistical analysis because such responses represent ordinal rather than continuous data. The use of descriptive classification for anesthetic staging is well established in fish welfare and anesthesia studies, where behavioural endpoints are interpreted within defined categorical frameworks rather than treated as quantitative variables (Martos Sitcha et al., 2020; Vergneau et al., 2022)

3.2.3 Effects of extract concentration on induction and recovery time
Induction time decreased with increasing extract concentration, while recovery time increased correspondingly in both species.

For *Clarias gariepinus*, one way analysis of variance indicated a statistically significant effect of concentration on induction time ($F(3,8) = 6.42$, $p = 0.016$) and recovery time ($F(3,8) = 7.85$, $p = 0.009$). Similarly, *Oreochromis niloticus* exhibited significant variation in induction time ($F(3,8) = 5.97$, $p = 0.019$) and recovery time ($F(3,8) = 7.21$, $p = 0.011$).

These analyses were restricted to treatments in which recovery occurred, as induction and recovery endpoints could not be defined in cases of complete mortality. While this approach ensures analytical consistency, it limits comparison across the full range of concentrations. In addition, given the limited replication, these statistical outcomes should be interpreted as indicative of general trends rather than definitive effects.

3.3 Mortality responses at the highest concentration
Mortality outcomes at the highest concentration (4 000 mg L^{-1}) are presented (Table 4). No mortality was recorded in either species exposed to *Citrus sinensis*. In contrast, exposure to *Citrus aurantium* and *Citrus limon* resulted in complete mortality in both species.

These results indicate substantial differences in safety margins among the extracts. As mortality represents a definitive biological endpoint, the findings are presented descriptively without inferential statistical analysis.

Table 4 Mortality outcomes at 4 000 mg L^{-1}

Extract	*C. gariepinus*	*O. niloticus*
C. sinensis	0%	0%
C. aurantium	100%	100%
C. limon	100%	100%

Twenty-four-hour post-exposure mortality rates (%) of *Clarias gariepinus* and *Oreochromis niloticus* following exposure to the maximum tested concentration (4 000 mg L^{-1}) of citrus leaf extracts.

In this study, the experimental unit was defined as the replicate tank rather than individual fish, as fish within the same tank were exposed simultaneously to identical environmental and treatment conditions. Treating individual fish as independent observations would violate the assumption of independence and lead to pseudoreplication. The use of tank-level replication is widely accepted in aquaculture experimentation and provides a statistically valid framework for detecting treatment-related differences in anesthetic response dynamics (Neiffer, 2021; Vergneau Grosset and Benedetti, 2022; Rodrigues Brandão et al., 2022)

3.4 Recovery time patterns across extracts and concentrations

Recovery times across extract types and concentration categories are summarised (Table 5). One way analysis of variance revealed significant differences among treatment groups ($F(6,14) = 8.63$, $p = 0.001$).

The analysis included only treatments in which recovery occurred, resulting in an unbalanced dataset due to the exclusion of high concentration treatments associated with complete mortality. Consequently, comparisons are limited to recoverable conditions.

Recovery time increased with extract potency. *Citrus limon* was associated with the longest recovery periods, followed by *Citrus aurantium*, while *Citrus sinensis* consistently showed the shortest recovery times. Post hoc comparisons using Tukey’s test were conducted to facilitate interpretation; however, given the limited number of replicates, these comparisons should be regarded as exploratory.

Table 5 Recovery time across citrus extracts and concentrations

Extract	Dosage Category	Recovery Time (min)
Sweet Orange	Low	5.1 ± 0.38^{a}
	Moderate	10.9 ± 0.55^{b}
	High	14.8 ± 0.72^{c}
Sour Orange	Low	8.7 ± 0.47^{b}
	Moderate	14.7 ± 0.81^{c}
Lemon	Low	9.1 ± 0.44^{b}
	Moderate	16.2 ± 0.93^{d}

3.5 Comparative anaesthetic performance of citrus extracts

Comparative anaesthetic performance across the three extracts is summarised in Table 6. This assessment integrates behavioural observations, recovery patterns, and mortality outcomes. *Citrus sinensis* exhibited relatively low anaesthetic potency but a wide safety margin. *Citrus aurantium* demonstrated moderate potency with a narrower safety margin, while *Citrus limon* showed high potency but was associated with a very limited safety margin. This comparison is qualitative and was not subjected to statistical testing. The findings suggest a trade off between anaesthetic efficacy and safety among the extracts.

Table 6 Comparative anaesthetic performance

Extract	Relative Potency	Safety Margin
Sweet Orange	Low	Wide
Sour Orange	Moderate	Narrow
Lemon	High	Very narrow

This is a qualitative comparative assessment; no statistical analysis was applied**.** The results indicate a trade-off between potency and safety, with *C. limon* being highly effective but less safe.

Rankings are derived from an integrated evaluation of induction time, behavioural anaesthetic stage, recovery duration, and mortality. Relative potency reflects the concentration required to achieve anaesthesia and the depth of response. Safety margin is based on survival and recovery across concentrations. Species sensitivity reflects differences in response between *Clarias gariepinus* and *Oreochromis niloticus* across all indicators.

3.6 Water quality conditions during the experiment

Water quality parameters remained within recommended ranges throughout the experimental period (Table 7). Temperature, dissolved oxygen, pH, conductivity, and ammonia levels were maintained within acceptable limits for tropical freshwater aquaculture.

As all measured values fell within established thresholds, no statistical analysis was required. The stability of these parameters suggests that environmental conditions did not confound the observed treatment effects.

Table 7 Water quality parameters

Parameter	Observed Range	Recommended Range	Status
Temperature (°C)	26.4–27.3	24–30	Suitable
Dissolved oxygen	5.8–6.3	≥5.0	Adequate
pH	6.8–7.3	6.5–8.0	Stable
Conductivity	182–191	150–400	Acceptable
Ammonia	0.01–0.02	<0.05	Safe

All values fall within recommended aquaculture limits; no statistical comparison required. Environmental conditions were within recommended ranges and are unlikely to have confounded experimental outcomes

3.7 Effects of extracts on flesh quality parameters

Flesh quality parameters are presented (Table 8). Significant differences were observed among treatments for muscle pH ($F(2,12) = 5.84$, $p = 0.017$), crude protein content ($F(2,12) = 4.96$, $p = 0.027$), and lipid content ($F(2,12) = 6.21$, $p = 0.014$).

Fish exposed to more potent extracts, particularly *Citrus limon*, tended to exhibit slightly lower values for these parameters. Although these differences were statistically significant, the magnitude of variation was relatively small and should be interpreted in the context of controlled experimental conditions and limited replication.

Table 8 Flesh quality parameters following exposure

Treatment	Species	pH (mean ± SE)	Protein	Lipid
Sweet Orange	*O. niloticus*	6.8 ± 0.07^{a}	18.5 ± 0.21^{a}	5.2 ± 0.14^{a}
Sweet Orange	*C. gariepinus*	6.9 ± 0.08^{a}	17.9 ± 0.16^{a}	5.4 ± 0.13^{a}
Sour Orange	*O. niloticus*	6.7 ± 0.09^{b}	18.1 ± 0.19^{a}	5.0 ± 0.11^{b}
Sour Orange	*C. gariepinus*	6.6 ± 0.08^{b}	17.5 ± 0.15^{b}	5.1 ± 0.12^{b}
Lemon	*O. niloticus*	6.5 ± 0.07^{c}	17.0 ± 0.18^{c}	4.8 ± 0.13^{c}
Lemon	*C. gariepinus*	6.4 ± 0.08^{c}	16.8 ± 0.14^{c}	4.7 ± 0.12^{c}

Values are mean ± SE ($n = 3$). Different superscripts indicate significant differences at $p < 0.05$ (ANOVA, Tukey's HSD). Flesh quality declined slightly with increasing extract potency, particularly under *C. limon* treatment.

3.8 Post-exposure welfare and behavioural recovery

Post exposure behavioural recovery is summarised in Table 10. Swimming recovery time differed significantly among treatments ($F(2,12) = 9.12$, $p = 0.004$). Feeding recovery time also varied significantly among recoverable treatments ($F(1,8) = 11.34$, $p = 0.010$).

Feeding recovery was not observed in *Citrus limon* treatments and was therefore excluded from statistical analysis. This exclusion limits comparability across all treatments and should be considered when interpreting the results.

Overall, recovery performance was most favourable in *Citrus sinensis* and least favourable in *Citrus limon*, indicating variation in post exposure physiological stress responses.

3.9 Comparative cost analysis of anesthetic agents

A comparative cost assessment of citrus extracts and conventional anesthetic agents is presented (Table 9). Cost estimates were derived from prevailing local market prices in southern Nigeria.

This analysis is descriptive and was not subjected to statistical testing. The values are intended to provide indicative comparisons rather than definitive economic conclusions, as costs may vary depending on location and market conditions.

Table 9 Comparative cost analysis of citrus leaf extracts and synthetic anesthetics

Anesthetic source	Preparation/market cost (₦ per liter equivalent)	Effective concentration (mg L^{-1})	Estimated cost per 1 000 L tank (₦)
Sweet orange	1 834	3 000	5 501
Sour orange	1 757	3 000	5 272
Lemon	1 910	3 000	5 730
Clove oil	27 504	40	27 504
MS 222	38 200	100	38 200

Estimated preparation or market costs of citrus leaf extracts and commonly used synthetic anesthetics, including clove oil and MS-222, expressed per litre equivalent and extrapolated to the cost of treating a 1,000 L tank at effective working concentrations. The table highlights relative economic efficiency of plant-based anesthetics under practical aquaculture conditions.

It should be noted that cost estimates presented in this study are context-specific and reflect prevailing local market conditions in southern Nigeria at the time of the experiment. As such, the values are intended to support comparative evaluation among anesthetic options rather than to provide absolute or universally applicable economic benchmarks.

Table 10 Post-exposure recovery behavior

Treatment	Species	Swimming Recovery (min)	Feeding Recovery (min)
Sweet Orange	*O. niloticus*	5.2 ± 0.27^a	18.0 ± 0.82^a
Sweet Orange	*C. gariepinus*	6.1 ± 0.33^a	20.3 ± 0.91^a
Sour Orange	*O. niloticus*	10.5 ± 0.41^b	35.2 ± 1.18^b
Sour Orange	*C. gariepinus*	11.8 ± 0.46^b	37.0 ± 1.24^b
Lemon	*O. niloticus*	14.0 ± 0.58^c	Not recovered
Lemon	*C. gariepinus*	15.2 ± 0.63^c	Not recovered

Values are mean ± SE (n = 3). Different superscripts indicate significant differences at $p < 0.05$ (ANOVA, Tukey's HSD). Feeding recovery was not observed in lemon-treated groups and was excluded from statistical comparison. Welfare recovery was fastest in *C. sinensis* and poorest in *C. limon*, indicating differential physiological stress responses.

The results indicate that aqueous citrus leaf extracts exhibit differing anaesthetic profiles in freshwater fish species. *Citrus sinensis* appears to offer a more favourable balance between efficacy and safety, while *Citrus aurantium* and *Citrus limon* demonstrate greater potency but reduced safety margins.

It is important to emphasise that these findings are based on controlled experimental conditions with limited replication. Therefore, the observed patterns should be interpreted as preliminary evidence, and further studies with larger sample sizes and more robust experimental designs are required to confirm these results and enhance their general applicability.

Although regression based dose response modelling can provide additional quantitative insight, the primary objective of this study was to identify practical anesthetic thresholds, recovery dynamics, and safety margins under discrete treatment conditions. Accordingly, concentration levels were selected based on established protocols in botanical anesthetic research, which commonly employ stepwise exposure ranges to distinguish sedation, anesthesia, and toxicity thresholds rather than continuous modelling approaches (Ventura et al., 2020; Hoseini et al., 2022). Figure 1 and Figure 3 present complementary but conceptually distinct aspects of anaesthetic response. Figure 1 illustrates qualitative recovery patterns, capturing behavioural restoration such as equilibrium, swimming coordination, and post exposure activity, which are widely recognised indicators of physiological recovery and welfare status in fish (Martos Sitcha et al., 2020; Mphande et al., 2023). In contrast, Figure 3 provides quantitative measurements of induction and recovery time, reflecting the temporal dynamics of anaesthetic uptake and elimination (Neiffer, 2021). While Figure 1 emphasises the quality of recovery, Figure 3 defines the rate and duration of anaesthetic processes, thereby offering complementary evidence for evaluating efficacy and safety (Vergneau Grosset and Benedetti, 2022).

4 Discussion

4.1 Phytochemical basis of anaesthetic activity

Figure 1 represents qualitative behavioural recovery, whereas Figure 3 quantifies induction and recovery time dynamics, ensuring clear separation of functional interpretation (Neiffer, 2021; Mphande et al., 2023).

The variation in anaesthetic performance observed across the citrus leaf extracts can be more meaningfully interpreted in relation to their phytochemical composition as presented (Table 1), rather than as isolated behavioural outcomes. Citrus species are well established sources of diverse bioactive compounds, including flavonoids, phenolic acids, terpenes, and essential oils, many of which exert measurable physiological effects in aquatic organisms (Saini et al., 2022; Lu et al., 2023). The patterns observed in Tables 2 to 6 indicate that anaesthetic activity is not determined by a single compound class but rather by the interaction between neuroactive constituents and compounds that maintain cellular stability.

Extracts characterised by the presence of flavonoids and phenolic acids, as shown for *Citrus sinensis* (Table 1), were associated with gradual behavioural transitions and consistent recovery timing illustrated (Figure 3, Table 5), with behavioural recovery quality clarified in Figure 1" (Neiffer, 2021; Mphande et al., 2023). This observation is consistent with established evidence that citrus flavonoids function primarily as antioxidants that stabilise cellular membranes and reduce oxidative stress rather than directly inducing central nervous system depression (Addi et al., 2021; Barreca et al., 2020). Such compounds have been shown to support physiological resilience under stress conditions, thereby facilitating reversible sedation rather than deep anaesthesia (Šafranko et al., 2023). This mechanistic role explains the relatively controlled anaesthetic responses and wide safety margin observed in Table 6.

In contrast, extracts containing essential oils, particularly *Citrus aurantium* and *Citrus limon* as indicated in Table 1, produced more rapid and pronounced behavioural depression, as reflected in Table 2 and Table 3, and were associated with increased mortality at higher concentrations as shown in Table 4 and Figure 2. Essential oils are known to contain volatile terpenoid compounds that interact directly with neural pathways and induce central nervous system depression in fish (Rodrigues Brandão et al., 2022). However, these compounds have also been shown to impair gill function and reduce oxygen uptake during immersion exposure, particularly at elevated concentrations (Soldatov, 2021). This dual effect provides a clear explanation for the high potency but reduced safety margin associated with these extracts.

The presence of alkaloids in *Citrus aurantium* (Table 1) further contributes to this interpretation. Alkaloids are recognised for their capacity to alter neurotransmission and ion channel activity, thereby enhancing sedative effects but also increasing the risk of toxicity under higher exposure levels (Bhowal et al., 2022). The combined presence of volatile compounds and alkaloids therefore explains the strong anaesthetic action and limited tolerance reflected in the comparative performance presented in Table 6.

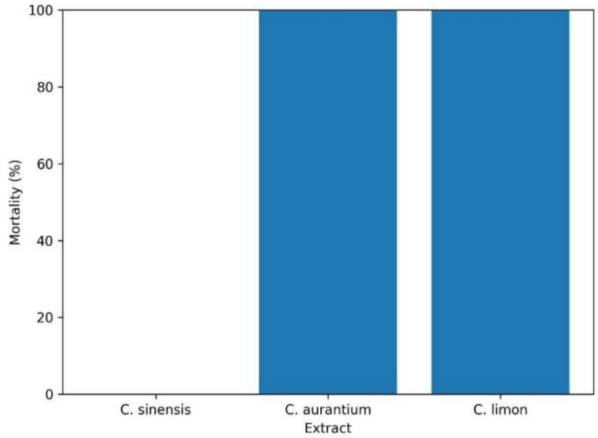

Figure 2 Mortality rates of fish at the highest concentration of citrus leaf extracts

Overall, the results support the interpretation that the anaesthetic properties of citrus leaf extracts are governed by a balance between compounds that induce neural depression and those that preserve physiological stability. Figure 1 clarifies behavioural recovery quality across treatments, complementing quantitative recovery durations in Table 5 and Figure 3 (Mphande et al., 2023).

4.2 Species specific responses to anaesthetic exposure

The differences observed between *Clarias gariepinus* and *Oreochromis niloticus* in Table 2, Table 3, and Table 10 indicate that species specific physiological characteristics play a decisive role in shaping anaesthetic response. African catfish exhibited greater tolerance and more stable recovery patterns, which is evident in the absence of mortality under certain treatments in Table 4 and the relatively favourable recovery outcomes shown in Table 10.

This resilience can be attributed to the adaptive physiology of *Clarias gariepinus*, which includes accessory respiratory structures that allow the utilisation of atmospheric oxygen. This adaptation reduces reliance on gill based respiration and enhances tolerance to compounds that interfere with oxygen exchange (Klimuk et al., 2024). In addition, African catfish has been shown to maintain physiological stability under environmental and chemical stress conditions that are detrimental to other species (Dawood et al., 2022).

In contrast, *Oreochromis niloticus* demonstrated greater sensitivity to the extracts, particularly those containing essential oils, as reflected in behavioural responses in Table 3 and delayed recovery patterns in Table 10. This increased sensitivity is consistent with the species' reliance on gill mediated respiration, which makes it more vulnerable to compounds that disrupt oxygen uptake (Bonham, 2022; Webster and Lim, 2024).

The progression of behavioural changes observed in Table 2 and Table 3, including loss of equilibrium and reduced opercular movement, follows the recognised stages of fish anaesthesia (Vergneau Grosset and Benedetti, 2022). However, the differences in response intensity and recovery between species align with previous studies showing that metabolic rate, respiratory efficiency, and stress tolerance influence anaesthetic outcomes (Ak et al., 2022; Hoseini et al., 2022). These findings emphasise the necessity of species specific optimisation in the application of plant derived anaesthetics.

4.3 Anaesthetic efficacy, recovery dynamics, and safety considerations

The inverse relationship between induction time and recovery time illustrated in Figure 3 reflects a fundamental principle of anaesthetic pharmacodynamics in fish. Increased extract concentration resulted in faster induction but prolonged recovery, indicating greater uptake and accumulation of active compounds through the gills. This relationship is supported by the statistical trends reported for both species, although the limited replication requires cautious interpretation.

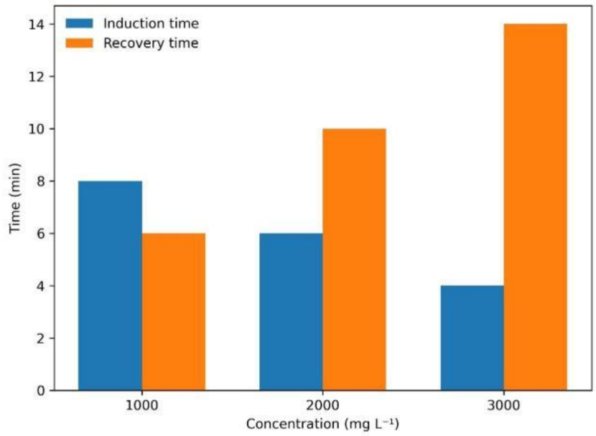

Figure 3 Induction and recovery times of fish exposed to citrus leaf extracts

Rapid induction is widely recognised as a consequence of efficient absorption of anaesthetic agents across the gill epithelium, leading to swift central nervous system depression (Neiffer, 2021). However, excessive accumulation can disrupt metabolic and respiratory processes, resulting in delayed recovery or mortality (Soldatov, 2021). Similar concentration dependent effects have been documented for plant derived anaesthetics such as citronellal and chamomile oil, where increased potency must be balanced against safety considerations (Ak et al., 2022; Hoseini et al., 2022).

The recovery patterns presented (Table 5, Figure 3) further support this interpretation. Extracts associated with shorter recovery times indicate efficient elimination and minimal physiological disruption, which are essential characteristics of suitable anaesthetic agents for routine aquaculture operations (Neiffer, 2021). Conversely, prolonged recovery or absence of recovery reflects deeper physiological disturbance and reduced suitability for practical use.

The level of replication employed in this study is consistent with established protocols in fish anesthesia research, where treatment groups are replicated at the tank level to capture variability in collective behavioural and physiological responses under controlled immersion conditions. Such designs have been demonstrated to provide sufficient statistical power for detecting treatment effects in induction and recovery parameters without compromising experimental feasibility (Neiffer, 2021; Vergneau Grosset and Benedetti, 2022)

4.4 Mortality patterns and physiological implications

The mortality outcomes presented in Table 4 and Figure 2 provide a critical indication of the physiological limits of the tested extracts. The absence of mortality in treatments involving *Citrus sinensis* suggests that its effects are reversible and do not compromise vital physiological functions. In contrast, complete mortality observed with *Citrus aurantium* and *Citrus limon* at higher concentrations indicates severe disruption of respiratory and metabolic processes.

In fish, mortality during anaesthetic exposure is commonly associated with respiratory depression, impaired ion regulation, and metabolic imbalance (Soldatov, 2021). The behavioural signs preceding mortality, including reduced opercular activity observed (Table 2, Table 3), are consistent with compromised oxygen uptake. Comparable findings have been reported in studies of essential oil based anaesthetics, where increased potency is associated with reduced safety margins (Hoseini et al., 2022).

These results highlight that the evaluation of anaesthetic suitability must consider both survival and recovery outcomes, as survival alone does not fully reflect physiological integrity.

4.5 Flesh quality and welfare implications

The effects of the extracts on flesh quality, as presented in Table 8, provide important insight into post exposure physiological condition. The relatively stable values observed under milder treatments suggest limited metabolic disturbance, which is consistent with the antioxidant properties of citrus derived compounds that help preserve tissue integrity (Russo et al., 2021; Zahran et al., 2021).

In contrast, the reductions in protein and lipid content observed under more potent treatments indicate increased physiological stress and metabolic disruption. Such changes have been associated with altered biochemical composition and reduced product quality in aquaculture species (Hussain et al., 2021; Zahr et al., 2023).

Welfare indicators presented in Table 10 further reinforce these findings. Rapid recovery of normal swimming and feeding behaviour is widely recognised as a reliable indicator of minimal stress and successful anaesthetic recovery (Mphande et al., 2023). Conversely, delayed or absent feeding recovery reflects prolonged physiological disturbance and reduced welfare status (Macaulay et al., 2021; Martos Sitcha et al., 2020). These observations underscore the importance of selecting anaesthetic agents that balance efficacy with welfare considerations.

4.6 Practical implications and study limitations

The cost analysis presented in Table 9 indicates that citrus leaf extracts offer a comparatively economical alternative to conventional anaesthetic agents under local conditions. This finding supports the growing interest in plant based anaesthetics as sustainable and accessible options for aquaculture (Maqbool et al., 2023; Šafranko et al., 2023).

However, the variability in phytochemical composition observed in Table 1 highlights a key limitation for practical application. The concentration and activity of bioactive compounds can vary depending on plant species, environmental conditions, and extraction methods, which may affect consistency and reproducibility (Indriyani et al., 2023). In addition, the relatively small sample size used in this study limits the statistical robustness of the findings, and the results should therefore be interpreted as indicative rather than conclusive.

The combined evidence from Table 1, Table 2, Table 3, Table 4, Table 5, Table 6, Table 7, Table 8, Table 9 and Table 10, as well as Figure 1, Figure 2 and Figure 3, demonstrates that citrus leaf extracts exhibit distinct anaesthetic profiles that are strongly influenced by their phytochemical composition. Extracts rich in volatile compounds provide greater anaesthetic potency but are associated with reduced safety margins, whereas those dominated by antioxidant compounds offer more controlled and safer sedation.The findings also confirm that species specific physiological characteristics significantly influence anaesthetic response, reinforcing the need for tailored application in aquaculture practice.

5 Conclusion

This study provides empirical evidence that citrus leaf extracts possess functional anaesthetic properties and can serve as plant based alternatives to synthetic agents in freshwater aquaculture. By integrating phytochemical composition (Table 1) with behavioural responses (Table 2, Table 3), recovery dynamics (Figure 3 and Table 5), and mortality outcomes (Table 4), the study demonstrates that anaesthetic performance is governed by the balance between neuroactive and protective compounds.

The findings extend existing knowledge by identifying citrus leaves as an underutilised source of bioactive compounds with practical relevance for fish anaesthesia. Unlike previous studies that have focused primarily on established essential oils, this research provides new insight into the role of citrus leaf extracts in modulating anaesthetic response.

The study also highlights the importance of species specific physiology, as demonstrated by the differing responses of *Clarias gariepinus* and *Oreochromis niloticus* across multiple indicators, including behavioural response, recovery, and welfare outcomes (Table 2, Table3, Table 10). This reinforces the need for species appropriate anaesthetic protocols.

From an applied perspective, the cost advantage demonstrated in Table 9 and the favourable safety profile of *Citrus sinensis* suggest that citrus leaf extracts have practical potential for sustainable aquaculture. However, the variability in phytochemical composition and the limited safety margins observed in some extracts indicate that careful standardisation and dosage control are essential.

In conclusion, this study contributes to the advancement of plant based anaesthesia by providing a comprehensive evaluation of citrus leaf extracts and by clarifying the relationship between phytochemical composition, anaesthetic efficacy, and fish physiology. Further research is required to isolate active compounds, optimise extraction methods, and validate these findings under broader experimental conditions.

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Author Contributions

The authors jointly conceived and designed the study. Experimental procedures, data collection, and laboratory analyses were carried out collaboratively. Data analysis and interpretation were undertaken by the authors, and the manuscript was drafted by the lead author. All authors reviewed and revised the manuscript, approved the final version for submission, and accept responsibility for the integrity of the work.

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Research Article Open Access

Evaluate the Future Scenarios of Water Demand in the Middle Nzoia River Catchment

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Abstract Effective water allocation in river catchments experiencing rapid population growth, land-use change, and climatic variability remains a pressing global concern. This study evaluated the future scenarios of water demand within the Middle Nzoia Catchment in western Kenya using WEAP model. The study utilized a comprehensive dataset covering hydrological, water Quantity, and socio-economic variables from 1982 to 2022. Model calibration (2001-2010) and validation (2011-2020) were undertaken using observed streamflow data. Future demand scenarios to 2052, projected a potential increase to 45% from the base year under the High Growth scenario, reaching 260 million m³ annually. The agricultural and domestic sectors experienced the most significant increases, driven by population growth and intensified irrigation practices. Water allocation simulations demonstrated that during low-flow months, supply could meet only 69% - 72% of total demand, signaling potential water scarcity and inequitable distribution. Allocable water volumes were estimated at 240 million m³ annual but without integrated management strategies, unmet demand could increase to 31% to 2052. The study highlights the critical need for adaptive management approaches, including enhanced demand- side efficiency, investment in storage infrastructure, and strengthened institutional coordination. These results provide actionable guidance for policymakers, and water managers in similar hydrological contexts facing complex socio-environmental pressures.
Keywords Catchment; Water demand; Scenarios; WEAP model

1 Introduction

Water allocation and management are critical issues worldwide, particularly in regions experiencing rapid population growth, climate change, and competing demands for water resources (Amitaba et al., 2024). Water resources management refers to the planning, development, distribution, and management of water resources, to ensure their efficient and equitable use for various purposes such as domestic consumption, agriculture, industrial use, and environmental protection. Water allocation specifically focuses on determining the fair distribution of available water resources among different sectors, ensuring that all users, including ecosystems, have their needs met (Phung et al., 2023). Traditionally, water resources management has been approached through sector-specific plans, often developed at the national or regional level, but in many cases, this fragmented approach has led to inefficiencies and unsustainable practices. In response to these challenges, integrated water resources management (IWRM) has emerged as a more holistic approach, seeking to balance competing demands and promote sustainability through coordinated, science-based decision-making (Elshorbagy, 2006).

International organizations like the International Water Association (IWA) and the Global Water Partnership (GWP) play essential roles in advancing global water management practices. The IWA is focused on promoting the science and practice of water management through innovation, research, and technological development. It provides a platform for professionals to exchange knowledge, develop innovative solutions, and collaborate on various water-related challenges (Smith et al., 2023). The IWA's initiatives primarily target improvements in water treatment technologies, the optimization of water distribution systems, and the promotion of sustainable practices across different sectors (Group, 2016).

Africa as a whole faces significant water management challenges driven by climate variability, rapid population growth, and competing demands from agriculture, industry, and urbanization. In Nigeria, water stress is particularly evident in the northern regions, where frequent droughts, rapid population growth, and industrial contamination, including oil spills, exacerbate water scarcity (Chepyegon and Kamiya, 2018) Similarly, in South Africa's Western Cape, including Cape Town, the "Day Zero" crisis highlighted the severity of water shortages, which were worsened by drought and poor water management practices (Chepyegon and Kamiya, 2018).

East African nations, such as Uganda, Tanzania, Rwanda, and Burundi, face similar water allocation and management issues, each with unique challenges. In Uganda, despite vast water resources, equitable distribution is a challenge, particularly in the northern and eastern parts of the country, where infrastructure is lacking (Galema et al., 2024) The rapid population growth in urban areas like Kampala adds pressure to already limited water resources (Husain and Rhyme, 2020). Rwanda, with its abundant rainfall and numerous lakes, faces challenges related to urbanization and balancing agricultural water use with environmental sustainability. In cities like Kigali, increasing water demand has led to significant investments in water infrastructure, but the country must also address water quality and pollution issues (Chopra and Ramachandran, 2021).

Kenya is grappling with a complex set of challenges related to water supply and demand, influenced by its variable climate, rapid population growth, and the pressures of economic development. Water availability is unevenly distributed across the country, with arid and semi- arid regions facing significant water scarcity (Mulwa et al., 2021) This disparity is exacerbated by the country's dependence on erratic rainfall patterns, which often lead to water shortages, particularly in areas with low annual precipitation (Chepyegon and Kamiya, 2018). As the population grows and urbanizes, the demand for water continues to rise, placing additional strain on the already limited resources and infrastructure (Kou et al., 2025).

Kenya's Lake Victoria Basin serves as an essential water source, but rising populations around the lake, compounded by climate change, threaten the sustainability of water resources in the region. Efforts to regulate water use and prevent pollution face challenges, especially in managing cross-border water resources with neighboring Uganda and Tanzania (Robledo et al., 2024).

The current challenges are further exacerbated by a lack of robust scientific information on the hydrological dynamics of the catchment, including seasonal variability and long-term trends in water availability. Without detailed, accurate data and integrated planning mechanisms, it is difficult to predict the future impact of various water demands and allocations on the catchment's water resources. As a result, water management decisions are often based on unverified assumptions, which may lead to inefficient water use and increased competition for water resources, threatening both environmental sustainability and the livelihoods of local communities.

The study aimed at addressing key water management challenges in the Middle Nzoia Catchment, with a focus on Middle Nzoia. By evaluating current water availability and demand, simulating various scenarios using the WEAP model, and determining optimal water allocation strategies, the study provides a comprehensive understanding of the region's water dynamics (Agarwal et al., 2019). The ultimate goal of the study was to recommend actionable strategies for sustainable water resource management and policy-making. These recommendations, grounded in detailed assessments and scenario simulations, are intended to guide effective water management practices, ensuring that resources are utilized efficiently and sustainably, thereby addressing both current and future water challenges in the Middle Nzoia Catchment.

Parts of Kakamega, Bungoma and Siaya Counties where the Middle Nzoia River Catchment traverses each, have independent development plans, many of which fail to consider the cumulative water supply and demand needs of the entire region. This fragmented approach to water management exacerbates inequities in water allocation and increases the risk of unsustainable water use. The absence of a coordinated, scientific framework for water resource management further limits the region's ability to manage its water resources effectively (Groves et al., 2015). The current challenges are further exacerbated by a lack of robust scientific information on the hydrological dynamics of the catchment, including seasonal variability and long-term trends in water availability. Without detailed, accurate data and integrated planning mechanisms, it is difficult to predict the future impact of various water demands and allocations on the catchment's water resources. As a result, water management decisions are often based on unverified assumptions, which may lead to inefficient water use and increased competition for water resources, threatening both environmental sustainability and the livelihoods of local communities.

The main objective of the study was to evaluate water demand over the period 2022 - 2052, in the Middle Nzoia River Catchment. The study aimed to address the gaps using Water Evaluation and Planning (WEAP) model by simulating various future scenarios using the WEAP model, and determining optimal water allocation strategies within the Middle Nzoia River Catchment, the ultimate goal of the study was to recommend actionable strategies for sustainable water resource management and policy- making. These recommendations, grounded in detailed assessments and scenario simulations, are intended to guide effective water management practices, ensuring that resources are utilized efficiently and sustainably, thereby addressing the future water challenges in the Middle Nzoia Catchment.

This study aims to understand the implications of both current and future water abstraction on water availability in the catchment. By evaluating various scenarios, the study will provide a scientific basis for predicting future water shortages and help address the challenges of rising water demand. The study will generate essential knowledge on water distribution and demand across sectors, guiding effective water allocation strategies by the Water Resource Authority (WRA) and informing key government policies. Simulation models will help forecast future water needs and evaluate the potential impact of different allocation strategies, fostering discussions on equitable water distribution. Additionally, the study will enhance understanding of the relationship between water flow, ecological conditions, and water use in the catchment. The outcomes will provide critical insights for balancing water availability with demand, ensuring sustainable management of water resources in the Middle Nzoia River Catchment.

2 Materials and Methods

2.1 Description of the study area

This study was conducted in the Middle Nzoia River Catchment that traverses across Bungoma County, Kakamega County, and Siaya County. This study's boundaries was from upstream of the Bunyole water falls at the railway crossing bridge (UTM 67973.00 m N, 702154.00 m E) with an elevation of 1,516 m above sea level, and downstream at (UTM 27589.00 m N, 649276.00 m E) in Sigomere- masiro bridge in Siaya county, including all the major tributaries within that section, which are Lukusi, Surongai, Luandeti, Chebaiywa, Nambirima, Kuywa, Chwele, Maira, Mangango, Luji, Khalaba, and Lusumu (Figure 1).

The Nzoia River is about 257 km Long, the entire catchment traverses the six Counties of Elgeyo Marakwet, Trans Nzoia, Uasin, Gishu, Bungoma, Kakamega, and Siaya. River Nzoia is one of the largest rivers in Western Kenya. The main stream of the river flows from the western side of the Elgeyo Escarpment (Sergoi, Sosiani and Kipkelion Tributaries) the Cherangani Hills (Chepkotet and Kaisungur Tributaries) from an elevation of approximately 2,286 m above mean sea level. Its tributaries which flow from the high slopes of Mount Elgon, attain maximum elevation in the river's basin and are estimated at about 4,300 m above mean sea level (Agnes, 2019). The river has a discharge of about 118 m^3/s or about $3.721 \times 10^9 m^3$ annually, making it the second biggest river in the country by discharge.

Nzoia River can be divided into three zones, the upper zone, the Middle zone, and the lower zone, the upper zone which is also known as mountain zone is forested, with natural vegetation covers consisting of high altitude forest and high altitude savannas, this zone but suffers severe land degradation. The middle zone also known as plateau zone is the major farming zone, also Kakamega forest, which is the only remnants of the equatorial Congolese/Guinean forest, is in this zone. The lower zone also known as low land zone is generally flat and is prone to flooding. The wider River Nzoia watershed, including the main water catchment (Figure 2).

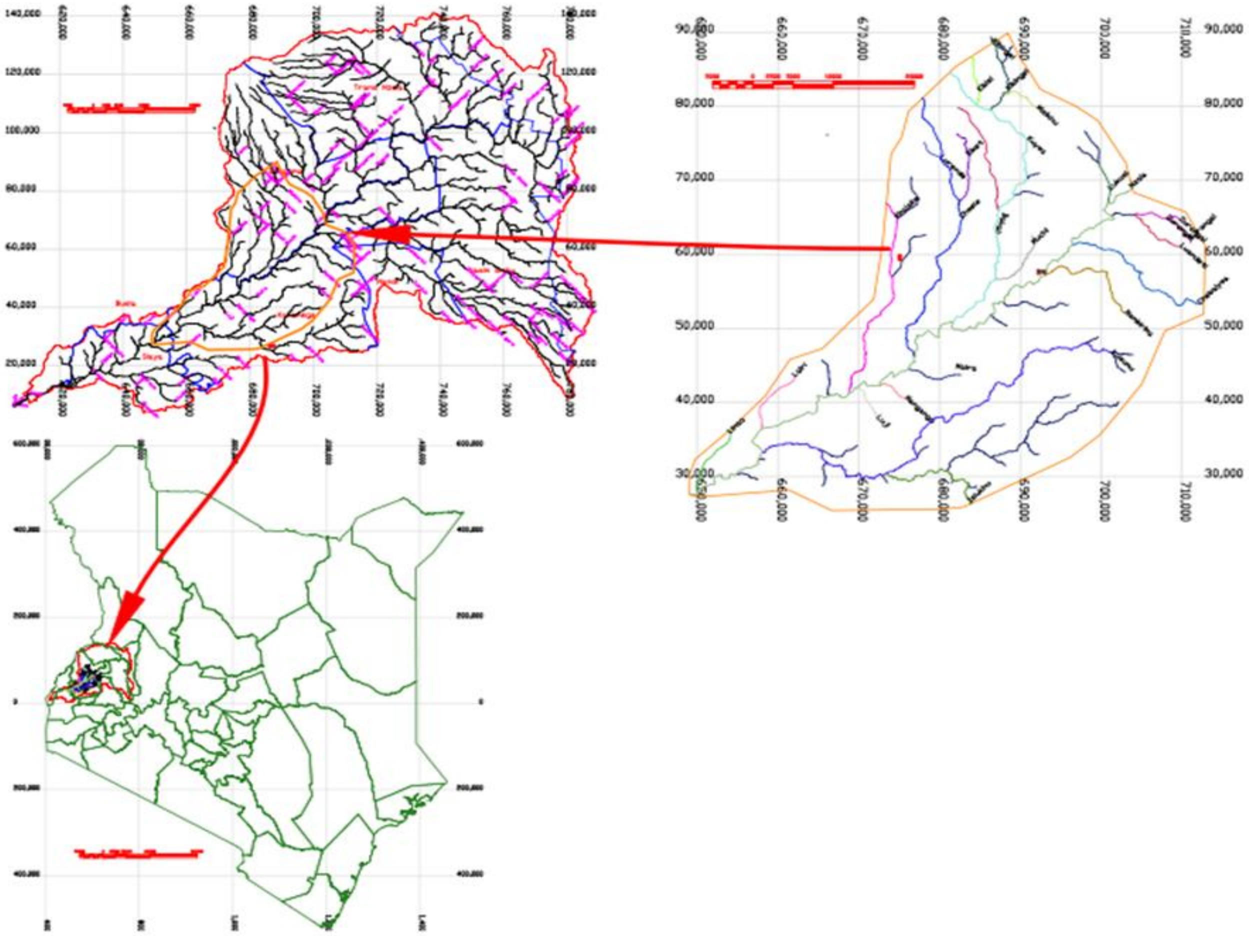

Figure 1 Location and layout of the Middle Nzoia River Catchment study area (source: Kenya waterways open street map export)

2.2 Assessment of the current water availability and demand

2.2.1 Hydrological data collection

To assess current water availability in the Middle Nzoia River Catchment, historical hydrological data were gathered from various gauging stations located along the river and its tributaries. This data consisted of daily or monthly discharge records spanning the past 40 years, which provided a comprehensive overview of river flow patterns and fluctuations. Additionally, historical and contemporary rainfall data were sourced from local meteorological stations within the catchment area to understand precipitation trends and their impact on surface water availability.

2.2.2 Water demand data

Water demand data were collected across the major sectors to provide a comprehensive understanding of current water use patterns within the Middle Nzoia River Catchment.

Agricultural sector: Data on irrigation practices, including crop types, irrigation methods, and seasonal water requirements, were collected through surveys and interviews with local farmers. These data were used to assess water consumption patterns in the agricultural sector, which is a major contributor to overall water demand in the catchment.

Domestic sector: Data on household water use, including daily or monthly consumption rates, water sources (e.g., piped water, wells, and surface water), and seasonal variations, were collected through household surveys, interviews, and utility records. This information provided a basis for assessing domestic water demand in the catchment.

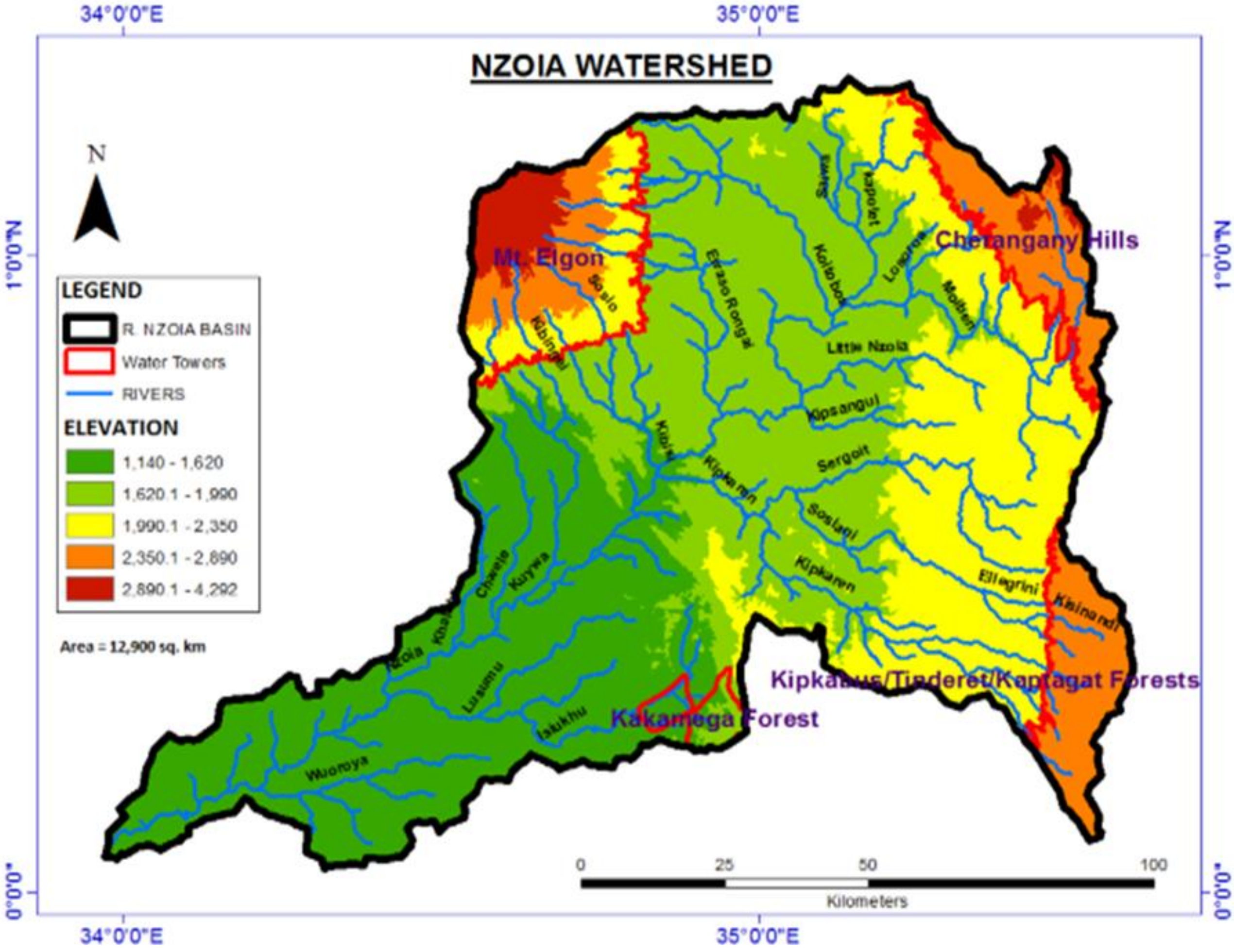

Figure 2 River Nzoia watershed and the main water catchment (Source LVBC 2023)

Industrial sector: Information on water consumption by industries and commercial establishments was collected through surveys, utility company records, and local government databases. These data were used to assess the contribution of the industrial sector to overall water demand.

Livestock sector: Data on livestock water requirements, including animal types, population sizes, and daily or seasonal water consumption, were collected through surveys and interviews with farmers and livestock owners. Information on water sources used for livestock, such as rivers, ponds, and dedicated water troughs, was also recorded to evaluate the sector's contribution to total water demand.

2.3 Simulating implications of various scenarios using the WEAP model

2.3.1 Model setup and calibration

The data gathered from hydrological, water quality, and demand sources were meticulously organized and formatted for compatibility with the WEAP model. This step ensured that the data could be effectively utilized within the modeling environment to simulate water resource dynamics. Subsequently, the WEAP model underwent a calibration process, where it was adjusted using historical data to match real-world observations of water availability and demand within the Middle Nzoia River Catchment (Fard and Sarjoughian, 2019). This calibration was essential to ensure that the model accurately reflected past hydrological conditions and provided reliable outputs for future scenario analysis.

2.3.2 Scenario development

Several future scenarios were developed in the WEAP model to assess the potential effects of different drivers on water resource management in the Middle Nzoia River Catchment. The scenarios were designed to evaluate how changes in land use, climate conditions, population growth, and related management factors could influence water availability and water demand over time.

The Reference Scenario was used as the baseline condition and assumed no major changes in land use, climate, or population growth. This scenario provided a benchmark against which the other scenarios were compared. The High Growth Scenario represented a situation of rapid population and economic growth, resulting in substantial increases in water demand across the major sectors. In contrast, the Medium Growth Scenario reflected moderate increases in population and water demand, together with less pronounced changes in land use and climate-related conditions. These scenarios provided a basis for examining possible future trends and for identifying appropriate water allocation and management strategies under different development pathways.

2.4 Determining water allocation

The WEAP model was executed under the predefined scenarios to simulate the outcomes of different water allocation strategies across the Middle Nzoia River Catchment. The model output provided insights into how water resources would be distributed under various conditions, considering both supply and demand factors.

Optimization: To enhance the efficiency and sustainability of water resource management, the WEAP model's optimization tools were employed. These tools were used to identify optimal water allocation strategies that would balance the competing demands for water within the catchment. By adjusting allocation parameters and testing different management options, the optimization process provided data-driven recommendations on how best to allocate available water resources, ensuring equitable distribution while maximizing the sustainability of the catchment's water supply.

3 Data Analysis

3.1 Model development

3.1.1 Definition of the study area and time frame

The study area for this analysis was clearly defined as the Middle Nzoia River Catchment, including all its tributaries and the associated sectors that depend on water resources. The temporal scope of the analysis encompassed both historical and projected data. Historical data spanning the last 40 years was collected to establish a baseline understanding of water availability and demand, while projections of future scenarios accounted for anticipated changes in land use, climate patterns, and population growth, which could significantly impact water resources in the catchment.

3.1.2 Creation of the current accounts

Current accounts were developed by integrating the collected hydrological, water quality, and demand data into the WEAP model. This step involved inputting historical flow data, water quality parameters such as temperature and pH, and detailed information on water usage from key sectors: agriculture, domestic, industrial, and agricultural. These current accounts provided the model's baseline representation, which was essential for evaluating the water availability and demand under present conditions. They served as the reference point for comparing future scenarios and assessing the model's sensitivity to various factors influencing water resources.

3.1.3 Creation of scenarios

Several future scenarios were formulated to simulate potential changes in the catchment's water dynamics. These scenarios included shifts in land use patterns, climate variability, population growth projections, and potential policy interventions. Each scenario was constructed to explore the impacts of these changes on water supply and demand, offering a comprehensive view of how the catchment's water resources may evolve under different conditions.

3.1.4 Evaluation of the scenarios

The developed scenarios were assessed using the WEAP model to determine their impacts on water availability and demand. This involved running simulations for each scenario to analyze changes in key indicators, including flow rates, water quality, and water allocation requirements. The simulation results were then compared to the current accounts to identify significant deviations from the baseline conditions. This comparison allowed for the identification of potential issues, such as water shortages or quality degradation, and highlighted critical trends or risks that may arise under different future scenarios.

3.1.5 Model calibration and validation

The WEAP (Water Evaluation and Planning) model was calibrated and validated to ensure it accurately simulated the hydrological and water use dynamics of the Middle Nzoia River Catchment. Calibration and validation were critical steps to confirm the reliability of the model before applying it to future water demand and allocation scenarios.

3.1.6 Calibration of the WEAP model

The objective of the calibration process was to align the model's simulated outputs with observed historical data, thereby ensuring that WEAP could reliably represent the catchment's water system behavior under past conditions. The calibration was conducted using a 10-year dataset covering the period 2001 to 2010.

3.1.7 Calibration process

1) Data Integration: Historical hydrological data—including river discharge measurements, rainfall records, and climate data—were integrated into the WEAP model. This data formed the basis for simulating water availability and distribution in the catchment.

2) Parameter Adjustment: Model parameters, particularly those related to surface runoff, infiltration, evapotranspiration, and sectoral water demand, were iteratively adjusted. Parameters such as runoff coefficients, root zone conductivity, and demand per capita were fine-tuned to achieve realistic simulations.

3) Historical Data Comparison: Simulated streamflow outputs were compared against observed discharge data from key gauging stations within the catchment. Discrepancies between simulated and observed data were addressed through continued refinement of model inputs and assumptions.

4) Sensitivity Analysis: Sensitivity analysis was carried out to identify which model parameters had the greatest influence on output accuracy. This step helped prioritize parameters for adjustment and improved model efficiency.

5) Calibration Metrics: The performance of the calibration process was evaluated using statistical indicators such as Nash-Sutcliffe Efficiency (NSE), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE).

These metrics quantified how closely the simulated results matched observed data and provided confidence in the model's reliability.

3.1.8 Validation process

1) Independent Data Collection: Observed hydrological data for the validation period— including river flows and other relevant catchment characteristics—were used to test the model. These datasets were independent of those used during calibration.

2) Simulation of Validation Period: The model was run using the calibrated parameters to simulate catchment behavior over the 2011–2020 period. No further parameter adjustments were made during this stage.

3) Performance Evaluation: The accuracy of the validation simulations was assessed using the same statistical metrics applied during calibration (NSE, MAE, and RMSE). High levels of agreement between observed and simulated data during this period further confirmed the model's predictive capacity.

4) Model Robustness Testing: The model's performance was evaluated under various conditions to test its stability. This included testing across wet and dry years to ensure the model's applicability under variable hydrological conditions.

5) Validation Results: The results demonstrated that the WEAP model could reliably simulate the water dynamics of the Middle Nzoia Catchment. The consistency of model performance across both calibration and validation periods affirmed its suitability for future scenario analysis and water resource planning.

3.1.9 Model performance metrics

Model performance was thoroughly assessed using key statistical metrics during the calibration phase. The Nash-Sutcliffe Efficiency (NSE) was employed to evaluate how well the WEAP model simulations matched observed data, with values nearing 1 indicating a good fit between simulated and real water dynamics. Additionally, the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were calculated to measure average deviations and squared differences between observed and simulated values, providing insight into the model's accuracy and precision in predicting river flow and water quality. During the validation phase, these metrics were recalculated using independent datasets not used in calibration, testing the model's robustness and ability to generalize to new data. The consistency of NSE, MAE, and RMSE across various time periods and scenarios was evaluated to confirm the model's reliability, ensuring that the WEAP model continued to provide accurate predictions and remained a trustworthy tool for future analysis. The mathematical expressions to compute the parameters mentioned above are:

Mean Absolute Error (MAE)…………………….…………………………………(i)

Root Mean Square Error (RMSE) ………………………………….…………..…(ii)

NB: The mean absolute error (MAE) and root mean square error (RMSE) are used to measure the deviation between the model outputs and the observed flows. Values tend to be zero for perfect agreement between observed and simulated values.

Error in Volume (VE in %)……………………………………………..……..….(iii)

Nash-Sutcliffe Coefficient(R)……………………..…………………….…….(iv)

Index of Agreement (IA)……………………….……………………..………..…(v)

The Index of Agreement =1 indicates the best (perfect) performance of the model.

Where:

Qoi is the observed streamflow at time (m^3/s)

Qsi is the simulated streamflow at time (m^3/s)

Vo is the observed streamflow volume (million m^3/month)

Vo is the simulated streamflow volume (million m^3/month)

Q is the average streamflow (m^3/s)

3.2 Scenario analysis

3.2.1 Sensitivity analysis

The scenario analysis involved a comprehensive sensitivity analysis to examine how changes in model parameters influenced the simulation results. rates were adjusted to assess their impact on the model's predictions.

3.2.2 Scenario comparisons

Statistical methods were utilized to conduct a comparative analysis of outcomes across various scenarios, focusing on the effects of altered land use, climate conditions, and water management strategies. This analysis quantitatively assessed the impact of each scenario on water supply and demand, facilitating the evaluation of the effectiveness of different water management strategies. The results of this comprehensive analysis formed the basis for developing evidence-based recommendations for sustainable water resource management.

4 Results

4.1 Calibration

Monthly simulated and observed streamflow data for the calibration period (2001-2010) for selected control stations in the Middle Nzoia Catchment (Figure 3). The model's ability to reproduce observed values depicts the relationship between simulated and observed flows.

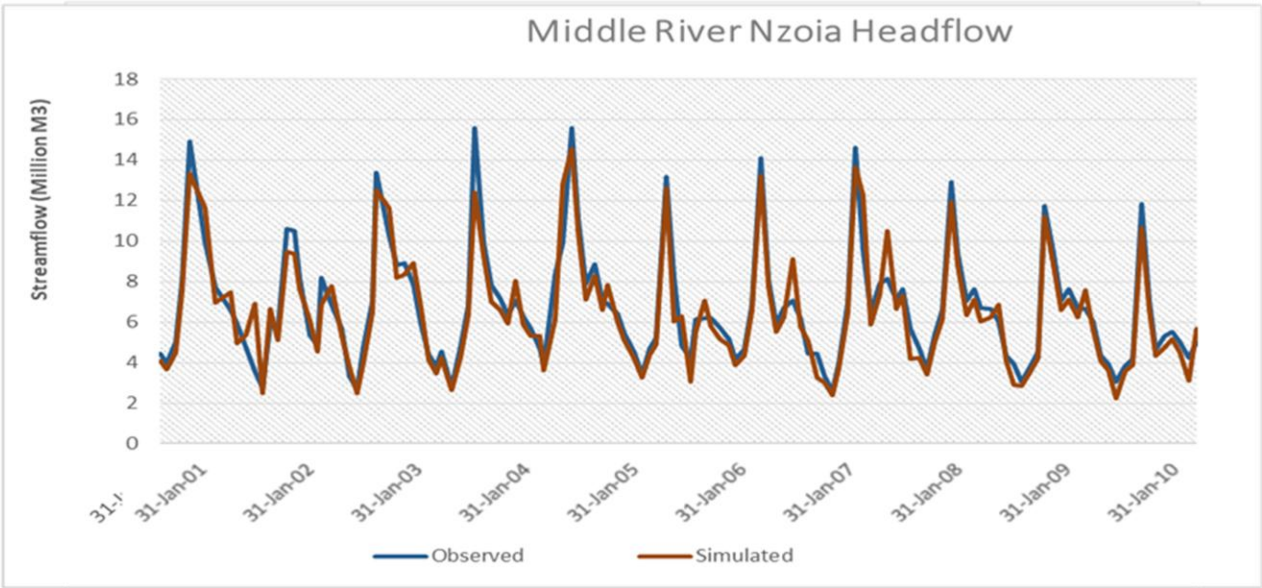

Figure 3 Calibration results showing observed and simulated monthly streamflows at selected stations in the Middle Nzoia Catchment (2001-2010) (Source: Researcher (2025))

This figure shows a time series plot of streamflow for the Middle River Nzoia Headflow. The time-series pattern for the Middle Nzoia Headflow indicates clear seasonal and interannual variability in streamflow between January 2000 and January 2010. Streamflow peaks generally occurred during the same periods each year, reflecting the influence of rainfall seasonality and catchment hydrological processes, whereas the lower flows corresponded to dry-season conditions. Overall, the simulated streamflow followed the observed pattern closely, indicating that the WEAP model was able to reproduce the temporal dynamics of streamflow reasonably well. The agreement between the two series was particularly strong during low-flow periods, where the simulated and observed values were nearly overlapping, suggesting that the model performed well under baseflow conditions. This close correspondence supports the suitability of the model for water resources assessment, planning, and forecasting in the Middle Nzoia Catchment.

The statistical fit indicators for the calibration period (2001-2010) are summarized in Table 1, which presents the performance of the WEAP model at Nzoia (IDD1) Gauging Station. The results show that the model achieved a Mean Absolute Error (MAE) of 5.552 m^3/s and a Root Mean Square Error (RMSE) of 11.921 m^3/s. In addition, the Nash–Sutcliffe Efficiency (NSE) was 0.712, the Index of Agreement (IA) was 0.913, and the Coefficient of Determination (R^2) was 0.757. These values fall within acceptable ranges for hydrological model evaluation and indicate good agreement between simulated and observed streamflow. A further comparison of observed and simulated monthly flows is presented in Figure 4, where the strong correlation between the two datasets ($r = 0.87009$) confirms that the model captured the observed streamflow trends satisfactorily.

Overall, the calibration results demonstrate that the WEAP model performed well in representing the hydrological behavior of the Middle Nzoia Catchment. The good model fit may be attributed to the ability of the model to capture the main physical characteristics of the basin, including the topographic variation between the middle and upper catchment, catchment size, and the seasonal response of runoff to rainfall. These findings provide confidence in the model's application for subsequent scenario analysis and water allocation assessment.

Table 1 Fit statistics of simulated data by WEAP and observed stream flow data for calibration

Fit Statistic	Range	Acceptable Range	Value
Mean Observed Flow (m^3/s)			9.009
Mean Simulated Flow (m^3/s)			7.760
Median Observed Flow (m^3/s)			8.998
Median Simulated Flow (m^3/s)			6.984
Standard Deviation (Observed) (m^3/s)			3.764
Standard Deviation (Simulated) (m^3/s)			5.001
Mean Absolute Error (MAE) (m^3/s)	0 to ∞	Lower is better	5.552
Root Mean Square Error (RMSE) (m^3/s)	0 to ∞	Lower is better	11.921
Nash-Sutcliffe Efficiency (NSE)	–∞ to 1	> 0.5	0.712
Index of Agreement (IA)	0 to 1	Closer to 1	0.913
Coefficient of Determination (R^2)	0 to 1	> 0.6	0.757

Source: Researcher (2025)

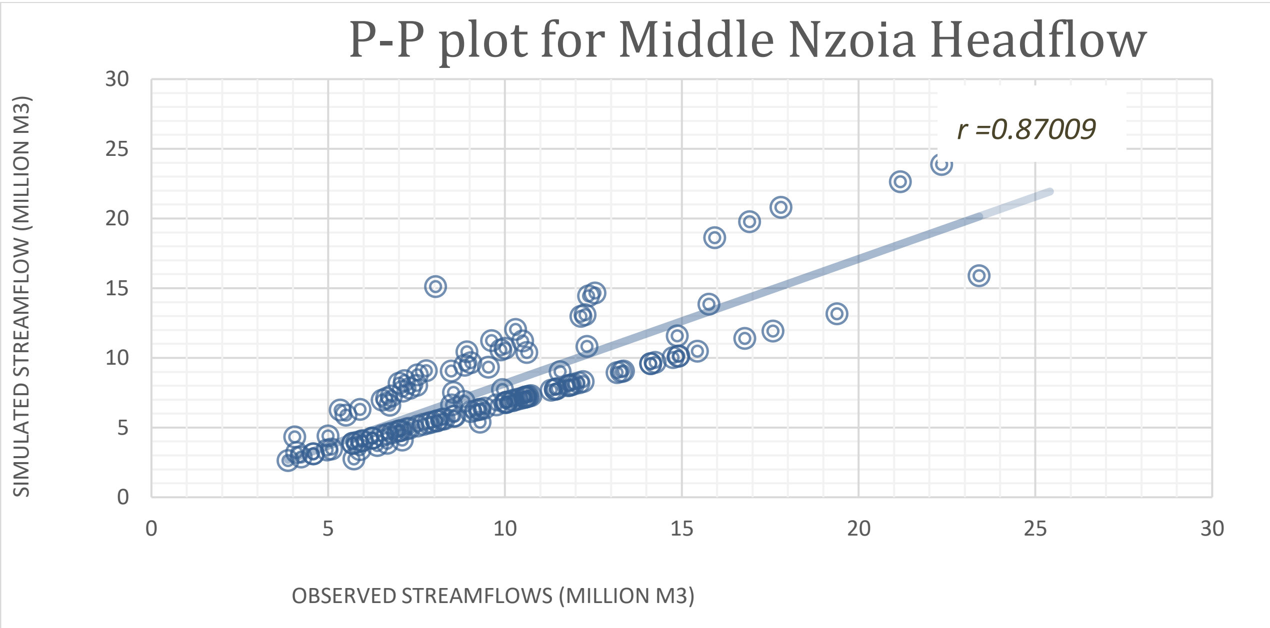

Figure 4 Calibration results showing Relationship between monthly observed and simulated streamflow in the Middle Nzoia Catchment (2001-2010) (Source: Researcher (2025))

Based on the performance metrics, the WEAP model demonstrates strong capability in simulating streamflow at Nzoia (IDD1) station during the 2001-2010 calibration period. The Nash-Sutcliffe Efficiency (0.712) which is above the acceptable range by 21%, R^2 (0.757) which is above the acceptable range by 16%, and IA (0.913) all reflect good agreement between simulated and observed values, confirming the model's reliability for use in future scenario analysis and water resource planning.

4.2 Validation

To assess the reliability and robustness of the calibrated hydrological model, a validation exercise was conducted using an independent dataset from Nabuyole gauge station covering the period 2011 to 2020. This period was selected to test the model's performance under different hydrological conditions from those used in calibration (which covered 2001-2010). The validation ensures that the model is not over fitted and can reliably simulate flows in varying conditions (Figure 5).

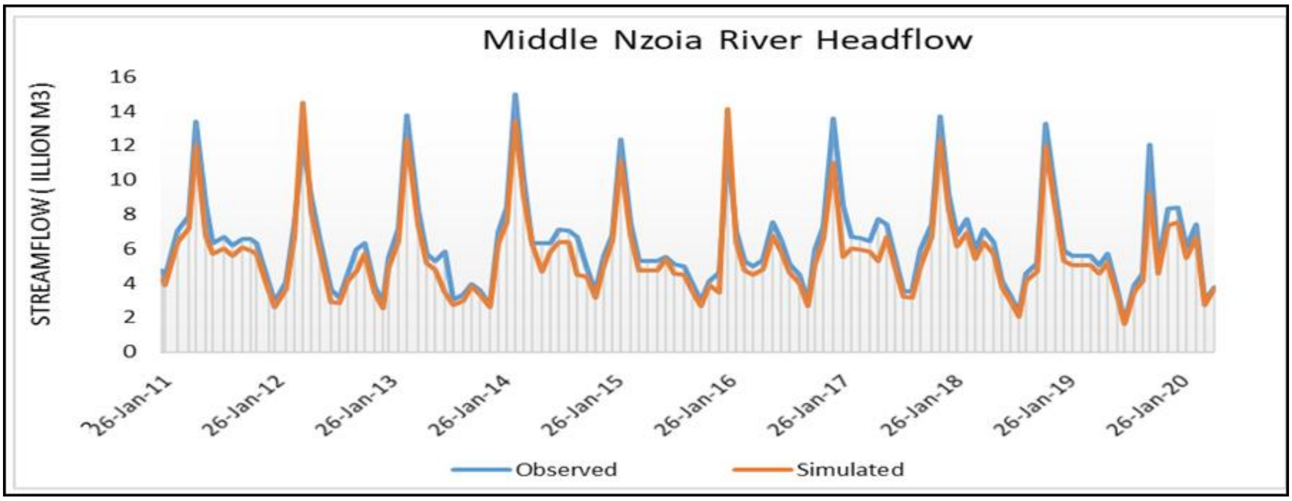

Figure 5 Validation results showing observed and simulated monthly streamflows at selected stations in the Middle Nzoia Catchment (2011-2020) (Source: Researcher (2025))

The above figure shows a time series plot of streamflow for the Middle River Nzoia Headflow. The y-axis represents streamflow (in Million cubic meters, M^3), and the x-axis represents the time period from 26-Jan-2011 to 26-Jan-2020. Two datasets are compared: Observed streamflow (blue line); Simulated streamflow (orange line).

The streamflow shows strong seasonal peaks almost every year, likely corresponding to rainy seasons in the catchment area. Peaks occur roughly once or twice a year, with values reaching 12×10^6 m³ to 15×10^6 m³. Dry-season flows drop significantly, sometimes below 4×10^6 m³.

The Middle Nzoia River streamflow has strong seasonal variability driven by rainfall cycles. The hydrological model simulates the streamflow quite well, matching observed data closely over the 2011-2020 period. Minor discrepancies exist at extreme flows, but overall, the simulation is reliable for hydrological and water management applications.

Summary of annual and monthly fit statistics for the simulated validation data generated by the WEAP model and the observed streamflow data at selected gauging stations in the Middle Nzoia River Basin is presented in Table 2. The statistics cover the validation period from January 2011 to December 2020, and they provide a quantitative evaluation of the model's performance in simulating streamflows using independent data not applied during calibration.

The calibration and validation results affirm the robustness and predictive reliability of the WEAP model in simulating hydrological processes within the Middle Nzoia Catchment. During the calibration phase (2001-2010), the model exhibited strong hydrological fidelity, with statistical indices such as the Nash—Sutcliffe Efficiency (NSE = 0.712), coefficient of determination (R^2 = 0.757), and index of agreement (IA = 0.913) indicating a high degree of correspondence between simulated and observed streamflow data. The validation phase (2011- 2020) yielded even stronger performance metrics, with NSE = 0.807, R2 = 0.821, and Pearson's correlation coefficient (r = 0.888), suggesting that the calibrated model structure and parameters are transferable and generalizable under varying hydroclimatic conditions.

The low values of Mean Absolute Error (MAE = 5.886 m³/s) and Root Mean Square Error (RMSE = 11.991 m³/s) during validation further reinforce the model's capability in minimizing predictive uncertainty. The model's skill in reproducing both temporal dynamics and magnitude of observed flows across sub-catchments supports its applicability for scenario analysis, future water demand forecasting, and integrated water resource management. The performance metrics meet accepted hydrological modelling thresholds, validating the WEAP model as a reliable decision-support tool for simulating surface water availability and allocation under dynamic climatic influences within the basin.

Table 2 Fit statistics of simulated data by WEAP and observed stream flow data for validation

Fit Statistic	Range	Acceptable Range	Value
Mean Observed Flow (m^3/s)			9.111
Mean Simulated Flow (m^3/s)			8.621
Median Observed Flow (m^3/s)			9.010
Median Simulated Flow (m^3/s)			8.345
Standard Deviation (Observed) (m^3/s)			4.786
Standard Deviation (Simulated) (m^3/s)			3.767
Mean Absolute Error (MAE) (m^3/s)	0 to ∞	Lower is better	5.886
Root Mean Square Error (RMSE) (m^3/s)	0 to ∞	Lower is better	11.991
Nash-Sutcliffe Efficiency (NSE)	—∞ to 1	> 0.5	0.807
Index of Agreement (IA)	0 to 1	Closer to 1	0.819
Coefficient of Determination (R^2)	0 to 1	> 0.6	0.821

Source: Researcher (2025)

4.3 Scenario analysis and projected water demand (2022-2052)

4.3.1 Sectorial trends in water demand

Domestic water use follows a gradual upward trajectory, driven primarily by population growth. Demand increases from 11.6 × 10^6 m³ annual in 2022 to nearly 36.8 × 10^6 m³ annual by the year 2052, necessitating infrastructure upgrades. Industrial demand use, though Higher than domestic demand is expected to rise steadily, increasing from 14.9 × 10^6 m³ annual in 2022 to 30.2 × 10^6 m³ annual by the year 2052. The table below summarizes the projection of the demands from base flow year to projected year 2052 (Table 3).

Table 3 Overrow base year demand 2022 and projected year 2052

SUMMARY OF WATER DEMAND PROJECTION					
No.		Supplied demand 2019	Base year 2022	2032	2052
1	Domestic Water Demand	11,039,060	11,648,610	16,753,865	36,871,205
2	Commercial Demand	7,212,035	7,653,320	8,791,390	3,063,350
3	Agricultural Demand	7,943,860	8,430,040	9,683,450	14,389,395
4	School Demand	5,818,100	6,173,975	7,091,950	10,538,280
5	Health Facility Demand	2,813,055	2,968,180	3,590,140	5,993,665
6	Industrial Demand	14,162,000	14,943,465	18,074,070	30,175,280
	TOTAL WATER DEMAND	48,988,110	51,817,955	63,985,230	111,031,175

Total water demand across all sectors is projected to 111 × 10^6 m³ annual, underscoring the importance of sustainable practices such as rainwater harvesting, wastewater recycling, and efficient irrigation. Policy actions must focus on seasonal conservation, infrastructure resilience, and equitable distribution to meet growing demand.

4.3.2 Comparison with 2022 baseline water demand

The 2022 baseline water demand under the current accounts scenario serves as a reference for assessing sectoral changes and planning needs. Total annual demand in 2022 was approximately 51.8 × 10^6 m³ annual. Industrial use accounted for the largest share (14.9 × 10^6 m³ annual) around 29%), followed by domestic (11.6 × 10^6 m³ annual) agriculture (28.4 × 10^6 m³ annual), commercial (7.6 × 10^6 m³ annual), school (6.2 × 10^6 m³ annual), and health sectors (2.9 × 10^6 m³ annual) (Figure 6).

Two datasets are compared were: Base year (blue color); Projected year (orange color)

The figure above compares total water demand from the 2022 baseline to projections for 2052. Demand is expected to rise from 51.8 × 10^6 m³ annual in 2022 to over 111 × 10^6 m³ annual in 2052 with a 53% demand increment. This is driven by population growth, urbanization, agricultural expansion, and industrial development. These trends highlight the need for adaptive management strategies, including wastewater recycling, rainwater harvesting, and improvements in irrigation and industrial efficiency. Infrastructure investment and policy interventions are essential to ensure sustainable water allocation.

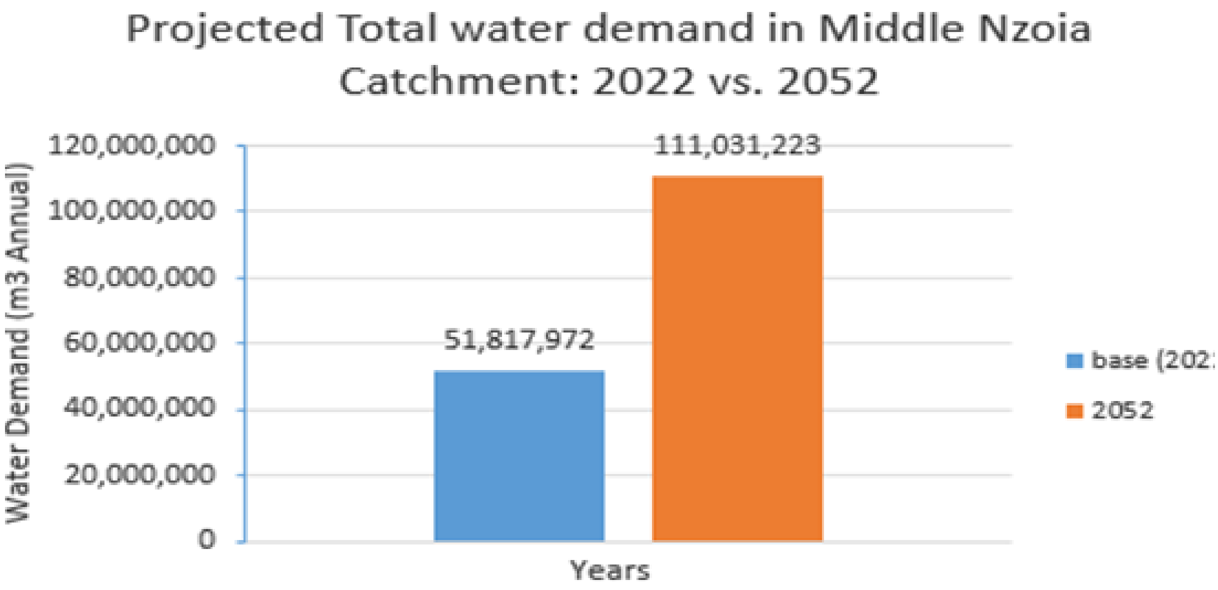

Figure 6 Projected total water demand in the Middle Nzoia Catchment (Source: Researcher (2025))

4.3.3 General water demand projections (2022-2052)

Seasonal and long-term inflow trends under the Reference Scenario between 2022 and 2052 (Figure 7).

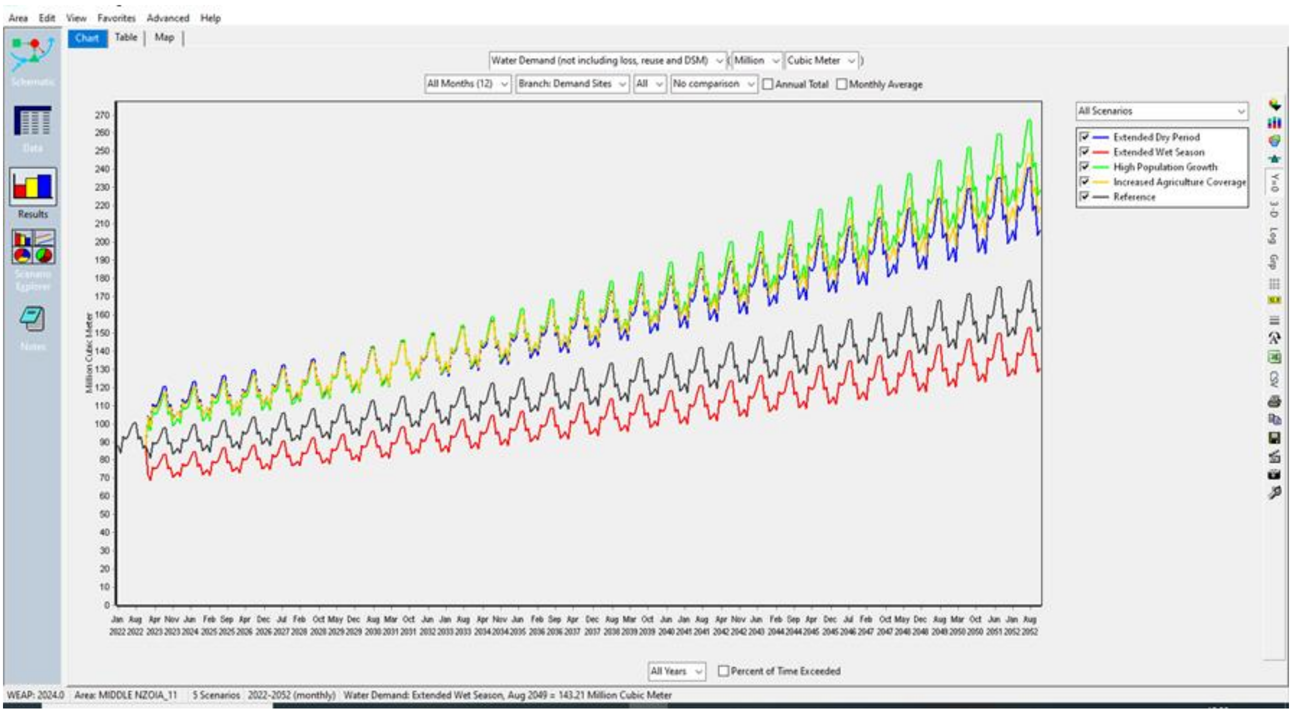

Figure 7 Monthly average inflows under the reference scenario (2022-2052) (Source: Researcher (2025))

Scenario-based analyses reveal varied demand patterns influenced by climate, population, and land use changes. The high population growth scenario shows the greatest increase, with peak demand reaching about 260 × 10^6 m³ to 50% rise over the base average (178 × 10^6 m³) in contrast, the extended wet season scenario shows reduced demand, peaking at around 152 × 10^6 m³ approximately 14% below the base average due to increased rainfall availability, reduced irrigation needs and higher soil moisture storage.

The increased agriculture coverage scenario shows a 39% rise, peaking at 248 × 10^6 m³ aligned with planting and harvesting periods. Among all scenarios, the extended dry period and high population growth show the highest increases in both volume and percentage. The extended wet season records the lowest demand and variability, while the extended dry period scenario shows moderate growth linked.

4.3.4 Domestic and institutional water demand relative to reference Scenario

Projected domestic water demand for high-potential and low-potential areas (Figure 8). Under the reference scenario, demand remains below 32 × 10^6 m³ by the year 2052.

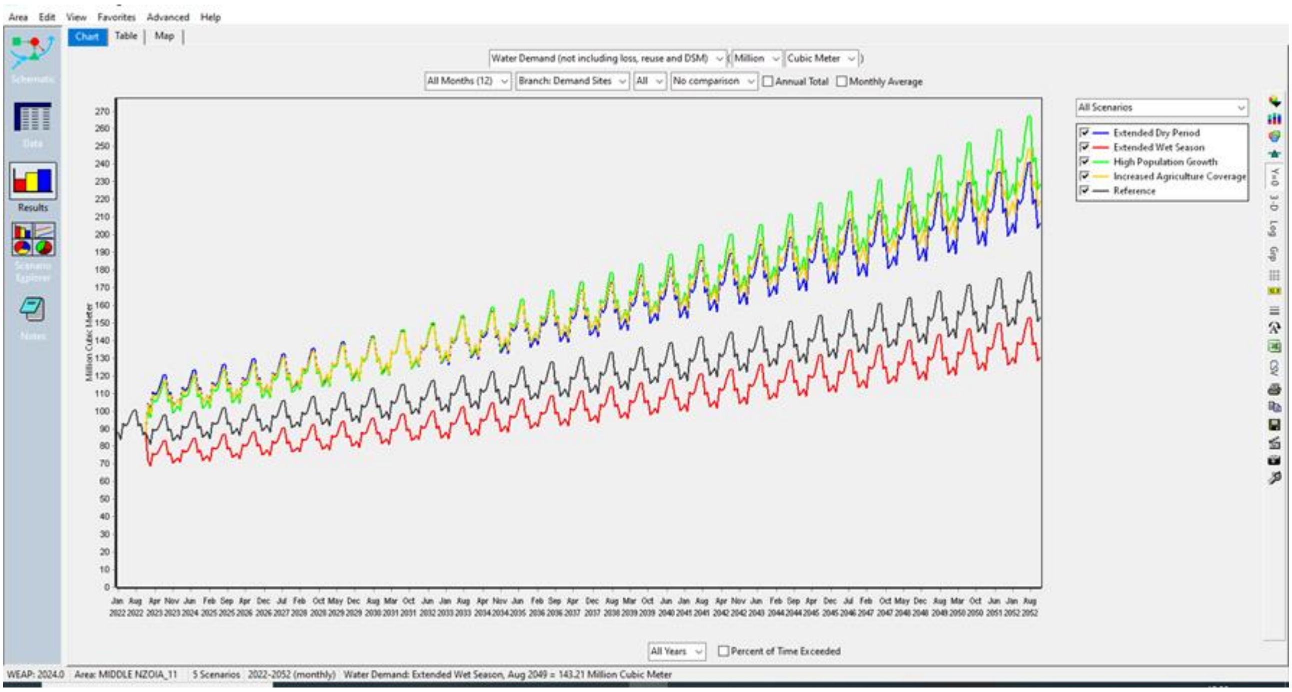

Figure 8 Domestic water demand in high-potential areas relative to the reference (Source: Researcher (2025))

The above image shows a WEAP system interface with a chart output displaying water demand projections under different scenariosY-axis: Water demand (Million Cubic Meters). X-axis: Time (Years from 2022 to 2052, with monthly resolution). The saw-tooth pattern reflects seasonal variation in water demand (wet vs. dry months), Extended dry period (green): Produces the highest water demand, steadily increasing over time, peaking to 30 × 10^6 m³ by the year 2052. Seasonal spikes are the largest, Extended wet season (blue): Lower than dry period but still significantly higher than baseline, showing the effect of more water use during longer wet conditions, high population growth (yellow): Moderate but steadily increasing demand, reflecting population-driven domestic demand pressures, increased agriculture coverage (red): Shows a small but steady increase in demand compared to the reference, reference (black/near zero line): The baseline case, serving as a comparison point.

Climate factors (dry/wet periods) create the largest deviations in demand compared to population or agriculture changes, extended dry periods strain water demand most severely, likely due to irrigation and domestic supply needs, population growth has a significant long- term impact but less seasonal fluctuation, agricultural expansion adds demand but is relatively smaller in this analysis compared to climate-driven factors (Figure 9).

Reference (black line) - The baseline scenario, extended dry period (red) - Shows decreased demand relative to reference, extended wet season (yellow) – Near-zero difference, suggesting minimal impact, high population growth (green) - Significantly increases demand over time, increased agriculture coverage (blue) - Also shows rising demand, though less than high population growth.

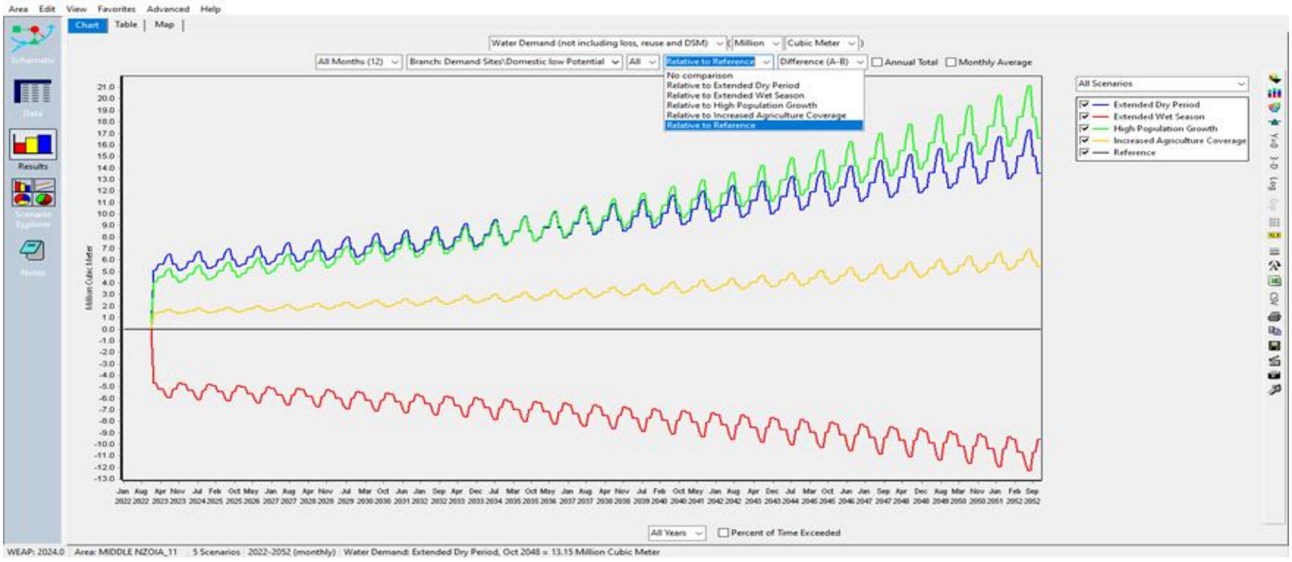

Figure 9 Domestic demand in low-potential areas relative to the reference scenario (Source: Researcher (2025))

The reference line is at zero, serving as the baseline, the red line (extended dry period) shows consistently negative values suggesting less water is available/demanded, the green line (high population growth) shows increasing positive deviation from the reference suggesting rising water demand due to population pressure. The blue line (increased agricultural coverage), similar upward trend to green but lower magnitude. The yellow line (extended wet season):

Close to the reference suggesting that wet conditions don't drastically affect domestic demand in high-potential areas, urbanization drives demand above 21 × 10^6 m^3 by the year 2052, requiring expanded infrastructure, efficiency improvements, and alternative water sources (Figure 10).

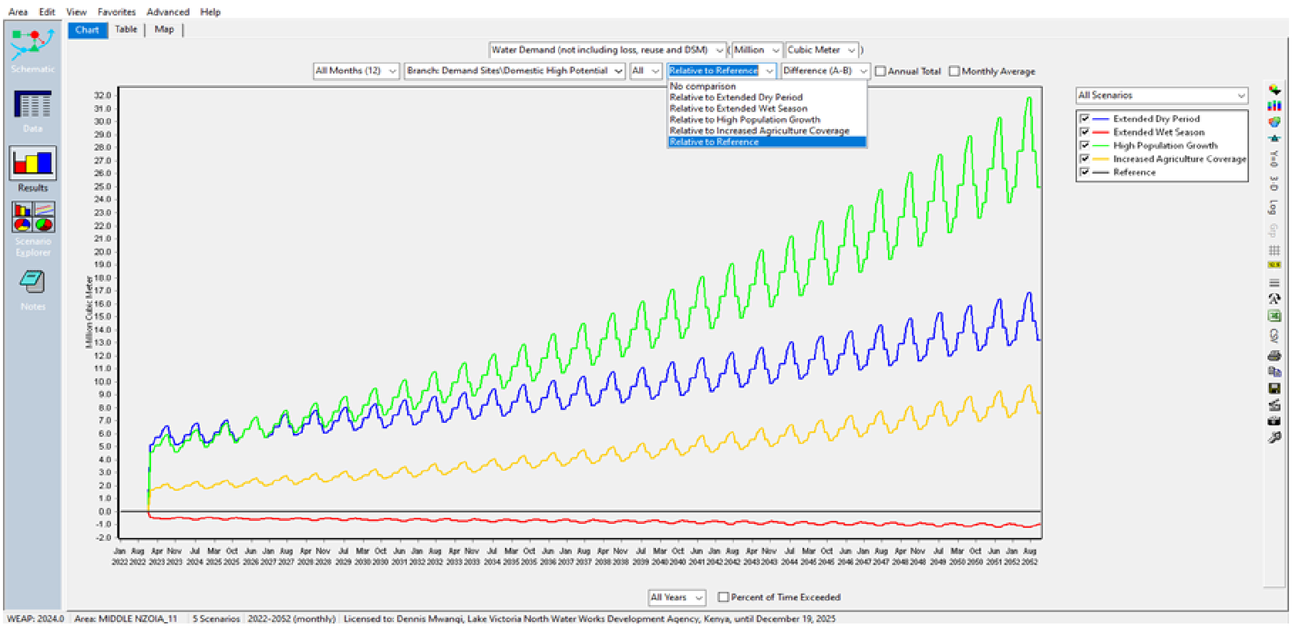

Figure 10 Institutional water demand relative to reference scenario (Source: Researcher (2025))

Each line shows how the institutional water demand in a given scenario deviates from the reference scenario. (black line) always at zero since other scenarios are being compared relative to it. High population growth (green line) shows a steady and sharp increase in institutional water demand over time, by the year 2052, demand is almost 4 million cubic meters higher than in the reference scenario. This scenario has the most significant impact on institutional demand. Increased agriculture coverage (blue line) also shows an upward trend, though lower than high population growth, suggesting increased institutional demand potentially due to support systems for agriculture (e.g., administration, irrigation management offices).

The extended wet season (yellow line) is slightly above zero and relatively stable over time. Suggesting minimal impact on institutional water use. Institutional water demand is likely not weather-dependent. The extended dry period (red line) stays below zero, indicating a slight reduction in water demand compared to the reference. This may imply either reduced availability, conservation measures, or lower usage due to reduced service delivery during droughts.

Institutional demand is highly sensitive to population growth but less affected by climate (wet or dry) conditions. The green scenario (high population growth) is a critical scenario to monitor for infrastructure planning. While agricultural expansion does affect institutional water use, its impact is moderate. Climate scenarios have a limited effect on institutional demand, possibly because such demand is more stable and less seasonal. This increase underscores the need for efficient technologies and wastewater reuse to support institutional expansion.

4.3.5 Agricultural and industrial water demand relative to reference scenario

Figure below presents agricultural demand under the increased agriculture coverage scenario. The demand needs increase significantly, especially during dry months. While dry-season shortfalls call for efficient irrigation, improved storage, and adaptive management (Figure 11).

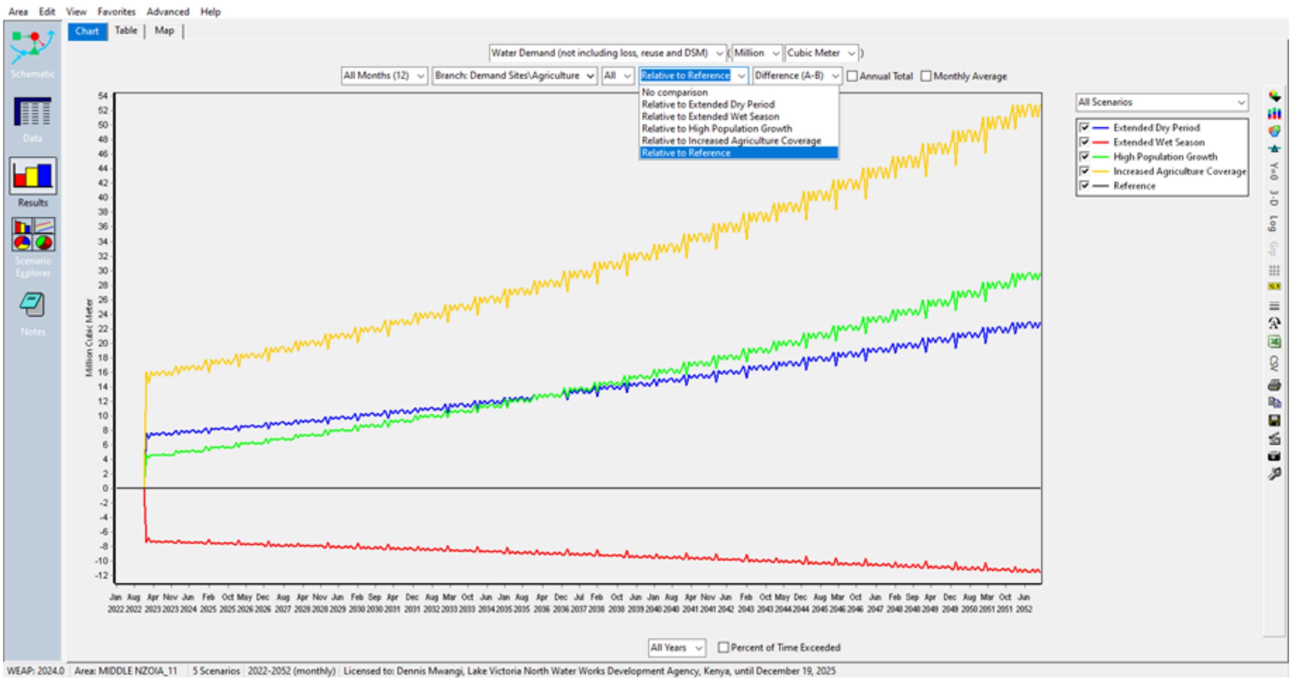

Figure 11 Agricultural water demand relative to reference scenario (Source: Researcher (2025))

Industrial demand, shown in Figure 4.19, rises steadily. The Industrial Growth Scenario surpasses 400 × 106 m^3 by the year 2052, compared to under 304 × 106 m^3 in the reference scenario.

The crisscrossing behavior between the extended dry period and high population growth scenarios is because of water demand composition difference ie. Extended dry Period affects agricultural water demand significantly, while high population growth impacts municipal and industrial demand more. As urban demand becomes more significant (due to exponential population growth), the high population growth scenario overtakes the dry period curve (Figure 12).

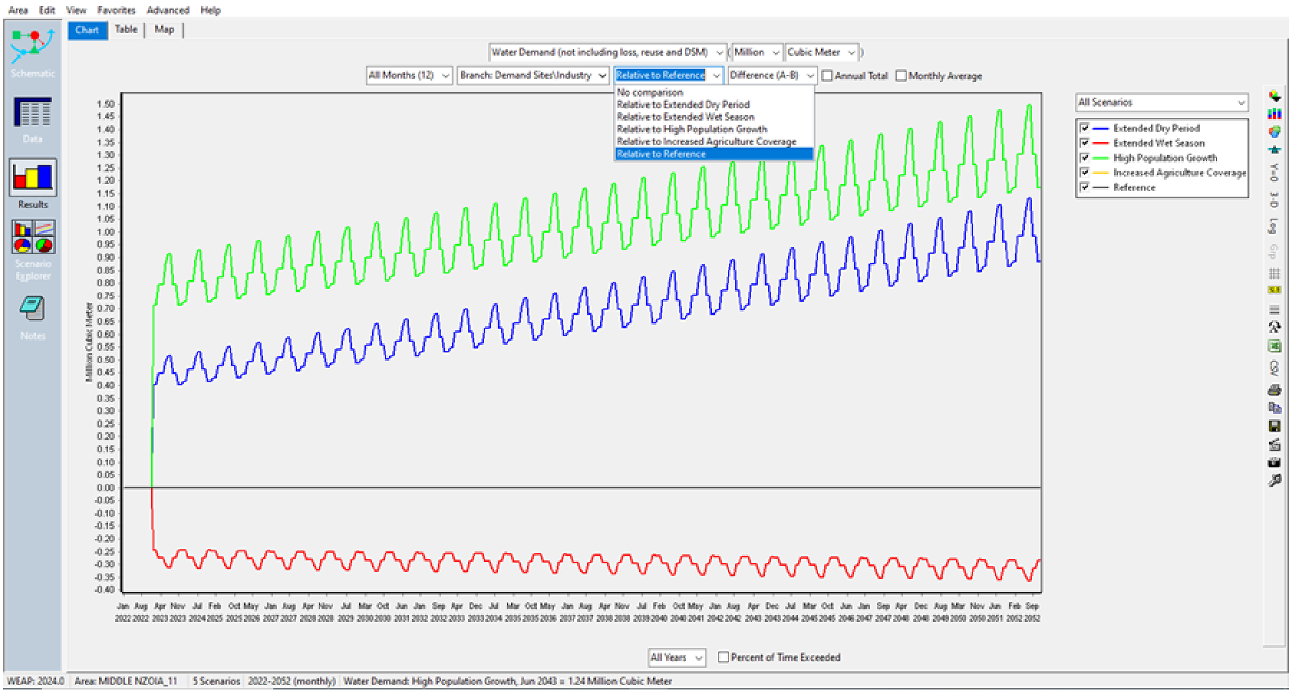

Figure 12 Industrial water demand relative to reference scenario (Source: Researcher (2025))

Industrial water demand relative to the reference scenario is presented in Figure 12. Overall, the results show that industrial water demand increases under both the high population growth and increased agriculture coverage scenarios, although the magnitude of increase differs between them. The high population growth scenario exhibits the greatest positive deviation from the reference scenario and continues to rise throughout the simulation period, indicating that industrial water demand is strongly influenced by demographic expansion and the associated growth in production activities, employment, and service needs. The increased agriculture coverage scenario also shows a positive upward trend, but its effect remains lower than that of population growth, suggesting a more moderate increase in industrial water demand, likely linked to the expansion of agro-processing activities and related infrastructure.

In contrast, the extended dry period scenario remains below the reference scenario over most of the simulation period, indicating reduced industrial water demand under prolonged dry conditions. This may be associated with limited water availability, operational constraints, water conservation measures, or reduced economic activity during drought periods. Seasonal fluctuations are evident across the scenarios; however, the long-term upward trends are more pronounced under the population growth and agricultural expansion scenarios. Overall, these results indicate that industrial water demand in the catchment is more sensitive to demographic and economic change than to seasonal wet conditions, and they highlight the need for improved water-use efficiency, recycling systems, and infrastructure upgrades to support sustainable industrial development.

4.3.6 Comparison between supply requirement, supply delivered, water demand and unmet demand

4.3.6.1 Supply requirement vs. supply delivered

Below is an integrated, technically detailed comparison which illustrates the water supply and demand dynamics in the Middle Nzoia Catchment from 2022 to 2052. This comparison addresses two key metrics: Supply requirement and supply delivered, while reflecting the influence of various scenarios such as high population growth, extended dry period, extended wet season, and increased agricultural coverage (Figure 13).

The left panel of Figure 13. Illustrates the supply requirement, an estimate that includes raw water demand adjusted for transmission losses, water reuse potential, and effects of demand- side management (DSM) interventions. This requirement consistently exceeds the supply delivered, as shown in the Figure 13 right panel.

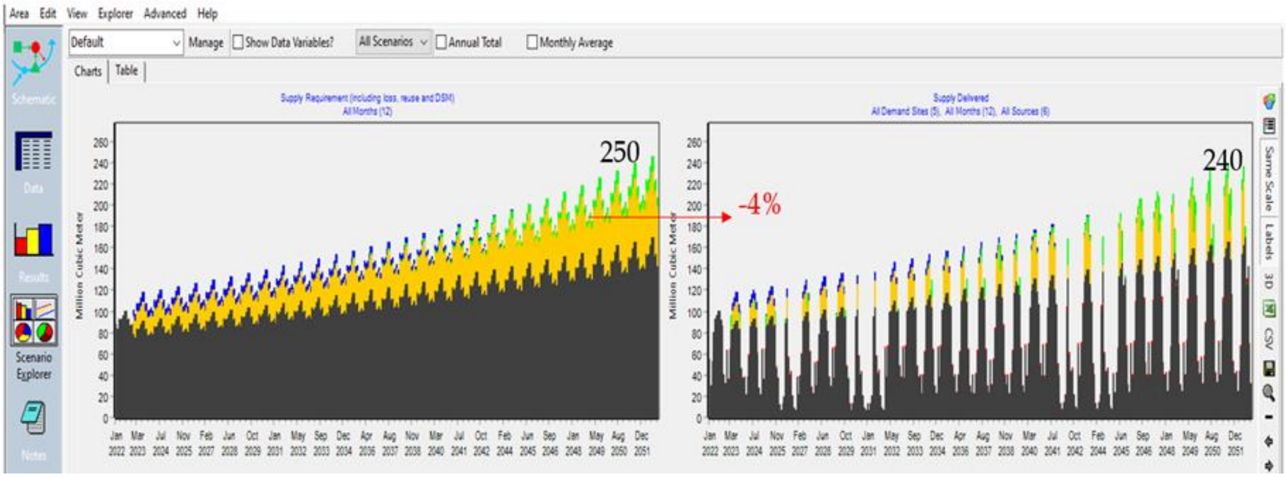

Figure 13 Comparative analysis of water supply and demand in the Middle Nzoia Catchment (2022-2052) (Source: Researcher (2025))

For instance, by the year 2052, the supply requirement was projected to reach approximately 250 × 10^6 m³, whereas the actual delivered supply lags behind at around 240 × 10^6 m³. This persistent supply deficit, averaging 4%, indicates chronic inefficiencies in distribution networks, water treatment capacities, and infrastructure operation.

This observation aligns with findings by Odwori (2021), who identified similar shortfalls in regional water utilities due to aging infrastructure and limited operational capacity.

4.3.6.2 Water demand vs. unmet demand

This comparison addresses two key metrics: water demand, and unmet demand, while reflecting the influence of various scenarios such as high population growth, extended dry period, extended wet season, and increased agricultural coverage (Figure 14).

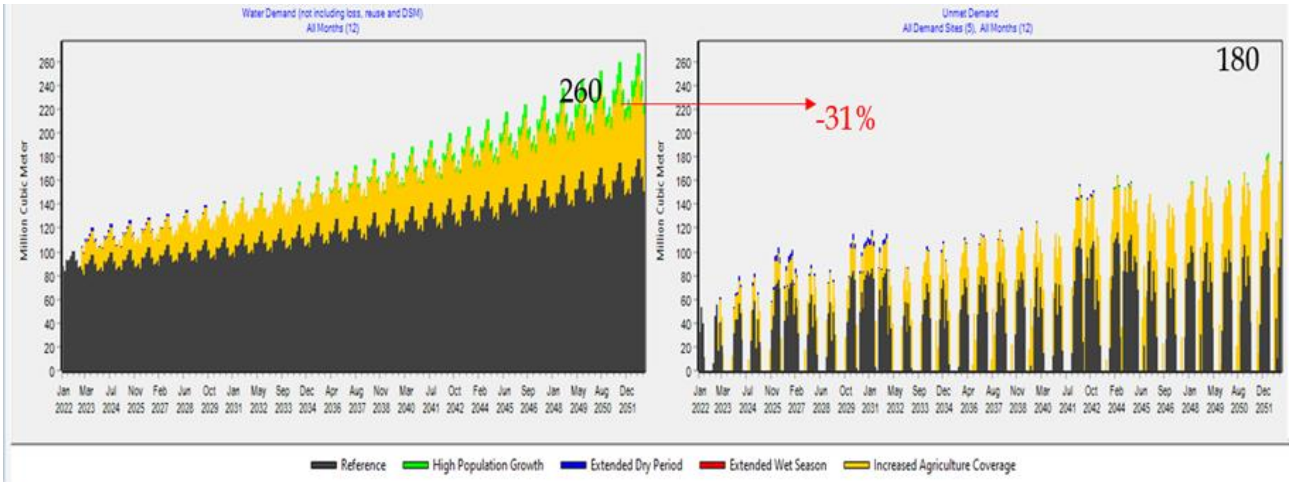

Figure 14 Comparative analysis of water supply and demand in the Middle Nzoia Catchment (2022-2052) (Researcher (2025))

The left panel of Figure 14 captures total water demand, which was projected to rise steadily from about 52 × 10^6 m³ in 2022 to nearly 260 × 10^6 m³ by the year 2052. This increase reflects growing population pressure, industrial expansion, and agricultural intensification.

In contrast, the unmet demand—shown in the lower right panel represents the volume of water required but not supplied. It starts at approximately 20 × 10^6 m³ in 2022 and was projected to climb to about 180 × 10^6 m³ by the year 2052, marking a 28% increase over the study period.

During extreme dry seasons and high-growth scenarios, unmet demand reaches to 31% of total demand on monthly average. These projections are consistent with studies by Odwori (2022) and Odaro, Obiri, and Masika (2025), which attribute rising deficits to climate variability, land use change, and inadequate water infrastructure.

4.3.6.3 Monthly average supply vs. unmet demand (2023-2052)

The monthly average supply delivered for all the demand sites from the year 2023 to the year 2052 reviewed that extended dry period, extended wet period, high population growth, increased agriculture coverage and reference scenario.

4.3.6.4 Supply delivered in all demand sites

The figure below shows the supply delivered in all demand sites, which include industrial demand, domestic demand, agricultural demand, commercial demand and institution demand. Subjected to; Extended dry period scenario, extended wet season scenario, high population growth scenario, increased agriculture coverage and the reference scenario (2023-2052).

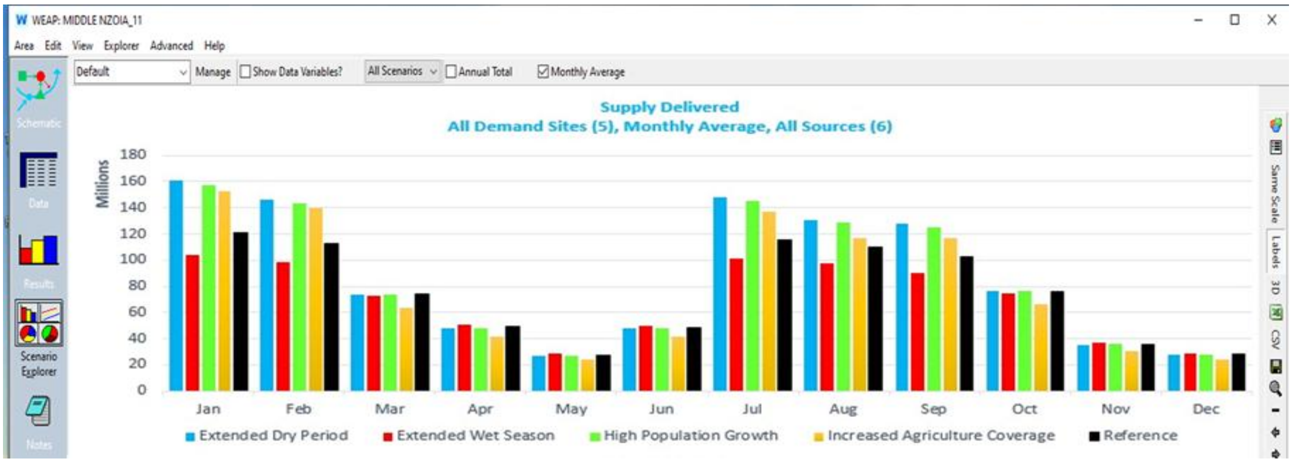

Figure 15 Supply delivered in all demand sites (Source: Researcher (2025))

January and February: Highest supply across all scenarios, particularly under the extended dry period and high population growth scenarios (160 × 10^6 m³), March to May: Significant decline in supply across all scenarios, with May having the lowest supply (20 × 10^6 m³ to 30 × 10^6 m³). June and July: Gradual recovery begins; July sees a major rise again, especially under the extended dry period and high population growth. August and September: Supply remains relatively high but slightly lower than the January-February peak. October to December: Declining trend again, reaching minimal levels by November and December (20 x 10^6 m³).

Supply delivery is highest at the start and middle of the year and lowest during late spring and end-year months. Extended dry period and high population growth scenarios often show higher supply deliveries, while extended wet season tends to have lower deliveries across most months.

4.3.6.5 Unmet demand in all demand site

The figure below shows the monthly average unmet water demand (in millions) for five demand sites under five different scenarios.

January-February very low unmet demand across all scenarios, almost negligible. March-June (Peak unmet demand period): Significant increase in unmet demand, peaking in April and May. The extended dry period and increased agriculture coverage have the highest unmet demand (110 × 10^6 m³ to 115 × 10^6 m³). Extended wet season consistently has the lowest unmet demand during this period. July-September: Notable drop in unmet demand across all scenarios. Still, increased agriculture coverage remains relatively higher. October-December: unmet demand rises again, peaking in December. High Population Growth and increased agriculture coverage show the highest unmet demand (120 × 10^6 m³). Extended wet season has significantly lower unmet demand than others.

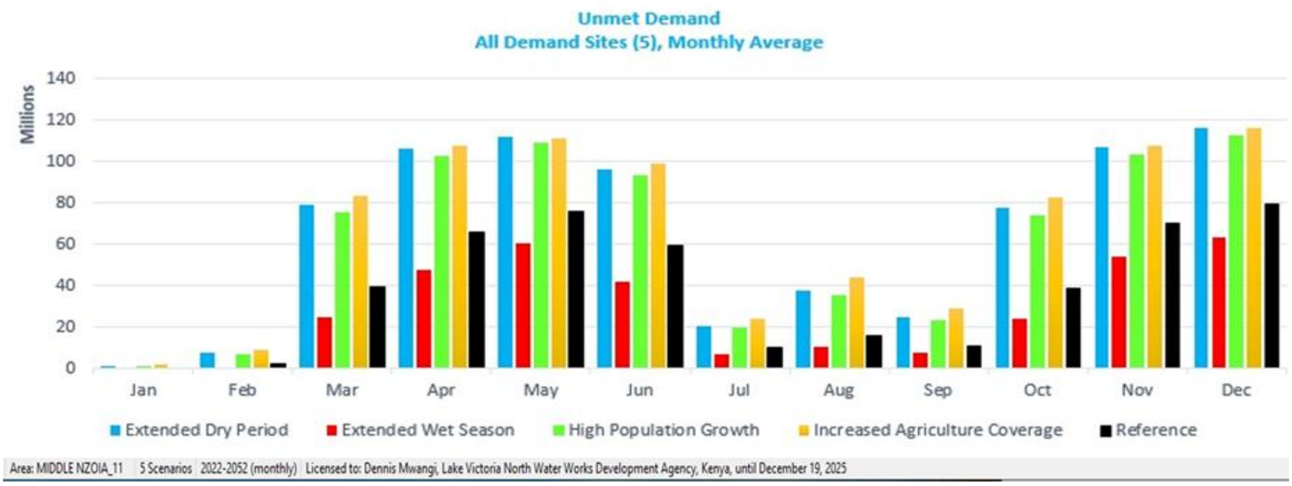

Figure 16 Unmet demand in all demand sites (Source: Researcher (2025))

5 Conclusion

Scenario simulations for the period 2023-2052 under varying assumptions (high population growth, extended dry season, extended wet season, and increased agricultural coverage) indicate a substantial rise in water demand, with projections exceeding 260 × 10^6 m³ annual by the year 2052. Scenarios combining population growth and climate stress the unmet demand, the volume of water required but not supplied started at approximately 20 × 10^6 m³ in 2022 and was projected to climb to about 180 × 10^6 m³ by the year 2052, marking a 28% increase over the study period. During extreme dry seasons and high-growth scenarios, unmet demand reaches to 31% of total demand. This underscores the vulnerability of the catchment to both demographic and climatic drivers, and highlights the need for integrated planning and water-efficient technologies.

The total water demand, which was projected to rise steadily from about 52 × 10^6 m³ in 2022 to nearly 260 × 10^6 m³ by the year 2052. This increase reflects growing population pressure, industrial expansion, and agricultural intensification.

The catchment has an estimated allocable surface water potential of 240 × 10^6 m³ annual, factoring in ecological flow requirements and infrastructure limitations. However, this potential is unevenly distributed and seasonally variable. Current allocation patterns disproportionately favor industrial and agricultural sectors, while essential domestic and institutional uses are under-prioritized. Without reforms, projected future demand will exceed sustainable supply. Therefore, equitable allocation mechanisms, demand management strategies, and resilience-building measures are critical for long-term sustainability.

The study advocates for the adoption of Integrated Water Resources Management (IWRM) to harmonize water allocation across domestic, agricultural, and industrial sectors. Emphasis should be placed on prioritizing essential water uses, particularly domestic and institutional demands, to ensure equitable access.

Enhancement of water storage capacity through construction and rehabilitation of reservoirs and small-scale storage systems is critical to buffer seasonal variability and drought periods. Additionally, promoting water-efficient irrigation techniques can significantly reduce agricultural water consumption while maintaining productivity.

Ecosystem-based management approaches, including catchment reforestation and wetland restoration, are recommended to improve natural water retention and baseflow sustainability. These interventions support both water availability and ecological resilience.

Furthermore, upgrading hydrological monitoring networks and data management systems is essential for real-time water resource assessment and adaptive management. Improved data collection will enhance the accuracy of modeling and decision-making processes.

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Conflict of Interest

The authors affirm that this research was conducted without any commercial or financial relationship that could be construed as a potential conflict of interest.

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Research Article Open Access

Hydrological Stress, Biodiversity Loss and Livelihood Collapse — Climate Change Challenges in Coastal Fisheries of Ondo State, Nigeria

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Abstract The coast of Nigeria is increasingly experiencing pressure due to climate change and its impact on small-scale and artisanal fisheries. This study analyzed the effects of changing rainfall patterns, rising temperatures, and hydrological variability on small-scale fisheries in Ilaje Local Government Area (LGA), Ondo State, Nigeria. Four fishing villages: Ayetoro, Bijimi, Idiogba, and Asumogha were randomly selected to represent the fishing population. Data collection combined 285 questionnaire responses with 30 years of rainfall and temperature records from the Nigeria Meteorological Agency (NiMet), complemented by government and fisheries data. Quantitative data were analyzed using SPSS (version 25) with descriptive statistics, Chi-square, ANOVA, and regression, while qualitative data captured adaptation strategies. Results revealed a measurable decrease in rainfall days (218 in 1996 to 182 in 2025), rainfall ranging between 1,700-2,200 mm, and a steady increase in mean annual temperature from 27.4°C to 28.5°C. Maximum temperatures rose from 32.6°C to 33.3°C, while minimum temperatures increased from 19.6°C to 21.3°C. Nearly all participants (98.6%) agreed that increased water levels result in greater fish catches, while 97.5% believed decreased water levels reduce catches. Climate variability in Ilaje has disrupted fisheries and livelihoods. Recommendations include improved water management, shoreline protection, livelihood diversification, stronger cooperatives, and resilience-building to sustain Nigeria's coastal blue economy.

Keywords Rainfall variability; Temperature trends; Hydrological changes; Ilaje fishing communities; Adaptation strategies

1. Introduction

Climate change is widely acknowledged as one of the most pressing global challenges of the 21st century, with profound implications for ecosystems, biodiversity, and human livelihoods. It is defined as long-term shifts in temperature, precipitation, wind patterns, and other climatic variables, largely driven by anthropogenic activities such as fossil fuel combustion, deforestation, and industrialization (IPCC, 2022). These changes are not uniform across regions; rather, they manifest differently depending on geographical, ecological, and socio-economic contexts. Coastal regions, in particular, are highly vulnerable to climate-induced stressors, including rising sea levels, flooding, saltwater intrusion, and shoreline erosion, all of which threaten both ecological integrity and human survival (FAO, 2018).

Small-scale fisheries, which provide food security, employment, and income for millions of households worldwide, are especially exposed to climate variability. Historically, artisanal fishers have endured climatic extremes such as floods, droughts, and storms. However, the intensification and increased frequency of these events under climate change have amplified ecological and socio-economic risks, undermining resilience and sustainability (IPCC, 2023). In Nigeria, where fisheries contribute significantly to nutrition and livelihoods, climate change has emerged as a critical threat to artisanal fishing communities, particularly in coastal regions such as Ilaje Local Government Area (LGA) of Ondo State.

Nigeria's fisheries sector is vital to national food security and economic development. Small-scale fisheries account for approximately 70% of total fish catches globally, and in Nigeria they contribute 3%-5% of the agricultural sector's GDP while employing over 1.48 million people (FAO, 2022). Yet, national demand for fish, estimated at 3.6 million metric tonnes annually, far exceeds local production, creating a supply gap that is exacerbated by climate variability. Artisanal fishers in coastal regions such as Ilaje face declining catches, rising operational costs, and increasing livelihood insecurity, reflecting the close link between climate variability and household welfare (Aderinola et al., 2021).

Studies in Lagos and other coastal areas have documented how fluctuations in rainfall, temperature, and hydrological systems directly affect fish productivity and fisher livelihoods. For example, declining rainfall reduces water levels in rivers and estuaries, disrupting spawning cycles and lowering fish availability, while rising temperatures increase physiological stress in fish populations, reducing survival and reproduction rates (Ezra et al., 2023). These ecological disruptions translate into reduced catches, biodiversity decline, and weakened resilience of fishing communities.

Globally, warming oceans, acidification, and deoxygenation are destabilizing marine ecosystems, reducing productivity, and altering fish distributions (IPCC, 2023). Coastal and inland fisheries in West Africa are particularly at risk due to reduced water flows, saltwater intrusion, and habitat degradation, including mangrove loss, which diminishes breeding and nursery grounds for key species (Lefcheck et al., 2019). Rising water temperatures exacerbate physiological stress in fish, increasing metabolic demands while reducing oxygen availability. This imbalance impairs growth, reproduction, and survival (Little et al., 2020). For example, African catfish (*Clarias gariepinus*) exhibit narrow thermal tolerance ranges, with survival rates declining sharply outside 18.9°C-33.2°C (Kłyszejko et al., 1993). Warmer waters have also been linked to smaller average fish sizes and reduced overall catches, despite faster growth in some species (Brander, 2013).

Hydrological variability further compounds these challenges. Rainfall, land use, and evaporation rates directly influence water systems that sustain fisheries. In Ilaje, heavy rains replenish estuaries, supporting fish breeding, while prolonged dry spells lower water levels, disrupt spawning, and stress fish populations. Seasonal flooding, critical for tropical fish reproduction, is increasingly disrupted, leading to biodiversity loss and reduced catches (Obayemi et al., 2024).

Coastal erosion intensifies these pressures. Satellite analyses reveal shoreline recession in Ilaje at an average rate of 56 meters per year, with some communities experiencing erosion exceeding 400 meters annually (Adagbasaa et al., 2024). Rising sea levels and stronger wave action threaten fishing villages and estuarine ecosystems, accelerating livelihood collapse. Small-scale fisheries, which contribute significantly to Nigeria's blue economy, face declining productivity against national demand. Without adaptive management, these communities risk ecological and socio-economic collapse.

The novelty of this study lies in its localized assessment of climate variability impacts on fisheries and livelihoods in Ilaje LGA, Ondo State. By integrating long-term climatic data (1996-2025) with community-level perceptions and adaptation strategies, the research provides context-specific evidence essential for designing adaptive management policies. Unlike previous studies that focused broadly on national or regional trends, this study emphasizes the lived experiences of artisanal fishers in Ilaje, offering insights into how climate variability disrupts fisheries and livelihoods at the community level. This approach contributes to broader efforts to sustain Nigeria's coastal blue economy and enhance resilience in vulnerable fishing communities.

2 Materials and Methods

2.1 Description of the study area

This research took place in four fishing villages: Ayetoro, Idiogba, Bijimi, and Asumogha within the Ilaje Local Government Area (LGA) of Ondo State, Nigeria. Fishing is the major way people earn a living in these areas, with most families depending on fishing activities for income. The area is geographically located between latitude 6°00′N and 6°30′N, and longitude 4°45′E and 5°45′E, including important fishing villages The geographical positioning of the study area was established through the determination of its latitude and longitude, as reported by Igejongbo (2020) and Omitoyin et al. (2021). The area has both freshwater and brackish water ecosystems, which allow for different kinds of fishing activities. The climate changes between wet and dry seasons, and rainfall impacts how much fish is caught. Ilaje has different fishing villages, each with its own culture and environment. For this study, ten major fishing villages along the Ilaje coast were picked: Ayetoro, Idiogba, Bijimi, Asumogha, Zion-Pepe, Ugbo-Nla, Ilepete, Awoye, Molutehin, and Ayila.

2.2 Study population and sampling procedure

The people in the study area were fishermen living in Ayetoro, Idiogba, Bijimi, and Asumogha. Estimates of the fishing population were gathered during early trips to the area and by talking with local leaders and fishing groups in 2025. These four villages were picked randomly using a lottery method to reduce bias and make sure they represented the larger fishing population. Data were gathered using questionnaires and interviews, similar to methods used in fisheries research in the Niger Delta (Omitoyin et al., 2021a). The respondents were majorly small-scale fishermen who use simple tools like nets, traps, and hooks, and are more at risk from environmental changes. While others like fish processors, traders, and community leaders play a role in the local fishing economy, this study focused on the fishermen themselves, since they are directly affected by climate-related risks in small-scale coastal fisheries (Adeyemi et al., 2021).

2.3 Sample size determination and allocation

To safeguard the representativeness of the study, a multistage sampling design that systematically incorporated variations across communities was employed, thereby ensuring that the distribution of respondents reflected the underlying population structure. From the many fishing villages in Ilaje, four: Ayetoro, Idiogba, Bijimi, and Asumogha were picked randomly. These villages were chosen because they were easy to get to and had a lot of fishing families. The sample size was worked out using Cochran's (1977) formula, a standard way to calculate sample sizes in social and environmental research. This method lowers sampling error and makes the results more reliable (Nwosu et al., 2022). It was decided to sample 50% of the fishing population in each village, as this amount captures variety and gives a good picture of the village structure (Adeleke and Oloruntoba, 2020). In total, 295 small-scale fishermen were picked through simple random sampling, ensuring fairness and equal representation across the villages studied.

The study also used Yamane's (1967) formula to figure out the sample size, shown as:

$n=N1+Ne^2$

Where:

n = sample size

N = total fishing population in the study area (as obtained from fisheries associations or local government records)

e = level of precision (set at 0.05 for a 95% confidence level)

For example, if the estimated fishing population equals 1,000 individuals, the sample size would be approximately 280 respondents.

To adequately represent the fishing population in Ilaje Local Government Area (LGA), 295 questionnaires were distributed to artisanal fishers. This number included a 5% buffer above our target of 280, meant to offset potential non-response and incomplete submissions and maintain dataset dependability. Four major landing sites: Ayetoro, Idiogba, Bijimi, and Asumogha were selected based on their importance to local fisheries and their role as socio-economic centers for fishing communities.

The estimated fisher population at each study site was calculated using the proportional allocation method as follows:

$F_i = (n_i / N_s) \times N_t$

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Where:

F_i = Estimated fisher population at site i

n_i = Number of fishers sampled or observed at site i

N_s = Total number of fishers sampled across all sites

N_t = Total fisher population (from census, registry, or extrapolated estimate)

Applying the proportional allocation formula, 84 questionnaires were assigned to Ayetoro, 73 to Idiogba, 76 to Bijimi, and 62 to Asumogha. Minor adjustments were introduced to maintain whole numbers, yielding a total of 295 questionnaires. This sampling strategy minimized bias and enhanced representativeness by aligning distribution with the fisher population of each community, thereby enabling robust comparisons across sites to capture differences in fishing practices, socio-economic conditions, and adaptive responses to climate change. Incorporating a non-response buffer further strengthened the validity of the analyses, establishing a reliable foundation for examining climate, fisheries, and livelihoods within Ilaje fishing communities. Ultimately, 180 fishermen returned fully completed questionnaires, providing the empirical basis for subsequent analyses.

2.4 Data collection

Primary and secondary sources were used to ensure thoroughness and unwavering accuracy. For the questionnaires, the social and demographic variables included age, gender, education level, household size, fishing tenure, and other livelihood activities. In addition to the climate-related data and adaptive measures, annual fish catch data, fish species data, fish size data, and data related to climate change were included. The climate context of the study region relied on data from Nigerian Meteorological Agency (NiMet) as the secondary data concerning the project's long-term rainfall, temperature, and water level data. Secondary sources for context regarding the coastal value fishery, climate change, and adaptive capacity included government documents, scholarly articles, books, the Ondo State Ministry of Agriculture and Fisheries, and departmental bulletins.

2.5 Data analysis

Quantitative data were analysed using SPSS (version 25), applying statistics to examine relationships between climate, fish catch, socio-economic factors, and adaptation practices (Aderinola et al., 2021).

For the goals of the research, rainfall and temperature data of the years 1996-2025 for the Ilaje Local Government Area (LGA) of Ondo State, Nigeria, were studied. The focus was on analyzing the climatic variables and identifying the presence of any trends over the years in the form of increases, decreases, or permanence. The author utilized linear trend models, which consist of a form of monotonic analysis to capture gradual changes, and step trend variability to identify sudden change in any of the climate variables (Olanrewaju, 2022).

Using Microsoft Excel, scatter plots with trendlines and moving averages to illustrate long-term variation were constructed for the purposes of time-series analysis. In order to facilitate analyses, the data were divided into three decades, which were the periods 1996-2005, 2006-2015, and 2016-2025. With this structure, both gradual and sudden changes in the variability of rainfall and temperature were detectable (Edokpa, 2020; Omitoyin et al., 2021a). SPSS (version 25) and Excel were used for the analyses, which refined the results and augmented the understanding of the climate trends of the study area.

The SPSS 25 software was used to analyze the quantitative data. Means, frequencies, and percentages were computed to describe the socio-economic variables. The relationships between rain, water levels, and fish catch volume were tested using Chi-square. ANOVA was used to test the differences among communities, and regression was used to evaluate the effects of climate variables on fish catch. The trends of rain and temperature were examined using linear monotonic and step-change models. Time series plots, scatter plots, and moving averages were created in Microsoft Excel. The qualitative data were used to adapt and analyze modifications to strategies, coding, and thematic analysis of the interviews and focus groups to the transcripts. These were the modifications of strategies to the adaptations of the gear, cooperatives, and diversification of livelihoods. The climate-livelihood relationships were best understood through the combination of quantitative and qualitative data.

The analysis of long-term climate variability in Ilaje Local Government Area (LGA) commenced with the systematic review of rainfall and temperature records spanning the period 1996-2025. Linear monotonic trend models were applied to detect directional changes in the climatic variables, identifying whether trends indicated increases, decreases, or stability. Gradual changes were assessed using monotonic trend analyses, while step-trend analyses were employed to capture abrupt shifts in climate conditions (Akinsanola and Ogunjobi, 2020). Preliminary data processing was conducted in Microsoft Excel 2010, where time-series graphs were generated using scatter plots, fitted trend lines, and moving averages. For comparative purposes, the dataset was partitioned into three decadal intervals: 1996-2005, 2006-2015, and 2016-2025, consistent with established practices in climate and fisheries research for detecting long-term variability. Exploratory data analysis was performed in Excel, whereas advanced statistical analyses were executed using SPSS (version 25).

In addition to quantitative analyses, qualitative data were collected through focus group discussions designed to capture community-level responses to climatic stressors. These discussions facilitated the documentation of adaptation strategies, which included modifications to fishing tools, the formation of cooperative associations, and diversification into alternative livelihood activities. Together, these methodological steps provided a robust framework for examining the interactions between climate variability, fisheries, and livelihoods within Ilaje fishing communities.

3 Results and Discussion

3.1 Fish catch volume and livelihood implications in Ilaje LGA

Table 1 presents data on fishing yields among Ilaje households. Results indicate that 39.3% of fishers harvest ≥500 kg annually, equivalent to about ten rice bags, while the majority (61%) record lower catches. This disparity highlights the influence of ecological conditions, access to productive waters, and fishing practices. The predominance of catches below 500 kg suggests subsistence-level livelihoods with limited savings potential. Evidence shows that small-scale fisheries in West Africa face persistent ecological and economic constraints (Neiland and Béné, 2010). In Ilaje, low yields exacerbate household vulnerability, reflecting broader challenges of climate change, overfishing, and habitat degradation that reduce fish stocks and undermine food security (FAO, 2022). Recent studies confirm that Nigerian coastal communities experience poverty and food insecurity linked to declining fisheries (Oparinde et al., 2025). Nonetheless, higher yields among some fishers demonstrate the potential of improved resource governance, climate adaptation, and livelihood diversification to strengthen resilience (Elezuo et al., 2024). Without such interventions, Ilaje fisheries risk further decline, deepening socio-economic hardship.

Table 1 Fish catch volume in Ilaje LGA

Annual Catch Volume (kg)	Respondents (%)	Number of Respondents	Equivalent in 50kg Rice Bags
≥ 500 kg	39.3%	110	≥ 10 bags
500 kg	15.5%	43	10 bags
400 kg	17.4%	49	8 bags
300 kg	17.8%	50	6 bags
200 kg	10.0%	28	4 bags
Total	100%	280	—

Source: Field survey, 2025

3.2 Perceived effects of water level on fish catch volume

Table 2 illustrates fishermen's perceptions of hydrological influences on fish catch volumes in Ilaje coastal waters. An overwhelming majority (98.6%) affirmed that high water levels enhance fish output, while 97.5% reported that low water levels reduce catches. This consensus reflects a clear understanding of the direct link between water availability and fishing productivity, consistent with established fisheries research (Welcomme, 2011). Furthermore, 86.8% acknowledged that river flow variations affect fish availability, and 85.7% observed significant declines in recent years, attributed to reduced rainfall, climate variability, and anthropogenic disruptions (Nwosu et al., 2022). These findings underscore that declining water levels pose both ecological and livelihood threats. Reduced flows diminish breeding grounds, nursery habitats, and migration corridors, undermining fish productivity and household income (FAO, 2022; Olusola et al., 2022). Addressing these challenges requires integrated water management, climate adaptation, and ecosystem conservation. Such interventions are vital for sustaining fisheries and safeguarding livelihoods in Ilaje LGA, where artisanal fishing remains central to food security and resilience (Ogunrayi et al., 2024).

Table 2 Effects of water level on fish catch volume in Ilaje coastal waters

Question	Agree	%	Disagree	%
High water level increases fish output	276	98.6%	4	1.4%
Low water level decreases fish output	273	97.5%	7	2.5%
Change in river flow affects fish availability	243	86.8%	37	13.2%
River water flow has considerably decreased	240	85.7%	40	14.3%
Total Respondents	280	100%		

Source: Field survey, 2025

3.3 Rainfall and temperature patterns in Ilaje LGA (1996-2025)

A longitudinal analysis of rainfall and temperature patterns in Ilaje Local Government Area (LGA) between 1996 and 2025 reveals significant variability in seasonal onset, cessation, annual rainfall totals, and mean annual temperatures (Table 3). Rainfall onset typically occurred between late March and early April, with cessation dates ranging from late September to late October. Shorter rainy seasons were observed in 2007 (179 days) and 2025 (182 days), compared to longer seasons in 1996 (218 days) and 2019 (208 days). This shortening trend indicates increasing unpredictability in rainfall duration, directly affecting river flow and fish breeding cycles. Similar disruptions have been reported in southeastern Nigeria (Nnaji and Nzeadibe, 2023), while Adetayo (2021) noted erratic onset but relatively stable cessation in southwestern Nigeria.

Annual rainfall totals also fluctuated, with above-average years such as 2004 and 2019 (2,200 mm, +8.9%) and deficits in 2015 (1,700 mm, –12.1%) and 2006 (1,740 mm, –11.0%). These alternating patterns mirror findings in the Niger Delta, where rainfall variability strongly influences fish catch volumes (Idogho et al., 2022a). In contrast, Ragatoa et al. (2020) documented prolonged dry spells across West Africa, suggesting Ilaje's variability may be less severe.

Temperature trends showed steady warming, with mean annual values rising from 27.4°C in 1996 to 28.5°C in 2025. Deviations shifted from –0.3°C in 1996 to +0.8°C in 2025, consistent with global climate change. Rising temperatures reduce dissolved oxygen and increase disease prevalence, threatening fish survival. These findings align with Akinsanola and Ogunjobi (2020), who reported nationwide warming, and Cohen et al. (2016), who linked warming in Lake Tanganyika to reduced nutrient mixing and fish productivity. Collectively, shortened rainy seasons, rainfall variability, and rising temperatures pose significant risks to Ilaje fisheries and livelihoods, underscoring the need for climate-resilient practices, improved water management, and livelihood diversification.

3.4 Decadal rainfall variation (1996-2025)

Table 4 presents decadal rainfall averages in Ilaje Local Government Area (LGA), highlighting notable shifts in intensity and duration. The first decade (1996-2005) recorded 929.2 mm, reflecting a slight decline that constrained water availability and disrupted fish breeding cycles. Similar declines were observed in southern Nigeria during the late 1990s, linked to reduced river discharge and agricultural productivity (Edokpa, 2020). In contrast, Adetayo (2021) reported relatively stable rainfall onset and cessation in southwestern Nigeria, suggesting Ilaje's decline may be localized. The second decade (2006-2015) showed a significant increase to 1,072.6 mm (+15.4%), supporting higher river flows and aquatic productivity, consistent with findings in the Niger Delta

(Idogho et al., 2022b). However, excessive rainfall also heightened flooding risks, as noted in West Africa (Ragatoa et al., 2020). Projections for 2016-2025 indicate further increases to 1,158 mm, consistent with national anomalies (Akinsanola and Ogunjobi, 2020). While increased rainfall may replenish habitats, extremes threaten ecosystem stability. Cohen et al. (2016) demonstrated similar climate-driven disruptions in Lake Tanganyika, underscoring the compounded risks of rainfall variability and warming. Overall, Ilaje's rainfall dynamics reflect regional climate trends, emphasizing the need for adaptive water management, flood control, and resilient livelihood strategies.

Table 3 Rainy season, rainfall and temperature in Ilaje LGA (1996-2025)

Year	Onset Date	Cessation Date	Length of Rainy Days	Annual Rainfall (mm)	Rainfall Deviation (%)	Mean Annual Temp (°C)	Temp Deviation (°C)
1996	Mar-25	Oct-28	218	1,820	-7.6	27.4	-0.3
1997	Mar-29	Oct-20	206	1,960	-0.6	27.7	0.0
1998	Apr-05	Oct-18	196	1,750	-10.4	28.0	0.3
1999	Mar-22	Oct-25	217	2,020	2.0	27.9	0.2
2000	Apr-02	Oct-15	196	2,120	7.6	28.1	0.4
2001	Mar-30	Oct-19	203	1,890	-3.9	27.6	-0.1
2002	Mar-28	Oct-17	203	2,050	3.4	27.8	0.1
2003	Apr-03	Oct-21	201	1,980	0.3	28.0	0.3
2004	Mar-27	Oct-12	199	2,200	8.9	28.2	0.5
2005	Apr-01	Oct-16	198	1,880	-4.6	27.5	-0.2
2006	Mar-25	Oct-18	207	1,740	-11.0	27.3	-0.4
2007	Apr-04	Sep-30	179	2,060	3.8	27.9	0.2
2008	Mar-29	Oct-14	199	2,180	8.3	28.0	0.3
2009	Apr-06	Oct-10	187	1,930	-1.1	27.7	0.0
2010	Mar-26	Oct-13	201	2,070	3.6	28.1	0.4
2011	Apr-03	Oct-11	191	1,860	-5.3	27.6	-0.1
2012	Mar-28	Oct-20	206	1,990	0.7	27.8	0.1
2013	Apr-01	Oct-16	198	2,150	6.8	28.3	0.6
2014	Mar-24	Oct-18	208	1,810	-6.0	27.5	-0.2
2015	Apr-05	Oct-12	190	1,700	-12.1	27.2	-0.5
2016	Mar-27	Oct-14	201	2,030	2.6	27.9	0.2
2017	Mar-30	Oct-15	199	2,090	5.5	28.0	0.3
2018	Apr-02	Oct-18	199	1,970	0.0	27.8	0.1
2019	Mar-26	Oct-20	208	2,200	8.9	28.4	0.7
2020	Apr-04	Oct-11	191	1,950	-0.5	27.9	0.2
2021	Mar-29	Oct-13	198	1,830	-5.8	27.6	-0.1
2022	Apr-03	Oct-15	195	2,040	3.1	28.1	0.4
2023	Mar-31	Oct-18	201	2,120	7.0	28.3	0.6
2024	Apr-02	Oct-10	191	2,010	1.0	28.4	0.7
2025	Apr-07	Oct-05	182	1,980	0.3	28.5	0.8

Source: Nigerian Meteorological Agency (NiMet), 2025

3.5 Decadal maximum temperature trends (1996-2025)

Table 5 presents rainfall data across three decades in Ilaje Local Government Area (LGA), revealing variability alongside a long-term upward trend. The first decade (1996-2005) averaged 929.2 mm, with fluctuations from 503 mm to over 1,300 mm. Such irregular distribution likely constrained water availability and disrupted fish breeding cycles, consistent with findings in southern Nigeria where declining rainfall reduced river discharge and agricultural yields (Edokpa, 2020). In contrast, Adetayo (2021) reported relatively stable rainfall onset and cessation in southwestern Nigeria, suggesting localized climatic dynamics in Ilaje. The second decade (2006-2015) showed a 15% increase to 1,072.6 mm, with exceptionally high years such as 2004 (1,451 mm) and 2005 (1,509 mm). While higher rainfall replenished rivers and wetlands, excessive precipitation heightened flooding and erosion risks, as observed in the Niger Delta (Idogho et al., 2022b) and across West Africa (Ragatoa et al., 2020).

Projections for 2016-2025 indicate continued increases to 1,158 mm, consistent with national anomalies linked to atmospheric circulation shifts (Akinsanola and Ogunjobi, 2020). Variability ranging from 990 mm to 1,400 mm underscores instability. Similar climate-driven hydrological changes in Lake Tanganyika disrupted nutrient cycling and reduced fish productivity (Cohen et al., 2016). Overall, Ilaje's rainfall dynamics reflect regional climate trends, highlighting the need for adaptive water management, flood control, and resilient livelihood strategies.

Table 4 Decadal average rainfall

Decade	Period	Decadal Rainfall (mm)	Trend Observation
Decade 1	1996-2005	929.2	Slight Decrease compared to the previous decade.
Decade 2	2006-2015	1072.6	Significant Increase (about 15.4% increase from the 1996-2005 decade).
Decade 3	2016-2025 (Modeled)	1158.0	Continued Increase (Based on projected trends of increasing rainfall intensity and duration in the region).

Source: Nigerian Meteorological Agency (NiMet), 2025

Table 5 Tabular presentation of decadal rainfall (mm)

Year Index	1996-2005 (Decade 1) Rainfall (mm)	2006-2015 (Decade 2) Rainfall (mm)	2016-2025 (Decade 3) Modeled Rainfall (mm)
1	1149	966	1050
2	633	1127	1280
3	1110	1133	1100
4	503	1451	1350
5	811	1509	1400
6	1307	840	1020
7	819	1119	990
8	989	733	1180
9	866	992	1070
10	1105	856	1140
MEAN	929.2	1072.6	1158.0

Source: Nigerian Meteorological Agency (NiMet), 2025

3.6 Decadal minimum temperature trends (1996-2025)

Table 6 presents decadal maximum temperatures in Ilaje coastal waters, showing gradual warming and variability across three decades. The first decade (1996-2005) recorded a mean maximum of 32.6°C, ranging between 32°C -33°C, reflecting relatively stable thermal conditions. Similar modest warming was observed in southern Nigeria during the late 1990s (Odjugo, 2010). The second decade (2006-2015) showed a rise to 33.3°C, with peaks at 34°C, consistent with regional climate change trends. Elevated temperatures reduce dissolved oxygen, disrupt breeding cycles, and increase disease prevalence, thereby stressing fisheries. Comparable warming patterns across Nigeria were documented by Akinsanola and Ogunjobi (2020), while Cohen et al. (2016) demonstrated that warming in Lake Tanganyika reduced nutrient mixing and fish productivity.

The third decade (2016-2025) recorded a modeled mean of 33.2°C, with variability from 31°C-34°C, highlighting dynamic coastal processes. Nwosu et al. (2022) reported similar variability in Niger Delta ecosystems, driven by rainfall anomalies and ocean-atmosphere interactions. Overall, Ilaje's warming trajectory underscores the need for adaptive fisheries management, habitat conservation, and climate-resilient livelihood strategies to safeguard artisanal fishing communities.

3.7 Decadal minimum temperatures for Ilaje LGA (1996-2025)

Table 7 presents decadal minimum temperatures in Ilaje Local Government Area (LGA), showing gradual warming trends. The first decade (1996-2005) recorded a mean minimum of 19.6°C, ranging between 19°C-20°C, reflecting relatively stable cooler conditions. Similar modest warming was reported in southern Nigeria during the late 1990s (Odjugo, 2010). The second decade (2006-2015) showed a slight increase to 19.9°C, with some years reaching 21°C, indicating rising nighttime and seasonal minimums. Warmer waters reduce oxygen solubility, alter breeding cycles, and stress fish habitats. Comparable increases were documented across Nigeria (Akinsanola and Ogunjobi, 2020), while Nnaji and Nzeadibe (2023) noted that elevated nighttime temperatures disrupted agricultural and fishing calendars in southeastern Nigeria.

Table 6 Decadal maximum temperatures for Ilaje LGA coastal waters

Year	Decade 1 (1996-2005)	Decade 2 (2006-2015)	Decade 3 (2016-2025)
1	33°C	33°C	33°C
2	33°C	34°C	31°C
3	32°C	33°C	33°C
4	33°C	34°C	34°C
5	33°C	33°C	33°C
6	32°C	33°C	32°C
7	32°C	33°C	34°C
8	33°C	32°C	33°C
9	32°C	34°C	33°C
10	33°C	34°C	33°C
Mean	32.6°C	33.3°C	33.2°C

Source: Nigerian Meteorological Agency (NiMet), 2025

The third decade (2016-2025) recorded a mean of 21.3°C, with several years reaching 22°C-23°C, marking a significant departure from earlier decades. Such warming reduces cooling effects of nights and intensifies ecological stress. Cohen et al. (2016) demonstrated similar impacts in Lake Tanganyika, where warming reduced nutrient mixing and fish productivity. Overall, Ilaje's rising minimum temperatures threaten artisanal fisheries, underscoring the need for climate-resilient practices, ecosystem monitoring, and livelihood diversification.

3.8 Effects of water level on fish catch volume in Ilaje coastal waters

Table 8 presents fishermen's perceptions of water level effects on fish catch volume in Ilaje coastal waters. Nearly all respondents (98.6%) agreed that high water levels increase fish output, while 97.5% confirmed that low levels reduce catches, underscoring the strong link between hydrological regimes and fishing productivity. Seasonal flooding creates breeding and feeding grounds that enhance yields (Welcomme, 2011), while rainfall variability in the Niger Delta has been shown to directly influence catch volumes (Idogho et al., 2022a). In Ilaje, 86.8% of respondents noted that changes in river flow affect fish availability, and 85.7% observed significant declines, reflecting broader challenges of reduced rainfall, climate variability, and human activities.

Table 7 Decadal minimum temperatures for Ilaje LGA

Year	Decade 1 (1996-2005)	Decade 2 (2006-2015)	Decade 3 (2016-2025)
1	20°C	20°C	21°C
2	20°C	20°C	20°C
3	20°C	20°C	23°C
4	19°C	19°C	21°C
5	19°C	19°C	21°C
6	20°C	19°C	20°C
7	19°C	19°C	21°C
8	20°C	21°C	22°C
9	19°C	21°C	22°C
10	20°C	21°C	22°C
Mean	19.6°C	19.9°C	21.3°C

Source: Nigerian Meteorological Agency (NiMet), 2025

Similar disruptions have been reported in southeastern Nigeria (Nnaji and Nzeadibe, 2023). Conversely, intensified rainfall in West Africa replenished wetlands but increased flooding risks (Ragatoa et al., 2020). Globally, reduced flows and blocked migration routes have contributed to an 81% decline in migratory freshwater fish populations (World Fish Migration Foundation, 2024). Cohen et al. (2016) further demonstrated that climate-driven hydrological changes in Lake Tanganyika reduced nutrient cycling and fish productivity. Overall, Ilaje's findings highlight that declining water levels threaten fisheries and livelihoods, requiring improved water management, climate adaptation, and ecosystem conservation.

Table 8 Effects of water level on fish catch volume in Ilaje coastal waters

Question	Agree	%	Disagree	%
High water level increases fish output	276	98.6%	4	1.4%
Low water level decreases fish output	273	97.5%	7	2.5%
Change in river flow affects fish availability	243	86.8%	37	13.2%
River water flow has considerably decreased	240	85.7%	40	14.3%
Total Respondents	280	100%		

Source: Nigerian Meteorological Agency (NiMet), 2025

3.9 Decadal variation of climatic variables: Rainfall (1996-2025)

Table 4 highlights rainfall and temperature trends in Ilaje LGA between 1996 and 2025, revealing significant climatic variability. The rainy season typically begins in late March or early April and ends by mid-October, but its duration has shortened from 218 days in 1996 to 182 days projected in 2025. This contraction reflects broader climatic shifts across Nigeria, where rainfall patterns have become increasingly erratic due to climate change (World Bank Climate Portal, 2024). Ishaku et al. (2024) similarly emphasized West Africa's rainfall sensitivity to oceanic and atmospheric circulation changes, leading to alternating wet and dry years. Annual rainfall fluctuates widely, ranging from 1,700 mm in 2015 to 2,200 mm in 2004 and 2019, with deviations exceeding ±10%. Sharp declines in 2006 (−11.0%) and 2015 (−12.1%) highlight risks for agriculture and water resources in coastal areas.

These findings are consistent with Ragatoa et al. (2020), who reported alternating wet and dry decades in West Africa, stressing the vulnerability of coastal livelihoods to rainfall variability.

Temperature trends show a gradual rise, from 27.4°C in 1996 to 28.5°C in 2025, with deviations between −0.5°C and +0.8°C. This warming trajectory aligns with national observations that Nigeria's average temperature has steadily increased over the past three decades. Cohen et al. (2016) demonstrated similar warming impacts in Lake Tanganyika, where rising temperatures reduced nutrient mixing and fish productivity. Combined rainfall variability and warming pose dual risks: flooding during wetter years and drought stress during drier periods. These climatic pressures directly affect Ilaje's fishing and farming communities, reducing water availability, altering fish habitats, and threatening food security. Omitoyin et al. (2021a) linked hydrological instability to declining fish productivity in Nigeria, reinforcing the need for adaptive water and fisheries management strategies.

3.10 Decadal rainfall analysis (1996-2025)

Table 5 presents a decadal analysis of rainfall in Ilaje LGA, offering valuable insights into long-term climatic variability and its implications for fisheries and water resources. The data reveal a general upward trend in rainfall across three decades. Decade 1 (1996-2005) recorded an average of 929.2 mm, reflecting a slight decrease compared to earlier baselines. Decade 2 (2006-2015) showed a significant increase to 1,072.6 mm, representing a 15.4% rise. The modeled projection for Decade 3 (2016-2025) indicates continued growth, with an average of 1,158.0 mm, consistent with regional climate studies predicting intensified rainfall in coastal Ondo State. These findings align with the World Bank Climate Portal (2024), which reported increasingly erratic but overall rising rainfall trends in Nigeria's coastal regions. Ishaku et al. (2024) emphasized that West African rainfall patterns are highly sensitive to oceanic and atmospheric circulation changes, leading to alternating wet and dry decades. The observed increase in Ilaje mirrors broader national trends, where rainfall variability has intensified due to climate change.

While rising rainfall may enhance water availability, it also poses risks of flooding, sedimentation, and habitat disruption. Such impacts directly affect artisanal fisheries, as noted by Omitoyin et al. (2021a), who linked hydrological instability to declining fish productivity. Thus, the decadal analysis underscores the need for adaptive water and fisheries management strategies in Ilaje.

3.11 Decadal rainfall and temperature trends in Ilaje LGA (1996-2025)

3.11.1 Rainfall variability

Table 6 presents a decadal analysis of rainfall in Ilaje LGA, showing variability across three decades with a general upward trend. Decade 1 (1996-2005) recorded a mean rainfall of 929.2 mm, reflecting relatively lower precipitation. Decade 2 (2006-2015) showed a significant increase to 1,072.6 mm, representing a 15.4% rise. The modeled projection for Decade 3 (2016-2025) indicates continued growth, with an average of 1,158.0 mm, consistent with regional climate studies predicting intensified rainfall in coastal Ondo State. This pattern aligns with the World Bank Climate Portal (2024), which reported increasingly erratic but rising rainfall trends in Nigeria's coastal regions. Similarly, Ishaku et al. (2024) emphasized that West African rainfall variability is strongly influenced by oceanic and atmospheric circulation, leading to alternating wet and dry decades. The observed increase in Ilaje mirrors these broader regional dynamics.

While rising rainfall may enhance water availability, it also poses risks of flooding, sedimentation, and ecosystem disruption. Such impacts directly affect artisanal fisheries, as noted by Omitoyin et al. (2021a), who linked hydrological instability and habitat degradation to declining fish productivity in Ilaje. Ragatoa et al. (2020) similarly observed that intensified rainfall in West Africa replenished wetlands but also heightened risks of erosion and flooding, underscoring the dual nature of rainfall increases. Thus, the decadal analysis underscores both opportunities and challenges: greater rainfall may support water resources, but variability and extremes demand adaptive fisheries and water management strategies.

3.11.2 Maximum temperature trends

Table 7 presents decadal maximum temperature trends for Ilaje LGA coastal waters between 1996 and 2025. The data show a gradual increase in mean maximum temperatures: 32.6°C in Decade 1 (1996-2005), rising to 33.3°C in Decade 2 (2006-2015), and stabilizing at 33.2°C in Decade 3 (2016-2025). This pattern reflects modest but consistent warming, with occasional fluctuations such as lower values (31°C) in Decade 3 and higher peaks (34°C) in decades 2 and 3. These findings align with broader climatic observations. Faweya et al. (2023) reported increasing rainfall intensity and high temporal variability in Ondo State, indirectly linked to rising temperatures that influence atmospheric circulation. Although their study did not break down data by LGA, the warming trend observed in Ilaje is consistent with regional patterns. Similarly, Ikezam et al. (2025), in a GIS-based study of wetland changes in Ilaje, highlighted how land use and climate variability, including temperature increases, affect wetland dynamics and fisheries.

The gradual rise in maximum temperatures also mirrors national climate records, which show steady warming across Nigeria's coastal zones. Such warming has implications for fisheries, as higher water temperatures alter breeding cycles, oxygen levels, and species distribution. As Omitoyin et al. (2021b) noted, temperature fluctuations in Ilaje contribute to declining fish productivity and shifts in species dominance, underscoring the need for adaptive strategies.

3.11.3 Minimum temperature trends

Table 8 highlights decadal minimum temperature trends in Ilaje LGA, showing a gradual warming pattern typical of tropical coastal regions. The mean minimum temperature rose from 19.6°C in Decade 1 (1996-2005) to 19.9°C in Decade 2 (2006-2015), and further to 21.3°C in Decade 3 (2016-2025). The lowest recorded value was 19°C, while the highest was 23°C in Decade 3, Year 3. This steady increase reflects regional warming influenced by global climate change, urbanization, and land-use changes. These findings align with Faweya et al. (2023), who reported increasing rainfall intensity and climate variability in Ondo State, indirectly linked to rising temperatures. Similarly, Ikezam et al. (2025) noted that warming trends and land-use change significantly affect coastal ecosystems in Ilaje. The observed rise in nighttime temperatures is consistent with global climate records, which show warming across West Africa's coastal zones (Odjugo, 2010).

Environmental implications are significant. Rising temperatures exacerbate coastal erosion, saltwater intrusion, and biodiversity loss, directly impacting Ilaje's fishing and farming livelihoods. As Omitoyin et al. (2021b) observed, temperature fluctuations disrupt fish breeding cycles and reduce productivity. Higher nighttime temperatures also affect crop viability and pest behavior. These trends underscore the urgent need for climate adaptation strategies, including coastal monitoring, early warning systems, and resilient infrastructure.

3.11.4 Effects of water level on fish catch volume in Ilaje coastal waters

Table 8 illustrates fishermen's consensus in Ilaje LGA that water level fluctuations critically influence fish catch volumes. Nearly all respondents (98.6%) affirmed that high water levels expand aquatic habitats, enhance oxygenation, and facilitate breeding, consistent with findings that seasonal flooding improves fish productivity by connecting breeding grounds and dispersing nutrients (Welcomme, 2011). Conversely, 97.5% reported that low water levels reduce oxygen, elevate temperatures, and restrict fish movement, echoing evidence of dry-season water stress leading to reduced catches and higher mortality (Idogho et al., 2022b).

Changes in river flow were also emphasized, with 86.8% acknowledging impacts on fish availability and 85.7% noting significant declines attributed to climate change, deforestation, and urban encroachment. Similar disruptions have been documented in southeastern Nigeria (Nnaji and Nzeadibe, 2023) and across coastal ecosystems (Globally, climate-driven hydrological changes have reduced nutrient cycling and fish productivity (Cohen et al., 2016). These findings highlight the urgent need for adaptive water management, sustainable fisheries practices, and ecosystem conservation to safeguard livelihoods in Ilaje.

4 Conclusion

The analysis demonstrates that rising temperatures and inconsistent rainfall have shortened rainy seasons, reduced river flows, and intensified ecological stress in Ilaje LGA. These climatic shifts diminish dissolved oxygen, disrupt breeding cycles, and lower fish productivity, thereby undermining artisanal fisheries and livelihoods. Survey evidence confirms hydrological parameters as critical determinants of catch volumes. Without adaptive management, ecosystem conservation, and livelihood diversification, climate variability will continue to compromise fisheries sustainability, exacerbate poverty, and threaten socio-economic resilience in Ilaje's coastal communities.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Review and Progress Open Access

Research Progress on Key Technologies for Disease Prevention and Control in Shrimp Aquaculture

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Abstract This study reviews the research progress and development trends of key technologies for disease prevention and control in shrimp aquaculture. With the shift toward high-density and intensive farming systems, viral, bacterial, and parasitic diseases have become increasingly prevalent, posing significant constraints on the sustainable development of the industry. This paper systematically summarizes the major disease types and their epidemiological characteristics, and analyzes the effects of pathogen-host interactions, environmental factors, and farming practices on disease occurrence. On this basis, recent advances in disease detection and monitoring technologies are reviewed, including conventional methods, molecular and immunological techniques, as well as rapid detection and intelligent monitoring systems. Furthermore, key prevention and control strategies are discussed, such as aquaculture management and ecological regulation, microbial modulation and antibiotic alternatives, immunostimulation, and disease-resistant selective breeding, along with their application outcomes. The current challenges are also addressed, including pathogen variation and emerging disease risks, antibiotic misuse and antimicrobial resistance, and the lack of technology transfer and standardization. Finally, future perspectives are proposed, highlighting a transition toward integrated management approaches centered on biosecurity. This study provides a reference for developing green, efficient, and sustainable shrimp health management systems.

Keywords Shrimp aquaculture; Disease control; Biosecurity; Microbial regulation; Intelligent monitoring

1 Introduction

With the rapid development of global aquaculture, shrimp farming has become one of the fastest-growing and most economically valuable sectors. It not only provides an important source of animal protein for regions such as Asia and Latin America, but also generates substantial export revenues. Among the major cultured species, Pacific white shrimp (*Litopenaeus vannamei*) and Chinese shrimp have been widely promoted worldwide due to their rapid growth, strong environmental adaptability, and high market demand. In crustacean aquaculture, marine shrimp dominate both production volume and economic value. However, while high-density and intensive farming systems have significantly increased production, they have also intensified environmental pressure and reduced system stability, leading to increasingly severe disease problems that have become a major bottleneck for sustainable industry development (Bhassu et al., 2024).

In recent years, viral and bacterial diseases have repeatedly occurred in major shrimp farming regions worldwide. Typical diseases include white spot syndrome virus (WSSV), acute hepatopancreatic necrosis disease (AHPND), Enterocytozoon hepatopenaei (EHP) infection, and vibriosis. These diseases are characterized by rapid transmission and high mortality, often causing large-scale outbreaks and severe economic losses within a short period (Chowdhury et al., 2024). Since the 1990s, such diseases have frequently affected major aquaculture countries such as India and Thailand, resulting in cumulative losses of billions of dollars. Studies have shown that disease outbreaks are not only closely associated with pathogenic microorganisms, but are also driven by multiple factors, including water quality deterioration, environmental degradation, inadequate biosecurity measures, and the globalization of seedstock and live animal trade. Their impacts extend beyond production losses to include reduced employment and socio-economic instability in coastal regions (Bhassu et al., 2024; Chowdhury et al., 2024).

Therefore, effective disease prevention and control has become a critical component for ensuring shrimp health and maintaining industry stability. Traditional approaches based on antibiotics, chemicals, and disinfectants may provide short-term benefits, but are limited in controlling viral pathogens. Long-term use can also induce antimicrobial resistance in Vibrio spp., disrupt host microbial communities, and pose risks to the environment and food safety (Khanjani et al., 2024). In addition, due to the lack of a typical adaptive immune system in shrimp, the application of conventional vaccination strategies remains limited. As a result, preventive health management approaches have gradually become the mainstream, including strengthening biosecurity systems, using specific pathogen-free (SPF) and disease-resistant (SPR) stocks, optimizing culture environments, and applying functional feed additives for immune regulation (Nguyen, 2024). However, disease outbreaks remain frequent in practice; for example, nearly half of the production cycles in some regions are affected by diseases, indicating that single management strategies are insufficient to control complex disease systems (Bhassu et al., 2024).

This study aims to review the progress of green, efficient, and sustainable technologies for disease prevention and control in shrimp aquaculture. Advances in pathogen detection technologies, such as PCR, quantitative real-time PCR, monoclonal antibody-based assays, and lateral flow test strips, have significantly improved detection sensitivity and accuracy. Meanwhile, emerging technologies, including high-throughput sequencing, nanotechnology, biosensors, RNA interference, and CRISPR-Cas systems, have enhanced our understanding of pathogen–host interactions and provided valuable tools for disease-resistant genetic improvement. In addition, microbial-based products such as probiotics, prebiotics, and synbiotics, as well as bioactive compounds derived from plants and microalgae, have shown promising potential in regulating gut microbiota, enhancing immunity, and improving disease resistance. This study systematically analyzes major disease types and their epidemiological characteristics, examines key mechanisms and influencing factors, and reviews advances in biosecurity systems, SPF/SPR breeding, immunostimulants and functional additives, microbial regulation, and molecular and omics technologies. Finally, future development trends are discussed to provide a theoretical basis and practical reference for establishing green, efficient, and sustainable shrimp health management systems.

2 Major Disease Types and Epidemiological Characteristics in Shrimp Aquaculture

2.1 Major disease types

Shrimp aquaculture is affected by a wide range of diseases, among which viral, bacterial, and parasitic infections are the most common. These diseases have significant impacts on survival rate, growth performance, and overall economic returns. Previous studies have shown that viral diseases account for the majority of losses in shrimp farming, contributing approximately 60% of total disease-related losses, while bacterial diseases account for about 20%. Fungal and parasitic diseases generally occur at lower frequencies but can still cause substantial damage under specific environmental conditions (Hasan et al., 2024). Therefore, a systematic understanding of major disease types from a pathogen spectrum perspective is essential for establishing healthy aquaculture systems and implementing precise disease control strategies.

Viral diseases are widely regarded as the most severe threat in shrimp aquaculture. They are characterized by rapid transmission, high mortality, and a broad host range, and can easily cause outbreaks under high-density farming conditions. Major viral diseases of concern include white spot syndrome caused by white spot syndrome virus (WSSV), Taura syndrome caused by Taura syndrome virus (TSV), yellow head disease caused by yellow head virus (YHV), as well as infections caused by infectious hypodermal and hematopoietic necrosis virus (IHHNV) and infectious myonecrosis virus (IMNV). These pathogens can enter aquaculture systems through infected seedstock, broodstock carriers, waterborne transmission, and farming practices, and can rapidly spread under conditions of environmental deterioration or host stress. Due to their high pathogenicity and potential for transboundary spread, many shrimp viruses have been listed as notifiable pathogens by the World Organisation for Animal Health.

Bacterial diseases are mainly associated with infections by Vibrio spp., which are among the most common disease types under conditions of high temperature, high organic load, and poor management. Vibrio infections can cause clinical manifestations such as red body disease, septicemia, and hepatopancreatic damage. Among them, acute hepatopancreatic necrosis disease (AHPND), caused by specific strains of Vibrio parahaemolyticus carrying virulence plasmids, is of particular concern. In addition, V. harveyi, V. alginolyticus, V. cholerae, and V. vulnificus can also act as primary or opportunistic pathogens (Chowdhury et al., 2024). Compared with viral diseases, bacterial infections are theoretically more controllable; however, due to their strong virulence, environmental adaptability, and increasing antimicrobial resistance, disease management is becoming more challenging.

2.2 Characteristics and impacts of typical diseases

Among various shrimp diseases, white spot syndrome virus (WSSV) and acute hepatopancreatic necrosis disease (AHPND) are considered the most widespread and economically devastating. WSSV is one of the most representative and highly pathogenic viruses in shrimp aquaculture. It is an enveloped double-stranded DNA virus with a broad host range, capable of infecting multiple decapod crustaceans and establishing persistent low-level infections in hosts. Under favorable conditions, infections can rapidly escalate into outbreaks. Clinical signs of WSSV infection include white calcified spots on the exoskeleton, reddish discoloration, reduced feeding, lethargy, and rapid mortality (Hasan et al., 2024). Studies have shown that WSSV outbreaks can result in cumulative mortality rates of 80%-100% within 3-10 days, demonstrating acute onset, high lethality, and strong transmissibility (Hasan et al., 2024).

Compared with WSSV, AHPND is a rapidly emerging bacterial disease that predominantly affects early culture stages. It is caused by specific strains of Vibrio parahaemolyticus carrying virulence plasmids encoding PirAB toxins. These toxins directly damage the hepatopancreas, leading to massive epithelial cell sloughing, necrosis, and functional failure. AHPND typically occurs within 20-30 days after stocking and is characterized by reduced feeding, empty gut, hepatopancreatic atrophy, and discoloration. Due to the lack of obvious external symptoms in some cases, early diagnosis is challenging. In severe outbreaks, mortality rates can exceed 70%, particularly affecting juvenile shrimp. The disease has been reported in multiple countries, including China, Vietnam, Thailand, and Mexico, and its spread is closely associated with seedstock movement, inadequate biosecurity, and environmental stress.

In addition to WSSV and AHPND, diseases such as Taura syndrome (TSV), yellow head disease (YHV), infectious myonecrosis (IMNV), and EHP infection also pose significant threats. Unlike acute high-mortality diseases, EHP infection typically causes chronic impacts, including slow growth, size variation, reduced feed efficiency, and prolonged culture periods, thereby reducing overall productivity. From an industrial perspective, shrimp diseases can be categorized into “acute lethal diseases” and “chronic debilitating diseases,” both of which contribute to economic losses. Moreover, pathogens do not act independently. Studies have shown that co-infection with AHPND and WSSV can exacerbate tissue damage and increase mortality. WSSV exposure can also enhance the susceptibility of Litopenaeus vannamei to AHPND-causing Vibrio strains. Therefore, disease understanding should extend beyond single pathogens to a framework incorporating multi-pathogen interactions and host stress responses.

2.3 Epidemiological Patterns of Diseases

Shrimp diseases exhibit pronounced seasonal patterns, closely associated with water temperature, salinity, water quality fluctuations, and farming-related stress. Studies have shown that WSSV outbreaks are strongly influenced by temperature variations. The virus shows high virulence at temperatures of approximately 25 °C-28 °C, while sudden temperature drops or low-temperature conditions can increase host stress and mortality rates (Hasan et al., 2024). In contrast, Vibrio pathogens proliferate rapidly under high temperature, high organic load, and low dissolved oxygen conditions, making bacterial diseases more prevalent during hot seasons. In addition, factors such as heavy rainfall, improper water exchange, and sediment deterioration can cause ammonia accumulation, pH fluctuations, and microbial imbalance, thereby increasing disease outbreak risks (Chowdhury et al., 2024).

These findings indicate that seasonal effects operate through combined influences on host physiology and environmental conditions.

Shrimp diseases also show clear regional variability. The dominant pathogen spectrum and epidemiological patterns differ among regions. Asia has experienced multiple disease outbreaks, including WSSV, YHV, AHPND, and EHP, making it one of the most complex and high-risk regions globally. In contrast, the Americas were initially dominated by TSV and WSSV, with increasing reports of AHPND in recent years. Even within a single country, significant differences may exist among farming areas. For example, studies in the east coast of India have shown varying combinations of EHP, Vibrio spp., and WSSV across different farming systems and regions. Coastal high-density farming areas generally face higher outbreak risks due to frequent seedstock movement and pathogen introduction, whereas inland low-salinity systems may experience lower disease frequency but still suffer significant losses once outbreaks occur due to limited monitoring capacity.

Furthermore, co-infection has become a prominent feature of shrimp disease epidemiology. Field observations and experimental studies indicate that multiple pathogens can coexist within the same system or host, such as EHP–WSSV and Vibrio–WSSV co-infections (Chowdhury et al., 2024). These co-infections often exhibit synergistic pathogenic effects rather than simple additive impacts. Viral infections can weaken host immune defenses and damage tissue barriers, facilitating bacterial invasion. Conversely, bacterial infections can promote viral replication through tissue damage and inflammatory responses. As a result, multi-pathogen interactions often lead to higher mortality rates, more complex clinical manifestations, and increased difficulty in diagnosis and disease control.

3 Mechanisms and Influencing Factors of Shrimp Diseases

3.1 Pathogen-host interactions and immune mechanisms

The occurrence of shrimp diseases is essentially the result of an imbalance among pathogens, the host innate immune system, and environmental factors. As invertebrates, shrimp lack a typical adaptive immune system and long-term specific immune memory; thus, their defense against infections mainly relies on innate immunity. This system consists of both cellular and humoral components, including phagocytosis, encapsulation, coagulation, and activation of the prophenoloxidase system. In addition, effector molecules such as antimicrobial peptides, lectins, and lysozymes play critical roles in immune defense. Upon pathogen invasion, the host initially recognizes pathogen-associated molecular patterns (PAMPs) via pattern recognition receptors (PRRs). This recognition subsequently activates key signaling pathways, such as NF-κB and JAK/STAT, leading to the expression of various immune effectors that contribute to pathogen clearance and restriction of their spread in hemolymph and tissues.

However, the intensity and duration of innate immune responses in shrimp are relatively limited, making it difficult to establish long-term protection similar to that observed in vertebrates. Consequently, shrimp are more susceptible to infections and disease outbreaks under conditions of high pathogen pressure or environmental stress. Transcriptomic and immunological studies have shown that multiple immune pathways are significantly modulated following infection with white spot syndrome virus (WSSV) or AHPND-causing Vibrio. Meanwhile, many pathogens have evolved sophisticated immune evasion and host manipulation strategies. For example, WSSV can interfere with host signal transduction, apoptosis, and antiviral responses, thereby creating a cellular environment favorable for viral replication and dissemination (Xiong et al., 2024). Therefore, pathogen-host interactions represent a dynamic and continuous interplay rather than a simple unidirectional process of host defense versus pathogen invasion.

In bacterial diseases, the pathogenic mechanisms of AHPND also demonstrate strong pathogen adaptability. The causative Vibrio parahaemolyticus strains typically harbor the pVA1 virulence plasmid encoding PirAB toxins, which directly damage hepatopancreatic tissues, leading to epithelial cell sloughing and necrosis. This enables rapid disruption of local immune defenses and results in high mortality (Chandran et al., 2023). Furthermore, an imbalance in host immune responses can exacerbate disease progression. Excessive inflammatory responses may cause additional tissue damage, whereas insufficient immune responses fail to effectively control pathogen proliferation. Therefore, disease outcomes depend not only on pathogen load but also on the regulation of host immune responses (Chandran et al., 2023).

3.2 Environmental factors

Environmental factors play a crucial role in shrimp health and disease occurrence. Their effects are reflected not only in regulating pathogen survival and transmission, but also in influencing host physiological homeostasis and immune competence. Among various environmental variables, water quality is one of the most critical. Parameters such as dissolved oxygen, pH, partial pressure of carbon dioxide, ammonia, and nitrite directly affect shrimp metabolism, osmoregulation, and immune function. When shrimp are exposed to suboptimal water conditions, either in the short or long term, they exhibit physiological stress responses accompanied by reduced hemocyte function, suppressed phenoloxidase activity, and weakened resistance to infection, thereby increasing mortality risk upon pathogen exposure (Hapsari et al., 2025). In addition, the accumulation of uneaten feed and waste elevates organic load, providing favorable conditions for opportunistic pathogens such as Vibrio spp.

Temperature is another key factor influencing disease dynamics. Studies have shown that WSSV exhibits high virulence at approximately 25 °C-28 °C, whereas higher temperatures (e.g., >30 °C) may reduce outbreak severity under certain conditions. However, the impact of temperature depends not only on absolute values but also on the magnitude and rate of fluctuations. Extreme weather events, such as cold spells, heatwaves, and large diurnal temperature variations, can induce significant physiological stress, impair immune function, and trigger the transition from latent to active infections (Chang et al., 2024). Therefore, maintaining stable temperature conditions is often more critical than controlling absolute temperature levels in aquaculture practice.

Salinity is also an important environmental determinant of shrimp health. Deviations from optimal salinity levels increase osmoregulatory stress and disrupt physiological balance, thereby reducing disease resistance. Rapid declines in salinity, often caused by heavy rainfall, large-scale water exchange, or low-salinity farming systems, are closely associated with outbreaks of AHPND and vibriosis (Chang et al., 2024). Recent studies further indicate that low-salinity stress not only affects host osmoregulation but also reduces gut microbiota diversity and alters microbial community functions. These changes can promote the proliferation and tissue invasion of pathogenic Vibrio strains, suggesting that salinity influences disease dynamics through multi-level interactions among host, microbiota, and pathogens (Chang et al., 2024).

3.3 Effects of farming systems and stress factors

Farming systems largely determine the levels of biotic and abiotic stress experienced by shrimp and thus represent key management factors influencing disease occurrence. High-density intensive aquaculture systems have significantly increased production efficiency but also elevated pathogen transmission rates, water quality deterioration risks, and chronic stress levels, thereby increasing disease incidence (Hapsari et al., 2025; Kumar et al., 2025). Under high stocking densities, increased contact among individuals facilitates rapid pathogen spread. Meanwhile, the accumulation of uneaten feed and metabolic waste increases environmental load, further promoting the growth of opportunistic pathogens such as Vibrio spp.

Site selection and farming infrastructure also influence disease risks. Aquaculture systems established in acid sulfate soils, polluted waters, or ecologically marginal environments may expose shrimp to acidification, heavy metals, or other contaminants, thereby increasing physiological stress and weakening disease resistance (Kumar et al., 2025). In addition, the large-scale transboundary movement of broodstock and seedstock, particularly in the absence of strict quarantine and biosecurity measures, has been identified as a major pathway for pathogen dissemination and a key driver of historical disease outbreaks.

Operational stressors in daily management further contribute to disease occurrence. Activities such as harvesting, grading, transportation, stocking, water exchange, and pond transfer can disrupt physiological and endocrine balance and suppress innate immune functions (Hapsari et al., 2025). In particular, improper management during early stocking stages or periods of abrupt environmental change can trigger the transition from subclinical infections to overt disease outbreaks. Chronic or repeated stress can also lead to long-term health impairment, manifested as reduced feeding, slower growth, and decreased survival rates. Moreover, the gut microbiota plays an important mediating role in this process. High-density culture and nutritional imbalance can disrupt microbial homeostasis, resulting in reduced beneficial bacteria and increased opportunistic pathogens, thereby further elevating disease risk (Chang et al., 2024; Murugan et al., 2024; Xiong et al., 2024).

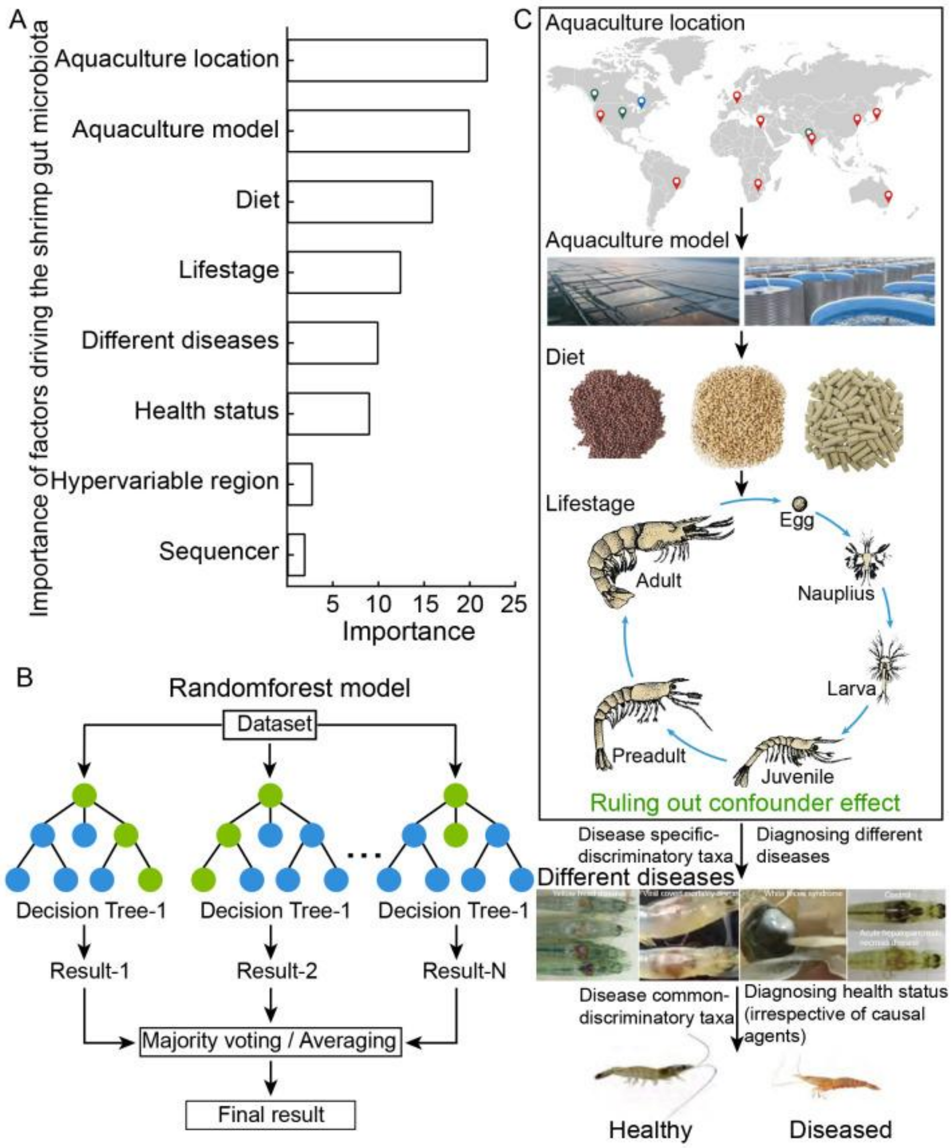

Figure 1 Flowchart screening disease common-discriminatory taxa for diagnosing shrimp health status (Adopted from Xiong et al., 2024)

Image caption: A: Quantifying relative importance of factors governing shrimp gut microbiota in descending order. B: Identifying discriminatory taxa for each factor using a random forest model. C: Identifying disease common-discriminatory taxa after progressive removal of effects of factors more important than health status in governing gut microbiota (Adopted from Xiong et al., 2024)

4 Advances in Disease Detection and Monitoring Technologies

4.1 Conventional detection methods and their limitations

In the early stages of shrimp disease diagnostics, conventional approaches primarily relied on clinical observations and classical laboratory techniques. These methods include visual inspection, microscopic examination, histopathological analysis, electron microscopy, and culture-based isolation of cultivable bacteria. In practical aquaculture, diseases are often preliminarily diagnosed based on external symptoms such as abnormal body coloration, appendage damage, white spots on the carapace, and empty gut. Post-mortem observations, including hepatopancreatic atrophy, gill damage, and muscle necrosis, are also used as supporting indicators. Parasitic infections and some bacterial pathogens can be identified morphologically using optical microscopy, while bacterial pathogens are typically isolated and characterized through culture and biochemical tests. These methods are technically mature and cost-effective, and they remain useful in small-scale farming operations and routine laboratory diagnostics.

However, conventional methods have clear limitations in terms of sensitivity, specificity, timeliness, and field applicability. Many important viral diseases lack specific clinical symptoms in the early stages, and some individuals may carry subclinical infections, making early detection based solely on visual observation unreliable (Zwetlana et al., 2023). In addition, morphological similarities among parasites, bacteria, and pathological changes can lead to misdiagnosis. For key viral pathogens such as WSSV, TSV, and DIV1, the lack of stable and applicable cell culture systems limits the effectiveness of traditional isolation and culture-based methods (Lee et al., 2023). Furthermore, culture-based techniques have limited ability to detect Vibrio spp. in the viable but non-culturable (VBNC) state, often underestimating the actual pathogen load (Bohara et al., 2023).

Conventional methods are also constrained by long detection cycles. Histopathology, microbial culture, and serological assays typically require several days to weeks and depend on specialized laboratories and trained personnel, which is inadequate in rapidly evolving disease scenarios (Bohara et al., 2023). In screening broodstock, seedstock, and asymptomatic carriers, these methods often fail to detect low-level infections, even though such carriers play a critical role in disease transmission (Zwetlana et al., 2023). Therefore, with the expansion of intensive aquaculture and global trade, traditional diagnostic approaches are no longer sufficient for precise diagnosis and early warning, driving the development of highly sensitive molecular and rapid detection technologies.

4.2 Molecular and immunological detection technologies

The widespread application of molecular biology has significantly advanced shrimp disease diagnostics from empirical observation to standardized and highly sensitive detection. Among these, nucleic acid amplification techniques have become the cornerstone of pathogen detection. Conventional PCR, nested PCR, quantitative real-time PCR (qPCR), loop-mediated isothermal amplification (LAMP), and recombinase polymerase amplification (RPA) have been widely applied for detecting major pathogens, including WSSV, IHHNV, DIV1, TSV, YHV, IMNV, as well as AHPND-causing Vibrio and EHP (Lee et al., 2023; Lou et al., 2025). These methods enable the detection of low-abundance nucleic acids, allowing early identification of pathogens during latent or initial infection stages, thereby supporting timely management decisions.

Among nucleic acid-based methods, qPCR has become the most widely used due to its high sensitivity, specificity, and quantitative capability. For example, standardized qPCR systems have been established for WSSV detection, while multi-target real-time PCR assays have been developed for emerging viruses such as DIV1, enabling dynamic monitoring and early warning (Lee et al., 2023). Similarly, PCR and qPCR have demonstrated high reliability and reproducibility in detecting bacterial and microsporidian pathogens such as AHPND-causing Vibrio and EHP (Lou et al., 2025).

Recent developments have further improved the efficiency and practicality of molecular detection. Direct PCR techniques eliminate the need for nucleic acid extraction, thereby shortening detection time and reducing contamination risks. In addition, multiplex qPCR enables simultaneous detection of multiple pathogens. For instance, a five-plex qPCR assay can detect WSSV, IHHNV, DIV1, AHPND-causing Vibrio, and EHP in a single reaction, with a detection limit of 10 copies/μL and high specificity validated in large-scale studies (Lou et al., 2025). These advances significantly enhance detection efficiency in complex disease systems involving multiple pathogens.

4.3 Rapid detection and intelligent monitoring technologies

In recent years, shrimp disease detection technologies have shifted from centralized laboratory-based systems toward field-based and rapid diagnostic approaches. Given the rapid transmission and short response window of aquaculture diseases, technologies that enable on-site detection within a short time frame have become a major focus of research and application (Bohara et al., 2023). These methods emphasize simplicity, rapid response, and minimal equipment requirements, providing immediate support for on-site management decisions.

Among rapid molecular detection methods, isothermal amplification technologies show great potential. RPA, in particular, has attracted attention due to its low reaction temperature, fast processing time, and minimal equipment requirements. For example, RPA combined with lateral flow strip (RPA-LFS) can detect WSSV within approximately 30 minutes at 37 °C, with a detection sensitivity of around 20 copies and results consistent with qPCR. Similar approaches have been applied for detecting AHPND and EHP, with detection times of 20-35 minutes and sensitivity ranging from 10 to 100 copies. These techniques do not require complex thermal cycling equipment, making them suitable for field applications.

In terms of detection platforms and monitoring systems, current developments are moving toward integration and intelligence. Microfluidic chip technology enables the integration of nucleic acid amplification and signal detection into a single platform, allowing simultaneous detection of multiple pathogens. For example, microfluidic-based RPA systems can complete multi-pathogen detection within approximately 20 minutes (Li et al., 2023). In addition, CRISPR-based diagnostics combined with LAMP amplification can achieve highly sensitive detection within 30 minutes and support visual readouts (Major et al., 2023). Furthermore, biosensors, environmental DNA (eDNA) detection, and monitoring systems based on the Internet of Things (IoT) and artificial intelligence are increasingly being applied in aquaculture management (Figure 2) (Bohara et al., 2023; Zwetlana et al., 2023). By integrating water quality parameters, pathogen data, and behavioral information, these systems enable disease risk assessment and early warning. Overall, disease detection technologies are evolving from single-point diagnostics toward integrated systems featuring real-time monitoring, risk prediction, and precision intervention.

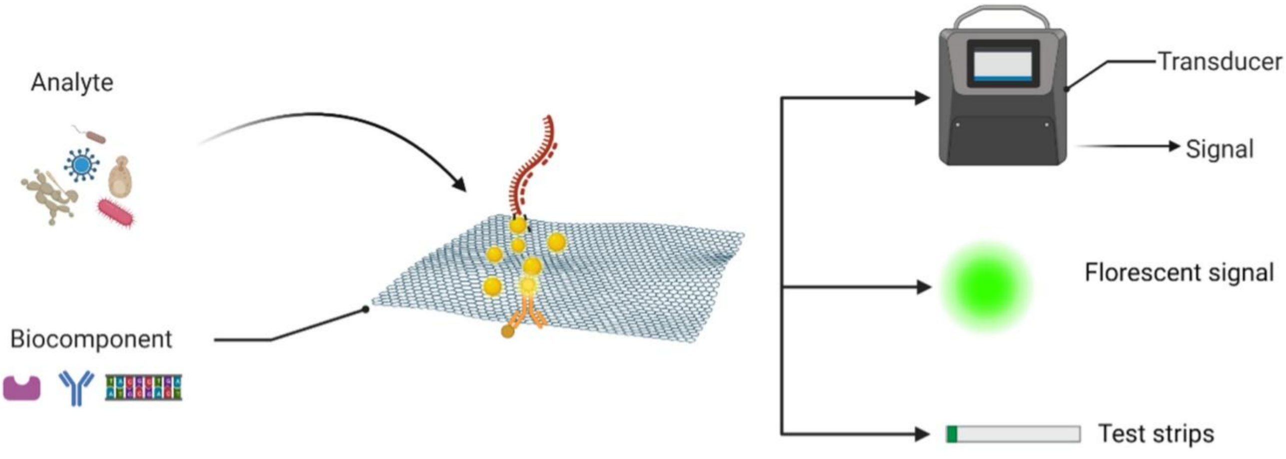

Figure 2 A chronological overview of disease diagnostic tool development (Adopted from Bohara et al., 2023)

5 Key Technologies for Disease Prevention and Control in Shrimp Aquaculture

5.1 Aquaculture management and ecological regulation

Aquaculture management and ecological regulation constitute the fundamental strategies for disease prevention and control in shrimp farming. Their core objective is to establish a stable aquaculture system characterized by low stress and low pathogen load through environmental optimization, standardized management practices, and reduced pathogen introduction risks. In recent years, disease control strategies have shifted from traditional drug-based treatments toward integrated management approaches centered on ecological regulation and biosecurity (Kumar et al., 2025). In this context, biosecurity systems based on specific pathogen-free (SPF) seedstock are widely regarded as a critical component of disease prevention. Strengthening quarantine measures, pathogen screening, and health assessments of broodstock and larvae can effectively reduce the introduction of major pathogens such as WSSV and AHPND at the source (Kumar et al., 2025).

During farming operations, appropriate stocking density remains a key factor in reducing disease incidence. Although high-density farming increases production per unit area, it also elevates contact frequency, water quality fluctuations, and chronic physiological stress, thereby facilitating pathogen transmission and disease outbreaks. Therefore, stocking density should be scientifically determined based on system carrying capacity, combined with adequate aeration, water exchange, and precision feeding management to maintain host health and reduce disease risks (Kumar et al., 2025). Water quality regulation is another critical component of ecological disease control. Maintaining parameters such as dissolved oxygen, pH, ammonia, and nitrite within optimal ranges helps alleviate physiological stress and suppress the proliferation of opportunistic pathogens such as Vibrio spp.

Sediment management also plays an important role in disease control. The accumulation of organic matter, including uneaten feed, feces, and dead algae, creates favorable conditions for pathogen proliferation, particularly benthic Vibrio and anaerobic metabolites that can negatively affect shrimp health. Measures such as pond sediment removal, the use of sediment conditioners, and the installation of settling systems can effectively reduce pathogen loads and improve system stability (Kumar et al., 2025). In recent years, ecological regulation has extended to the microbial level. Studies indicate that regulating water and gut microbiota composition can help maintain immune homeostasis and enhance disease resistance (Harpeni et al., 2024). In addition, comprehensive biosecurity practices—including water source disinfection, facility management, and personnel zoning—are essential for minimizing pathogen introduction and are integral to sustainable shrimp farming systems (Kumar et al., 2025).

5.2 Antibiotic alternatives and microbial regulation

Antibiotics have historically played a role in disease control in shrimp aquaculture; however, their overuse has led to increasing concerns regarding antimicrobial resistance, drug residues, and ecological risks. Consequently, antibiotic-free farming and alternative strategies have become major research and application priorities (Noman et al., 2024). In this context, environmentally friendly disease control approaches based on microbial regulation have rapidly developed, with probiotics, prebiotics, synbiotics, and biofloc technology emerging as key strategies.

Probiotic application is one of the most widely used microbial regulation methods. Beneficial microorganisms such as Bacillus, lactic acid bacteria, and Pseudomonas can be introduced into feed or water to inhibit pathogen colonization through competitive exclusion, competition for nutrients and adhesion sites, and the production of antimicrobial substances. Additionally, probiotics can modulate host immune responses and improve gut health (Tamilselvan and Raja, 2024). Studies have shown that probiotics enhance growth performance, survival rates, and stress resistance, thereby reducing reliance on antibiotics (Muthu et al., 2024). However, their effectiveness is influenced by factors such as strain selection, dosage, and environmental conditions, highlighting the need for standardized and optimized application strategies (Noman et al., 2024).

In addition to probiotics, prebiotics and synbiotics also play important roles in microbial regulation. Prebiotics promote the growth and colonization of beneficial microbiota, thereby enhancing gut microbial stability, while synbiotics combine the synergistic effects of probiotics and prebiotics to further improve host immunity and metabolic functions (Noman et al., 2024). Biofloc technology (BFT) represents a system-level application of microbial regulation. By adjusting the carbon-to-nitrogen ratio, BFT promotes the growth of heterotrophic microorganisms that convert nitrogenous wastes into microbial biomass, thereby improving water quality and reducing toxic compounds (Harpeni et al., 2024). The resulting bioflocs also serve as supplementary nutrition and help stabilize microbial communities, suppressing pathogen proliferation. Studies have demonstrated that microbial consortia derived from native microbiota can effectively reduce AHPND incidence and improve shrimp growth performance (Figure 3) (Guo et al., 2023). Microbial regulation strategies are shifting disease control approaches from pathogen suppression to ecological balance restoration.

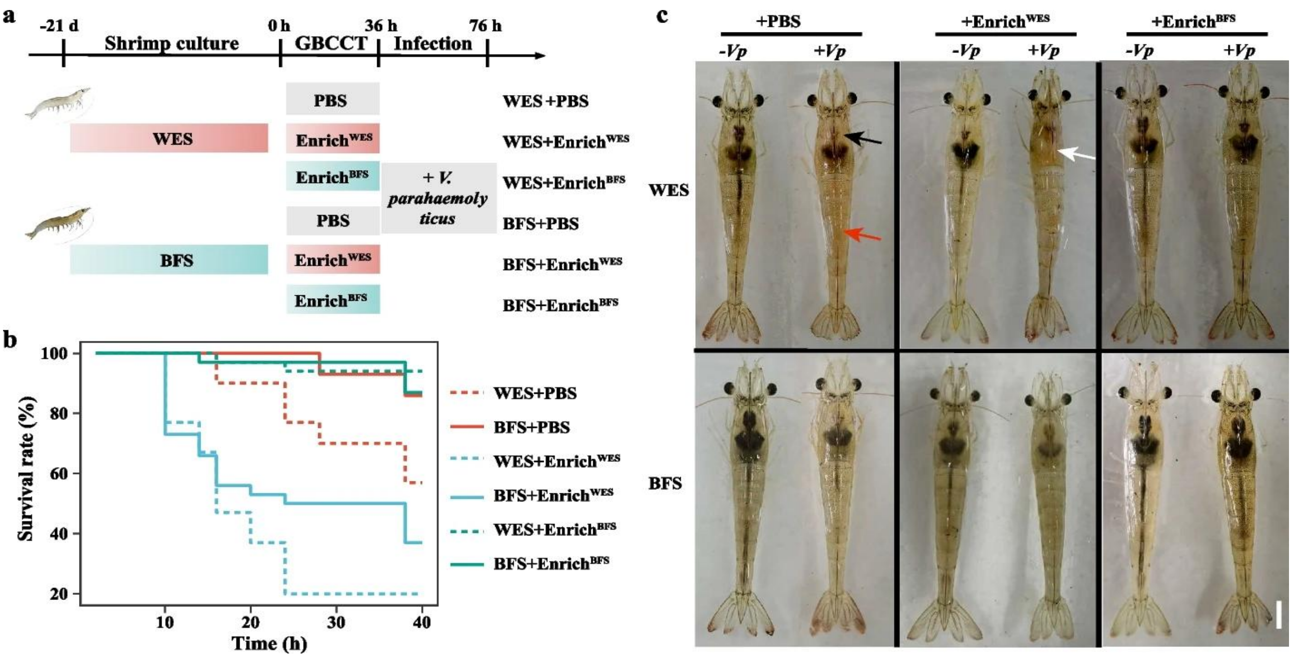

Figure 3 The Vibrio infection resistance, and phenotypic characteristics of shrimp after cross-transplantation of bacterial consortia enriched from WES and BFS shrimp (Adopted from Guo et al., 2023)

Image caption: (a) Schematic diagram of the experimental procedure. The bacterial consortia were obtained from the shrimp cultured in the WES and BFS for 21 days, and the bacterial consortia were cross-transplanted to WES and BFS shrimp. After 36h of cross-transplantation, the shrimp that received PBS and bacterial consortia were infected by the pathogenic Vibrio parahaemolyticus. (b) The effects of cross-transplantation on the shrimp survival curves after infection; c Phenotypic characteristics of shrimp after infection. Black, white, and red arrows indicate the stomach, hepatopancreas, and gut of shrimp in (c), respectively. Bar=1 cm in (c); WES, Water exchange system; BFS, Biofloc system; PBS, Phosphatic buffer solution; EnrichWES, Bacterial consortium obtained from WES shrimp; EnrichBFS, Bacterial consortium obtained from BFS shrimp; -Vp, non-Vibrio infection; + Vp, Vibrio infection (Adopted from Guo et al., 2023)

5.3 Immunoregulation and genetic breeding

Due to the absence of a typical adaptive immune system in shrimp, conventional vaccination strategies are limited in their ability to provide long-term protection. Therefore, enhancing innate immunity and improving host resistance through genetic approaches have become key strategies for long-term disease control. Immunoregulation techniques aim to enhance host resistance through immune priming and functional additives. Common immunostimulants include polysaccharides derived from plants, algae, and microorganisms, as well as vitamins and minerals. These compounds can activate pattern recognition receptors, regulate signaling pathways such as NF-κB, and upregulate antimicrobial peptide expression, thereby improving resistance to WSSV and Vibrio infections.

In recent years, the concept of “trained immunity” has gained increasing attention in shrimp health management. Studies suggest that early stimulation or nutritional interventions can induce an enhanced innate immune state, thereby improving resistance to subsequent infections. Furthermore, broodstock nutrition and epigenetic regulation may influence offspring resistance, providing new perspectives for disease prevention (Wikumpriya et al., 2023). Mechanisms such as DNA methylation, histone modification, and non-coding RNA regulation are believed to play roles in immune gene expression and transgenerational resistance (Wikumpriya et al., 2023).

In terms of genetic breeding, the development of disease-resistant strains offers a long-term and stable solution for disease control. Traditional selective breeding has already achieved progress in certain cultured populations. With advances in molecular technologies, approaches such as marker-assisted selection (MAS), genomic selection, and genome-wide association studies (GWAS) are increasingly applied to elucidate disease resistance traits. Studies indicate that resistance to WSSV in Litopenaeus vannamei exhibits relatively high heritability, demonstrating the feasibility of genetic improvement (Nguyen, 2024). In addition, emerging technologies such as RNA interference and CRISPR/Cas provide new tools for understanding disease resistance mechanisms and enabling precise genetic improvement. However, their practical application must consider ecological safety, regulatory frameworks, and cost factors (Wikumpriya et al., 2023). Overall, immunoregulation and genetic breeding are driving disease control strategies toward a host-centered approach focused on enhancing resistance.

6 Typical Prevention and Control Models and Practical Applications

6.1 Green ecological farming model

Eco-friendly shrimp aquaculture models achieve disease control by stabilizing pond ecosystems, reducing pathogen pressure, and minimizing chemical inputs. Integrated multi-trophic aquaculture (IMTA) and polyculture systems combine shrimp with fish, shellfish, and/or seaweeds, enabling nutrient recycling, improving water quality, and reducing the accumulation of opportunistic pathogens, thereby enhancing system stability (Arriesgado et al., 2025; Uddin et al., 2025). Studies have shown that IMTA systems in China exhibit diverse combinations, such as shrimp–crab, fish, sea cucumber, jellyfish, and shellfish, which can be optimized according to local ecological conditions. These systems not only improve resource utilization efficiency and reduce waste discharge but also significantly enhance economic returns compared to monoculture systems, while lowering disease risks and environmental pressure (Uddin et al., 2025). Furthermore, IMTA effectively removes excess nutrients, balances nutrient budgets, and reduces carbon emissions, making it an important approach for achieving both environmental and economic sustainability (Uddin et al., 2025).

Polyculture systems also serve as effective ecological disease control strategies. For example, a fish–shrimp co-culture model developed in China introduces specific fish species that actively consume dead or moribund shrimp, thereby interrupting the transmission of white spot syndrome virus (WSSV) within ponds. This approach does not require complex biosecurity infrastructure, is easy to implement, and is suitable for small- and medium-scale farmers. It has been widely adopted in China, effectively reducing WSS-related losses while increasing overall production. In addition, green water systems, biofloc technology, and the application of probiotics and prebiotics are considered effective alternatives for controlling bacterial diseases such as vibriosis. These approaches not only improve water quality but also promote growth, enhance stress resistance and disease resistance, and reduce environmental pollution (Noman et al., 2024; Arriesgado et al., 2025; Kumar et al., 2025).

6.2 Industrialized and recirculating aquaculture systems (RAS)

At the other end of the intensification spectrum, industrialized aquaculture and recirculating aquaculture systems (RAS) achieve disease control through enhanced biosecurity and environmental regulation. The future of sustainable shrimp farming lies in the development of efficient, biosecure systems based on SPF seedstock and genetically improved strains, combined with strict pathogen monitoring and quarantine measures throughout the production cycle. RAS and inland closed systems reduce reliance on open water sources and minimize contact with wild hosts. At the same time, indoor environmental control stabilizes key parameters such as temperature and salinity, thereby reducing pathogen exposure and disease risks associated with climate variability (Kumar et al., 2025). Although RAS offers advantages such as water conservation, high productivity, and reduced ecological impacts (e.g., habitat destruction, eutrophication, and escape events), its high energy consumption and capital costs limit its widespread adoption, particularly in developing countries.

Technological innovations are improving the sustainability and disease resistance of intensive aquaculture systems. For example, a high-density, low-salinity culture system for Litopenaeus vannamei integrating zero water discharge (ZWD) and RAS has demonstrated the ability to maintain good water quality at stocking densities up to 1000 individuals/m^3, with optimal survival and feed conversion efficiency achieved at 500 individuals/m^3, indicating strong potential for urbanized inland aquaculture. Membrane-based RAS (MRAS), incorporating microfiltration, ultrafiltration, and membrane bioreactors, can effectively remove suspended solids, toxic substances, pathogens, and excess nutrients, thereby improving water reuse efficiency and reducing environmental impacts. However, membrane fouling, energy consumption, and operational costs remain key challenges (Widiasa et al., 2023). In addition, maintaining the stability of filtration systems is critical; for instance, studies have shown that certain antimicrobial agents can suppress Vibrio without affecting nitrifying bacteria or shrimp health, highlighting the need for disease control strategies compatible with RAS systems.

6.3 Successful cases and integrated control strategies

Sustainable disease control increasingly relies on integrated management approaches. Case studies from Asia indicate that repeated outbreaks of WSSV and AHPND have driven a transition from traditional flow-through pond systems to more closed and controlled systems. By incorporating water storage ponds, wastewater treatment systems, reduced water exchange, and RAS components, higher levels of biosecurity can be achieved (Kumar et al., 2025). In China, the widespread adoption of IMTA and polyculture systems has not only increased production but also reduced wastewater treatment costs and alleviated disease and environmental pressures, demonstrating both economic and ecological benefits (Uddin et al., 2025). Similarly, an IMTA trial in the Philippines showed that co-culturing tiger shrimp with fish, seaweed, and shellfish reduced pathogen loads, prevented AHPND occurrence, lowered WSS outbreaks, and significantly improved total production, net income, and return on investment (Arriesgado et al., 2025). These findings highlight the practical value of IMTA in both disease control and economic performance.

At the technical and management levels, integrated disease control strategies are equally critical. Studies emphasize the need to combine SPF/SPR seedstock, biosecurity measures, molecular diagnostics, and antibiotic-free approaches such as probiotics, immunostimulants, nanotechnology, and biological control methods (Bondad-Reantaso et al., 2023; Noman et al., 2024). Aquaculture systems based on water recirculation and reuse, combined with non-antibiotic antimicrobial strategies, are considered effective pathways to reduce antimicrobial resistance risks and achieve sustainability goals (Bondad-Reantaso et al., 2023; Natrah et al., 2025). In addition, sensor-based automated systems can regulate the application of probiotics and water conditioners based on real-time water quality and microbial data, thereby reducing organic load and pathogen levels, improving water quality, and lowering labor costs (Kumar et al., 2025).

7 Challenges and Future Issues

7.1 Pathogen variation and emerging disease risks

With the continuous expansion of shrimp aquaculture and the increasing intensity of high-density farming and transregional trade, pathogen evolution and emerging disease risks have become major challenges to the sustainable development of the industry. Previous studies indicate that shrimp diseases are not static but represent a dynamic system that evolves under the combined influences of industry expansion, ecological disturbances, and global trade. Viral pathogens, in particular, exhibit high mutation rates and transmission efficiency, and under changing host and environmental conditions, they tend to show increased virulence, expanded host range, and cross-regional dissemination. Since the 20th century, major viral diseases such as white spot syndrome virus (WSSV), yellow head virus (YHV), infectious myonecrosis virus (IMNV), and the recently emerging DIV1 have caused repeated outbreaks and sustained impacts across multiple aquaculture regions. Continuous emergence of new viruses and ongoing evolution of existing ones impose persistent challenges on current diagnostic systems and control strategies.

In this context, the transboundary movement of seedstock and live aquatic products, expansion of aquaculture into new regions, and environmental fluctuations driven by climate change create favorable conditions for pathogen spread and adaptation. Meanwhile, emerging bacterial and microsporidian diseases further increase the complexity of the disease spectrum. Pathogens such as AHPND-causing Vibrio and Enterocytozoon hepatopenaei (EHP) often occur as co-infections, leading to higher mortality and greater challenges in diagnosis and control. Field investigations indicate that multi-pathogen coexistence and alternating outbreaks are common in aquaculture systems. In addition, intensive farming practices, antibiotic selection pressure, and rising water temperatures may accelerate pathogen adaptation and evolution (Nguyen, 2024). Therefore, reliance on single-pathogen-based or fixed control strategies is no longer sufficient. Strengthening molecular epidemiological surveillance, pathogen tracing, and cross-regional early warning systems is essential to improve the identification and response capacity for emerging and evolving pathogens (Bhassu et al., 2024).

7.2 Antibiotic misuse and antimicrobial resistance

Antibiotics have long been used in shrimp aquaculture for disease prevention and treatment, and in some regions even for growth promotion. Although this practice may alleviate disease pressure in the short term, it has led to significant concerns regarding antimicrobial resistance (AMR), drug residues, and ecological risks (Bondad-Reantaso et al., 2023; Devadas et al., 2023). Studies have shown that various antibiotics, including fluoroquinolones, tetracyclines, and sulfonamides, are still used in shrimp farming, with some of these substances restricted or banned in food-producing animals. The frequent and often suboptimal use of these antibiotics increases the selection pressure for resistant bacteria and resistance genes within aquaculture systems (Devadas et al., 2023).

Additionally, aquaculture effluents interact with pollutants from urban, livestock, and medical sources, turning aquaculture environments into hotspots for the dissemination and exchange of resistance genes. This phenomenon reflects a typical “One Health” issue, where aquatic environments, animal health, and human health are closely interconnected (Natrah et al., 2025). The rise of antimicrobial resistance not only reduces treatment efficacy but also complicates disease management. For instance, Vibrio strains associated with AHPND may harbor multiple resistance genes, thereby limiting the effectiveness of antimicrobial treatments (Devadas et al., 2023). Moreover, antibiotic use disrupts aquatic and gut microbiota, suppresses beneficial bacteria, and promotes opportunistic pathogens, creating a reinforcing cycle of disease pressure and drug dependence. Therefore, integrated strategies—including strengthened biosecurity, adoption of alternative technologies, monitoring of residues and resistance, and farmer training—are essential to reduce antibiotic reliance and mitigate associated risks (Bondad-Reantaso et al., 2023; Natrah et al., 2025).

7.3 Insufficient technology transfer and standardization

Despite significant advances in shrimp disease prevention technologies—such as SPF/SPR seedstock, molecular diagnostics, ecological aquaculture, and genomic approaches—their application at the production level remains limited. In many aquaculture regions, insufficient laboratory capacity, limited infrastructure, and a shortage of skilled personnel hinder the effective translation of advanced technologies into practical tools for farmers (Zwetlana et al., 2023; Bhassu et al., 2024; Nguyen, 2024). Furthermore, the predominance of small- and medium-scale farms, coupled with limited financial and technical resources, often leads farmers to rely on low-cost and experience-based management practices rather than investing in high-standard biosecurity and diagnostic systems. Studies indicate that barriers to the transition toward sustainable aquaculture are not solely technological but also involve institutional, financial, informational, and supply chain constraints.

In addition, insufficient technology dissemination is closely linked to gaps in training and standardization systems. In many regions, farmers lack adequate training in pathogen detection, risk assessment, and standardized management, limiting the effectiveness of available technologies (Zwetlana et al., 2023). The absence of unified standards for seedstock management, water quality control, and antimicrobial use further restricts data comparability and knowledge transfer across regions (Devadas et al., 2023). Even advanced technologies such as genetic breeding and genome editing face challenges related to ecological safety, regulatory requirements, and public acceptance (Nguyen, 2024). Therefore, promoting technology standardization, regional adaptation, and demonstration-based dissemination is essential for transforming research outcomes into practical productivity gains in shrimp aquaculture.

8 Future Trends and Perspectives

Future strategies for disease prevention and control in shrimp aquaculture are gradually moving away from reliance on antibiotics toward integrated approaches centered on ecological sustainability and multi-target regulation. These approaches aim to enhance host resistance while reducing pathogen pressure. Emerging technologies, including nanomaterials, plant-derived bioactive compounds, algal extracts, probiotics, prebiotics, synbiotics, biofilm-based vaccines, bacteriophage therapy, quorum sensing inhibition, RNA interference, and DNA/physicochemical biosensors, have shown great potential as alternatives to traditional chemical treatments. These innovations can maintain productivity while minimizing the risk of antimicrobial resistance. In addition, immunostimulants and antiviral compounds derived from plants, animals, and synthetic sources, when combined with strict disinfection measures, can effectively and safely enhance innate immunity in shrimp, particularly for the control of WSSV. Epigenetic regulation and "trained immunity" represent promising research frontiers, offering the potential to achieve heritable or long-term disease resistance through modulation of immune gene expression. Furthermore, microbiome-based engineering strategies, such as customized probiotics, synthetic microbial consortia, and fecal microbiota transplantation, are expected to become key components of future disease control, although their ecological adaptability, safety, and resilience to climate change require further investigation.

With the rapid development of the Internet of Things (IoT), artificial intelligence (AI), and their integration (AIoT), shrimp health management is increasingly shifting toward precision aquaculture. Sensor- and microcontroller-based monitoring systems can now provide real-time measurements of key water quality parameters, including temperature, pH, salinity, turbidity, total dissolved solids (TDS), and electrical conductivity. These systems enable remote management, anomaly detection, and automated regulation (e.g., aeration and chemical dosing) through cloud platforms and mobile applications. Machine learning models, including regression and classification algorithms, have been successfully applied to predict water quality changes and evaluate production performance with high accuracy, allowing early intervention to reduce mortality and optimize yields. Studies indicate that the integration of AIoT with precision aquaculture enables intelligent decision-making in feed management, disease monitoring, biomass estimation, and environmental regulation through the combination of sensor data, AI analytics, and remote sensing technologies. However, high investment costs, data privacy concerns, and limitations in model generalization remain key challenges. Additionally, emerging "smart dosing systems" can automatically apply probiotics and water quality regulators based on microbial and environmental data, effectively reducing organic load and pathogen levels in biofloc systems while lowering labor costs and improving sustainability.

Overall, existing studies suggest that future shrimp disease control will evolve toward comprehensive systems centered on biosecurity, integrating host, pathogen, environmental, and management factors. Sustainable shrimp aquaculture will depend on high-level biosecure facilities, the use of SPF seedstock and genetically improved disease-resistant strains, and the implementation of efficient pathogen monitoring systems and rapid diagnostic technologies, such as high-throughput sequencing, CRISPR-based detection, and culture-independent biosensors. Current research emphasizes the need to establish dynamic, risk-based management frameworks that integrate physical, biological, and operational biosecurity measures with emerging technologies and multi-stakeholder collaboration. Key future research directions include microbiome-based disease regulation, genetic and epigenetic improvement of disease resistance, detection technologies for emerging pathogens, and the development of climate-resilient aquaculture systems, such as IMTA, RAS, and hybrid models. The integration of green control technologies, precision monitoring, genetic breeding, epigenetic regulation, and comprehensive biosecurity systems will facilitate the transition of shrimp aquaculture from traditional "reactive treatment" to a "prevention-oriented and system-regulated" health management model, thereby ensuring long-term sustainability and contributing to global food security.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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