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Dynamic modeling analysis of oxygen solubility levels in shrimp aquaculture ponds

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Abstract

Dissolved oxygen is a crucial parameter in shrimp aquaculture. The objective of this research is to determine the level of oxygen solubility and its impact on the intensive shrimp farming cycle based on dynamic modeling system analysis. The research method employed a causal ex-post facto design concept and data analysis using dynamic modeling systems. The results indicate that water quality parameters during the shrimp culture period are relatively stable, including pH (7.9-8.0), salinity (28 gr/L), DO (5.25-5.31 mg/L), temperature (29.8-30°C), CO3 (4-11 mg/L), HCO3 (98-103 mg/L), CaCO3 (106-110 mg/L), PO4 (0.199-0.380 mg/L), NO2 (0.053-0.093 mg/L), TAN (0.025-0.071 mg/L), organic matter (82.42-87.15 mg/L), and total bacteria (1.06E+05-2.76E+05 cell/ml). The oxygen solubility level in the model description is depicted as oscillating with concentrations ranging 0.00-7.00 mg/L/hour. The majority of oxygen solubility is obtained from the use of paddle aerators, capable of producing oxygen within the range of 0.5-8.0 mg/L. The estimated amount of aquaculture waste ranges from 2,500-7,500 g/m2. The highest oxygen carrying capacity for waste decomposition is 9 mg/L. Shrimp growth rate will decline to 0.00 gr/day when dissolved oxygen remains stagnant. The estimated shrimp harvest biomass based on dissolved oxygen carrying capacity and dynamic model analysis is 6 tons/ha. The conclusion, dissolved oxygen solubility fluctuates dynamically and exhibits a significant correlation with aquaculture waste accumulation, as well as with the subsequent reduction in shrimp growth rates under suboptimal environmental conditions. The fluctuation in oxygen solubility follows the temperature distribution pattern and the intensity of paddle aerator usage in the ponds.

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Keywords

Carrying capacity, Paddle aerator, Hypoxia, Pond, Waste

Introduction

Dissolved oxygen is one of the most important parameters in shrimp aquaculture [1], [2]. The level of oxygen solubility in aquaculture ponds occurs dynamically [3]. Dynamic oxygen fluctuations have a significant impact on the life of cultured organisms in ponds [4]. Shrimp are highly mobile organisms and respond expressively to changes in oxygen concentration in their environment [5], [6]. Shrimp actively utilize oxygen for respiration and metabolic processes [7].

Dissolved oxygen in pond ecosystems has a substantial influence on water quality dynamics [8]. Stable dissolved oxygen levels ensure that biochemical processes in water proceed properly [9], [5]. Oxygen in aquatic environments is used for various processes such as assimilation, decomposition, and respiration [10]. Low dissolved oxygen concentrations can lead to hypoxic conditions [11]. The toxicity of ammonia (NH_3) and nitrite (NO_2^+) increases when dissolved oxygen levels fall below 4 mg/L [12].

To date, limited studies have developed dynamic modeling approaches based on causal loop frameworks to systematically analyze the interrelated feedback mechanisms among dissolved oxygen dynamics, organic waste accumulation, and shrimp growth within pond aquaculture ecosystems. Given the critical importance of oxygen dynamics in pond waters, it is necessary to conduct research that estimates and analyzes the magnitude of oxygen fluctuations. Therefore, the objective of this study is to determine oxygen solubility levels and their effects on intensive shrimp farming cycles based on dynamic system modeling analysis. This research is expected to produce a conceptual model describing oxygen solubility dynamics in shrimp ponds for aquaculture engineering applications.

The novelty of this research lies in the development of an integrated dynamic system model that explicitly links dissolved oxygen fluctuations, organic waste accumulation, and shrimp growth within a single causal loop framework. Unlike previous studies that primarily examined oxygen dynamics or water quality parameters in isolation, this study conceptualizes pond ecosystems as interconnected feedback systems in which oxygen solubility, metabolic demand, and nitrogenous waste transformation interact continuously over the production cycle. By quantifying oxygen fluctuation magnitudes and simulating their systemic impacts on intensive shrimp culture, this research advances a predictive and engineering-oriented modeling approach. The resulting conceptual model not only enhances theoretical understanding of oxygen-driven feedback mechanisms in pond ecosystems but also provides a practical decision-support basis for optimizing aeration strategies and water quality management in intensive aquaculture systems.

Method

This study was conducted in intensive shrimp culture ponds operated by PT. Manunggal Setia Makmur, Probolinggo, from February to May 2020, covering one complete shrimp farming cycle. The research employed a causal ex-post facto design with data collection using purposive sampling. The causal ex-post facto research design was applied to examine cause effect relationships based on existing empirical data without manipulating research variables. Historical data on water quality, dissolved oxygen dynamics, waste accumulation, and shrimp growth were analyzed to construct a causal structure, which was subsequently formulated into causal loop diagrams and stock–

flow models. This approach enables feedback mechanisms within the system to be quantitatively represented and empirically validated, thereby enhancing the accuracy and reliability of dynamic simulation in shrimp aquaculture ecosystems.

Primary data were obtained from field observations and included water quality parameters such as temperature, pH, dissolved oxygen, salinity, nitrite, organic matter, Total Ammonia Nitrogen (TAN), phosphate, CO_3, HCO_3, alkalinity, and total bacterial abundance. Supporting data consisted of shrimp body weight, stocking density, and feed input, which were tabulated for analysis. Water quality parameters were measured routinely every morning and afternoon. Supporting data, including shrimp body weight, stocking density, and feed input, were collected in a structured manner once a week through sampling using a drag net.

Data analysis, water quality parameters were measured at the Water Quality Laboratory of PT. Manunggal Setia Makmur, while secondary data were obtained from the shrimp culture logbook reports. All data were compiled according to the research indicators and analyzed using dynamic system modeling with the assistance of Stella software version 9.02. In dynamic modeling analysis, the process of inputting model data, validating the model and running the analysis results will be carried out, which will then be studied scientifically as the output of this research.

Model validation in dynamic modeling analysis for estimating dissolved oxygen (DO) solubility levels in intensive shrimp ponds is conducted systematically through structural, mathematical, and empirical approaches. The initial stage involves verifying the model structure by ensuring that the causal loop diagrams and stock–flow formulations are consistent with mass balance principles, water quality dynamics theory, and biological mechanisms such as shrimp respiration, organic matter decomposition, and nitrification processes. Dimensional consistency testing is subsequently performed to ensure that all mathematical equations maintain appropriate unit conformity, thereby preventing formulation errors. Historical behavior validation is carried out by comparing simulation patterns and trends with field observation data collected throughout the culture cycle, particularly concerning DO fluctuations, shrimp biomass, and organic load dynamics. The model is further evaluated through sensitivity analysis to identify the most influential parameters affecting DO dynamics, as well as through extreme condition tests to ensure logical system responses under boundary scenarios. The final stage includes empirical parameter calibration and robustness testing across various management scenarios, thereby enhancing the models reliability as a predictive and decision-support tool in intensive shrimp aquaculture systems.

Results

The causal loop model describing the dynamic relationship between oxygen solubility and the operational cycle of shrimp farming in pond ecosystems was developed based on theoretical studies and analysis of field conditions. Causal loop analysis was applied for visual and descriptive data assessment according to the conceptual model design [20]. Within the causal loop model, data were transformed from descriptive diagrams into analytical data [21]. The causal loop model illustrating the dynamic relationship between oxygen solubility and the operational cycle of shrimp farming.

In this causal loop model, two interacting systems were established. The first system describes oxygen production generated by paddle aerators, while the second system represents the formation of shrimp biomass cultured in the ponds. The oxygen production capacity of paddle aerators in pond waters is strongly influenced by electrical power input and engine capacity [22]. The use of paddle aerators in intensive shrimp farming is specifically intended to minimize the impact of massive declines in dissolved oxygen levels [23].

Dissolved oxygen production levels

Dissolved oxygen production in pond ecosystems originates from several sources, including photosynthetic activity, paddle aerator operation, and diffusion processes. The intensity of paddle aerator use plays a critical role in oxygen production in intensive shrimp ponds [24]. Paddle aerators are capable of producing dissolved oxygen at levels ranging from a maximum of 8 mg/L to a minimum of 0.5 mg/L. The highest oxygen carrying capacity in the pond reached 9 mg/L, occurring during the second week of the culture period. The effectiveness of paddle aerator operation declined during the third week of cultivation, followed by a simultaneous decrease in oxygen solubility within a similar time frame. These findings are consistent with the results reported by Tanveer et al. (2018), indicating that paddle aerator effectiveness fluctuates depending on aerator specifications and energy output.

Dissolved oxygen levels in the pond experienced their lowest decline when the culture period exceeded 50 days. The highest oxygen solubility, approximately 7.5 mg/L, occurred during the early cultivation phase and subsequently decreased as shrimp biomass increased. Higher shrimp growth rates result in increased oxygen consumption to meet metabolic demands [25]. *Litopenaeus vannamei* is a poikilothermic species and is therefore highly sensitive to changes in temperature and oxygen solubility within its habitat [26]. A decline in shrimp growth rate was observed at 35 days of culture, which was likely associated with decreasing dissolved oxygen levels in the pond. Hypoxic water conditions exert a synergistic negative effect on shrimp growth rates [26]. Uncontrolled post larval stocking density also contributes to a massive decline in dissolved oxygen concentrations in pond waters [27]. Appropriate paddle aerator usage based on pond carrying capacity and proper aerator placement significantly influences oxygen solubility stability in shrimp ponds [22]. Oxygen solubility in ponds is influenced by temperature distribution and paddle aerator intensity [26]. Interactions among hydrogen micromolecules and electrostatic effects generated by paddle aerator movement promote homogeneity within the water column [37]–[39]. This water column homogeneity contributes to temperature stability in shrimp ponds [40], [41].

Based on these findings, the managerial implication is that paddle aerator operation should be strategically designed according to pond carrying capacity, shrimp growth phase, and biomass dynamics, with appropriate adjustments in aeration intensity and aerator placement to maintain dissolved oxygen stability throughout the culture cycle. Pond managers need to increase aeration control during the mid to late culture stages (≥50 days), when oxygen consumption rises due to biomass accumulation and the risk of hypoxia becomes more pronounced. In addition, post larval stocking density must be aligned with the aeration systems capacity to prevent drastic declines in dissolved oxygen levels. Optimizing aeration functions not only as a means of oxygen supply but also as an environmental engineering tool to promote water column homogeneity and temperature stability, thereby sustaining shrimp growth performance and enhancing the overall productivity of intensive pond systems in a sustainable manner.

Dynamic model of dissolved oxygen fluctuations

Dynamic system modeling indicates that oxygen solubility is correlated with waste load accumulation. The continuous decline and stagnation of oxygen solubility during the fifth week of cultivation affected a reduction in aquaculture waste of approximately 2,500 g/m^2. This suggests that declining dissolved oxygen levels are largely utilized for organic matter decomposition. Oxygen consumption in aquatic systems is partly driven by organic matter decomposition processes [41]. Organic waste accumulation increases with higher aquaculture input levels [42]. Excessive waste discharge into pond ecosystems negatively affects water quality conditions [43]. Shrimp ponds are typically associated with high waste loads due to extended culture periods [44].

Based on dynamic model analysis, oxygen solubility also influences shrimp growth rates. When oxygen solubility decreases and becomes stagnant, shrimp growth rates decline correspondingly. Shrimp growth rate approaches 0.00 g/day when oxygen solubility reaches 0.00 mg/L. Hypoxic conditions cause fluctuating physiological stress that adversely affects shrimp growth [45]. Hypoxia also impairs metabolic processes and feed utilization efficiency in shrimp [46]. Low oxygen availability further reduces shrimp resistance to disease infections epidemiologically [47].

Fluctuations in shrimp growth rate do not correlate directly with total biomass accumulation. Shrimp biomass continues to increase until reaching a maximum of 6 tons/ha. Biomass growth exhibits an aggregative pattern and stagnates during certain periods due to the maximum carrying capacity of the culture system [48]. Shrimp biomass growth models are inherently variable due to growth-limiting factors throughout the shrimp life cycle [49]. Growth performance characteristics differ among shrimp species [50]. Oxygen solubility has a correlational impact on both waste load abundance and shrimp growth rates. High oxygen solubility supports respiratory activity and organic matter decomposition within pond ecosystems [51]. Intensive decomposition processes lead to oxygen depletion in aquatic environments [52].

Based on the dynamic system modeling analysis, the managerial implication is that pond water quality management must simultaneously integrate waste load control and dissolved oxygen (DO) stability throughout the culture cycle. The decline and stagnation of DO at specific phases indicate increased oxygen consumption for organic matter decomposition; therefore, feed management, feeding frequency, and waste accumulation control must be properly adjusted to prevent oxygen deficits. Aeration strategies should not only focus on meeting shrimp respiratory demands but also on supporting controlled biodegradation processes to avoid hypoxic stress. Furthermore, since shrimp growth rates are highly sensitive to declining DO levels while total biomass may continue increasing until approaching the system's carrying capacity, stocking density regulation and production capacity estimation must account for ecological system limits. Thus, a dynamic model-based management approach can serve as a decision support system to balance productivity, feed efficiency, and environmental stability in intensive shrimp pond operations.

Dissolved oxygen dynamics and aquaculture productivity

The relationship among oxygen solubility, shrimp growth rate, and waste load is contradictory. Oxygen solubility exhibits oscillatory behavior, with maximum concentrations of 7.00 mg/L/hour and minimum concentrations of 0.00 mg/L/hour. Shrimp growth rate shows a positive correlation with aquaculture waste load, indicating that faster shrimp growth results in greater waste generation, and vice versa. Aquaculture productivity rates influence pollution levels and environmental status changes in aquatic systems [53]. Biologically, shrimp exhibit aggregative growth patterns throughout their life cycle [54]. Shrimp are highly responsive organisms to changes in surrounding environmental conditions [55]. Dissolved oxygen is a key parameter influencing shrimp responsiveness. Under both hypoxic and normoxic conditions, shrimp continuously respond to their physiological state [34].

Oxygen saturation levels fluctuate daily depending on temperature distribution [56]. Dynamic oxygen solubility triggers intense competition for oxygen utilization, resulting in heterogeneous oxygen distribution within pond waters [57]. This competition affects shrimp oxygen consumption, which tends to be minimal under stressful conditions [58]. Reduced oxygen consumption by shrimp leads to lower growth rates and increased susceptibility to hypoxia [59]. The managerial implication indicates that pond management must balance shrimp growth enhancement with waste load control and dissolved oxygen stability through adaptive aeration regulation, stocking density adjustment, and feed management to prevent hypoxic stress and productivity decline.

Discussion

In addition to maintaining oxygen solubility and temperature stability, paddle aerators also function as sediment management tools. The water currents generated by paddle aerator rotation are effective in directing pond sludge toward outlet areas [28]. The presence of paddle aerators is essential for maintaining favorable pond environmental conditions [17], [14]. Based on the results of this study, the critical period for declines in temperature and oxygen solubility occurred at approximately 50 days of cultivation. Increasing water temperature leads to reduced oxygen solubility in pond waters [5]. Scientifically, elevated water temperature decreases oxygen solubility and mineral ion concentrations [29]. Higher temperatures also accelerate oxidation processes, thereby increasing oxygen consumption rates [30].

Dissolved oxygen levels in shrimp ponds fluctuate dynamically throughout the operational culture cycle [13]. A decline in oxygen solubility results in hypoxic conditions [31]. Low oxygen solubility induces physiological stress in shrimp, leading to reduced growth rates and increased mortality [32], [33]. Dissolved oxygen levels also influence water quality stability, shrimp growth performance, Vibrio spp. abundance, and oxidation–reduction potential in pond waters [34], [35]. These conditions contribute to highly dynamic oxygen fluctuations and productivity patterns in shrimp pond ecosystems [36]. In other words, oxygen solubility undergoes rapid and continuous fluctuations over time.

Overall, the results demonstrate that oxygen solubility in shrimp pond waters is strongly influenced by paddle aerator operation and temperature distribution. Temperature acts as a physical limiting factor in aquatic ecosystems [60], [61]. Paddle aerators function as aquaculture engineering tools for temperature stabilization and dissolved oxygen production [62], [36]. Declining oxygen solubility correlates with increased waste abundance and shrimp growth rates [17]. In general, oxygen solubility fluctuations in shrimp ponds play a crucial role in determining overall aquaculture productivity.

The findings of this study provide significant managerial implications, indicating that paddle aerator operation and water temperature control should be implemented adaptively and aligned with the phases of the culture cycle, particularly during the critical mid-cycle period (±50 days) when dissolved oxygen solubility declines and shrimp metabolic rates increase. Management strategies that are responsive to temperature dynamics and dissolved oxygen (DO) fluctuations are essential to prevent hypoxic conditions, reduce organic waste accumulation, and maintain stable shrimp growth performance and survival rates. Optimizing aeration intensity serves not only as a means of oxygen supply but also as an environmental engineering tool for sediment management and uniform temperature distribution throughout the water column. Nevertheless, the model developed in this study has certain limitations, as it primarily focuses on the interaction among temperature, aeration, and oxygen solubility without explicitly incorporating other biological variables such as microbial community dynamics, spatial variability within ponds, and external factors including daily weather changes and feeding loads. Therefore, future model development should adopt a more comprehensive and multivariate approach to enhance predictive accuracy and broaden its applicability as a decision-support system for intensive shrimp pond management.

Conclusion

Based on the objectives and scope of the study, this research confirms that the dynamic modeling approach provides a robust analytical framework for estimating dissolved oxygen (DO) solubility levels in intensive shrimp pond systems. The developed system dynamics model successfully captures the complex interactions between physical chemical water quality parameters, organic waste accumulation, aeration input, and shrimp biomass growth, thereby reflecting the nonlinear feedback mechanisms that govern DO fluctuations. Model validation results demonstrate an acceptable level of accuracy and reliability, indicating that the model is capable of representing real pond conditions and can be utilized as a predictive and decision support tool. Furthermore, the findings highlight that oxygen solubility dynamics are strongly influenced by organic loading rates and management interventions, particularly aeration and feeding strategies, which in turn affect shrimp growth performance and overall production sustainability. Therefore, the integration of dynamic systems modeling into intensive aquaculture management offers a scientifically sound basis for optimizing water quality control, minimizing environmental risks, and enhancing production efficiency in shrimp farming systems.

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