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The Effect of Stocking Density on Fish Growth and Survival in Intensive Cultivation Systems

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Abstract
Stocking density is one of the most critical management variables in intensive aquaculture, directly influencing fish growth, survival, feed efficiency, physiological health, and economic profitability. While higher densities may maximize space utilization, they simultaneously impose cumulative stress through water quality deterioration, competition, and physiological disruption. This study examines the effects of stocking density on growth performance and survival of cultured fish through a descriptive quantitative analysis of 31 peer-reviewed publications (2021–2023). Quantitative descriptive statistics were calculated for thematic distribution, annual publication frequency, and key performance indicators including specific growth rate (SGR), feed conversion ratio (FCR), survival rate, and physiological stress biomarkers. Results demonstrate that excessive stocking density reduces SGR by 8–42%, increases FCR by 10–35%, and decreases survival by 5–28% relative to optimal levels. Dissolved oxygen declines of 12–38% and total ammonia nitrogen increases of 25–80% were the primary water quality mechanisms mediating these effects. A non-linear optimal density range was identified across species: 1.8–14.6 kg/m³ for juveniles (0–28 g) and 14.6–38.4 kg/m³ for sub-adults (29–98 g). Biofloc technology mitigated 20–40% of water quality degradation at high densities but did not eliminate biological stress ceilings. This study concludes that medium stocking density consistently yields the best balance of individual growth, survival, and economic return across diverse species and production systems.
Keywords: *aquaculture; descriptive quantitative analysis; fish welfare; growth performance; stocking density*

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Introduction

Global aquaculture production has grown at an average annual rate of about 5.3% over the past two decades, now accounting for more than half of all fish consumed by humans (FAO, 2024). Intensification of production,increase the number of fish farmed per unit volume of water,Stocking density has become a dominant strategy to meet the growing demand for seafood without disproportionately expanding the land or water area used. Within this intensification trajectory, stocking density has emerged as one of the most influential and controversial management variables (Saraiva et al., 2022; Li et al., 2021). Too low a density results in wasted expensive infrastructure and reduced production volume; too high a density creates mutually reinforcing biological stressors that erode growth performance, survival, and profitability.

The relationship between stocking density and fish performance is non-linear. Meta-analytic evidence across species shows a characteristic non-linear response: growth performance is maintained or increases slightly from very low to moderate densities, then declines progressively.,and in some cases suddenly,at high densities as water quality deteriorates and individual space requirements exceed physiological compensation thresholds (Li et al., 2021). This nonlinearity means that identifying optimal stocking densities is not simply about selecting the maximum technically feasible loading rate, but rather finding a density range within which growth, survival, feed efficiency, and economic returns are simultaneously optimized for a given species, life stage, and production system.

The mechanisms by which excessive stocking densities harm fish performance are multiple and interacting. High fish biomass increases metabolic waste production, reduces dissolved oxygen (DO), increases total ammonia nitrogen (TAN), nitrite, and carbon dioxide, and destabilizes pH.,collectively creates a deteriorating aquatic environment and induces chronic respiratory and osmoregulatory stress (Manduca et al., 2021; Mramba & Kahindi, 2023; Ani et al., 2021). At the cellular and endocrine levels, crowding activates the hypothalamic-pituitary-interrenal axis, increases cortisol and glucose, suppresses growth hormone sensitivity, and triggers an oxidative stress cascade that reduces antioxidant enzyme capacity and promotes lipid peroxidation (Jia et al., 2022; Onxayvieng et al., 2021; Barton & Iwama, 1991). Digestive enzyme activity,including amylase, lipase, and trypsin,is also suppressed at high densities, which directly reduces nutrient assimilation efficiency and increases FCR (Upadhyay et al., 2022; Ni et al., 2021).

Despite a substantial and growing body of primary research on the effects of stocking density across species and production systems, there has been no comprehensive descriptive quantitative synthesis that systematically characterizes the thematic distribution, temporal evolution, and magnitude of effects within this literature. Most existing reviews focus on a single species or production system, without providing a quantitative cross-thematic overview that would enable practitioners to identify consistent patterns and knowledge gaps. This analytical deficit hampers evidence-based stocking density decision-making in both commercial and small-scale aquaculture (Saraiva et al., 2022; Khan et al., 2021).

This study fills this gap through a descriptive quantitative analysis of 31 scientific publications (2021–2023) covering the effects of stocking density in intensive aquaculture systems. The specific objectives are: (1) to characterize the thematic distribution of research using frequency and percentage statistics; (2) to describe annual publication trends; (3) to quantify the magnitude of the effects of high stocking densities across performance indicator categories; (4) to compile species-specific optimal stocking density data across various system types; (5) to mechanistically synthesize pathways through which overstocking impairs fish biology; and (6) to prioritize management challenges using a composite assessment framework.

Methodology

This study employed a descriptive quantitative research design through a systematic literature review. A descriptive quantitative approach was chosen because the research objective was to characterize and quantify patterns, thematic distributions, and effect sizes within an existing corpus of primary research, rather than to test causal hypotheses (Creswell & Creswell, 2018). This methodology has been established as an appropriate approach for aquaculture technology synthesis (Li et al., 2021; Saraiva et al., 2022) and allows for reproducible numerical comparisons across studies.

2.1 Research Design

Descriptive quantitative analysis yielded systematic frequency counts, percentage distributions, arithmetic means, and observed ranges without inferential statistical testing. The unit of analysis was individual peer-reviewed scientific publications. Five analytical dimensions were addressed: (a) thematic distribution of research; (b) annual publication frequency; (c) quantitative effect sizes per theme; (d) species-specific optimal stocking density results; and (e) mechanistic pathway analysis. Management challenge priority scores were calculated as the product of the impact dimension (1–5) and the strength of evidence (1–5), resulting in a composite index ranging from 1–25.

2.2 Literature Search and Feasibility

A systematic search was conducted in Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar from September to December 2024, using terms such as "stocking density" AND "fish" OR "aquaculture" and "crowding stress" AND "aquaculture." The temporal scope was limited to 2021–2023, supplemented by background references on fish stress physiology and aquaculture management.

Articles were included if they: (1) reported primary experimental findings on the effects of stocking density on fish or crustacean species; (2) provided quantitative data on at least one performance indicator.,SGR, FCR, survival, water quality, stress biomarkers, or digestive enzymes; (3) indexed in Scopus or Web of Science; and (4) written in English. Nutrition studies without density variation, terrestrial livestock studies, and conference abstracts were excluded. The final corpus consisted of 31 articles.

2.2 Data Extraction and Coding

The extracted variables included: author and year; journal; country of study; species, life stage, and initial weight; type of culture system (pond, biofloc, aquaponics, cage, raceway, RAS); density range tested; and quantitative results per performance indicator. Articles were classified into six thematic categories: (1) Growth Performance & Feed Efficiency; (2) Water Quality & Environmental Stress; (3) Physiological & Oxidative Stress Response; (4) Survival, Immunity & Disease Resistance; (5) Economic Optimization & Welfare; and (6) Biofloc & Technology-Based Systems.

2.4 Descriptive Quantitative Analysis

All statistics were calculated using Microsoft Excel v.16.0. Absolute (n) and relative (%) frequencies were tabulated for categorical variables. For continuous indicators, minimum, maximum, and arithmetic mean values were calculated per thematic cluster. No meta-analytic pooling of effect sizes was performed due to the fundamental heterogeneity of species, density ranges, system types, and measurement protocols across the corpus.

Results and Discussion

3.1 Thematic Distribution of Research

Table 1 presents the frequency and percentage distribution of the 31 publications analyzed across six thematic categories. The corpus is dominated by "Growth Performance & Feed Efficiency" (n=9; 29.0%), reflecting the primacy of production-oriented metrics in both scientific and commercial aquaculture research. "Water Quality & Environmental Stress" and "Physiological & Oxidative Stress Response" each contributed 19.4% (n=6), together comprising 38.7% of the corpus.,confirms that a mechanistic understanding of how density-induced environmental and physiological deterioration drives production losses is a key and evolving research priority.

Table 1. Thematic distribution and frequency of reviewed publications on the effects of stocking density in intensive aquaculture (n=31, 2021–2023)

Research Theme	n	%	Period	Representative References
Growth Performance & Feed Efficiency	9	29.0	2021–2023	Li et al. (2021); Jia et al. (2022); Ni et al. (2021)
Water Quality & Environmental Stress	6	19.4	2021–2023	Manduca et al. (2021); Ani et al. (2021); Mramba & Kahindi (2023)
Physiological & Oxidative Stress Response	6	19.4	2021–2022	Jia et al. (2022); Upadhyay et al. (2022); Onxayvieng et al. (2021)
Survival, Immunity & Disease Resistance	5	16.1	2021–2022	Karnatak et al. (2021); Mahmoud et al. (2021); Shourbela et al. (2021)
Economic Optimization & Welfare	3	9.7	2021–2022	Manduca et al. (2021); Saraiva et al. (2022); Khan et al. (2021)
Biofloc & Technology Based Systems	2	6.5	2022	Khanjani et al. (2022a,b); Shourbela et al. (2021)
TOTAL	**31**	**100.0**	**2021–2024**	**,**

"Survival, Immunity & Disease Resistance" (n=5; 16.1%) links upstream physiological effects to downstream health outcomes,particularly increased vulnerability to the most economically damaging diseases (Mahmoud et al., 2021; Karnatak et al., 2021). The smallest cluster,"Economic Optimization & Welfare" (n=3; 9.7%) and "Biofloc & Technology-Based Systems" (n=2; 6.5%),revealed two critical gaps: the translation of biological data into an economic framework remains underrepresented (Saraiva et al., 2022; Khan et al., 2021), and the evidence base for technological mitigation remains thin relative to its commercial adoption (Khanjani et al., 2022a). Bridging the gap between research and practice is necessary for the scientific community to move from describing density effects to prescribing actionable management strategies (Saraiva et al., 2022).

3.2 Temporal Trends of Research Output

Table 2 shows the annual publication frequency and dominant thematic focus throughout the study period. The corpus is highly concentrated in 2021 (n=14; 45.2%) and 2022 (n=9; 29.0%), which together account for 74.2% of all publications.

Table 2. Annual publication frequency and dominant research themes in the stocking density literature (n=31, 2021–2023)

Year	n	%	Dominant Theme	Main Author
2021	14	45.2	Growth, survival, feed efficiency, cage & pond culture	Li et al.; Manduca et al.; Ani et al.; Karnatak et al.; Ni et al.; Onxayvieng et al.; Shourbela et al.; Khan et al.
2022	9	29.0	Oxidative stress, physiological response, biofloc system	Jia et al.; Upadhyay et al.; Saraiva et al.; Khanjani et al. (a, b)
2023	4	12.9	Water quality, disease, dryland pond management	Mramba & Kahindi (2023)
Supporting Ref.	4	12.9	Meta-analysis background & context of well-being	FAO; Boyd; Brett; Barton & Iwama
2021	14	45.2	Growth, survival, feed efficiency, cage & pond culture	Li et al.; Manduca et al.; Ani et al.; Karnatak et al.; Ni et al.; Onxayvieng et al.; Shourbela et al.; Khan et al.
TOTAL	**31**	**100.0**	**,**	**,**

The high output in 2021 reflects the convergence of post-COVID-19 intensification pressures, rising aquaculture costs, and mature multi-parameter experimental designs (Manduca et al., 2021; Karnatak et al., 2021; Ni et al., 2021). The 2022 cluster marked a shift towards oxidative stress and welfare frameworks (Jia et al., 2022; Upadhyay et al., 2022; Saraiva et al., 2022), reflecting growing regulatory pressure for animal welfare compliance. The 2023 corpus (n=4; 12.9%) introduced geographic diversification to dryland pond aquaculture (Mramba & Kahindi, 2023).

3.3 Descriptive Statistics of Effect Size per Theme

Table 3 presents the range and arithmetic mean of the primary effect size indicators for each thematic cluster, allowing cross-thematic comparisons of the biological significance of the effects of overstocking density.

Table 3. Descriptive statistics (range and mean) of the effect size of high stocking density per research theme (n=31)

Research Theme	n	Effect Range	Average Effect	Main References
Growth Performance & Feed Efficiency	9	SGR reduction 8–42% at high density vs. low; FCR increase 10–35%	24.5%	Li et al. (2021); Ni et al. (2021)
Water Quality & Environmental Stress	6	DO reduction 12–38%; 25–80% increase in TAN at high density	31.2%	Manduca et al. (2021); Mramba & Kahindi (2023)
Physiological & Oxidative Stress Response	6	18–65% increase in cortisol; 15–40% decrease in antioxidant capacity	32.8%	Jia et al. (2022); Onxayvieng et al. (2021)
Survival, Immunity & Disease Resistance	5	5–28% decrease in survival; 10–35% decrease in lysozyme at high density	18.6%	Karnatak et al. (2021); Mahmoud et al. (2021)
Economic Optimization & Welfare	3	Optimal profit at medium density; BCR is highest at low–medium density	N/A (qualitative)	Manduca et al. (2021); Saraiva et al. (2022)
Biofloc & Technology Based Systems	2	BFT mitigates 20–40% of the negative effects of density on water quality	30.0%	Khanjani et al. (2022a,b)

The "Physiological & Oxidative Stress Response" cluster showed the highest average effect (32.8%). Jia et al. (2022) documented a 40–65% increase in cortisol and upregulation of hepatic lipid peroxidation in largemouth bass, accompanied by suppression of superoxide dismutase and catalase.,indicates a failure of the cellular antioxidant defense system. Onxayvieng et al. (2021) reported a 25–40% decrease in antioxidant capacity and an increase in plasma glucose in gibel carp.

The "Water Quality & Environmental Stress" cluster (31.2%) highlights environmental pathways as the primary proximate mechanisms. A 12–38% decrease in DO inhibits aerobic metabolism, appetite, and digestion (Manduca et al., 2021; Boyd, 1998), while a 25–80% increase in TAN causes gill damage and immune suppression at NH_3 concentrations exceeding 0.02–0.05 mg/L. The "Growth Performance & Feed Efficiency" (24.5%) and "Survival, Immunity & Disease Resistance" (18.6%) clusters reflect the integrated biological outcomes of all these upstream stressors (Li et al., 2021; Karnatak et al., 2021; Mahmoud et al., 2021).

3.4 Species-Specific Optimal Stocking Densities in Various Production Systems

Table 4 summarizes the species-specific optimal stocking density ranges and corresponding performance outcomes identified across the reviewed literature, covering nine species and species groups across five types of production systems.

Table 4. Species-specific optimal stocking density ranges and key performance outcomes across intensive aquaculture systems

Species	Optimal Stocking Density	Cultivation System	Key Results	Reference
Various spp. (meta-analysis)	0–28 g: 1.8–14.6 kg/m³; 29–98 g: 14.6–38.4 kg/m³	Pond/RAS/cages	Highest SGR at low–medium density; non-linear relationship	Li et al. (2021)
Nile tilapia (O. niloticus), BFT	~33 tails/m³ (medium)	Biofloc pond	Maximum biomass at high density; best FCR & profit at medium	Manduca et al. (2021)
Tilapia, aquaponics	150 birds/m³ (lowest tested)	Aquaponic tank	SGR & SR decrease linearly with density; lowest density best	Ani et al. (2021)
Largemouth bass, rice fields	40 g/m³ (low density)	Integrated rice fields	Low density: best growth & lipid metabolism; HD → oxidative stress	Jia et al. (2022)
Largemouth bass, IPRS	113.6 tails/m³ (medium)	Raceway system in the pool	Medium density: best growth, immunity & profit ratio	Ni et al. (2021)
Puntius means, cages	10 tails/m³ (lowest)	Open water cages	Growth, digestive & hemato-immune enzymes are best at lowest density	Upadhyay et al. (2022)
Labeo bata, reservoir cage	50 tails/m³ (lowest)	Reservoir cages	SGR, survival & BCR were all highest at 50 fish/m³	Karnatak et al. (2021)
Gibel goldfish, intensive pond	1.47 kg/m³ (low)	Intensive pool	Highest antioxidant capacity & growth at lowest density	Onxayvieng et al. (2021)
Banana shrimp, biofloc	Low–medium PL/m³	Biofloc nursery	Growth & survival are optimized at low–medium densities under BFT	Khanjani et al. (2022b)

The main finding of Table 4 is the lack of a universal optimal density across species or systems. In tilapia (Oreochromis niloticus), the optimal density differed between biofloc systems (~33 individuals/m³; Manduca et al., 2021) and aquaponics (150 individuals/m³; Ani et al., 2021).,reflect differences in system-specific carrying capacity. Largemouth bass data from two contexts illustrate this:

Jia et al. (2022) identified an optimal density of 40 g/m³ in rice paddies, while Ni et al. (2021) found a moderate density (113.6 fish/m³) optimal in IPRS due to continuous water circulation. Li et al.'s (2021) meta-analysis ranges,1.8–14.6 kg/m³ (0–28 g) and 14.6–38.4 kg/m³ (29–98 g),is the most generalizable framework, but must be calibrated through species-specific and system-specific pilot trials.

3.5 Mechanistic Pathways: How Excessive Stocking Densities Damage Fish Biology

Table 5 presents a systematic mechanistic synthesis of the biological pathways by which excessive stocking densities impair fish performance, quantifying the magnitude of effects based on those reported in the reviewed literature.

Table 5. Mechanistic pathways by which excessive stocking density impairs fish performance: biological effects and quantitative range

Mechanism	Biological Effects	Quantitative Range	Supporting References	Mechanism
Deterioration of water quality	DO ↓; TAN, nitrite, nitrate ↑; pH instability	DO –12 to –38%; TAN +25–80%	Manduca et al. (2021); Ani et al. (2021); Mramba & Kahindi (2023)	Deterioration of water quality
Physiological stress	Cortisol ↑; glucose ↑; lactate ↑; thyroid hormone ↓	Cortisol +18–65%	Jia et al. (2022); Upadhyay et al. (2022); Shourbela et al. (2021)	Physiological stress
Oxidative stress	SOD, CAT, GSH-Px ↓; lipid peroxidation (MDA) ↑	Antioxidant capacity –15–40%	Onxayvieng et al. (2021); Jia et al. (2022)	Oxidative stress
Suppression of digestive enzymes	Amylase, lipase, trypsin activity ↓; FCR ↑	FCR +10–35%	Upadhyay et al. (2022); Ni et al. (2021); Manduca et al. (2021)	Suppression of digestive enzymes
Immune susceptibility & disease	Lysozyme, complement ↓; pathogen susceptibility ↑	Lysozyme –10–35%	Mahmoud et al. (2021); Karnatak et al. (2021); Khanjani et al. (2022a)	Immune susceptibility & disease
Decrease in growth rate	SGR ↓; DWG ↓; final weight ↓ due to competition	SGR –8–42%	Li et al. (2021); Jia et al. (2022); Onxayvieng et al. (2021)	Decrease in growth rate
Decrease in survival	Death due to overcrowding; disease outbreaks; aggressiveness ↑	Survival –5–28%	Ani et al. (2021); Karnatak et al. (2021); Mahmoud et al. (2021)	Decrease in survival

Mechanistic evidence reveals a cascade structure in which water quality degradation is the primary proximate cause. A 12–38% decrease in DO suppresses the aerobic scope that drives growth, immunity, and swimming performance (Brett, 1979; Boyd, 1998), while a 25–80% increase in TAN causes gill lamella damage and neurological dysfunction (Wendelaar Bonga, 1997).

Physiological stress cascade,increased cortisol (18–65%), glucose, and lactate,Suppresses growth hormone receptor sensitivity, reduces IGF-1, and shifts metabolism from anabolic to catabolic, explaining the documented decrease in SGR (Barton & Iwama, 1991; Schreck et al., 2016). Chronic cortisol also suppresses lymphocyte proliferation and phagocytic activity, resulting in immune suppression that increases disease susceptibility (Mahmoud et al., 2021; Karnatak et al., 2021). Suppression of digestive enzymes,amylase, lipase, and trypsin,is a separate mechanism that interferes with nutrient assimilation independently of appetite effects (Upadhyay et al., 2022; Ni et al., 2021).

3.6 Priority Management Challenges: Quantified Score Assessment

Table 6 presents the results of the management challenge prioritization analysis, where each identified challenge is scored on a 1–5 impact scale and a 1–5 strength of evidence scale based on the weight of the literature reviewed, resulting in a composite priority score (range 1–25).

Table 6. Analysis of management challenge priorities for stocking density optimization in intensive aquaculture (composite score of impact × strength of evidence)

Management Challenges	Impact (1–5)	Strength of Evidence (1–5)	Priority Score
Lack of species-specific optimal density guidelines	5	5	25
Water quality degradation at high density	5	5	25
Accumulation of physiological & oxidative stress	4	5	20
Immune suppression & increased risk of disease	4	5	20
Declining economic returns at extreme densities	4	4	16
Limitations of BFT mitigation/technology at very high densities	3	4	12

Two challenges achieved the maximum score of 25: the lack of species-specific guidelines and water quality degradation. The lack of validated guidelines is the most fundamental barrier to rational management.,The meta-analytical framework (Li et al., 2021) provides a broad range that is insufficient for commercial precision at the species-system-season level (Saraiva et al., 2022). Water quality degradation confirms that DO and ammonia management are the primary mitigation levers. Physiological and oxidative stress (score: 20) and immune suppression (score: 20) are the next priorities. The decline in economic returns (score: 16) confirms that financial metrics must be integrated into the optimization framework.,Manduca et al. (2021) showed that maximum biomass and profitability occur at different densities. The low score for BFT limitations (score: 12) reflects that although BFT mitigates 20–40% of water quality degradation (Khanjani et al., 2022a,b), it does not eliminate intrinsic biological stress constraints. Technology-based systems should be viewed as tools that shift the optimal density range upward, rather than completely eliminating density constraints.

Conclusion

A descriptive quantitative analysis of 31 publications confirmed that excessive stocking density reduces SGR by 8–42%, increases FCR by 10–35%, and decreases survival by 5–28%. Water quality degradation (DO –12–38%; TAN +25–80%) and physiological stress cascades (cortisol +18–65%) are the primary mediating mechanisms. Optimal density ranges are species- and system-specific: juveniles 1.8–14.6 kg/m³, subadults 14.6–38.4 kg/m³. Moderate densities consistently provide the best balance between growth, survival, and economic returns. Development of species-specific guidelines and integrated real-time water quality monitoring are the highest priority management interventions.

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