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Review Article

A novel Body Mass Index (sfBMI) approach to fish health assessment in fisheries and aquaculture: Prototype framework and species-specific considerations

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ABSTRACT: Assessing the health and condition of fish is essential in Fisheries and Aquaculture, as it reflects nutritional status, ecological well-being, and environmental quality. Traditional indices such as Fulton's condition factor (K) and relative condition factor (Kn) have been widely used by fisheries scientists and environmentalists. Still, these often assume isometric growth and may be less insightful for stakeholders. This paper proposes a novel Body Mass Index (BMI) framework, adapted from the human BMI concept, which incorporates fish length–weight parameters. The method produces a standardised fish BMI (sfBMI) and a classification system for scientific interpretation. This approach bridges the gap between biological precision and stakeholder (farmers, extension agents, and policymakers)-friendly communication, enabling more effective decision-making in fish health management. As a prototype, the sfBMI framework establishes preliminary condition thresholds (<90%, 90–97%, 98–102%, >110%) that can be used to distinguish between under-conditioned, healthy, and over-conditioned or obese fish. Compared with Fulton's K and Kn, the sfBMI shows potential for providing more consistent and simple classification across species and various environmental conditions. Looking ahead, this prototype index could be further validated and applied in both aquaculture and wild fisheries, with future integration into an image-based system to support real-time decision-making in fish management.

Keywords: Aquaculture, Body Mass Index, environmental condition, fish condition, fisheries, Fulton's Condition Factor (K), Relative Condition Factor (Kn).

INTRODUCTION

Body condition indices are basic tools for evaluating fish health, growth and physiological performances (Brosset *et al.,* 2015). They provide direct and indirect measures of energy reserves, feeding history, physiological state and more in terms of the health history of the fish (Brosset *et al.,* 2023). In aquaculture, monitoring conditions can help identify feed inefficiency, overcrowding stress, while in both Fisheries and Aquaculture identify disease onset, or environmental degradation (Blackwell *et al.,* 2000). In wild fish populations, declining health condition often indicates habitat deterioration, food scarcity, or environmental pollution (Froese, 2006).

Traditionally or previously used methods to assess the condition of a fish include Fulton's condition factor (K) or relative condition factor (Kn). However, if K assumes an isometric growth exponent (*b* = 3), this makes K biased for species or size classes with allometric growth patterns (Lugert *et al.,* 2016). Kn, but its interpretation is less intuitive for non-specialists.

To address these issues, this paper presents the allometric Body Mass Index (BMI), which is a new biologically robust and user-friendly metric that frames fish condition assessment in a familiar BMI-like format.

FULTON’S CONDITION FACTOR (K) AND RELATIVE CONDITION FACTOR (Kn)

Fulton’s Condition Factor was first proposed by Fulton in 1904. This index is calculated as:

$$K= W/L^3 \text{------------------------------} I$$

Where *W* is weight in grams and *L* is length in cm. It assumes *b* = 3, which is not always valid across life stages or species (Froese, 2006). However, this assumption is rarely met in reality (Nash *et al.,* 2006). Many fish species, especially during early ontogeny or under varying environmental conditions (Duffy-Anderson *et al.,* 2025), exhibit allometric growth (*b* ≠ 3), causing Fulton’s K to be biased toward overestimating the condition of small fish (Fingerlings and Juvenile) and underestimating that of larger individuals or big fishes (Ogle, 2013). Environmental factors such as temperature, salinity or any other water quality parameters and food availability can also influence growth exponent (*b)*, compounding this bias. (Lugert *et al.,* 2016). To address this, Le Cren (1951) introduced the relative condition factor (Kn):

$$\mathrm{Kn} = \frac{100 \times \mathrm{W}}{\mathrm{aL}^{b}} \text{---------------} II$$

Where *a* and *b* are empirically derived from the species’ length–weight relationship. Kn adjusts for allometric growth, making it statistically more robust and biologically relevant than Fulton’s K. However, while Kn reduces the size-related bias, it is less intuitive for non-technical stakeholders such as small-scale farmers, who may struggle to interpret raw Kn values without contextual reference ranges. Additionally, both K and Kn remain sensitive to reproductive stage, gut fullness, and sampling inconsistencies, which can introduce further interpretational bias if measurements are not standardised.

BMI in Human health and cross-disciplinary adoption for fish condition monitoring formula development

Human BMI relates weight to height squared and is widely used to classify underweight, normal, overweight, and obese statuses. Analogous adaptations have been made in veterinary science (Dugdale *et al.,* 2012), but have not been fully developed for fish condition monitoring.

sfBMI is expressed as a percentage, where 100% equals the expected condition, >100% means the fish weighs more than expected, and <100% indicates the fish weighs less than expected fish and can be computed using:

$$sfBMI=W/We \text{-------------------} XIII$$

Where: sfBMI = Standardised Fish Body Mass Index, W = Observed body weight of the fish, We = Expected body weight of the fish.

Table 1 mirrors human BMI (Quetelet, 1842) categories for ease of scientific interpretation in Fisheries and Aquaculture, thus this parameter can be combined with indices such as hepatosomatic index (HSI) to provide a more comprehensive health profile. Figure 1 shows a schematic diagram illustrating the relationship between sfBMI percentage and physiological condition categories reflecting changes in growth performance and health status.

This sfBMI thresholds (Figure 1) were derived by integrating empirical studies on fish condition factors such as CF-Fulton’s K, hepatosomatic index and relative weight (Wr) of fish, which typically use 100% as a reference for condition assessment (Anderson and Neumann, 1996; Froese, 2006). Comparative metabolic physiology has also shown that deviations below around ~90% is often linked to depleted lipid reserves and reduced reproductive capacity in fish (Love, 1980; Lambert and Dutil, 1997). According to NRC (2011), optimal nutrient levels promote maximal growth and feed efficiency, while both underfeeding and overfeeding can reduce performance and increase risks of metabolic disorders such as hepatic steatosis. The sfBMI framework is dual-calibrated for aquaculture systems and wild fisheries, thus ensuring that the same physiological signal can be interpreted differently in management terms in aquaculture and fisheries

In grass carp (*Ctenopharyngodon idella*) for instance, dietary lipid levels above 4% increased the feed conversion ratio (from 1.25 to 1.60), this doubled the hepatosomatic index (HSI from 1.3% to 2.8%), and also raised liver lipid content from 3.5% to 7.2%, indicating hepatic lipid accumulation and mild fatty liver symptoms (Du *et al.,* 2005). Similarly, in marble goby (*Oxyeleotris marmorata*) a fish found in freshwater and brackish water of south-east Asia, excessive feeding beyond the 10% optimal lipid level elevated feed conversion ratio from 1.18 to 1.54, thus the HSI (1.6% to 3.2%), and liver lipid content (4.2% to 8.5%), without further growth improvement, demonstrating overfeeding-induced hepatic steatosis (Yong *et al.,* 2015). In blunt snout bream (*Megalobrama amblycephala*), a cyprinid of aquaculture importance, having dietary lipid increased beyond the 8% optimum, increases the feed conversion ratio (FCR) (1.30 to 1.55), hepatosomatic index (HIS) (1.9% to 3.4%), and liver lipid (3.8% to 8.1%), leading to accompanied inflammatory responses and hepatic lipid deposition.

For tilapia (*Oreochromis niloticus*), however, diets exceeding the 8–10% lipid range led to a rise in FCR (1.25 to 1.48), hepatosomatic index -HSI (1.5% to 3.0%), and liver lipid (3.6% to 7.4%), with signs of hepatic steatosis, and autophagy dysfunction (Jia *et al.,* 2020).

In large yellow croaker (*Larimichthys crocea*), high-fat diets beyond the 10–12% optimal lipid range increased FCR (1.20 to 1.42), hepatosomatic index -HSI (1.8% to

Table 1. Prototype fish health condition classification based on sfBMI (%).

sfBMI (%)	Condition Category	Field Interpretation (Aquaculture)	Field Interpretation – Wild Fisheries	Reference Justification
<90	Under-conditioned	Starved: Feed shortage, high intra competition, poor water quality and acute and chronic disease.	Depleted: Prey scarcity in the wild, habitat degradation as a result chronic pollution stress and climate change.	Derived from condition factor K studies where Wr < 90 indicating poor condition and 90-100 been normal body condition (Anderson and Neumann, 1996; Froese, 2006)
90–97	Lean/Thin	Stressed: Suboptimal feeding or recent physiological stress activities.	Nutritionally limited: Little nutritional (food availability) or reproductive challenge.	Linked to suboptimal feeding or environmental stress response as a result of parameters such as water quality (NRC, 2011).
98–102	Normal	Healthy: good growth with optimal feeding	Balanced: Healthy growth.	Matches Wr = 100 standard; normal growth and feeding efficiency (Anderson and Neumann, 1996; Froese, 2006; NRC, 2011).
103–115	Robust	Thriving: Above-average growth, but watch for overfeeding risk.	Abundant: Excellent food or prey abundance in a good environment with strong recruitment potential.	Observed in periods of food/ prey abundance or well-fed aquaculture NRC, 2011).
>115	Over-fat	Obese: Risk of fatty liver disease (Hepatic steatosis)	Imbalanced: Possible trophic imbalance (e.g., excessive prey or low predation pressure); monitor ecosystem dynamics.	Supported by studies on fatty liver and overnutrition in fish (NRC, 2011).

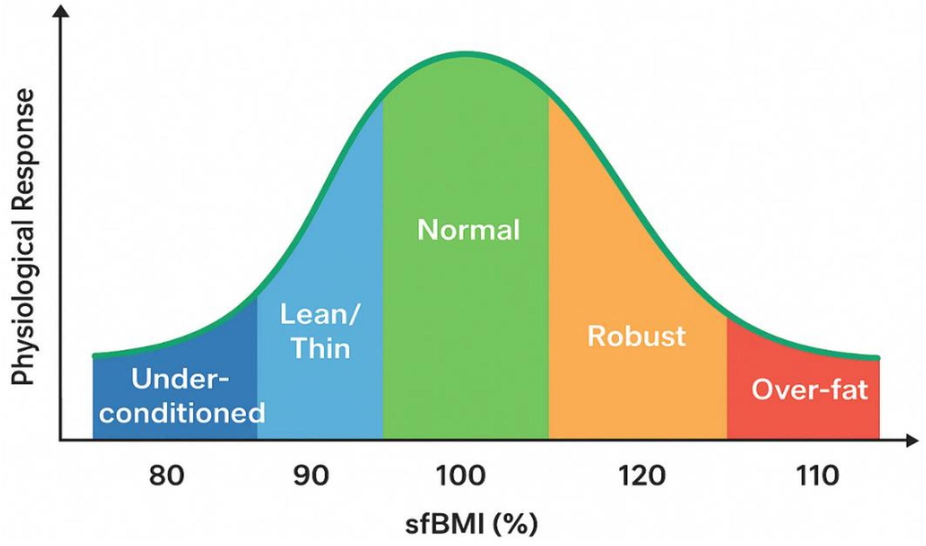

Figure 1. Conceptual schematic diagram illustrating the relationship between sfBMI % and physiological condition.

3.1%), and liver lipid content (4.0% to 9.0%), leading to an increase in hepatic steatosis and inflammation, though ω-3 PUFA supplementation will help to mitigate the adverse effects (Henderson and Tocher, 1987). According to the National Research Council (NRC, 2011), each fish species has a specific nutrient requirement, which is the level of protein, lipid, vitamin, or mineral intake to achieve optimum growth and feed efficiency.

However, because of biological variability, fish will maintain near-optimal performance within a narrow tolerance range, typically ±2% of the requirement. Hence, the 98–102% range is the “biological optimum window” where nutrient supply perfectly matches physiological or metabolic demand, feed utilisation and growth are maximised, and physiological stress and lipid imbalance are minimal. Feeding below 98% (underfeeding) or above 102%

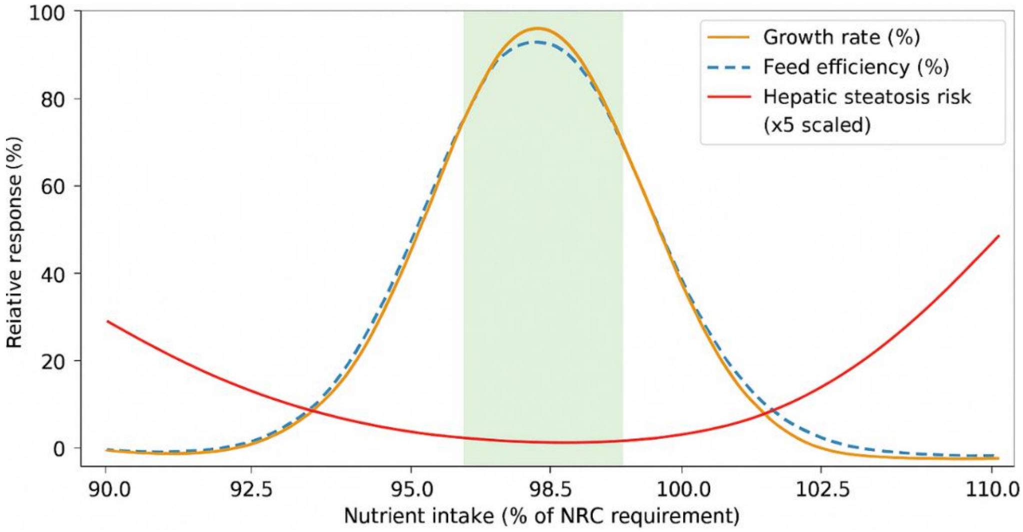

Figure 2. Schematic graph illustrating the relationship between nutrient intake (% of NRC requirement) and fish growth performance, feed efficiency, and hepatic steatosis risk.

(overfeeding) (Figure 2), pushes fish out of this homeostatic zone, reducing efficiency and triggering metabolic stress responses.

Results from previous feeding trials review across species show that feeding, feed efficiency and growth remain optimal only within a narrow nutrient tolerance window. Within approximately 98–102% of the species-specific requirement, growth performance is maximised, and metabolic stability is maintained. However, nutrient intake beyond this range could result in increased feed conversion ratios, high hepatosomatic indices, and hepatic lipid accumulation, thus indicating the onset of steatosis and oxidative stress (Du *et al.,* 2005; Jia *et al.,* 2020). These findings confirm that both nutrient deficiency and excess impair fish performance (Figure 2), hence validating the use of a 98–102% benchmark to describe the functional optimum in aquaculture nutrition.

The proposed BMI and sfBMI framework provide several advantages over traditional condition indices. By incorporating species-specific length–weight parameters, BMI adjusts for all growth patterns, avoiding the systematic over- or underestimation seen in Fulton's K (Lugert *et al.,* 2016). The transformation into sfBMI allows the condition to be expressed as a percentage of expected growth (weight in relation to length), a format that is easily grasped by both scientists and non-fisheries specialists, such as small-scale farmers and fishermen.

In aquaculture, sfBMI will enable rapid detection of changes from expected growth trajectories, allowing timely interventions in feeding regimes, stocking density management, and water quality control. For example, sustained sfBMI values below 90% in a production unit could signal underfeeding, disease onset, or environmental stress, while values above 115% may indicate overfeeding and associated health risks.

In wild fisheries and ecological monitoring, sfBMI offers a robust, standardised metric for comparing condition across populations, habitats, and seasons. Its intuitive interpretation aids in communicating findings to policy makers, conservation managers, and local communities, thereby supporting adaptive management.

Future research should focus on robustly validating sfBMI across a wide range of species, life stages, and environmental conditions via the use of FishBase or similar databases that already provide length–weight parameters (a, b) for thousands of species (Froese and Pauly, 2024), as well as testing its responsiveness to short-term stressors. Establishing standard reference ranges for economically important species in different climatic zones would further enhance their practical utility in both aquaculture and fisheries management.

APPLICATION OF sfBMI

The standardised fish Body Mass Index (sfBMI) provides a biologically robust metric that is applicable in fisheries and aquaculture contexts. Its flexibility lies in its ability to express fish condition as a percentage of expected weight for a given length, thereby offering an intuitive yet scientifically grounded measure of growth and health status. The following are how it could be applied in the Fisheries and Aquaculture context

Aquaculture applications

Aquaculture systems are man-made, where fish growth is strongly influenced by feed quality, stocking density, water quality, and disease pressures. Monitoring fish condition in these settings is crucial for the productivity and profitability of the venture (Tidwell and Allan, 2001). sfBMI offers a novel tool for aquaculture managers by providing rapid, standardised insights into fish health through:

Feed efficiency monitoring

Feed is the highest cost in aquaculture production, accounting for up to 70% of aquaculture operational expenses (Naylor *et al.,* 2021). An ineffective feed conversion rate reduces profitability and also contributes to feed wastage and water quality degradation. Traditional feed conversion ratio (FCR) measures provide aggregate efficiency estimates but do not capture individual or cohort-level health, thus sfBMI can complement FCR by serving as a new diagnostic tool. For example, in tilapia (*Oreochromis niloticus*) culture, inadequate protein supply can result in reduced growth efficiency, which sfBMI would detect as systematic under-conditioning across the population. This provides actionable and simple information, allowing managers to adjust feed formulations, increase ration frequency, or reduce competition.

Stocking density and welfare assessment

Stocking density directly affects fish welfare, growth, and survival (Ellis *et al.,* 2002). High stocking densities increase competition for feed, hypoxia, and elevate cortisol or stress levels, which impair growth and immune (innate and acquired) function. Deviations in sfBMI between various statistical treatment(tanks) or production units can show density-induced increased cortisol or stress even before mortality occurs.

For instance, salmonid aquaculture often operates near or close to optimal density thresholds; beyond this, salmonid growth performance declines. If two tanks/treatment of similar genetic stock and feed regime show contrasting sfBMI values, fish managers can attribute the discrepancy to density-related welfare differences (Ellis *et al.,* 2002). This enables quick interventions such as grading or sorting of fish to reduce size disparity.

A typical case study is the Atlantic salmon (*Salmo salar*) aquaculture in Norway and Chile, where cage crowding has been linked to reduced growth and lowered immune response (Turnbull *et al.,* 2005). However, by integrating sfBMI monitoring, operators, fish farmers could identify welfare decline before mortalities occur. This would be particularly valuable for precision aquaculture approaches that require robust, quantitative welfare metrics.

Disease diagnosis and monitoring

Fish diseases pose major threats to aquaculture socio-economic sustainability, with bacterial, viral, and parasitic infections leading to great losses globally (Pridgeon and Klesius, 2012). Diagnosing disease at early stages is challenging, because clinical signs most time emerge only after substantial physiological decline. sfBMI provides a sensitive and important tool for detecting sharp declines in condition that may precede visible symptoms.

A sudden drop in sfBMI in a fish group or cohort despite consistent feeding and optimal environmental parameters may suggest the onset of subclinical infections. For example, *Streptococcosis* in tilapia or infectious salmon anaemia (ISA) in salmon often causes reduced feeding activity before outward morbidity (Blackwell *et al.,* 2000). By integrating sfBMI into routine monitoring procedures, farmers can initiate diagnostic testing very early, which improves treatment outcomes and reduces the farmers' economic losses.

In channel catfish (*Ictalurus punctatus*) farms in the United States, for instance, outbreaks of enteric septicemia caused observable declines in body condition before mortality surges. Incorporating sfBMI into regular health assessments could thus improve biosecurity and enable earlier interventions, reducing both mortality and economic losses.

Overfeeding and obesity risks

While under-conditioning is a major concern from the metrics table, excessive sfBMI (>115%) also shows a potential health risk. Overfeeding in aquaculture could possibly lead to fat accumulation, metabolic disorders, reduced reproductive fitness and more. In addition, uneaten feed Ca pollute the water, leading to eutrophication of surrounding waters, causing long-term environmental harm (Boyd and Tucker, 2012).

For species such as catfish and salmon, high-energy diets designed for rapid growth can inadvertently induce hepatic steatosis (fatty liver disease). sfBMI provides a quantifiable means to detect these trends, prompting feed ration adjustment before irreversible pathology develops. Thus, sfBMI serves as an important balanced tool, identifying both nutrient deficiency and nutrient excess.

Wild fisheries applications

In capture fisheries, assessing the condition of wild populations is crucial to understanding ecosystem and stock dynamics in this era of environmental change. Traditional indices have been useful but are often context-specific. sfBMI provides a standardised framework that can enhance comparative analyses across species and habitats and is crucial the for determining the following:

Stock assessment and recruitment potential

Stock assessment models need biological reference points to estimate recruitment. Fish condition strongly influences reproductive success, larval survival, and recruitment variability (Brosset *et al.,* 2020). sfBMI provides a robust, comparable indicator of energy reserves across populations.

For instance, Atlantic cod (*Gadus morhua*) populations exhibit marked interannual variability in recruitment success (Brander, 2000), Lower condition indices during spawning seasons have been correlated or linked with reduced egg quality and larval viability (Yildiz *et al.,* 2025). By applying sfBMI, fisheries managers can quantify reproductive potential more consistently than with Fulton's K, which often underestimates condition in larger individuals (Froese, 2006).

A key example is the European sardine (*Sardina pilchardus*) fishery in Iberian Spain, where changes in body condition have been used to monitor spawning stock biomass and recruitment success. By expressing fish condition in relative percentage terms, sfBMI could improve comparability between Individuals, groups or cohorts and across years, enhancing predictive accuracy in species population models. This is particularly important for small pelagic fisheries, where recruitment variability strongly influences management decisions.

Environmental monitoring

Fish incorporate environmental conditions through their growth and feeding dynamics; thus, monitoring the aquatic environment is crucial to the population dynamics of fish. For instance, pelagic fish such as sardines and anchovies show rapid condition responses to fluctuations in plankton availability (Brosset *et al.,* 2023). Monitoring sfBMI across seasons and regions will provide real-time information on the aquatic ecosystem productivity.

Climate change indicators

Climate change alters the aquatic ecosystems through warming, acidification, and shifting prey distribution. These changes cascade via the food webs, influencing fish condition and population dynamics (Pörtner and Peck, 2010). sfBMI can act as a climate sentinel, providing early evidence of ecosystem change.

For instance, warming-induced northward shifts in small pelagic fish distribution have been accompanied by changed body condition patterns (Duffy-Anderson *et al.,* 2025). sfBMI allows managers to disentangle whether observed declines are due to prey mismatch, physiological stress, or density effects and more. Long-term monitoring of sfBMI across latitudinal gradients can therefore improve climate adaptation strategies in fisheries.

Conservation applications

Conservation biology increasingly relies on condition metrics to assess the impacts of habitat degradation, pollution, and restoration interventions. sfBMI offers a versatile and communicable tool in this context.

Habitat degradation assessment

Wetlands, estuaries, and rivers are critical habitats for juvenile and adult fish but are often degraded by anthropogenic/human activities. Declines in sfBMI within these systems can reveal the ecological consequences of various anthropogenic activities. For instance, reduced sfBMI in mangrove-associated fish species may signal loss of nursery habitat and reduced prey availability.

Pollution monitoring

Chronic pollutant exposure, including heavy metals, pesticides, and hydrocarbons, will limit growth efficiency in fish (van der Oost *et al.,* 2003). Unlike mortality counts, which reflect acute toxicity, sfBMI provides a sensitive measure of sublethal stress. By integrating sfBMI into biomonitoring programs, operators or farm managers can detect long-term pollutant impacts and evaluate the success of remediation efforts.

Policy and community communication

A key advantage of sfBMI lies in its insightful interpretation. Expressing condition as a percentage of expected weight for a given fish length enables policymakers, fishers, and local communities to understand ecological findings without advanced statistical training. This bridges the gap between scientific assessment and practical decision-making, thus facilitating community-based fisheries management (bottom-top approach) and policy adoption.

For instance, presenting findings that "fish in River X are only at 85% of expected weight" is more compelling to stakeholders than reporting abstract Kn or K values. This simplicity enhances sfBMI's role as a science–policy communication tool. Table 2 compares side-by-side Fulton's K, Kn, and sfBMI, indicating their strength and weaknesses with their scientific assumptions.

LIMITATIONS AND FUTURE RESEARCH

While sfBMI offers considerable promise, several limitations must be acknowledged.

Species-specific validation

Length–weight relationships vary across species, life stages, and environments. For sfBMI to be applied universally, species-specific baselines must be established

Table 2. Comparison of condition indices.

Index	Formula	Assumptions	Strengths	Weaknesses
Fulton's K	W/L^3	Assumes b=3	Very simple, easy to calculate	Allometry; size-dependent biased
Relative Kn	$W/(aL^b)$	Uses values derived a, b	Allometrically correct	Less intuitive for stakeholders
sfBMI	$W/W_e \times 100$	Species-specific Length-Weight Relationship needed	Intuitive % scale; farmer- and policymaker-friendly; robust	Needs calibration for fish species

(Lugert *et al.,* 2016). Without such calibration, comparisons may be misleading, especially between taxa with different body morphologies (Froese, 2006).

Environmental and physiological influences

Condition indices, including sfBMI, are influenced by reproductive stage, gut fullness, and seasonal cycles (Le Cren, 1951). This variability necessitates careful sampling protocols and interpretation frameworks to avoid misattribution of sfBMI fluctuations.

Integration with digital technologies

One promising direction is the integration of sfBMI with digital aquaculture technologies. Automated image analysis and machine vision could allow non-invasive estimation of fish length and weight, enabling real-time sfBMI monitoring (Zhao et al., 2021). Coupling sfBMI with IoT-based water quality sensors could further enhance precision management.

In practical applications, sfBMI could be estimated using image-based and sensor-assisted systems without the need for manual measurements. Computer vision algorithms can detect fish outlines from photographs or video streams. By applying morphometric calibration via stereo imaging, the Standard length (SL) can be automatically extracted. Once length (SL) is estimated, expected weight (We) is calculated using the stored length–weight equation.

The actual weight (W) can be either predicted by machine learning models trained on large image datasets linking fish morphometrics to true body mass, or directly obtained from Internet of Things (IoT)-enabled smart weighing devices.

Once Standard Length (SL), observed weight, and predicted weight are available, the system computes sfBMI(W/We) automatically in percentages, which can then be visualised on dashboards for farmers, extension officers, or managers.

CONCLUSION AND RECOMMENDATION

The BMI (BMI) and standardised fish BMI (sfBMI) present a novel, robust, and intuitive method for assessing fish health and condition. By combining the biological precision of length–weight relationships with the communicative clarity of the BMI concept, this approach can improve monitoring efficiency in aquaculture and ecological research. Future work should validate this method across species, seasons, and environmental conditions.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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