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Insights into Decapod Sentience: Applying the General Welfare Index (GWI) for Whiteleg Shrimp (*Penaeus vannamei*—Boone, 1931) Reared in Aquaculture Grow-Out Ponds

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Abstract: The rapid growth of shrimp farming, particularly of *Penaeus vannamei*, accounts for about 80% of the global production of farmed shrimp and involves the cultivation of approximately 383 to 977 billion individuals annually, which highlights the urgent need to address the ethical and technical implications of raising potentially sentient beings. This study builds on the state-of-the-art assessment of sentience, consciousness, stress, distress, nociception, pain perception, and welfare to adapt the General Welfare Index (GWI) for farmed shrimp. The GWI is a quantitative index developed by our research group to measure the degree of welfare in aquaculture, and it has been previously applied to grass carp and tilapia. Using the PRISMA methodology and the creation of a hypothetical shrimp farm, the GWI, with 31 specific and measurable indicators across various welfare domains, is adapted to *P. vannamei*, offering a comprehensive assessment framework. The inclusion of quantitative welfare indicators promises to improve living conditions in alignment with legislation adopted on decapods' sentience and contemporary scientific advances.

Keywords: animal ethics; nociception; shrimp aquaculture; welfare index; welfare monitoring

Key Contribution: This research significantly contributes to the aquaculture sector by providing a practical and quantifiable tool for welfare assessment, encouraging the industry to adopt more responsible and sustainable practices, and envisioning a future where shrimp welfare is recognized and enhanced.

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1. Introduction

The rapid growth in farmed shrimp production and international trade meets the global demand for high-quality protein-rich seafood, consolidating shrimp as the most traded seafood worldwide [1–3]. In 2022, the shrimp market reached about USD 68.40 billion, with USD 40.12 billion (approximately 58%) coming from aquaculture, with projections to reach USD 65.04 billion by 2030 [4]. *Penaeus vannamei* stands out as the leader among cultivated species, representing approximately 80% of the global production, with almost 5 million tonnes [5] of farmed shrimp generating USD 30.9 billion in revenue in 2022 [4,6]. Despite a slight contraction of 0.4% in global production in 2023, aquaculture supplied the market with about 5.6 million tonnes, with optimistic projections for a 4.8% increase in production in 2024 [7].

The average slaughter weight of *P. vannamei* farmed varies from 10 to 26 g. Based on estimates considering the variation in average slaughter weight from 10 to 20 g, obtaining

5.6 million tonnes of shrimp necessitates cultivating between 280 and 560 billion individuals. When adjusted for survival rates in ponds, which range from 57.3% to 73% [8], the requisite number of individuals increases to between 383 and 977 billion (Figure 1).

	Parameter	**Details**
Global Shrimp Market	Value (2022)	USD 68.40 billion
	Contribution from Aquaculture (2022)	USD 40.12 billion
	P. vannamei Production Share (2022)	Approximately 80% (~5 million tonnes)
	Farmed Shrimp Revenue (2022)	USD 30.9 billion
	Estimated Production for 2024	5.6 million tonnes
***P. vannamei* slaughtered**	Average Slaughter Weight Range	10-20 g
	P. vannamei Projected Production (2024)	280-560 billion individuals
	Estimated Survival Rates	57.3% to 73%
	Adjusted for Survival Rates	383-977 billion individuals

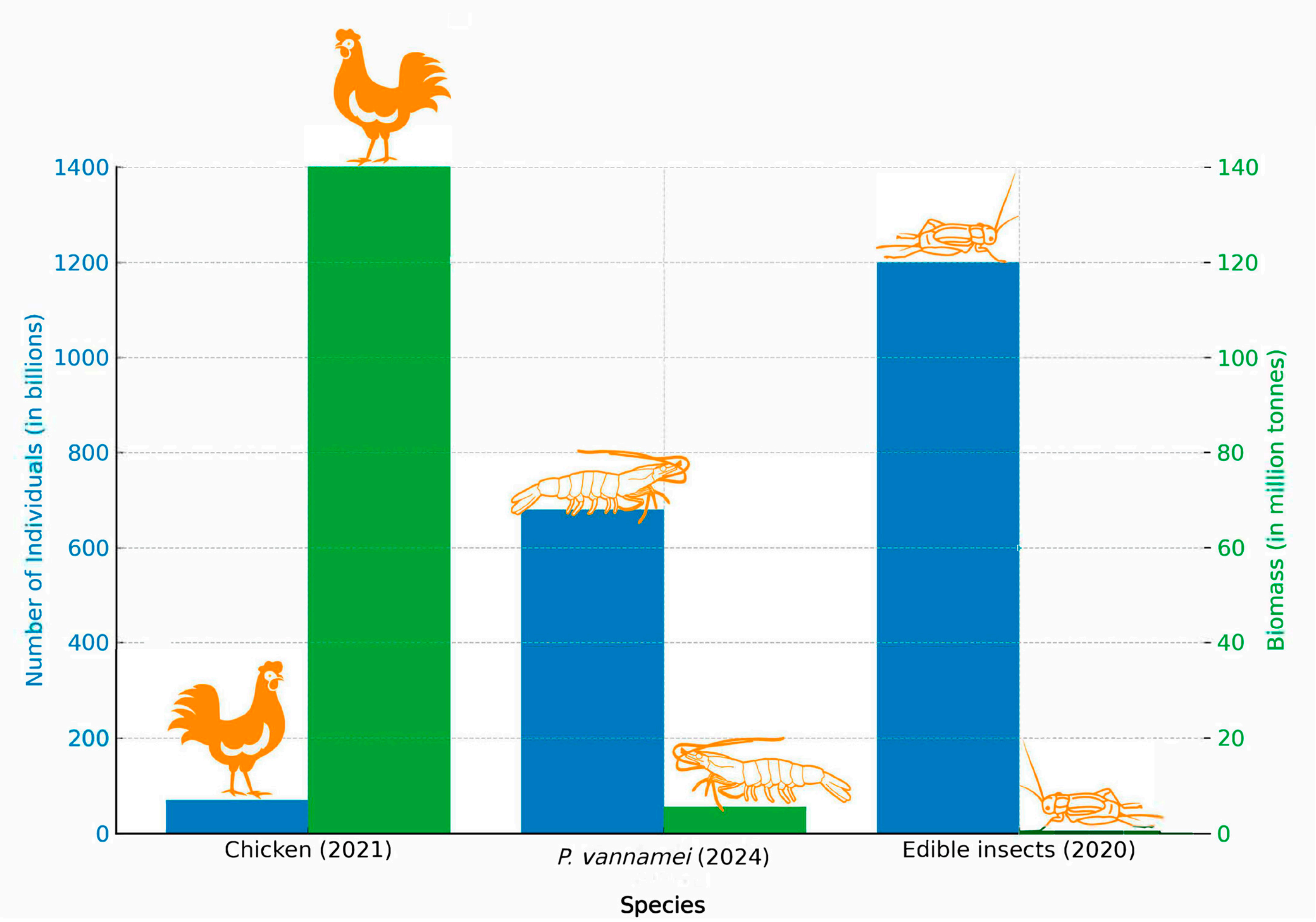


Figure 1. Assessment and comparison of aquacultured *Penaeus vannamei* shrimp quantities and biomass to other farmed organisms.

The figures do not account for the animals that die during the larval and post-larval stages. The numbers exceed those estimated by Waldhorn and Autric [9], which range between 300 and 620 billion shrimp and highlight the magnitude of shrimp production compared to other species used for human food, significantly surpassing the output of vertebrates such as chickens, with over 70 billion slaughtered in 2021, resulting in a biomass of 157.5 million tonnes [10]. They also indicate that shrimp are numerically among the most farmed organisms for human food worldwide, second only to insects, whose annual production is expected to exceed 1.2 trillion organisms, with a total biomass of 0.6 million tons [11]. However, it should be emphasised that this comparison involves just one species (*P. vannamei*) with several species of edible insects.

In light of these figures, inevitable questions arise about the scientific advancements concerning the potential sentience of shrimps and how such findings might necessitate substantial reforms in one of the most significant and influential food industries worldwide [9,12]. The acknowledgement of sentience in these crustaceans challenges traditional viewpoints and spurs a profound reflection on the necessity of reassessing our relationship with species cultivated for consumption. This turning point in the debate emphasises the importance of animal welfare in aquaculture, highlighting the urgent need to value and respect non-human life.

In this study, we discuss essential concepts about sentience, consciousness, stress, distress, nociception, pain perception, and the welfare of decapod crustaceans, focusing on farmed shrimp. We adopt a quantitative index, the General Welfare Index (GWI), developed by our research group [13,14]. Based on parameters readily observable in farming contexts, the GWI seeks to incorporate scientific advancements regarding shrimp sentience and health into production routines, encouraging practices that enhance animal welfare, productivity, and sustainability in aquaculture.

1.1. Contextualisation and Foundations

1.1.1. Welfare, Stress, and Distress

Animal welfare science evolved from the Five Freedoms Model [15] to the Five Domains Model developed by Mellor and Reid [16], reflecting an advancement in understanding animal needs. This model has been continually revised [17–20] and focuses on enhancing animal welfare across five critical aspects—(1) Environment: related to physical space, promoting comfort, adequate stimulation, and challenges; (2) Nutrition: encompassing access to water and food, preventing hunger and thirst (initially considered for terrestrial animals); (3) Health: Preventing and treating diseases and injuries, as well as minimising pain and discomfort; (4) Behaviour: allowing the expression of natural behaviours, minimising restrictions, and avoiding abnormal behaviours; (5) Mental State: considering the animal's emotional experiences, both negative emotions (fear, frustration) and positive emotions (pleasure, contentment).

According to Mellor, Beausoleil, Littlewood, McLean, McGreevy, Jones, and Wilkins [20], the first three domains focus on the animal's physical stability and its disturbance's adverse effects. In contrast, the fourth and fifth domains address conscious interactions and mental states, highlighting the importance of positive and negative emotional experiences. Unlike the Five Freedoms Model—which is based on freedoms from hunger and thirst, discomfort, pain, injury or disease to express normal behaviour and from fear and distress—the Five Domains Model proposes a holistic approach that transcends mere prevention of suffering, valuing the promotion of positive welfare and the harmonisation of physical and mental welfare, thus establishing a more comprehensive foundation for animal care.

Stott [21] defines "stress" as ranging from general responses to environmental challenges to specific stimuli reactions. It involves the disturbance of homeostasis by external factors, requiring adaptations that can be both beneficial and harmful. Moberg [22] and Bayne [23] provide definitions of stress, highlighting it as a biological response to threats disrupting internal equilibrium or measurable physiological changes due to environmental factors. Therefore, yes, shrimps do feel stress.

Morton [24] differentiates "distress" as a state of intense and prolonged mental suffering that negatively affects the animal's physical and psychological welfare, contrasting with stress, which is an adaptive response. Wuertz et al. [25] note that in crustaceans, distress may compromise health and elevate disease vulnerability, adversely affecting populations.

In 2009, the Farm Animal Welfare Committee introduced a tripartite hierarchy of comprehensive assessments on an animal's quality of life (QOL) throughout its life, involving a Life Not Worth Living, a Life Worth Living (LWL), and a Good Life [26]. The current trend in research is to define animal welfare as related to life satisfaction, considering the balance between positive and negative experiences [26–30]. A "good life", indicative of a high degree of welfare, would be characterised by positive experiences. Beings with higher levels of consciousness may have more complex needs that must be addressed to ensure their welfare.

The idea of "a life worth living" introduces subjectivity akin to human perceptions of happiness, highlighting the challenge of applying human standards to animal welfare. This parallel can be problematic in scientific discussions on animal welfare, potentially leading to the so-called "barn logic" [31]. This reasoning defends raising animals for consumption as positive, arguing that it allows animals to exist, even under brief and often adverse circumstances. This perspective promotes the idea that merely existing is better than not existing, neglecting the quality of that existence and the complexities of welfare. Justifying raising animals for consumption as a guarantee of their existence overlooks the degree of animal suffering. It minimises the relevance of lives marked by welfare and freedom, turning sentient beings into products for human consumption. This simplification distorts the essence of the debate on animal welfare.

To navigate this complexity, we adopt the definition of animal welfare by the World Organisation for Animal Health [32]: "Animal welfare means how an animal copes with the conditions in which it lives and dies. An animal is in a good state of welfare if (as indicated by scientific evidence) it is healthy, comfortable, well-nourished, safe, able to express innate behaviour, and not suffering from unpleasant states such as pain, fear, and distress. Animal welfare requires disease prevention, veterinary treatment, appropriate shelter, management, nutrition, humane handling, and humane slaughter/killing".

1.1.2. Nociception and Pain Perception

Rowe [33], in a very didactic manner, explains that the International Association for the Study of Pain (IASP) characterises pain in humans as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage". The ISPP defines nociceptors as "a high-threshold sensory receptor of the peripheral somatosensory nervous system capable of transducing and encoding noxious stimuli". According to the author, while the activation of nociceptive pathways alone does not constitute pain, the experience of pain is inherently subjective, varying significantly among human individuals, who may report their pain experiences by comparing them with past experiences. However, the private nature and the impossibility of objective quantification make the absolute proof of pain experience unattainable in animals, given the absence of communication comparable to humans. Other authors agree that animal pain is an aversive sensory and emotional experience associated with injury. Still, pain is crucial in promoting protective behaviours and avoidance learning [34,35].

The consensus on crustaceans' capacity for pain perception remains elusive, underscoring a complex study area. Comstock [12] posits variability in pain sensitivity among decapods, with Pleocyemata possibly more receptive than Dendrobranchiata, challenging the assumption of uniform nociceptor distribution. Passantino et al. [36] challenge the view that decapods' responses to noxious stimuli are merely reflexive, pointing to the complexity of these reactions as possible indicators of painful experience. Elwood [37] notes that behaviours suggestive of pain are more prevalent in crustaceans and insects of the clade *Mandibulata* than in spiders of *Chelicerata*.

Nociception is the sensory mechanism that allows animals to detect noxious stimuli and avoid tissue damage [38,39]. Nociception can result in sensitisation post-injury and is modulated by TRP channels and brain opioids [40,41]. Research on decapod crustaceans shows nociceptive behaviours controlled by known mechanisms, but primary nociceptors have only been found in *Procambarus clarkii* [42–44]. Given the nascent research stage, our understanding of pain perception and sentience in decapods largely relies on behavioural and physiological studies.

1.1.3. Sentience and Consciousness

In contemporary neuroscience, consciousness is investigated through processing brain information and the emergence of conscious experience [45,46]. Thus, sentience is just one of several components of consciousness, which ranges from sensory perception to more complex cognitive elements, such as reflection on experiences and projection about the past and future [47,48]. Dung and Newen [49] defined conscious experience as the subjective quality of the lived state, highlighting the ability of conscious beings to experience a range of sensations and emotions.

Bridging the gap between the exploration of consciousness in contemporary neuroscience and historical perspectives on animal cognition, we must examine how past beliefs, notably those of Descartes, contrast sharply with modern understandings. “Animals are like robots: they cannot reason or feel pain.” This statement is commonly attributed to Descartes, a 17th-century French philosopher and mathematician renowned for his contributions to rationalism and his theories on the mind and body [50], exemplifies a simplistic and widely disseminated, albeit controversial, view on the nature of animals. Descartes, famously or infamously depending on the perspective, believed that only humans possessed a rational mind, a thinking substance (“res cogitans”), capable of reasoning and sensation, in contrast with “res extensa”, the principle constituting the physical world, including non-rational living beings [51]. He viewed animals as automata or machines devoid of mind and rationality, operating purely through mechanical and physical processes [52]. Despite no evidence that the quoted phrase was uttered or written in that form by Descartes, it encapsulates a form of thought that has long influenced human relations with the animal kingdom. Until the mid-last century, any mention of “feelings” or “suffering” in animals was seen as unscientific, for example, [53]. However, advances in sciences and philosophy began to challenge and reshape this Cartesian and mechanistic view [54]. The shift from this historical paradigm to a contemporary understanding of animal sentience started with the publication of “Animal Machines” [55]. It reflected an advancement in human thought, marked by a growing appreciation of the complexity and richness of non-human life forms.

The concept of “sentience” in non-human animals is a central theme in discussions on ethics, bioethics, and animal welfare (* The term “well-being” is sometimes used interchangeably with “welfare”, but “well-being” can be less precise in its usage and may be interpreted more in a positive sense, whereas the concept of welfare needs to encompass both negative and positive aspects. “Welfare” is the term used in the English versions of European legislation) [56] and has been gaining increasing international recognition [57–59]. This recognition drives significant changes in practices affecting various species. The understanding that animals can feel pain, pleasure, and other emotions is the starting point for fostering studies and practices aimed at animal welfare, reformulating production techniques, and promoting a more ethical and responsible relationship with the species that serve as our food [60,61]. Thus, the perception of animal sentience becomes a foundation for adopting more conscious and respectable welfare practices with farmed animals [57,62,63].

Sentience is an animal’s ability to have subjective experiences, also known as “phenomenal consciousness” [57]. An animal is considered sentient if, under the right conditions, there is “something that it is like” to be that animal [64,65]. In a more restricted sense, sentience may refer to the animal’s capacity to have subjective experiences with positive or negative valence—experiences that feel good or bad—such as pain, pleasure, anxiety, distress, boredom, hunger, thirst, warmth, joy, comfort, and excitement [66–74]. In this more restricted sense, sentience is sometimes known as “affective sentience” and is very close to an essential meaning of the common word “feeling” [75,76]. Other definitions of sentience include the innate ability of some animals to experience emotions and feelings, with the former being neurobiological adaptive responses and the latter subjective interpretations influenced by individual and social contexts [77,78]. Broom [79] discusses the capacity to possess levels of consciousness and the cognitive ability necessary to have feelings. Sentience also includes the response to sensory stimuli and their perceptions of the animal's mental state [62,79].

"Consciousness", unlike sentience, encompasses a broader range of cognitive and metacognitive experiences whose complete understanding remains challenging for science [80–83]. Consciousness includes self-perception, recognition of the self as a unique entity, and integrated reflection on thoughts, sensations, and perceptions [70,84]. It goes far beyond sensory experience, involving self-awareness, advanced cognitive capabilities, and formulating complex thoughts and intentions [85].

1.1.4. Sentience in Decapod Crustaceans

The analysis of sentience in decapod crustaceans, encompassing interdisciplinary assessments that consider behavioural, physiological, and health aspects, reveals a complex domain lacking consensus. Walters [86] points out gaps in understanding sensations in decapods, particularly in distinguishing affective components like suffering, despite observable pain-related behaviours also noted in cephalopods. Critically, Diggles [87], through an extensive literature review, questions the reliability and interprets existing studies, pointing out the following:

- The scientific basis is still very controversial
- Questionable criteria for defining the experience of pain in crustaceans
- Experimental limitations and misinterpretations of data
- The use of anthropomorphic criteria leads to false equivalences with the human experience of pain
- The creation of animal welfare legislation in countries like Switzerland and the UK may reflect ethical considerations and societal pressures more than robust scientific evidence, potentially leading to unwarranted restrictions on research and the food industry
- The risk of imposing unnecessary restrictions on research and the food industry is based on a few scientific studies.

Diggles et al. [88] emphasise the need for scientific scepticism and critical thinking in assessing sentience and pain in fish and invertebrates, warning about the consequences of legislation based on precarious evidence and the importance of rigorous and evidence-based scientific debate. In contrast, Reber et al. [89], supported by the Cell-Based Theory of Consciousness (CBC), argue that sentience is a universal feature of living beings not restricted to animals with complex nervous systems. Andrews [90] proposes that science should focus on how animals are conscious, promoting advancement in understanding animal consciousness and grounding discussions on ethics and animal welfare. Browning and Veit [91] highlight the challenges in comparing welfare between species, both empirical and moral. At the same time, Comstock [12] underscores the relevance of understanding decapods' capacity to feel pain, considering the ethical, scientific, and economic implications. Ng [92] advocates recognising animal sentience based on behavioural evidence while critiquing the need for certainty for such recognition. Deckha [93] points to the need for a new ethical perspective in treating animals, especially crustaceans, in the industry.

Decapods and cephalopods, considered among the most intelligent and cognitively developed invertebrates, possess neuroendocrine systems analogous to vertebrates [94–96]. Decapods can process sensory information through brain regions, such as the hemiellipsoid body, which is involved in learning and memory [97]. Lobsters (*H. americanus*) can integrate information from multiple sensory sources and demonstrate learning and memory capabilities after associative training [98]. Hermit crabs (*Pagurus bernhardus*) make complex shell choices, considering shell quality and associated risks [99]. Crayfish (Procambarus virginalis) learned to avoid a stimulus (blue light) associated with electric shocks [100]. Injured crustaceans exhibit behaviours such as rubbing, limping, or caring for the affected area, suggesting awareness of the injury and attempts to minimise damage [37,101–103]. Autotomy, or the shedding of a limb, has been interpreted as a response mediated by an experience similar to pain [104–106]. Behavioural changes consistent with an increased state of anxiety after exposure to aversive stimuli have been observed in crayfish, indicating changes in emotional state that were attenuated by anxiolytic drugs, suggesting mechanisms of anxiety similar between crustaceans and humans [107–109].

The advanced stress response systems in decapods, evidenced by metabolic and physiological adaptations to stress, support the notion of their sentience and environmental responsiveness [110]. Changes in L-lactate levels in the hemolymph, indicative of a transition from aerobic to anaerobic metabolism in intense stress, point to this capacity for stress response [111–113]. Increased urea, glucose, and ammonia levels in the hemolymph under stress conditions reflect metabolic adaptations to face adversities [110]. A decrease in the number of hemocytes in the hemolymph may indicate compromised health and immunity due to stress [114]. Decapod crustaceans can generate robust and possibly adaptive responses to physical stressors [110,115,116].

Rotllant et al. [117] highlight that decapods meet at least 14 of the 17 criteria, and Sneddon, Elwood, Adamo and Leach [101] proposed decapods to be sentient. Crump, Browning, Schnell, Burn and Birch [43] developed a framework based on eight neural and behavioural criteria to assess sentience and applied this methodology to decapods. They found that Brachyura crabs show strong evidence of sentience, meeting five criteria, while Anomura crabs and Astacidea lobsters met three, indicating substantial sentience. However, the proof of penaeid shrimps is weaker, suggesting further studies are needed.

1.1.5. Shrimp Sentience

Sentience, defined as the capacity for valenced experiences, is inferred in shrimps through physiological and behavioural evidence, given the impossibility of directly observing these experiences [118]. However, these conclusions remain provisional. Shrimps display nociceptive behaviours like the tail-flip reflex when threatened [119], indicating a potential for pain perception. Weineck, et al. [120] suggest these behaviours might be reflexive, not definitively indicating central processing associated with subjective experiences. McKay, McAuliffe and Waldhorn [118] observed similar behaviours induced by anaesthetics, casting doubt on their definitive association with pain. Taylor, et al. [121] observed that lidocaine reduced disoriented swimming behaviours in *P. vannamei*. However, McKay, McAuliffe and Waldhorn [118] argue that anaesthetics could reduce responses to threatening stimuli by lowering overall alertness rather than pain.

Behavioural indicators suggest sentience and are crucial for the early detection of health problems in aquaculture, highlighting their role in welfare assessment [122]. However, further research is required to link these behaviours with specific physiological or morphological markers to understand better sentience [25,123]. Avoidance learning, anxiety, long-term alterations, responses to the site of injury, and autotomy as a defence mechanism are indicative of this behavioural complexity [124]. Increased stocking density leads to notable behavioural changes in juvenile *P. vannamei*, suggesting stress responses [125]. Applying local anaesthetics and coagulating agents, such as the eyestalk ablation in *P. vannamei*, can attenuate the stress response, influencing feeding resumption and recovery of swimming patterns [121]. Although shrimps are less prone to cannibalism than other crustaceans [126], this behaviour can intensify under adverse conditions, such as diseases or individuals with soft shells [127,128]. Harvesting, a critical phase of the production cycle involving physical handling, can trigger escape behaviour and stress, leading to injuries and decreased meat quality [129] and causing increased heart rates [130].

Other studies point to sentience in shrimps based on cognitive behaviours and responses to various stimuli [131]. Albalat et al. [132] contend that the complex environmental interactions and adaptations of shrimps, such as *P. vannamei*, imply possible sentience. They cite the relationship between gonadal maturation and spawning in response to environmental variables such as temperature and salinity and the complexity of shrimps' immune system, which includes physical barriers and cellular and humoral responses, as evidence of sentience [133–135]. Furthermore, physiological stress responses, such as metabolic changes and immunological dysfunction under prolonged stress, could signal the capacity to experience negative internal states, a component of sentience [118,132]. Freire et al. [136] and Jerez-Cepa and Ruiz-Jarabo [137] show that shrimps manifest complex physiological and behavioural responses to stress, directly affecting their welfare. Such responses, reflecting the principles of homeostasis and allostasis, indicate the capability of these crustaceans to experience complex internal states under stress. Integrative neural centres, such as the medullary terminals and hemiellipsoid bodies, point to an advanced level of cognition and neural processing, suggesting potential sentience [138].

Wuertz, Bierbach, and Bögner [25] highlight that shrimps can experience distress through a complex neuroendocrine response similar to that observed in vertebrates through the crustacean hyperglycemic hormone (CHH). This hormone regulates glucose homeostasis, immune response, and anti-predatory behaviours, indicating significant neuroendocrine complexity [139,140] [141]. Changes in serotonin (5HT) levels signal behavioural and metabolic stress, potentially leading to anxious behaviours [109,142]. It is also known that CHH secretion is vital in the stress response, affecting osmoregulation, energy metabolism, and the response to chronic stressors, negatively impacting survival, growth, and disease resistance in shrimp [25].

1.1.6. Sentience of Decapods and Legislation

According to Robertson and Goldsworthy [73], legislation related to sentience should align with the concept of animal welfare proposed by Mellor [143], which conceives it as the animal's capacity to have meaningful subjective experiences. Understanding sentience in non-human animals is crucial for providing more ethical and practical care. Incorporating animal sentience into legislation and legal guidelines constitutes a significant milestone in animal protection. It promotes safeguarding their rights and fosters practices prioritising welfare by recognising and validating their capacity to feel and interact [144–146]. This valuation of animal sentience is gradually expanding beyond vertebrates to include invertebrates, with notable reflections in national policies and regulations. New Zealand has been a pioneer in protecting various species of crustaceans in its legislation since the end of the last century [147,148], followed by other countries such as Austria [149], Australia [150], United Kingdom [151], Norway [152], and Switzerland [153], where decapod crustaceans are recognised as sentient beings.

1.1.7. The Application of Animal Welfare in Shrimp Farming

Integrating scientific insights and legal standards into shrimp farming presents notable challenges. Certification standards, such as those proposed by the Aquaculture Stewardship Council [154], highlight the importance of animal welfare in shrimp farms. Yet, ultimately, adopting sustainable practices across this industry demands continuous endeavour. There is a contrast between the laws and the daily reality of global aquaculture, as Krause et al. [155] observed, "a chasm between people and policies". According to a Rabobank report [156], the shrimp farming sector has 16 critical economic, health, operational, and production concerns derived from FAO, GOAL Survey, and Rabobank data. However, the producers do not mention the welfare of farmed shrimp.

Prioritising shrimp's welfare positively impacts aquaculture's technical, operational, and financial aspects. Practices that ensure an optimal environment for the species to grow and thrive, balanced nutrition, careful management, and effective disease prevention will lead to better health, greater productivity, and higher meat quality [157–161]. Alignment with the demand for ethical and sustainable products broadens market acceptance, positioning the product in more lucrative niches [162,163]. Moreover, investing in animal welfare minimises operational risks, such as diseases, reducing treatment expenses and production losses [164,165]. Consequently, prioritising shrimp welfare enhances industry sustainability, bolsters economic resilience, and access to higher-value markets [163,166]. So, even if producers have yet to realise it, their main concerns are intrinsically linked to the welfare of farmed shrimp, directly impacting the sector's viability and success.

Developing and implementing tools like the GWI are pivotal in narrowing the divide between scientific understanding and practical farming methods. The GWI offers a practical, evidence-based approach to assessing and monitoring shrimp welfare, assisting producers in adopting superior practices for improved health, productivity, and meat quality. Moreover, by demonstrating a commitment to animal welfare through the GWI, shrimp farmers can enhance their market competitiveness, access premium niches, and contribute to a more responsible and sustainable aquaculture industry. As the debate on animal sentience and welfare continues to evolve, the integration of the GWI into shrimp farming practices represents a significant step towards a future where the welfare of these animals is recognised, valued, and actively promoted.

2. Materials and Methods

2.1. Systematic Review

A systematic literature review guided by the PRISMA guidelines—Preferred Reporting Items for Systematic Reviews and Meta-Analyse [167]—was conducted to identify quantitative welfare indices developed or adapted for aquatic animals farmed in aquaculture. The comprehensive search, encompassing scientific articles, technical reports, books, book chapters, case studies, dissertations, and theses, was conducted on Google Scholar and Semantic Scholar platforms from February 2023 to January 2024. Document selection was influenced by the inclusion of specific terms related to the quantitative assessment of the welfare of aquatic animals, as detailed in Table 1.

Table 1. Terms used in the systematic literature review on methods for quantitatively assessing the welfare of farmed aquatic animals.

Group	Combinations
I	"shrimp welfare", "aquaculture", AND "INDEX" AND "measure"
II	("aquaculture" OR "fish farming") AND ("well-being index" OR "welfare index" OR "welfare assessment" OR "welfare metric") AND ("mathematical model" OR "quantitative formula" OR "evaluation index") AND ("crustaceans" OR "fish" OR "shellfish" OR "aquatic organisms" OR Decapod)
III	"aquaculture" AND ("shrimp" OR "decapod" OR "Shellfish" OR "Crustacea" OR "Fish") AND ("well-being assessment" OR "welfare assessment" OR "welfare Index" OR "well-being Index")

Subsequently, documents were meticulously filtered based on pre-defined criteria, such as:

- Mandatory presentation of indices or methodologies for estimating the degree of welfare of fish, crustaceans, or molluscs;
- The article should provide a detailed description of the mathematical logic and calculations employed to assess the welfare of the respective target animals;
- The proposed method directly applies to animals farmed commercially within aquaculture systems.

Following the removal of duplicates, studies were evaluated and selected based on the relevance of their title, abstract, and subsequently, their whole content, adhering to the structure of the PRISMA framework for identifying methods and strategies for calculating the welfare level of animals farmed in aquaculture, as summarised in Table 2.

Table 2. Sequential selection stages adopt the PRISMA framework for identifying methods and strategies for calculating the welfare level of animals cultivated in global aquaculture.

Phase 1: Pre-Identification	**Number of Documents**
Number of identified documents	1510
Documents from not academic sources (manuals, technical standards, scientific dissemination articles)	40
Total number of identified documents	1550
Duplicate documents	453
Phase 2: Selection	**Number of documents**
Documents selected, excluding duplicates	1097
Documents excluded for not meeting the defined criteria	961
Phase 3: Eligibility	**Number of documents**
Documents assessed for eligibility	136
Documents excluded for not meeting the defined criteria	76
Documents evaluated through full reading	60
Documents excluded for not meeting the defined criteria	50
Result: Total number of included documents	10

2.2. Mathematical Model and Welfare Indicators Used in the GWI

The General Welfare Index (GWI) was initially developed for grass carp, *Ctenopharyngodon idella*, cultivated in earthen ponds [13]. However, it was designed to apply to animals and aquaculture systems after the necessary adjustments of applicable indicators. It has been adapted here for *P. vannamei* based on specific indicators and their respective reference levels and weighting factors see [168]. The Partial Welfare Indexes (*PWIx*) were calculated, according to the formula presented in Equation (1), for four of the five domains proposed by Mellor and Reid [16] (environmental, health, nutritional, and behavioural).

$$PWI_x = \left(\sum Y / \sum (S \times Y) \times 1.4925 - 0.4925\right) \tag{1}$$

where we have the following:

PWI_x: Partial Welfare Index, calibrated to consistently range from 0, indicating a critical risk to the welfare of farmed shrimp, to 1, representing optimal welfare conditions or the minimal risk of harm to animal welfare. This scale is maintained irrespective of the number of indicators applied to each aspect of freedom.

X: Domain (Environmental—En; Behavioural—Be; Nutritional—Nu or Health—He).

S: Score (1, 2, or 3, with 1 being the best and 3 the worst) assigned to the indicators in the analysed shrimp farm.

Y: Denotes the weighting factor allocated to a particular indicator.

Each indicator's assignment of Y values was based on bibliographic analysis via Google Scholar using the following fixed terms: *Penaeus* AND *vannamei* AND welfare, plus the "specific keywords" related to each indicator. These Y values, defined as the integer part of the natural logarithm of the number of publications identified in the searches (Equation (2)), act as a weighting factor for the defined welfare indicators for the species.

$$Y = INT\ (ln(n)) \tag{2}$$

The GWI is calculated as the arithmetic mean of the *PWIx*, modulated by a knockout factor (*kl*), as delineated in Equation (3). This factor is affected by the mortality rate observed during the period under review. Consequently, mortality is the pivotal criterion in the welfare evaluation, according to the GWI. Whenever the mortality rate exceeds 30%, the kl is set to zero (0), denoting a "critical" condition for the *GWI*. Conversely, if the rate is under 30%, the kl is adjusted to one (1), facilitating the welfare calculation based on the chosen indicators, their scores, and their respective weights (Equation (3)).

$$GWI = \frac{((PWI_{En} + PWI_{Be} + PWI_{Nu} + PWI_{He}) \times kl)}{4} \tag{3}$$

where we have the following:

GWI: General Welfare Index, which varies from 0 (critical risk of harm to farmed shrimp welfare) to 1 (maximum welfare or, otherwise, minimum risk of injury to animal welfare).

kl: Knockout level (risk of whole impairment of the degree of welfare).

The designated Partial Confidence Levels (*CLs*) for each PWIx are calculated based on the number of indicators effectively examined in the field, as specified by Equation (4). An increase in the number of evaluated indicators relative to the proposed indicators elevates the confidence level of the findings. The General Confidence Level (*GCL*) is ascertained by the arithmetic mean of the *CLs*, as according to Equation (5). The PWIx, *GWI*, *CLs*, and *GCL* are categorized and interpreted based on the values achieved (Equation (4) and Table 3).

$$CL_x = \left(\frac{\sum W_{An}}{\sum W_{max}}\right) \tag{4}$$

where we have the following:

Table 3. Rank values for the Partial Welfare Indexes (*PWIx*), General Welfare Index (*GWI*) and the respective partial Confidence Level (*CL*) and General Confidence Level (*GCL*) arbitrated for shrimp (*Penaeus vannamei*).

Welfare Rating	PWI_x and GWI	CL_x and GCL
Critical	0	-
Low	>0 and ≤0.50	>0 and ≤0.50
Medium	>0.50 and <0.75	>0.50 and <0.70
High	≥0.75	≥0.70

CL_X: PWIx confidence level.

$\sum W_{An}$: Sum of the weights of the indicators analysed for the freedom x.

$\sum W_{max}$: Sum of the weights of all the defined indicators for the freedom x.

$$GCL = \frac{(IR_{En} + IR_{Be} + IR_{Nu} + IR_{He})}{4} \tag{5}$$

2.3. Application of the GWI for Diagnosing the Welfare Degree of P. vannamei Cultivated in Ponds

To exemplify the application of the GWI and the assessment of the welfare of shrimp cultivated in ponds, we used a hypothetical scenario proposed by Cozer et al. [169]. This scenario was constructed from a comprehensive literature review on the structural characteristics and typical management of a modal marine shrimp farm in Brazil, representative of the sector's average (illustrated in Figure 2 and detailed in Table 4).

The parameters and values for water quality necessary for calculating the PWI_{En} were extracted from the Technical Manual of Good Practices of the Brazilian Association of Shrimp Breeders (ABCC) [170], as presented in Table 5.

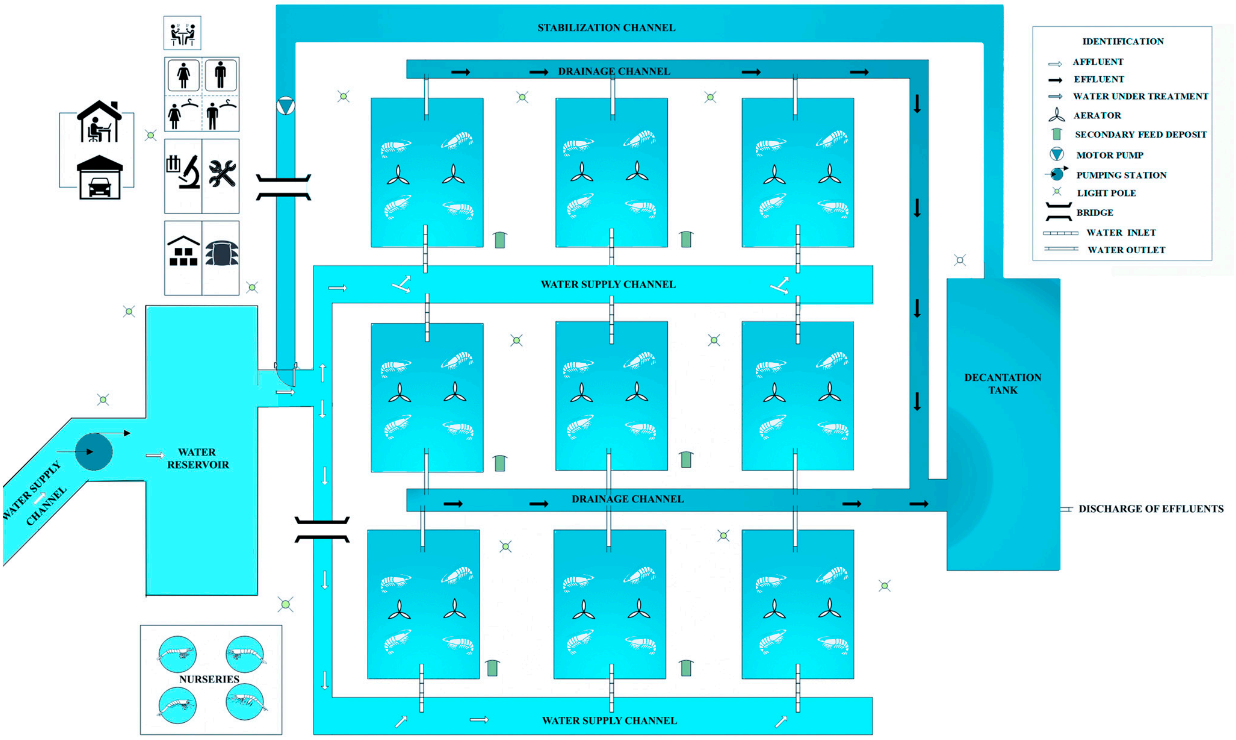


Figure 2. Schematic representation (not to scale) of the modal marine shrimp fattening farm in ponds in Brazil. Adapted from Cozer, Pont, Horodesky, and Ostrensky [169].

Table 4. Description and specification of the management, operational parameters, and technical data used during the fattening phase in the hypothetical farm intended for shrimp cultivation. Source: Cozer, Pont, Horodesky, and Ostrensky [169].

Item	Description/Value	Unit
Water surface area	9	ha
Operating system	Biphase	-
Production regime	Semi-intensive	-
Post-larvae (PL_{20})	Specific pathogen-free (SPF)	-
Stocking density	43	shrimps/m^2
Biometry	1	time/week
Diet composition	Natural feed + pellets	-
Feeding frequency	4	times/day
Feed quantity	2.0–5.0	% biomass
Use of feeders	35	feeders/ha
Feed size	1.0–3.0	mm
Crude protein in feed	35–40	%
Apparent Feed Conversion rate	1.5	-
Stunning during slaughter	Ice	seconds
Method for controlling aquatic predators	Screens	-
Final shrimp weight	12	g
Cycle duration	90	days
Survival	72	%

Table 5. Water quality parameters adopted to simulate and calculate the Environmental Partial Welfare Index (PWI_{En}). Source: ABCC [170].

Parameter	Value	Unit
Temperature	25–32	°C
pH	6.5–7.5	-
Transparency	30.0–35.0	cm
Alkalinity	120.0–200.0	mg/L $CaCO_3$
Ammonia	0.00–0.12	mg/L NH_3
Dissolved Oxygen	68.0	% saturation
Nitrite	0.0–0.5	mg/L NO_2^-
Salinity	10.0–40.0	PSU

Due to the absence of data for the hypothetical farm's digestive tract filling index indicator (nutritional domain), we resorted to the study by Costa [171]. This author, who analysed stocking density and its impact on the growth and feeding behaviour of *P. vannamei*, identified a digestive tract filling frequency of 46% for densities up to 50 shrimp/m^2, similar to the hypothetical enterprise employed here. The hypothetical scenario also lacked data on swimming and escape behaviours (behavioural domain), as well as information on the health of the shrimp (indicators such as the state of antennae, rostrum, eyes, gills, hepatopancreas, motor appendages, musculature, and exoskeleton). To fill these gaps, we used photographs and videos registered from visits to marine shrimp farms in the Brazilian Northeast in 2022, which share characteristics similar to those of the hypothetical enterprise (up to 10 hectares of water surface—classified as small aquaculture properties by the ABCC [172]. This approach made it possible to determine the scores of the indicators.

3. Results

Table 6 presents the number of citations and the weights assigned to each indicator, estimating their influence on the welfare assessment of *P. vannamei*. In the Environmental domain, parameters such as pH, temperature, salinity, ammonia, and stocking density were highlighted with the highest weights assigned. In the Health domain, mortality is underlined as the most significant indicator. Regarding Nutrition, the importance of feeding frequency is emphasized, and in Behaviour, the focus is on the animals' swimming behaviour.

Table 6. The number of documents identified through Google Scholar using the terms *Penaeus* AND *vannamei* AND juvenile OR adult AND aquaculture AND "keyword" and their respective weights (Y = Int(ln(n)).

Domain	Keyword	Number of Documents (*n*)	Weight (*Y*)
Environmental	"pH"	25,700	10
	"Temperature"	24,700	10
	"Salinity"	19,000	10
	"Stocking density"	16,660	10
	"Ammonia"	14,200	10
	"Dissolved oxygen"	13,200	9
	"Nitrite"	7590	9
	"Alkalinity"	2850	8
	"Terrestrial" AND "predator" OR "competitor"	1730	7
	"Transparency"	1550	7
	"Aquatic" AND "predator" OR "competitor"	778	7

Table 6. *Cont.*

Domain	Keyword	Number of Documents (*n*)	Weight (*Y*)
Health	"Mortality"	16,100	10
	"Hepatopancreas"	11,100	9
	"Gills"	7800	9
	"Eyes "	3950	8
	"Exoskeleton"	2750	8
	"Motor appendages"	2290	8
	"Musculature"	1620	7
	"Rostrum "	1230	7
	"Antennae"	781	7
Nutritional	"Frequency food"	26,100	10
	"Apparent feed conversion rate"	12,660	9
	"Crude protein"	9970	9
	"Use of trays"	1960	8
	"Distribution food"	119	5
	"Size food "	164	5
	"Amount of initial food"	147	5
	"Digestive tract filling index"	7	2
Behavioural	"Swimming behaviour"	258	6
	"Escape behaviour"	153	5
	"Stunning"	132	5

Applying the protocol by Pedrazzani, Cozer, Quintiliano, Tavares, da Silva, and Ostrensky [168] on the hypothetical farm developed by Cozer et al. 61 revealed that shrimp farming in Brazil stands out for the welfare provided to animals in the environmental and nutritional domains, which obtained the best PWIx. On the other hand, the lowest scores were attributed to the Health and Behavioural domains, which were observed as the main critical welfare points (Table 7).

Under the simulated conditions, the average GWI of Brazilian farms reached 0.46 (with 0 being the minimum and 1 the maximum), indicating a low degree of welfare for shrimp produced in Brazil (Figure 3). The GCL reached 0.98, reflecting high confidence in these estimates, given that the average number of indicators effectively analyzed per domain was 96.7% (29 indicators measured out of 30 possible).

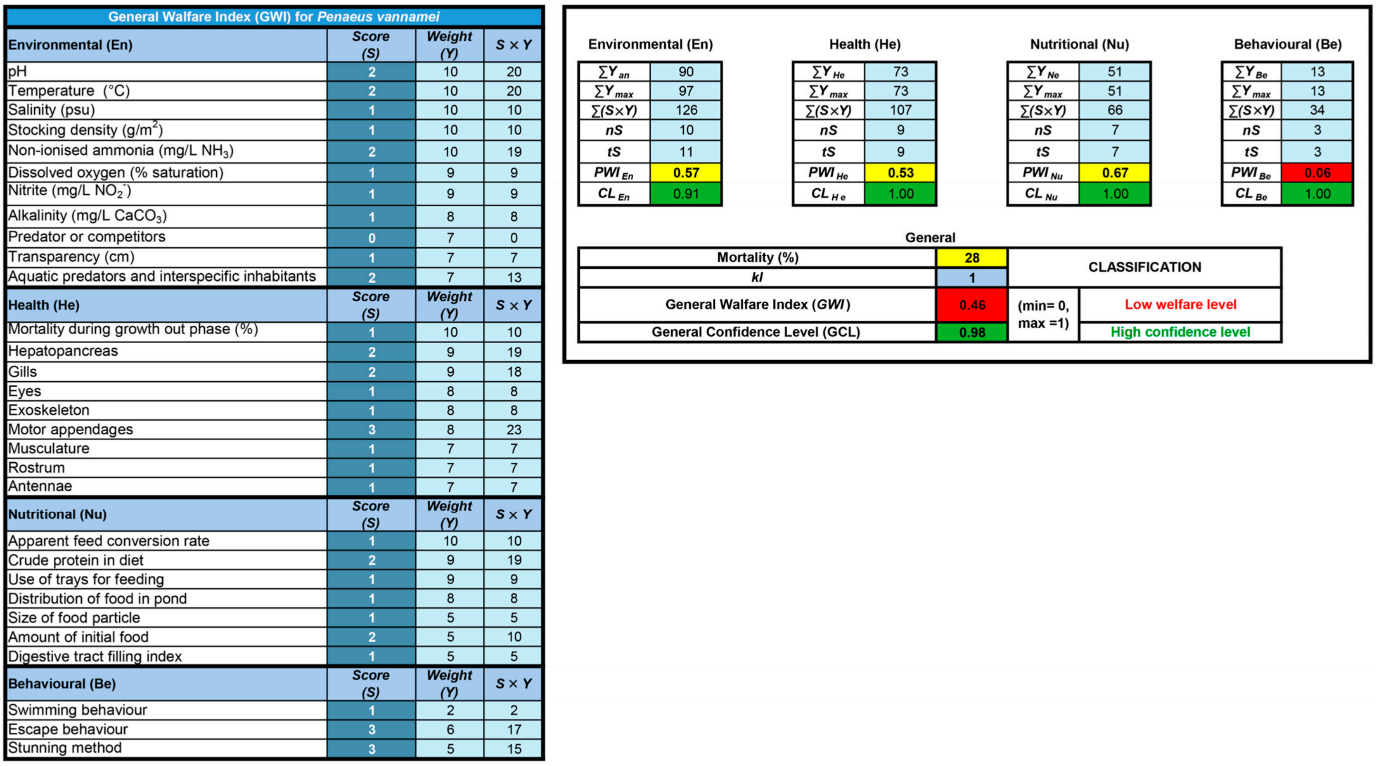
Table 7. Application of the protocol proposed by Pedrazzani, Cozer, Quintiliano, Tavares, da Silva, and Ostrensky [168] on the hypothetical farm developed by Cozer, Pont, Horodesky, and Ostrensky [169].

Domain	Indicator	Value or Criteria Described at the Hypothetical Farm	Value or Criteria Considered for Scoring	Scores Obtained in Hypothetical Farm *
Environmental	Temperature	25.0–32.0	25.0–32.0	1
	pH	6.5–7.5	6.5–8.5	1
	Transparency	30.0–35.0	35.0–50.0	2
	Alkalinity	120.0–200.0	100.0–140.0	2
	Ammonia (NH_3)	0.00–0.12	0.00–0.10	2
	Dissolved Oxygen	68.0	$\geq$65.0	1
	Nitrite	0.0–0.5	0.0–0.6	1
	Salinity	40.0	10.0–40.9	1
	Stocking density	43.0	$\leq$40.0	2
	Aquatic Predators	Screen 500 um^{-1} mm	Controlled presence	2

Table 7. *Cont.*

Domain	Indicator	Value or Criteria Described at the Hypothetical Farm	Value or Criteria Considered for Scoring	Scores Obtained in Hypothetical Farm *
Behavioural	Swimming behaviour	Figure S1	Few animals on the pond surface or irregular swimming	1
	Escape behaviour	Figure S2	Few jumping shrimps, but with high frequency and/or intensity during harvesting	3
	Stunning at slaughter–clinical reflexes	Figure S3	Slaughter using water and ice. Progressive loss of response to external stimuli; balance; movement of pleopods and pereiopods within >30 seconds	3
Nutritional	Size of food	1.0–3.0	2.1–3.0	1
	Amount of food (% biomass)	2.0–5.0	2.0–3.9	2
	Feeding frequency (times/day)	4.0	≥2	1
	Crude Protein (%)	32.0–40.0	≥32.0	1
	FCR	1.5	≤1.5	1
	Distribution of feed (% of pond surface)	>75	>75	1
	Use of feeders (no./ha) **	35.0	≥20.0	1
	Digestive tract filling index	46% full	Full	1
Health	Antennae	Figure S4	Focal lesion, shortening, or darkening	2
	Rostrum	Figure S5	Mild injury, erosion, or necrosis	2
	Eyes	Figure S5	Healthy appearance, no changes	1
	Gills	Figure S6	Healthy appearance, no changes	1
	Hepatopancreas	Figure S4	Healthy appearance, no changes	1
	Motor appendages	Figure S7	Focal absence or erosions	2
	Exoskeleton	Figure S7	Slight lesion or focal darkening, presence of debris	2
	Musculature	Figure S7	Healthy appearance, no changes	1
	Mortality (%)	28.0	≥26.0	3

* In the evaluation system, 1 represents the optimal welfare value or range for the species; 2 indicates a value that may compromise the animal's welfare; and 3 signifies severe welfare impairment, potentially resulting in the individuals' deaths. ** Feeders are considered an indicator of distributing the feed over >75% of the pond surface area.



General Walfare Index (GWI) for *Penaeus vannamei*

Environmental (En)	***Score (S)***	***Weight (Y)***	***S × Y***
pH	2	10	20
Temperature (°C)	2	10	20
Salinity (psu)	1	10	10
Stocking density (g/m^2)	1	10	10
Non-ionised ammonia (mg/L NH_3)	2	10	19
Dissolved oxygen (% saturation)	1	9	9
Nitrite (mg/L NO_2^-)	1	9	9
Alkalinity (mg/L $CaCO_3$)	1	8	8
Predator or competitors	0	7	0
Transparency (cm)	1	7	7
Aquatic predators and interspecific inhabitants	2	7	13
Health (He)	***Score (S)***	***Weight (Y)***	***S × Y***
Mortality during growth out phase (%)	1	10	10
Hepatopancreas	2	9	19
Gills	2	9	18
Eyes	1	8	8
Exoskeleton	1	8	8
Motor appendages	3	8	23
Musculature	1	7	7
Rostrum	1	7	7
Antennae	1	7	7
Nutritional (Nu)	***Score (S)***	***Weight (Y)***	***S × Y***
Apparent feed conversion rate	1	10	10
Crude protein in diet	2	9	19
Use of trays for feeding	1	9	9
Distribution of food in pond	1	8	8
Size of food particle	1	5	5
Amount of initial food	2	5	10
Digestive tract filling index	1	5	5
Behavioural (Be)	***Score (S)***	***Weight (Y)***	***S × Y***
Swimming behaviour	1	2	2
Escape behaviour	3	6	17
Stunning method	3	5	15

Environmental (En)		**Health (He)**		**Nutritional (Nu)**		**Behavioural (Be)**	
$\sum Y_{an}$	90	$\sum Y_{He}$	73	$\sum Y_{Ne}$	51	$\sum Y_{Be}$	13
$\sum Y_{max}$	97	$\sum Y_{max}$	73	$\sum Y_{max}$	51	$\sum Y_{max}$	13
$\sum(S \times Y)$	126	$\sum(S \times Y)$	107	$\sum(S \times Y)$	66	$\sum(S \times Y)$	34
nS	10	nS	9	nS	7	nS	3
tS	11	tS	9	tS	7	tS	3
PWI_{En}	0.57	PWI_{He}	0.53	PWI_{Nu}	0.67	PWI_{Be}	0.06
CL_{En}	0.91	CL_{He}	1.00	CL_{Nu}	1.00	CL_{Be}	1.00

General

Mortality (%)	28	**CLASSIFICATION**	
kI	1		
General Walfare Index (*GWI*)	0.46	**(min= 0, max =1)**	**Low welfare level**
General Confidence Level (GCL)	0.98		**High confidence level**

Figure 3. The outcome of applying the General Welfare Index (GWI) for *Penaeus vannamei* shrimp cultivated in ponds during the fattening phase under conditions representing the modal practices in Brazil. The red colour indicates a low degree of welfare, and the green colour indicates a high Confidence Level (CL).

4. Discussion

The debate over invertebrate sentience, especially in decapods like *P. vannamei*, raises ethical concerns in aquaculture and emphasises the need for better welfare management practices. In this context, Wahltinez, et al. [173] contend that while the evidence of sentience is pivotal to ethical discussions, it should not detract from the urgent need to implement practices that promote welfare in shrimp farming. This study echoes such sentiment, underscoring a substantial amount of scientific literature that illustrates the impact of farming practices on the welfare of shrimp, both positively and negatively, and demonstrating that evidence of this is readily available.

Appropriate stocking density is crucial, as overcrowding can limit growth and survival and increase harmful behaviours like cannibalism. This density must be determined based on available resources and interactions between individuals [174–176]. The quality of water, as indicated by salinity, temperature, pH, and dissolved oxygen levels, is imperative for sustaining optimal conditions in shrimp cultivation, directly impacting the animals' behaviour, physiology, and stress response [118,177–180]. Furthermore, lighting conditions and photoperiods are critical in influencing behaviours such as locomotor activity and feeding patterns, which are crucial for establishing efficient feeding protocols in shrimp farming [181,182].

Optimised feed management, designed around the feeding behaviours of shrimp, has proven to enhance feed efficiency significantly and, thus, the productivity of cultivation [158,183]. On the flip side, food deprivation is associated with weakened cellular immunity in *P. vannamei*, diminishing their disease resistance [184,185], while an increase in stress is directly linked to a higher susceptibility to illnesses [184,186,187]. Moulting is a pivotal physiological process that significantly impacts the feeding, growth, and reproduction of shrimps, governed by hormonal regulation and influenced by environmental conditions and developmental and physiological states [188–193]. Feed management strategies that oscillate between fasting periods and refeeding can sometimes boost productivity but may also compromise animal welfare, adversely affect productivity and exacerbate harmful behaviours like cannibalism [194,195]. Consistent and repetitive personality traits significantly influence the interaction with food and the consumption rates of shrimps [196,197]. Incorporating substrates at the bottom of the ponds and employing artificial structures benefit shrimp behaviour, providing refuges during moulting, reducing aggressive interactions, and increasing the available area for grazing [183,198,199].

These measures are prime examples of how fostering a cultivation environment tailored to the needs of shrimps goes beyond "mere" ethical compliance, reflecting concrete enhancements in animal welfare, shrimp health, and, consequently, the productive efficiency and profitability of the aquaculture operation. Implementing management practices that address these crustaceans' behavioural, health, and physiological needs improves productivity and reduces stress. These practices include optimised feeding, proper stocking density, supportive structures for moulting, and maintaining ideal environmental conditions. Given the complexity of factors affecting shrimp welfare, applying integrated and holistic management in cultivation systems is pivotal for achieving success and sustainability in aquaculture. Therefore, the adoption and implementation of measures that improve the welfare degree of these entities are imperative not only for enhancing production in terms of quality and quantity but also as an expression of more responsible, sustainable aquaculture in line with ethical standards.

In cultivation farms, shrimps face several welfare threats, including diseases, poor water quality, challenges in nutrition and feeding, and heightened stress, which are especially noticeable during the harvesting and slaughtering phases. These welfare critical points, which vary according to the intensity of farm production [118], highlight the need for accurate welfare measurement to ensure practices are sustainable, ethical, and profitable, even though current methods are often subjective and ineffective [200]. In response to this, the GWI was developed in close alignment with the animal welfare concept proposed by the World Organisation for Animal Health [32], directly incorporating four of the five domains identified by Mellor and Reid [16]. This approach is due to the lack of reliable and practical indicators for assessing the mental domain of animals in the field. The development of the GWI adopted the perspective of Nilsson et al. [201], acknowledging the impossibility of directly asking shrimps about their perceptions and, thus, using welfare indicators to gauge their conditions. These indicators are divided into direct health, physical condition, behaviour indicators, and indirect indicators connected to management, resources, and the environment provided. Direct indicators accurately reflect the shrimps' welfare, while indirect indicators identify potential risks before they visibly impact the animal. The integrated use of these indicators is vital for a comprehensive welfare assessment in aquaculture, encouraging ethical and sustainable management practices. This approach promotes consistent cultivation conditions and highlights the need for proper management practices.

Utilising the PRISMA methodology, we identified ten distinct methods for assessing the welfare of aquatic animals in cultivation systems. Table 8 contrasts the GWI with these indices, underlining its applicability and effectiveness, as detailed in Supplementary Tables S1–S7. This comparison accentuates the innovative nature of the GWI in evaluating the welfare of *P. vannamei* in cultivation, signalling a significant leap forward in terms of precision, practicality, and scope of the assessment. To date, the sole index for gauging the welfare of decapod crustaceans was the Animal Welfare Assessment Grid (AWAG), which is an adaptation of an index initially designed for primates [202] and later modified by Narshi et al. [203] for evaluating the welfare of decapods and cephalopods in zoos and aquariums, albeit not explicitly tailored for shrimps.

Table 8. Methodological, conceptual, and operational comparisons between different methods developed for measuring the welfare degree of organisms cultivated in aquaculture.

	INDEX									
Name	**GWI** [1]	**AWAG** [2]	**Welfare Meter** [3]	**SWIN 1.0** [4]	**SWIN 2.0** [5]	**FishEthoScores** [6]	**fWEI** [7]	**MyFishCheck** [8]	**Not Named** [9]	**FISHWELL** [10]
Application	Aquaculture organisms	Decapods and cephalopods in zoo and aquarium	Caged Salmon	Caged salmon	Caged salmon	Farmed fish	Farmed trout	Farmed fish	Farmed tilapia	Farmed salmon and trout
Is it already applied to shrimps?	Yes	No	No	No	No	No	No	No	No	No
Domains of welfare directly addressed	4/5	1/5	2/5	4/5	2/5	4/5	4/5	4/5	4/5	4/5
The number of welfare indicators	30	19	7	18	10	10	12	19	25	23
Time required for measurement of indicators	Medium	Long	Automatic	Medium	Short	Long	Short	Long	Medium	Medium
Invasiveness of the indicators	Low	Low	Low	Low	Low	Low	Low	High	Low	High
Does it use factor weighting for the indicators?	Yes	No	No	Yes	Yes	No	Yes	No	No	No
Number of scores for each indicator	3	10	Not applied	2–6	3–7	3	4	Not applied	4	4
Ease of field measurement of indicators	Moderate	Moderate	Easy	Moderate	Moderate	Moderate	Easy	Difficult	Moderate	Difficult
Is there a calculation of a quantitative welfare index?	Yes	No	Yes	Yes	Yes	No	Yes	No	No	No
Is it calculated the confidence interval of the indices?	Yes	No	No	No	No	No	No	No	No	No

References: [1]—Present study; [2]—Narshi, Free [203]; [3]—Stien, Gytre [204]; [4]—Stien, Bracke [205]; [5]—Pettersen, Bracke [206]; [6]—Saraiva, Arechavala-Lopez [207]; [7]—Weirup, Schulz, and Seibel [208]; [8]—Toomey, Gesto [209]; [9]—Lertwanakarn [210]; [10]—Gismervik [211].

This study adapts the GWI specifically for *P. vannamei*, offering a new approach to address the complex needs of commercial shrimp farming. It also sets a distinct milestone when compared to indices traditionally employed for the welfare assessment of other cultivated aquatic species, such as fish and cephalopods. This novel approach, encompassing up to 30 specific indicators for the cultivation of shrimps in earthen ponds that can be directly measured within the aquaculture farm environment without resorting to complex or invasive laboratory techniques, coupled with the meticulous weighting of these indicators, the incorporation of an exclusion factor (kl) based on mortality rates, and the creation of specific indices to evaluate different welfare domains culminating in a general index, represents a significant methodological development. Incorporating the calculation of confidence intervals within the indices enhances the precision and reliability of the assessments, laying a solid foundation for scrutinising the impacts of management practices on shrimp welfare.

This index is versatile and adaptable to various shrimp species and a broad array of cultivation systems, with plans for periodic updates of its indicators to mirror the scientific and technological progress within the sector. This strategy facilitates highly reliable comparative studies, enabling temporal analyses within a single operation and comparisons across different enterprises and cultivation systems. Ultimately, it ensures that the welfare of shrimps remains in step with the latest scientific advances and sustainable practices, reinforcing the significance and effectiveness of the GWI in fostering responsible and ethically committed aquaculture management.

5. Conclusions

This study marks a significant advance in the interface between shrimp aquaculture and animal welfare, introducing the General Welfare Index (GWI) as an innovative tool to monitor and enhance the cultivation conditions of *P. vannamei*. The development and application of the GWI extend beyond the scientific debate on crustacean sentience, offering a practical, evidence-based methodology that drives tangible improvements in cultivation practices. The implementation of the GWI not only addresses discussions about decapod sensory capacities but also adopts a pragmatic approach, acknowledging that the aquaculture industry bears both an ethical responsibility and an economic interest in adopting practices that optimise the welfare of these organisms.

This study also points to promising avenues for future research, including the continuous refinement of welfare indicators, investigations into the correlations between GWI scores and production outcomes, and the development of automated real-time welfare monitoring technologies. The widespread adoption of the GWI can potentially redefine aquaculture standards, fostering a more holistic and ethically defensible approach.

By aligning cultivation practices with the growing demands for sustainability and ethical responsibility, the GWI objectively assesses animal welfare across different systems and species. This enables aquaculture to become more resilient to global challenges such as climate change and food security. Its potential to drive innovation and optimise productivity places animal welfare at the forefront of aquaculture's future.

With the adoption of the GWI, the industry can achieve greater competitiveness and market acceptance and more responsible and sustainable practices, ensuring better living conditions for billions of shrimp cultivated annually worldwide.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fishes9110440/s1. Table S1. Synthesis of the GWI (General Welfare Index) proposed in this study; Table S2. Summary of the AWAG (Animal Welfare Assessment Grid) adapted for measuring the welfare level of Decapods and Cephalopods; Table S3. Summary of the Welfaremeter, used to generate continuous and automated data on the welfare level of salmon in cages; Table S4. Summary of SWIM 1.0 (Salmon Welfare Index Model 1.0), developed for monitoring the welfare level of salmon in cages; Table S5. Summary of SWIM 2.0 (Salmon Welfare Index Model 2.0), developed for monitoring the welfare level of salmon in cages; Table S6. Synthesis of FishEthoScores, developed for monitoring the welfare level of fish in aquaculture enterprises;

Table S7. Synthesis of the fWEI (Fish Welfare Evaluation Index), developed for monitoring the welfare level of rainbow trout in flow-through systems; Table S8. The synthesis of MyFishCheck developed to monitor the level of fish welfare in aquaculture; Table S9. Synthesis of the proposed index for assessing the welfare of tilapias in semi-intensive and intensive farming systems in Thailand; Table S10. Synthesis of FISWELL developed to monitor the level of salmon and trout welfare in different aquaculture systems; Figure S1. There are few animals on the pond surface, in this case, near the water inlet of the pond; Figure S2. A breeding pond where the animals display escape behaviour, jumping during harvesting; Figure S3. Shrimp being slaughtered directly in ice water; Figure S4. A healthy shrimp (left) and another with shortened antennae and atrophied hepatopancreas (right). Figure S5. Standard eye and deformed rostrum; Figure S6. Shrimps with dark gills and shrimps with gills of healthy appearance; Figure S7. A shrimp displaying erosions in pleopods, erosions and redness in the uropods, lesions and focal darkening on the exoskeleton (above), another healthy one (in the middle), and a shrimp displaying muscular necrosis (below). Reference [212] is cited in the Supplementary Materials.

Author Contributions: Conceptualisation, A.S.P. and A.O.; methodology, A.S.P., N.C. and A.O.; validation, A.S.P. and N.C.; formal analysis, A.O.; investigation, N.C.; resources, A.S.P. and N.C.; data curation, A.O.; writing—original draft preparation, A.S.P., N.C. and A.O.; writing—review and editing, M.H.Q.; visualisation, A.S.P.; supervision, M.H.Q. and A.O.; project administration, M.H.Q.; funding acquisition, M.H.Q. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: No animal collection or experimentation was conducted during the course of the work. The research was based solely on observational data gathered from aquaculture practices, without any direct interaction or manipulation of the animals.

Data Availability Statement: The datasets generated and/or analysed during the ongoing study are available from the corresponding author upon reasonable request.

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