REVOLUTIONIZING PENAEID SHRIMP FEEDING MONITORING: AN AI-BASED APPROACH TO FEEDING BEHAVIOUR ANALYSIS

Abstract

Shrimp production in the aquaculture business has increased significantly, increasing by a factor of five between 2000 and 2018. Nearly eighty percent of the world's farmed shrimp supply comes from the Pacific white shrimp (Litopenaeus vannamei Boone). Even while we have come a long way in terms of output, there is cause for concern due to inefficiencies associated with feeding techniques, which may account for as much as half of the entire production costs. Complications in shrimp feeding behaviour, such as delayed pellet ingestion and varying feeding responses dependent on physiological and environmental variables, lead to feed losses and exacerbate feed conversion ratios, water quality difficulties, and environmental implications. Therefore, efficient feed management becomes an urgent necessity, both economically and environmentally. Due to economic and environmental obligations, studying shrimp feeding behaviour has risen to the top of the research agenda. Monitoring shrimp in real time is also crucial because it helps them bounce back faster after stressful events like illness outbreaks. Shrimp have a unique digestive capacity, characterized by modest and steady meal consumption, which has a negative impact on pellet stability and nutrient absorption, ultimately resulting in slowed growth. Shrimp, which are omnivorous benthic feeders, use chemical signals heavily to find food in shrimp ponds. They have a complex system of chemoreceptors all over their bodies, which allows them to detect and understand these cues with ease. Individual qualities, environmental conditions, and water quality parameters all play a role in determining how

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and when shrimp feed. Whether or if photoperiod affects L. vannamei's food consumption is a mystery, as it plays a different function in shaping foraging behavior in different species. Crustacean physiology and behavior are profoundly affected by variables in water quality such as temperature, salinity, dissolved oxygen, pH, and nitrogenous substances. Their complete individual and cumulative impacts, however, have not yet been investigated. Understanding the feeding behaviour of L. vannamei, a staple species in aquaculture, has been made significantly easier with the development of AI. By analyzing large datasets, AI-driven methods may decode subtle behavioural dynamics and uncover adaptive reactions to novel stimuli. Previously unseen preferences in feeding times, locations, and behaviours can now be understood thanks to this technique. Artificial intelligence helps L. vannamei farms by unraveling these mysteries to improve feeding tactics, reduce waste, and boost output. Understanding the complex relationships between eating habits and environmental factors is becoming increasingly important as AI develops. This development ensures environmental protection while guiding the aquaculture sector toward more sustainable methods of operation.

Keywords: Shrimp production surge, Pacific white shrimp dominance, feeding inefficiencies' costs, complex feeding behavior, water quality impact, AI-enhanced understanding for sustainability.

I. INTRODUCTION

The aquaculture industry produced 6 million tons of shrimp in 2018 which was fivefold compared to levels of production in 2000 [1]. Penaeid shrimps, particularly Pacific white shrimp (*Litopenaeus vannamei Boone*), produce almost 80% of all farmed shrimp [2]. Nevertheless, even with the considerable level of production, shrimp farming is susceptible to notable inefficiencies related to feeding, potentially contributing to as much as 50% of the total production expenses [3]. Shrimp frequently exhibit delayed pellet ingestion after being fed, and feeding behavior can vary depending on the physiological status of the shrimp as well as environmental circumstances [4]. Farmers lose feed, which increases the feed conversion ratio (FCR), chemical and microbiological water quality, nutrient discharge rates, and water exchange demand. Hence, effective feed management is of utmost importance to the industry, considering both economic and environmental perspectives [5]. Because of this, knowing how shrimp feeding behaviour has become a top priority [6]. Similarly, there is widespread agreement that peak monitoring of aquaculture animals accelerates their recovery from stress-inducing circumstances and diseases through early detection of their behavioural pattern [7]. Owing to the confined storage capacity within their digestive tracts, shrimp consistently consume moderate amounts of food [8]. This, in turn, has a detrimental impact on both the stability of the pellets (more than 30 minutes) and the nutrient retention capacity of feed, leading to reduced growth of the shrimp [9]. Being omnivorous benthic feeders, shrimp primarily depend on chemical signals to locate food on the pond bottom [10]. To achieve this, they possess an extensive array of chemoreceptors distributed across their bodies, including antennae, legs, and mouthparts [11]. These receptors enable them to efficiently detect and decipher these sensory cues [12]. There are four distinct behavioural responses of shrimp to chemical stimuli, including antennal flicking, pereiopod exploration, locomotion modifications, and mouthpart movements. Several authors have extensively discussed the diverse factors that influence shrimp feeding behaviour [13]. Among these factors, three major categories stand out as crucial: individual-level considerations, environmental influences, and the effects of water quality [14]. Photoperiod has also been shown to exert a substantial effect; however, the direction in which light availability affects foraging behavior appears to be highly species-dependent [14]. Moreover, it remains uncertain whether *L. vannamei*, the most widely cultivated shrimp species, exhibits a preference for the dark or light phase regarding its nutritional intake [15]. Water quality parameters exert significant influences on crustacean physiology, thereby affecting shrimp feeding behaviour [16]. Notably, temperature, salinity, dissolved oxygen, pH, and nitrogenous wastes have established impacts on crustacean behaviour [17]. However, the precise consequences of alterations in these water parameters, both at the individual and group levels, remain largely unexplored [18]. Artificial Intelligence (AI) has emerged as a pivotal tool in enhancing our understanding of the feeding behaviour of *L. vannamei*, a crucial species in aquaculture [19]. Through the utilization of AI-driven techniques, researchers have been able to unravel complex patterns and relationships within the intricate dynamics of shrimp feeding [20]. AI facilitates the processing of vast amounts of behavioural data, enabling the identification of nuanced responses to various stimuli, such as feed availability, environmental conditions, and individual characteristics [21]. This technology empowers scientists to discern subtle preferences in feeding times, locations, and behaviours that might otherwise remain obscured [22]. By unraveling these intricacies, AI contributes to optimizing feeding strategies, minimizing resource wastage, and ultimately bolstering the growth and productivity of *L. vannamei* farms [23]. As AI continues to evolve, its role in decoding the

multifaceted interactions between feeding behavior and various factors becomes increasingly invaluable, driving advancements in sustainable and efficient shrimp aquaculture practices [24].
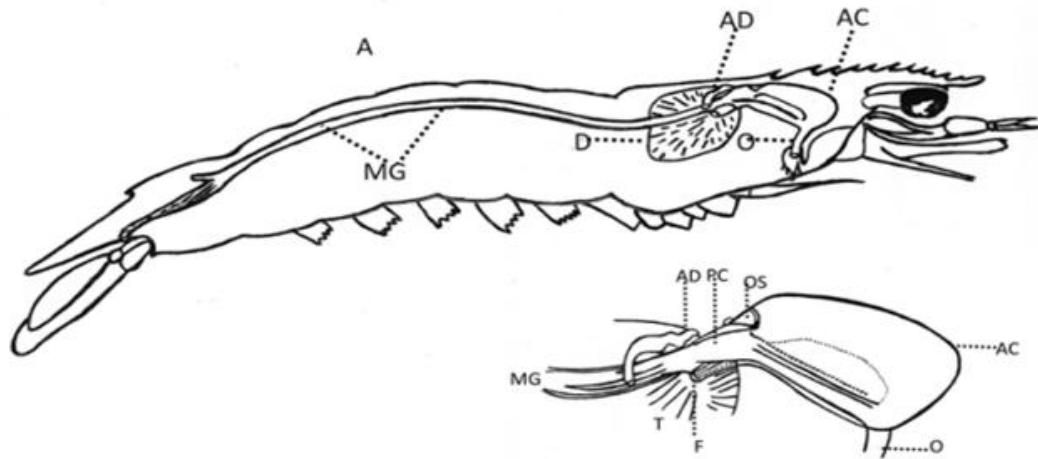
Figure 1: Digestive system in shrimps A, anus; AC, anterior chamber of proventriculus ("stomach"); AD, anterior diverticulum of mid-gut (this is a paired structure); D, digestive gland; F, opening (paired) from "filter press" of posterior diverticulum into digestive gland; M, mouth, MG, mid-gut; O, oesophagus, OS, ossicles of gastric mill; PC, posterior chamber of proventriculus; PD, posterior diverticulum of mid-gut; R, rectum; T, tubules of digestive gland.

II. FUNDAMENTALS OF SHRIMP FEEDING BEHAVIOUR

1. Physiology of the Nutrition in Shrimps

The digestive system of decapods can be categorized into three main sections: the anterior digestive tract, the middle intestine, and the posterior intestine as depicted in Figure 1 [25]. The anterior and posterior digestive tracts, originating from the ectoderm, are coated with a delicate cuticle that is shed and replaced during each moulting cycle. On the other hand, the middle intestine stems from endodermal origins [26].

- **Anterior Digestive Tract:** The anterior digestive system of decapod crustaceans comprises three distinct segments: the mouth, the esophagus, and the stomach. Multiple pairs of specialized appendages encircle the mouth as shown in Figure 2 for detecting and grabbing chemicals [27]. The esophagus of Peneidae shrimp is short and muscular, and its inner lining is made of a pliable chitinoprotein substance. The stomach has two chambers: the cardiac chamber and the pyloric chamber. In Peneidae shrimp, the anterior-ventral region of the cardiac chamber is adorned with a series of fourteen calcified and articulated ossicles [28]. The gastric mill consists of these distinct muscle-containing components [29]. Ossicles and teeth, along with the walls of the esophagus and stomach, undergo renewal during each molting process [30]. Within the pyloric chamber, calcified structures remain intact [31]. This chamber is characterized by folds, calcified spines, and fine threads that act as a filter, permitting only the tiniest particles of food to pass through [32]. Particles that effectively pass

through this filter are routed to the middle intestine and the organ of absorption known as the hepato-pancreas [33]. The majority of species have neutral or mildly alkaline stomach contents. Notably, no glands or cells that secrete acids or enzymes are present in this organ [34].
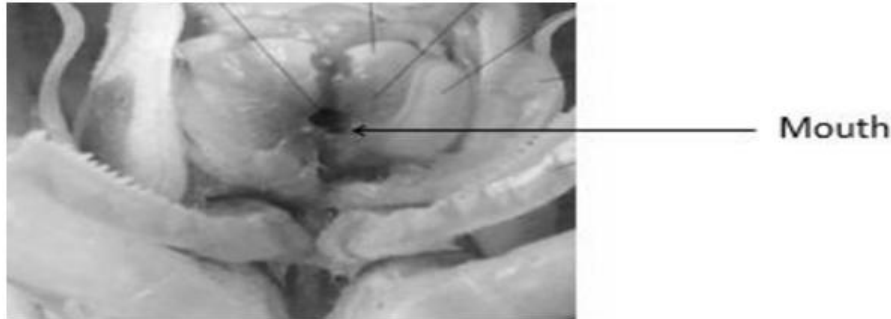
Figure 2: Mouth of Shrimp

- **Intestinal and Hepato-Pancreatic Tissue:** Spanning from the pylorus to the rectum, the middle intestine retains a straight structure. Its epithelial lining contains distinguishable nervous cells, hemocytes, and endocrine cells [35]. This particular epithelium produces mucus, which covers the solid refuse from the stomach, as well as a chitin film that forms the excretory peritrophic membrane [36]. The hepato-pancreas, also known as the digestive gland, is a substantial organ found in Peneidae crustaceans. It consists of two lobes made of conjunctive tissue, symmetrically wrapped around each other [37]. Situated beneath the heart in the dorsal part of the cephalo-thorax, each tubule's inner space is enveloped by a double-layered unicellular epithelium [38]. This epithelium is surrounded by circular muscular fibres that aid in peristaltic contractions, facilitating the movement of liquid phases within the organ. Histological examinations unveiled the presence of four distinct cell types within the epithelium of these tubules [39]. In contrast to crustaceans, which do not possess biliary salts, specific compounds with surface-active properties are present [40].

- **Posterior digestive tract:** The tubular formation features longitudinal folds housing circular muscles, which are vital for promoting defecation through peristaltic motions and aiding in water reabsorption, particularly in marine settings [41].

III. FEED OF SHRIMPS

1. Natural Diet of Shrimps

Shrimp possess a diverse diet that includes carnivorous, omnivorous, and omnivorous behaviors with a preference for carnivory, along with occasional detritivory [42]. During their larval stage, shrimp engage in water filtration to feed on planktonic cells [43]. Analysis of the gastrointestinal contents in most shrimp species demonstrates their omnivorous tendencies, encompassing behaviors like planktivory, insectivory, piscivory, and detritivory. Moreover, a considerable number of crustaceans exhibit the ability to withstand extended periods of fasting [44]. Shrimps weighing less than 5 grams are not commonly found on the seafloor [45].

They often attach themselves to the roots of mangroves or aquatic plants [46]. This behavior is primarily focused on searching for prey and scavenging for organic material. While larger shrimps tend to exhibit more benthic behavior, they also feed on vertical substrates [47]. In a semi-intensive shrimp farming system, the determination of the ideal quantity of pellets to distribute becomes a complex problem due to the availability of natural food sources, including live prey, aquatic plants, and diverse organic components, in addition to pelletized feed [48]. It is indeed a challenge to establish the theoretical composition of supplementary feed to complement natural sources. One approach is to utilize formulated feed, similar to what's used in intensive farming, along with local resources to fulfill the nutritional requirements of the species [49]. The experiment proves that incorporating this feed enhances the growth of the crustaceans [50]. Nonetheless, it's uncertain whether the pellets are consumed directly by the shrimp, initially ingested by other organisms, or subject to degradation by microorganisms [51].

2. Feed of Shrimps in Intensive System

There are scientific, technical, and even technological challenges associated with feeding prawns only artificial feed, devoid of any natural sources of nutrition [52]. First, addressing the study of the types and proportions of various nutrients required by shrimp entails addressing the palatability and water stability of the provided feed particles. Certainly, these particles are ingested at a slow rate, and they experience varying degrees of dissolution based on the components' nature [53]. This granule dissolution can render the intended composition of the feed theoretically inaccurate and significantly impact its nutritional efficacy [54]. To mitigate these losses, two strategies can be employed: Firstly, the use of binders with or without nutritional value, like gelatin, or modified starches for the former category, or carboxymethyl cellulose (CMC); Secondly, employing a specialized particle agglomeration process, such as cooking-extrusion [55]. Controlling these processes is an essential prerequisite for producing high-quality shrimp feed [56]. To achieve effective pelletized shrimp feed, it's crucial to consider factors such as feed formulation and ingredient quality, manufacturing techniques, and the physical attributes of the pellets [57]. Additionally, the method and manner of distribution, the aquatic environment, and the natural production process should all be considered [58].

3. Food and Feeding Mechanism

Almost all crustaceans possess the same fundamental mouthparts, despite the enormous diversity in form and function [59]. Shrimps primarily consume plant matter, microorganisms, small crustaceans, and worms as the main elements of their diet. In controlled aquaculture settings, shrimps are supplied with artificial diets [60]. The majority of metabolic processes take place rapidly, typically reaching completion within a span of six hours. Utilizing chemosensory hairs on their pereopods, prawns investigate the ocean substrate in search of food [61]. When they find sustenance, they use their maxillipeds, which are appendages on their heads, to seize it [62]. The teeth or mandibles are utilized to either bite or tear food into smaller fragments [63]. In addition, the maxillipeds play a dual function in the fragmentation of food into more manageable portions by pushing larger food fragments aside while the mandibles secure them [64].

4. Key Factors Shaping the Feeding Behaviour of Shrimp

Unlike terrestrial farm animals and farmed fish, which can be fed based on visual cues and the animals' appetite, or according to predetermined feeding levels, pond-raised shrimp pose a different challenge which are illustrated in Fig 3 [65]. These shrimps are not easily observable by the farmer during feeding, requiring a feeding approach that essentially occurs "in the dark" [66]. In real-world farming scenarios, the feeding response, feed intake (measured as a percentage of shrimp body weight), feed utilization efficiency, and shrimp growth exhibit fluctuations due to a multitude of biological, environmental, and human-related elements [67]. These factors encompass various elements, among which is the shrimp body weight [68]. As the body weight of shrimp increases and their metabolic rate decreases throughout the culture cycle, the intake of compound feed diminishes [69]. Water temperature also plays a significant role. Compound feed intake and shrimp growth tend to rise as water temperature increases, reaching an optimal range (usually around 29 to 31 degrees Celsius for species like *L. vannamei and P. monodon*) [70]. However, water temperatures, and consequently dissolved oxygen levels, can fluctuate considerably during a working day due to the culture system employed and the prevailing season [71]. The availability of natural food is another crucial factor [72]. Compound feed intake tends to rise as the availability of natural food decreases within the culture system. This pertains to both natural food present in the water column and on the pond bottom [73]. Notably, the availability of natural food at the pond bottom usually declines with higher shrimp stocking density, greater shrimp weight, and an overall increase in total shrimp biomass throughout the culture cycle [74].

The formulation of compound feed and its nutrient density are also pivotal [75]. The intake of feed and the growth of shrimp hinge on factors such as the diet's water stability, palatability, and nutrient composition [76]. A diet with superior water stability, enhanced palatability, and a greater nutrient content holds the potential for heightened feed intake and a more robust feeding response [77]. The method of applying shrimp feed, encompassing factors like frequency and timing of application, along with the approach to monitoring feed consumption, is noteworthy [78]. In smaller hand-fed intensively stocked ponds, managing and observing compound feed intake and shrimp growth tends to be more manageable during daylight hours compared to larger semi-intensively stocked ponds [79]. The ideal feeding frequency and timing of application are contingent on the shrimp size and the nutrient density of the provided diet [80]. Typically, these factors reach their peak for small, fast-growing shrimp and subsequently decrease as the shrimp size increases [81]. The technical knowledge and proficiency of the feeding technician also hold significance [82]. In many cases, feeds are distributed within larger farms by employees who receive the lowest or minimum salary [83]. These workers typically lack substantial incentives for enhancing worker earnings through the attainment of enhanced feed performance and shrimp growth, as established by farm owners [84]. The shrimp moult cycle and the phase of the lunar cycle are interlinked with feeding behavior [85]. The intake of feed and the growth of shrimp are contingent on the shrimp's physiological state and condition [86]. Typically, feed intake tends to decrease just before and during the moulting cycle [87]. Moreover, the highest levels of natural feeding activity usually occur during hours when daylight is absent [88]. The health and overall well-being of shrimp, along with the health of the ecosystem they inhabit, have a direct impact on feeding behavior [89]. Shrimp feed intake and growth are commonly at their lowest for shrimp that are stressed or diseased. This includes shrimp residing in polluted or environmentally strained pond ecosystems [90]. In the context of this paper, the term 'on-farm

shrimp feed management' encompasses all actions undertaken by shrimp farmers and their personnel concerning the manipulation, preservation, and utilization of shrimp feed within the farm setting [91]. This includes a range of feed types such as commercially produced feeds, feeds produced on the farm itself, and live/natural food resources [92]. Generally, the nutritional efficacy of a shrimp feed hinges on several interrelated elements [93].

Figure 3: Illustrates the essential environmental factors that need to be taken into account to safeguard the well-being of fish within the contexts of research and aquaculture.

The effectiveness of on-farm shrimp feed management hinges on a comprehensive consideration of multiple interconnected factors [95]. These factors include the nutrient content and composition of the diet that is administered to the shrimp [96]. Additionally, the physical characteristics and water stability of the provided diet play a crucial role in influencing the overall nutritional outcome [97]. Furthermore, the proper handling, transportation, and storage of the feed before it is utilized on the farm significantly impact its quality [98]. The method chosen for applying and distributing the feed, as well as its subsequent usage on the farm, further contribute to the successful management of the feeding process [99]. Equally important is the expertise of the individuals responsible for overseeing these operations, as their proficiency ensures that these elements come together cohesively to optimize shrimp feed management practices [100]. The intricacies of successful shrimp feed management encompass several essential aspects, including the specific farming system employed, the stocking density of shrimp, and the intricacies of water management along with the availability of natural food sources [101]. Among these, the commercial shrimp feed

manufacturer wields direct control over the initial two factors, whereas the farmer and their workforce retain direct influence over the remaining three [102]. It follows, therefore, that the ultimate nutritional efficacy and financial viability of a shrimp feed hinge on a tightly-knit collaboration and partnership between the feed producer and the farmer, along with their team [103]. Shrimp feeds and the associated feeding protocols generally account for the largest share of operational costs, typically ranging from 40 to 60 percent, within the framework of most semi-intensive and intensive farming endeavors [104].

IV. ADVANCEMENTS IN AQUACULTURE MONITORING

Traditional Methods of Feeding Behaviour Observation

1. **Direct Visual Observation:** Direct visual observation is a fundamental method used in the field of ethology and behavioral ecology to study the feeding behavior of aquatic organisms (Table 1), including shrimp [105]. This method involves directly observing the behavior of organisms in their natural habitat or a controlled environment while documenting their interactions with their surroundings, including food sources [106]. By closely monitoring and recording these behaviors, researchers can gain valuable insights into the feeding preferences, patterns, and strategies of shrimp [107].

   Methodology: The process of direct visual observation typically involves setting up observation points near the habitat of the shrimp, such as ponds, tanks, or natural bodies of water [108]. Researchers position themselves discreetly to minimize disturbance and to ensure that the observed behavior remains as natural as possible [109]. Binoculars, underwater cameras, and even submerged observation hides can be used to enhance the accuracy and detail of the observations [110].

   Key Elements of Direct Visual Observation

   - **Feeding Frequency and Timing:** Researchers note the frequency at which individual shrimp engage in feeding activities. This information helps determine how often shrimp search for and consume food [117].
   - **Feeding Movements:** The detailed analysis of feeding movements includes behaviors such as capturing, handling, and manipulating food items. Understanding these motions sheds light on the complexity of feeding strategies employed by shrimp [118].
   - **Food Preferences:** By observing which food sources shrimp are attracted to and consume more frequently, researchers can discern their preferences for certain types of food [119].
   - **Interaction with Habitat:** Researchers also observe how shrimp interact with their habitat while feeding. This could involve interactions with aquatic plants, substrates, or other organisms [120].
   - **Behavioral Patterns:** Longer observation sessions can reveal patterns in feeding behavior, such as diurnal or nocturnal feeding habits and changes in behavior due to environmental conditions [121].

Advantages and Limitations

- **Advantages:** Direct visual observation provides a holistic understanding of feeding behavior in the natural context. It allows for real-time documentation of behaviors, and researchers can directly witness interactions between shrimp and their environment [122].
- **Limitations:** One of the main limitations is the potential disturbance caused by the observer's presence, which might alter the natural behavior of the shrimp. Additionally, certain behaviors might be missed due to the limitations of human perception [123].

Scientific Significance: Direct visual observation offers valuable data that can be used to answer a variety of scientific questions, such as:

- How do shrimp adapt their feeding behavior to changing environmental conditions?
- What are the specific strategies shrimp employ to capture and manipulate food items?
- How do different species of shrimp exhibit varying feeding behaviors?
- Are there social interactions among shrimp during feeding activities?

2. **Feeding Trays:** Feeding trays or containers are practical tools employed in aquatic ecology and aquaculture research to observe and quantify the feeding behavior of shrimp in a controlled setting [124]. This method involves placing a known quantity of food in a confined space, allowing researchers to monitor how shrimp interact with the food source and make precise measurements of consumption rates and preferences [125].

Methodology: The feeding trays or containers used in this method are designed to mimic the natural feeding environment of the shrimp while providing a controlled environment for observation [126]. The process involves several key steps:

- **Selection of Trays/Containers:** Researchers select appropriate trays or containers that are large enough to accommodate the shrimp and the provided food. The container should have minimal impact on the natural behavior of the shrimp [127].
- **Food Placement:** A predetermined quantity of food is placed inside the container. This food can vary depending on the research objectives, ranging from live prey organisms to formulated pellets [128].
- **Observation Period:** The shrimp are introduced into the container, and their feeding behavior is observed for a specific period. During this time, researchers document various aspects of behavior, such as consumption rates, feeding movements, and interactions with the food [129].
- **Data Collection:** Measurements are taken to quantify the amount of food consumed by the shrimp during the observation period. This often involves weighing the remaining food and subtracting it from the initial quantity to determine consumption [130].
- **Statistical Analysis:** The collected data can be subjected to statistical analysis to identify trends in feeding behavior, preferences for certain food types, and variations in consumption rates among different shrimp individuals [131].

Key Elements of Feeding Trays or Containers

- **Consumption Rates:** By measuring the amount of food consumed within a defined period, researchers can calculate the consumption rates of shrimp. This information provides insights into the efficiency of feeding and energy acquisition [132].
- **Food Preferences:** Researchers can place different types of food in separate containers to assess shrimp preferences. The choice of food and its presentation can help reveal their natural feeding tendencies [133].
- **Feeding Movements:** Observations within the confined space allow researchers to analyze the intricate feeding movements of shrimp, such as capturing, handling, and manipulating food items [134].

Advantages and Limitations

- **Advantages:** Feeding trays or containers offer a controlled environment where researchers can precisely measure consumption rates and assess food preferences. This method allows for the manipulation of variables to test specific hypotheses [135].
- **Limitations:** While controlled, the confined space might not fully replicate the shrimp's natural habitat, potentially leading to altered behavior. Additionally, the stress caused by confinement can influence feeding behavior [136].

Scientific Significance: Feeding trays or containers provide valuable quantitative data that contributes to our understanding of:
- How different food types impact shrimp consumption rates.
- The role of environmental factors in influencing feeding behavior.
- Shrimp preferences for specific food items.
- Interactions between multiple individuals within a confined feeding space.

3. **Other Methods:** The utilization of transparent tanks or aquaria, discussed as method number four, extends distinct advantages in unraveling feeding behavior intricacies [137]. This methodology harmonizes the virtues of controlled environments with unobstructed visual access, affording a panoramic window into the dynamics of shrimp feeding [138]. This clear medium not only encapsulates behaviors within a controlled realm but also offers researchers a front-row seat to observe feeding behaviors as they unfold in an environment analogous to their natural habitat [139]. Subsequently, method number five employs the lens as a portal to capture the ballet of feeding [140]. Through the adept utilization of cameras, images, and videos, researchers freeze moments in time, immortalizing the intricacies of feeding movements [141]. With the aid of high-speed cameras and time-lapse techniques, a tapestry of rapid feeding actions emerges, deciphering the nuances that shape these swift maneuvers [142]. Moving to method number six, the ultimate sacrifice of individual shrimp opens portals to the exploration of digestive tales [143]. Sacrificial dissection unfurls stomach content analyses and the meticulous examination of gut tracts [144]. Within these anatomical corridors lie secrets of consumption, offering insights into the dietary tapestry woven by the shrimp [145]. Method number seven, conducted within the controlled confines of laboratory experimentation, emerges as a scientific crucible. Here, the intricacies of feeding behavior

are subjected to controlled variables, enabling the quantification of feeding rates and preferences [146].

Under the methodical gaze, feeding dynamics find numerical expression, unearthing patterns etched within the meticulous fabric of controlled conditions [147]. Ethograms, method number eight, transmute observation into comprehensive documentation [148]. Through the lens of behavioral ethograms, feeding behaviors are meticulously chronicled, creating a multifaceted mosaic that illuminates the spectrum of strategies woven into the shrimp's feeding tapestry [149]. Method number nine dances in the realm of quantification, where the measurement of feeding rates becomes an eloquent articulation of behavior [150]. The monitoring of food consumption over time metamorphoses into an equation of feeding rates, unfurling the cadence of feeding patterns [151]. These varied methodologies, like the notes of a symphony, harmonize to unveil the multifaceted choreography of shrimp feeding behaviors [152].

Table 1: Presents the Conventional Methods for Observing Dietary Behaviors, as well as their Benefits and Drawbacks

Method	Advantages	Disadvantages	References
Direct Visual Observation	Captures natural behavior and provides real-time data	Observer presence may alter behavior and Limited visibility of certain behaviors	[153]
Feeding Trays/Containers	Controlled environment and Quantifiable data	Confinement stress can affect behavior and May not replicate natural habitat fully	[154]
Clear Tanks/Aquaria	Transparency for observation and Controlled setting	Artificial environment may impact behavior as well as Limited space for natural behaviors	[155]
Photography and Videography	Detailed visual documentation and Analysis of rapid movements	Limited to two-dimensional view and requires specialized equipment	[156]
Stomach Content Analysis/Gut Dissection	Identifies consumed food items and provides direct evidence	Invasive and terminal procedure, disruptions natural behavior and physiology	[157]
Laboratory Experiments	Controlled variables for testing hypotheses and Quantifiable data	May not fully replicate natural conditions and potential stress from confinement	[158]
Behavioral Ethograms	Comprehensive behavioral records	Requires expert interpretation and Time-consuming data collection	[159]
Quantitative Feeding Rate Measurement	Precise measurement of consumption rates and Quantifiable data	Focuses on rates rather than behavior detail and may not account for variations	[160]

Automated Technology	Continuous monitoring, Reduced observer bias	Initial setup and calibration required and limited to specific behaviors	[161]

V. THE NECESSITY TO EXPAND BEHAVIOURAL OBSERVATIONS

As the comprehension of the influence of individual-level and environmental aspects on shrimp behavior progresses, there remains a lack of published direct observations concerning shrimp behavior in aquaculture ponds [163]. These ponds demonstrate a considerably broader array of extreme environmental parameters (such as stocking density and light exposure) as well as fluctuations in water quality (encompassing pH, dissolved oxygen, temperature, and visibility) compared to laboratory studies. Recent indoor research on shrimp behavior revealed that the optimal water quality parameters include a temperature of approximately 26^0C and dissolved oxygen levels exceeding 5 milligrams per liter (Mg/L) [164]. Due to direct exposure to climatic fluctuations and weather incidents such as rainfall and high heat events, managing the environmental conditions of outdoor systems such as pond and tank facilities often becomes a more challenging task [165]. In shrimp ponds, as an example, it's common to observe fluctuations in dissolved oxygen and pH levels between day and night [166]. These ponds are susceptible to experiencing multiple instances of phytoplankton blooms and crashes throughout a production cycle [167]. Also, it's not clear how well findings from smaller-scale observations can be applied to bigger groups with hundreds of thousands of individuals, where differences in size can be much more noticeable [168]. Also, the way lab studies are set up can hide other important effects, like the size of the field or pond, which can make it hard for everyone to get enough food [169]. Numerous methods exist to monitor the activities of aquatic animals [170].

Nevertheless, directly observing shrimp feeding behavior in their natural habitat can prove to be challenging due to the specific conditions found in aquaculture ponds and the way shrimp feed on the pond bottom, rendering direct surface observations difficult [171]. For example, ways of using cameras need to be changed because shrimp are usually grown in water that is not very clear and does not have much light. Tracking crabs with telemetry methods might not be the best choice because crustaceans frequently molt their shells, and this shedding can result in the loss of external tags [172]. Furthermore, the small size of shrimp can create a challenge when using large tags, as highlighted [173]. As a result, the conventional approach to monitoring feeding activity on shrimp farms has involved the use of feeding trays [174]. However, this method is labour-intensive, can be influenced by personal judgments, and might lead to inaccurate estimations of feed requirements. Therefore, the provided table seeks to outline the primary inquiries concerning shrimp feeding behavior in commercial contexts and explore how advanced implementations of tools frequently utilized in marine ecology and fish farming can offer solutions [175]. The existing constraints of these technologies are underscored, with the aspiration of fostering multidisciplinary investigations that can furnish farmers and researchers with enhanced insights into shrimp feeding behaviors within pond environments [176].

Table 2: Key Questions for Comprehending Shrimp Feeding Behavior in Ponds and how they may be Addressed using Cutting-Edge Techniques [177;65]

	Crucial Challenges	Possible Resolution	Technological Restrictions
Feed Management	Feeding time and feed quantity Place of feeding (correct locations or sites according to production cycle)	Passive acoustics attached to automatic feeders can estimate feed demand locally and in real-time.	Pond sounds from aerators, rain, etc. Financial investment needed by farmers
	Relation of nutrient density with feeding behaviour How pond conditions and farming practices influence feeding behavior? Observing the daily routines of feeding pattern	Image segmentation (thresholding) on pond bottom photos helps analyze leftover feed.	Limited contrast is caused by water turbidity and uneven lighting.
Behavior observation and interpretation	Interaction of swarming, feeding regime on environmental factors	Using object detection, deep learning algorithms can recognize shrimp in real time or during playback. Shrimp can be tracked in two- or three-dimensions using footage.	The software needs to be trained with the previous video from the same pond. High turbidity reduces contrast and provides insufficient lighting at the pond's bottom, severely limiting visibility.
	How shrimps react to feeders when they are feeding, and how this changes the number of shrimps in the area.	Echo sounders can also be used to find clusters of shrimps in or near their food sources.	Locating shrimp can pose a challenge due to their absence of a swim bladder and their preference for resting on the pond bottom.

| **Movement in the vicinity of feeders** | Does the intrinsic homing behavior, which can be seen in a great number of other species of crustacean, also take place within ponds that are home to penaeid shrimp? Does the introduction of manmade shelters alter the patterns of mobility or, eventually, homing behavior? Do significant shrimp migrations from non-fed areas to fed regions occur when food is supplied? Do hierarchical access patterns exist among individuals when it comes to accessing fed areas? | By utilizing telemetry methods like PIT-tags in combination with underwater antenna systems strategically positioned at key locations within ponds, it becomes possible to uncover comprehensive movement patterns on a larger scale. | PIT-tags can introduce contamination to a farm if not removed before harvest. The high cost of PIT-tag readers, often exceeding $2000 USD, presents a financial obstacle. Furthermore, the technique is invasive, requiring the trapping and manipulation of a potentially large number of individuals. |

VI. ELEVATING COMMERCIAL PRACTICES: FROM CONVENTIONAL FEED MANAGEMENT TO PRECISION SHRIMP FARMING THROUGH INNOVATIVE MONITORING TOOL APPLICATIONS

In order to enhance feeding efficiency for farmers, there is a need for more comprehensive research into the diverse aspects of feeding within penaeid shrimp farming [178]. Table 2 presents the fundamental research queries alongside potential methodologies for obtaining solutions [179]. The trajectory of shrimp feed management is focused on three principal avenues: maximizing feed utilization, observing, and comprehending feeding behaviours, and monitoring and visualizing animal movements within feeding areas [180]. Historically, the focus of in-situ research within aquaculture has primarily centered around salmon farming [181]. This implies that methods initially developed for fish farms could hold potential benefits for the shrimp farming industry [182]. Currently, the predominant methods being employed and refined to examine the feeding behaviours of fish within aquaculture settings involve acoustics, computer vision, and tracking techniques [183]. Passive acoustics have historically been prominent in observing marine mammals from afar [184]. More recently, these techniques have discovered fresh applications in commercial shrimp farming, where they are employed to monitor feeding activity within larger populations [185]. Computer vision systems are a new area of research in shrimp aquaculture, but they are

already used in fish farms to keep an eye on feeding and watch how fish swim and group together [186]. Telemetry, which involves measuring from a distance [187], is used to study decapods in water right now [188]. But it needs more work before it can be used in commercial shrimp farming because shrimp are small and shed their shells often (molting) [189]. Still, the use of passive internal tags, which have not been used before to track shrimp behaviour, could be useful in study ponds [190]. This method could give new information about how large numbers of shrimps move around feeding zones [191]. Precision aquaculture is a wider concept that includes the use of these tools together to improve the monitoring of feeding behaviour and concepts of control engineering to control engineering principles to improve tracking and control of biological processes on aquatic farms [192]. In the next parts, we will look at how these tools have been used recently or could be used in the future to help reach this goal [193].

1. Passive Acoustic Monitoring

Passive Acoustic Monitoring (PAM) is the process of using passive acoustic devices like hydrophones to record and use sounds [194]. Marine mammals are often watched from a distance using these devices. In addition to its traditional use, PAM is now used in modern shrimp farming to make it easier to control how feed is spread in the ponds [195]. This technology uses a hydrophone to find the specific "clicking" sounds or "feeding signatures" that penaeid shrimp make when they eat [196]. An algorithm uses the unique spectral properties of these sounds to figure out how many recorded fingerprints there are at any given time [197]. Researchers have found that the resonant frequency band is one way to tell a feeding signal apart [198]. This band is described by its highest frequency, its lowest frequency, its highest frequency, and its total bandwidth. Peixoto et al. (2020a), on the other hand, picked sound duration, minimum and maximum frequency, peak frequency, and maximum energy as the variables to describe feeding signatures. This methodology has been employed to characterize the feeding behavior of the white shrimp (*Penaeus setiferus*), the black tiger prawn (*Penaeus monodon*), and more recently, the *Litopenaeus vannamei* [199]. These characterizations are based on the analysis of their distinct feeding sounds [200]. Table 3 gives a quick summary of the most important results of these studies [201]. In aquaculture ponds, the number of feeding marks found is a good way to measure how much the fish are eating [202]. Notably, study done in 2013 by Smith and Tabrett showed a strong link between this measure and pellet consumption. Consequently, shifts in the count of marks between two feeding events can effectively demonstrate alterations in the amount of food being dispensed [203]. Such discrepancies might necessitate an adjustment in the feed ratio [204]. Moreover, Passive Acoustic Monitoring (PAM) facilitates the identification of individuals in proximity to a sensor [205]. So, the system can figure out how many people are in a certain place by counting how many there are [206]. Also, it can give a rough idea of where they are by using binaural technology along with methods based on the time the sound arrives [207]. Nonetheless, Passive Acoustic Monitoring (PAM) lacks the capability to track individuals over time or to uniquely identify each detected individual [208]. This technology is hard to use because the background noise in a shrimp pond is often made by machines like paddlewheel aerators, air diffusers, and pumps [209]. Noise pollution is also caused by things like rain, wind, and even the sounds of cars and trucks [210]. In some cases, it can be hard to tell the difference between the spectral features of feeding signs and background noises [211]. Smith and Shahriar (2013) made and explained a context-aware sound method to solve this problem. This new method makes it easier to find feeding events by reducing the problems

caused by signal confusion in ponds [212]. The authors fixed this problem by adding a filter to the sound recordings of the pond [213]. This filter made a picture of the background noise that aerators make [214]. Then, they found possible cases of feeding signals and used a method called "spectral subtraction" to look at these cases [215]. Different spectral characteristics were taken from these possible options [216]. Using a Gaussian mixture model, these traits were then put into two groups: feeding marks and interference noise [217]. A Context-Aware Dynamic Bayesian Network (CADBN) was made to improve the accuracy of this ranking [218]. This network considered when feed was distributed in the pond [219]. This made it easier to classify feeding patterns with more accuracy [220]. Peixoto et al. (2020a) highlighted the significance of incorporating acoustically responsive feed in ponds equipped with such feeders. This approach enhances the precision of detecting feeding events. The study demonstrated that sound recordings of shrimp consuming pelleted feed were less intense compared to recordings of shrimp consuming dry extruded diets [221]. Consequently, recorded sounds are more inclined to effectively indicate the consumption of extruded meals [222]. For improved identification of feeding indicators, it is advisable for the feed to be consumed promptly after being dispensed [223]. This is due to the tendency of wet feed to lose its firmness and absorb more moisture, resulting in quieter feeding sounds, as highlighted by Peixoto et al. (2020a). Acoustic automatic feeders, exemplified by products from Eruvaka Technologies Pvt. Ltd. in Vijayawada, India, employ passive acoustic principles to distribute food within ponds [224]. As illustrated in Figure 4, these feeders are currently operational in regions such as Ecuador and Southeast Asia, recognized for their significant penaeid shrimp production [225]. These systems provide an alternative to conventional feeding approaches involving feeding trays, offering several advantages [226]. Acoustic feeders facilitate the targeted delivery of feed to areas where shrimp are most likely to consume it [227]. This strategy helps mitigate unnecessary feed wastage. Recent studies have shown that sound feeders are better for P. monodon and *L. vannamei*

Table 3: Overview of Studies on Utilizing Passive Acoustic Monitoring for Intelligent Feed Management in Shrimp Aquaculture

	Species	Important Finding	References
Preliminary investigations	*Penaeus monodon*	In ponds, the spectral aspects of how animals eat could be used to figure out what they are doing while they ingest feed. With correlation values (R2) of 0.95 and 0.96, there is a strong link between the rate of pellet consumption and the average number of feeding patterns in ponds.	[232]
	L. vannamei	The sounds produced by Litopenaeus vannamei can be utilized to determine the feeding status of an organism within a tank by monitoring the emitted sounds.	
		The size of the shrimp didn't change how they sounded. Using both click rate and high-frequency energy can give you an idea of how much feed is being consumed. L. vannamei made different sounds when it	[233]

		ate, and those sounds were closely tied to what it ate. Despite alterations in the diet duration, the acoustic properties of clicks remained consistent. Increasing the length of the pellets by twofold resulted in a corresponding doubling of the number of clicks produced by shrimp per pellet. There was a robust connection between the quantity of food consumed by shrimp and the level of sound energy they emitted (with P-values spanning from 0.003 to 0.007, varying according to diet lengths).	
Evaluation in ponds against traditional feeding strategies	*L. vannamei*	When compared to hand feeding and feeding with a timer, sound-based feeding led to an increase of 8.6 grams and 7.58 grams in the average body weight at harvest.	[234]
		The average weight of shrimp went up by 46% after 16 weeks. This growth was a lot faster than the growth seen when shrimp were fed by hand twice a day. When compared to shrimp that were fed six times a day with timer feeders, the average body weight of shrimp that were fed by hand increased by 25% by harvest time.	[235]
		The ponds with acoustic feeders had the highest amounts of ammonia and nitrite out of all the treatments.	[236]
		The employment of acoustic feeding yielded larger shrimp in comparison to various conventional feeding methods, with final individual weight increases ranging from 3.49 to 6.24 grams.	[237]

than automatic timed feeders or feeding by hand [228]. This edge means a higher yield per hectare, even if the number of animals per hectare stays the same. Indeed, sound feeders play a crucial role in informing farmers about feeding patterns by indicating when animals are consuming food [229]. This information, as outlined in Table 3, assists farmers in determining optimal feeding schedules and the appropriate quantity of feed to be dispensed in ponds. According to Smith and Tabrett (2013), the simultaneous use of multiple automatic feeders equipped with different hydrophones in the same pond can potentially provide insights into the preferred feeding areas of shrimp. Researchers can use passive sounds as a useful tool to find out more about the circadian rhythms that may control the feeding habits of farmed shrimp on a larger scale [230]. As shown in Table 3, most of the study in this area has been done in labs where the conditions can be controlled. Certainly, Peixoto et al. (2020b) conducted a fascinating study using passive acoustic tracking. They utilized hydrophones to

investigate how the feeding behavior of *L. vannamei* varies in response to different meal durations. The researchers discovered that smaller pellets were consumed more rapidly than larger pellets, although the overall quantity consumed remained consistent regardless of the diet's duration and additionally, the intensity of clicking sounds was closely correlated with the amount of food consumed. This suggests that passive acoustic monitoring has the potential to provide precise estimations of food consumption [231].
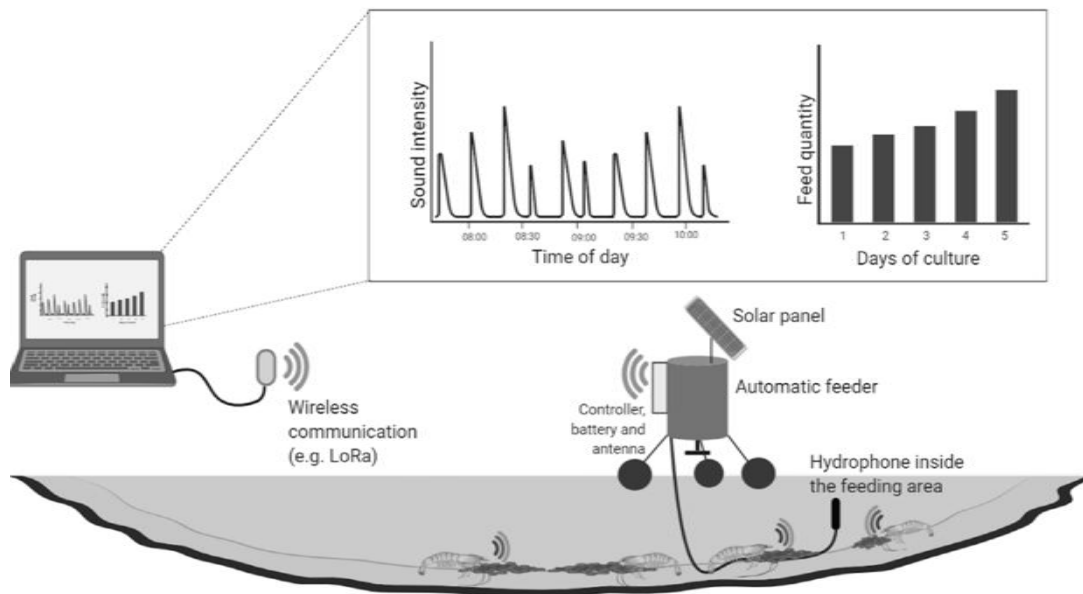

Figure 4: Provides an illustration of a sound-based feeding system: Acoustic signals within the pond are captured by a hydrophone, which then transmits these signals to a controller located either on the feeder or along the shore. The controller monitors the extent of feeding activity and adjusts the food composition according to its observations. Acoustic and feeding data are periodically transmitted to a computer located in the farm office. BioRender.com was used to make the picture [238].

VII. ARTIFICIAL INTELLIGENCE

The origin of Artificial Intelligence (AI) can be traced back to the mid-20th century when the concept emerged as an ambitious pursuit within computer science as depicted in Figure 5 [239]. The term "Artificial Intelligence" itself was coined in 1956 during the Dartmouth Workshop, a seminal event where early AI pioneers convened to explore the possibilities of creating machines that could exhibit intelligent behavior. The pioneers envisioned creating systems that could replicate human thought processes, reasoning, problem-solving, and decision-making. Early AI research focused on symbolic reasoning and logic, which aimed to represent knowledge and use rules to derive conclusions [240]. However, progress in AI faced challenges due to limited computational power and inadequate algorithms [241]. This led to what became known as the "AI winter," a period of reduced enthusiasm and funding for AI research [242]. The field experienced a resurgence in the 1980s with the emergence of new computational techniques and approaches, such as expert systems and neural networks. Expert systems aimed to encode human expertise into computer programs, while neural networks sought to mimic the interconnected neurons of the human

brain to process information [243]. Despite these advances, significant limitations remained in achieving human-like intelligence [244].

The 21st century has seen remarkable advancements in AI, driven by exponential growth in computational power, the availability of massive datasets, and breakthroughs in machine learning [245]. Machine learning techniques, particularly deep learning, have revolutionized AI by enabling computers to learn patterns and make predictions from data [246]. These developments have led to AI systems that excel in tasks like image recognition, natural language processing, and even complex games like Go and chess [247]. In recent years, AI has permeated various aspects of our lives, from virtual assistants and self-driving cars to medical diagnostics and financial analysis [248]. The journey of AI continues to evolve, fueled by ongoing research, collaboration, and the quest to achieve the vision of creating machines that can truly simulate human intelligence [249;250].
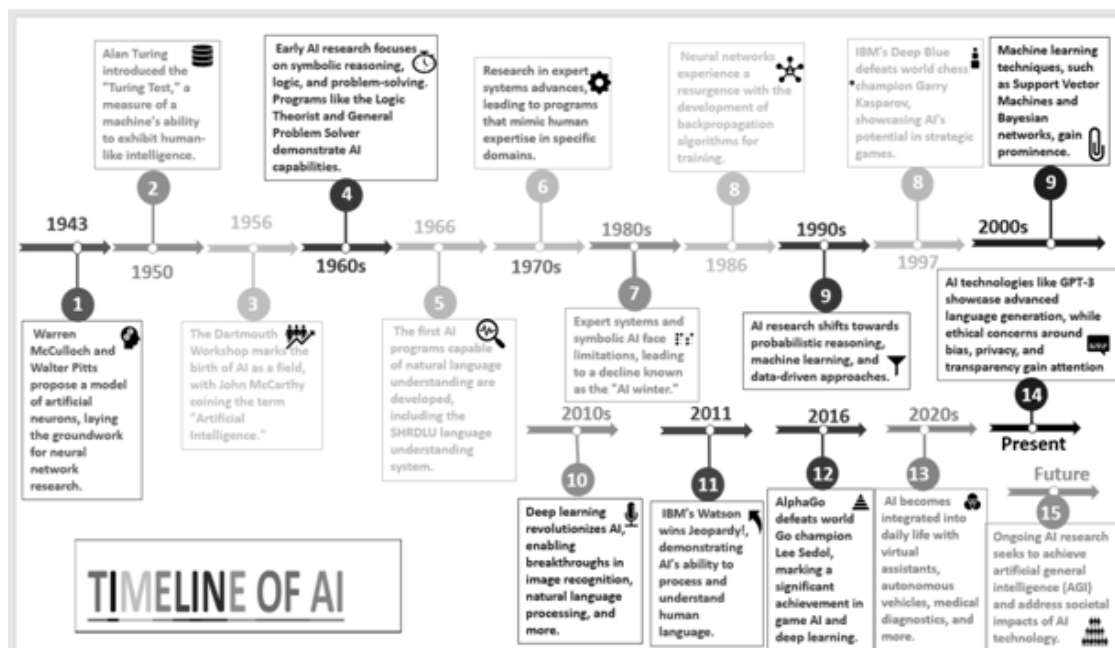
Figure 5: Illustrates the Progression of Artificial Intelligence

1. Exploring Shrimp Feeding Behaviors through Computer Vision and Artificial Intelligence

Computer vision has gained popularity in fish farming as a method for understanding feeding behavior and optimizing management (Figure 6) and Fig. 7 represents the telemetry system to monitor shrimp movements [251]. Numerous studies, such as Zhou et al. (2018b), have presented feeding decision systems for tilapia. This novel strategy is based solely on real-time behavioral surveillance, such as food snatching and group flocking. Zhou et al. discovered that the Feed Conversion Ratio (FCR) decreased by 10.77% when compared to fish biomass evaluation-based feed management. Computer vision in shrimp aquaculture is still understudied. However, deep-learning algorithms and picture thresholding have been tested in shrimp environments [252]. These efforts improve shrimp feed optimization and illness management [253].
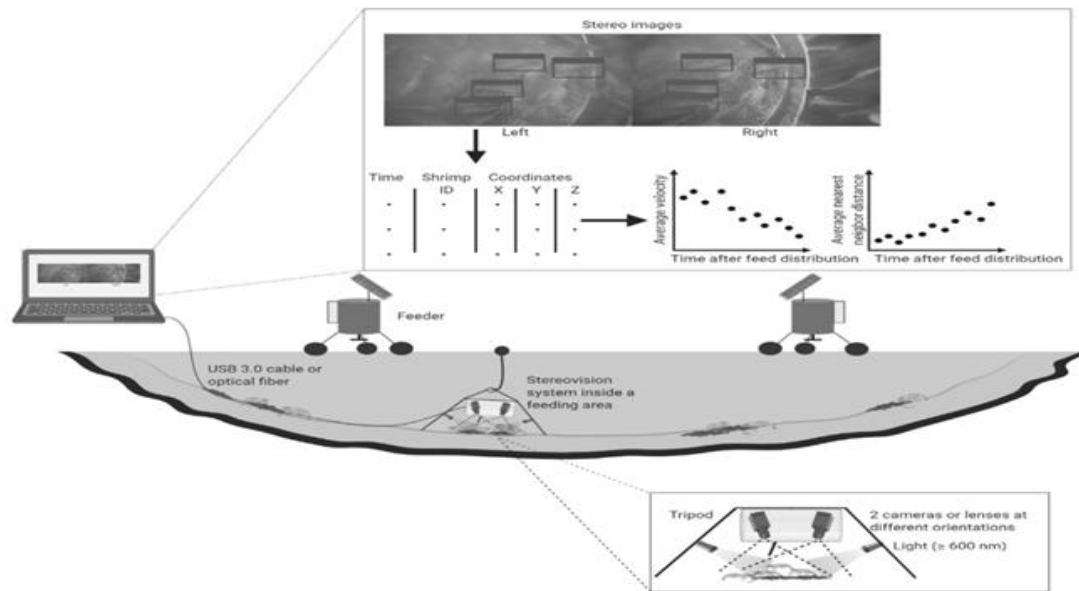
Figure 6: Representation of a computer vision system to monitor shrimp behaviour. The stereo camera provides two views of the scene, enabling its 3D mapping. Object-detection algorithms are then applied on the frames to spot the shrimp, from which 3D coordinates are computed. Coordinates enable the calculation of various metrics such as orientation, velocity and nearest neighbour distances which can be linked to feed distribution events. Created with BioRender.com (Darodes *et al.,* 2021)

Visual quality deterioration is a notable issue in underwater video recordings [254]. This decline stems from the absorption and scattering of light by water, particularly noticeable at significant depths and in conditions of heightened turbidity [255]. The realm of computer vision demonstrates remarkable efficacy in real-time monitoring of various aspects related to the feeding behavior of penaeid shrimp [256]. Cutting-edge deep learning algorithms, exemplified by neural networks like YOLO (You Only Look Once, as proposed by Redmon et al. in 2016), have been successfully employed for the automated identification of aquatic organisms. Li et al. (2016), Pedersen et al. (2019), and Mahmood et al. (2020) show that this method can accurately identify submerged organisms. Its industrial integration potential is promising. Huang et al. (2018) developed a prototype underwater surveillance system for real-time shrimp enclosure and tank monitoring. This device included an underwater camera, an image enhancement algorithm to reduce image haze, and YOLO to identify shrimp in the camera's visual range. Additionally, object-detection algorithms can provide underwater footage's specific positions of recognized humans. Stereovision systems, which use two cameras at various angles (e.g., Stereolabs Inc., San Francisco, CA, USA), enable three-dimensional detection of inter-individual distance and speed (Fig. 2). Osterloff et al. (2016) proposed an alternative to deep learning methods, which require large training datasets.

Their idea uses a random forest algorithm to track shrimp population changes on a deep-sea coral reef. This method uses stationary underwater observatory frames [257].Interestingly, the software was trained with 80 annotated frames, mostly of Pandalus

spp. (Leach) shrimp species [258]. This software then allowed accurate shrimp abundance estimations and trustworthy comparisons within and between frames and locales [259].
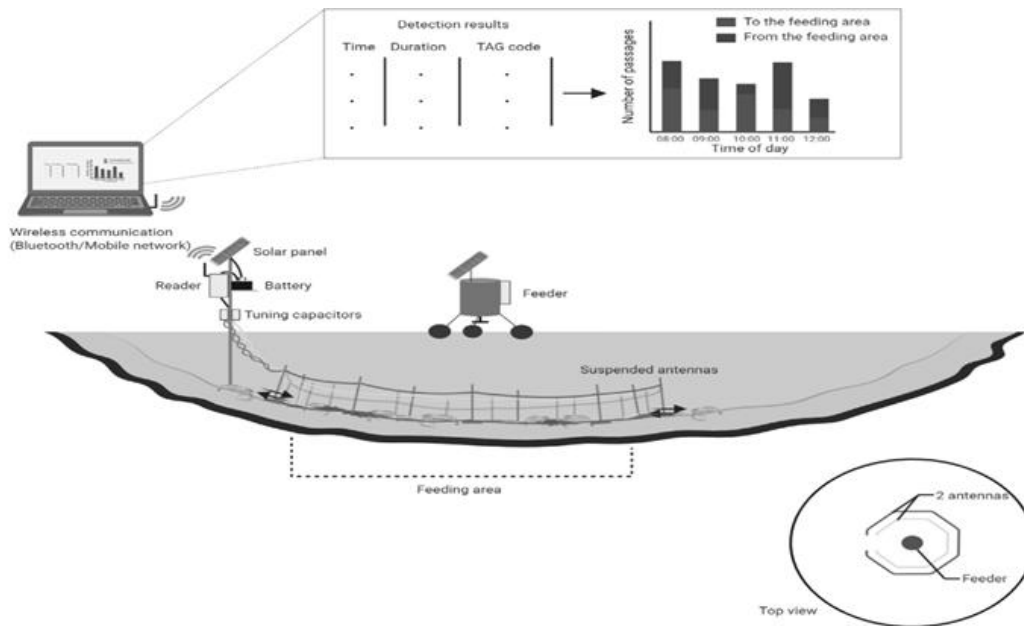
Figure 7: Representation of a telemetry system to monitor shrimp movements in ponds. Two antennas are used side by side in order to provide both speed and orientation of the tagged individuals that enter and leave the area covered by the feeder. The reader sends detection reports to a nearby computer, from which graphs on the number and directions of passages through time can be drawn. Created with BioRender.com (Darodes et al., 2021). Telemetry has emerged as a crucial instrument for observing animal behavior within aquaculture settings, proving particularly effective in salmon farming. Within fish enclosures, implanted acoustic transmitters serve as communicators, transmitting signals to receivers like hydrophones. These transmitters, when paired with pressure sensors, can offer insights into swimming depth, while their integration with accelerometers can collectively reveal activity levels.

Object-detection algorithms can assist scientists in comprehending crustacean behavior and feeding station movements [260]. Existing research does not examine shrimp concentrations in relation to feed dispersion events near feeding locations [261]. Analyzing underwater footage with such tools could assist in determining the number of visible individuals at feeders over time [262]. Cao et al. (2020) demonstrated that object detection increases the spatial accuracy of foraging in Chinese mitten crab (Eriocheir sinensis H. Milne-Edwards) ponds. The researchers developed "Faster MSSDLite," a real-time object detection framework for pond crustaceans in aquaculture [263]. This method eliminated crab irregularities and underwater issues. SSD is a deep convolutional neural network similar to YOLO, which was proposed by Liu et al. in 2016.However, it was established to outperform YOLOv3, achieving a remarkable detection speed of 74.07 frames per second and an average precision rate of 99.01% [264]. This advanced computer vision system can seamlessly integrate onto an automated feeding boat, alongside a GPS (Global Positioning System) device [265]. Through this integrated configuration, the system is poised to accurately map crab density across the pond, allowing for the automatic determination of feeding needs at

various locations within the pond, similar to the approach adopted by Terayama et al. (2019) for fish, augmenting video observations with data from echo sounders holds promise. In their study, they converted low-quality nighttime video footage and high-resolution sonar images into realistic depictions of fish during the day. However, the relationship between sonar images and crustacean density remains unexplored, with no published results to our knowledge.It is essential to note that the audible frequency sounds emitted by echo sounders may affect the behavior of shrimp [266]. Recent focus has been placed on the development of sonar technologies for shrimp biomass monitoring despite this factor [267]. Notably, companies such as Marine Instruments (Spain) and Minnowtech (United States) have expressed interest in advancing sonar technologies to monitor shrimp populations in wetlands more effectively. This indicates a developing interest in innovative shrimp research and monitoring techniques. ntation and velocity in close proximity to primary feeding zones could shed light on the dynamics that drive local animal concentrations near these feeders. Similar to what Oppedal *et al.* (2011) observed in Atlantic salmon (*Salmo salar Linnaeus*), the presence of anticipatory behavior in shrimp when feeders initiate particle dispersion is unexplored. Although scuba observations of large shrimp swarms or units in ponds (McNeil, 2001) exist, the use of computer vision, particularly stereovision, offers a promising avenue for future research (see Table 2). The configuration of these swarms, size distribution, movement patterns, and the causes of their formation in penaeid crustaceans within commercial contexts remain unexplored [268]. Indirectly monitoring residual feed at specific locations, such as on feeding trays, is another potential application of computer vision in the monitoring of feeding behavior and activity [269]. Such systems have been described in both fish and shrimp ponds in recent investigations. By refining feed distribution, such systems could ultimately result in reduced feeding costs. The responses of shrimp towards feeders remain mainly incomprehensible [270]. Consequently, gathering data regarding their orientation and velocity in close proximity to primary feeding zones could shed light on the dynamics that drive local animal concentrations near these feeders. Similar to what Oppedal *et al.* (2011) observed in Atlantic salmon (*Salmo salar Linnaeus*), the presence of anticipatory behavior in shrimp when feeders initiate particle dispersion is unexplored. Although scuba observations of large shrimp swarms or units in ponds (McNeil, 2001) exist, the use of computer vision, particularly stereovision, offers a promising avenue for future research (see Table 2). The configuration of these swarms, size distribution, movement patterns, and the causes of their formation in penaeid crustaceans within commercial contexts remain unexplored [271]. Indirectly monitoring residual feed at specific locations, such as on feeding trays, is another potential application of computer vision in the monitoring of feeding behavior and activity [272]. Such systems have been described in both fish and shrimp ponds in recent investigations [273]. By refining feed distribution, such systems could ultimately result in reduced feeding costs [274]. In addition to utilizing YOLO for shrimp detection, Huang et al. (2018) introduced a program grounded in neural networks to distinguish between feed and non-feed pixels. This program facilitates the automated evaluation of the feeding tray's surface area covered by feed over time. Similarly, Chirdchoo and Cheunta (2019) successfully devised and tested a cost-effective software solution to automatically identify remaining feed pellets on shrimp feeding trays. Their approach employs a segmentation program that segregates pixels based on the color of the feed samples. However, it's worth noting that challenges related to turbidity and uneven illumination still pose significant limitations for segmentation algorithms utilized for feed detection in pond environments (Li et al. 2017). For farmers, employing segmentation-based algorithms with real-time footage could offer insights into when feeding should be ceased, particularly if a substantial amount

of feed is still present at the pond bottom after the initial distribution [275]. This technology has the potential to guide informed decisions about feeding cessation, as depicted in Table 2.

VIII. CONCLUSION

The shrimp farming industry continues to face challenges in terms of feeding inefficiencies, which hinder its progress and hinder efforts to enhance sustainability [276]. The feeding behaviour of shrimp is intricate, and our comprehension of it is currently in its nascent stage [277]. Conventional methods employing feeding trays and feed tables remain prevalent, however their reliability and subjectivity might be constrained [278]. Farmers that have used rigorous monitoring systems have already shown improved economic benefits and a positive return on investment as a result of greater crop yields [279]. There is an expectation that the shrimp farming industry would increasingly adopt more advanced feeding management strategies, akin to the successful implementation observed in salmon farming [280]. From a scholarly standpoint, the application of the aforementioned technical techniques holds promise in facilitating new understandings of shrimp behavior in relation to feeding mechanisms [281]. Passive acoustics has emerged as a highly promising technology among the different options being examined [282]. It has already been extensively applied in shrimp farms worldwide. The efficacy of its capacity to provide reliable and up-to-date projections of feed requirements has been validated, resulting in improved feed management protocols [283]. Future research efforts should focus on further expanding the technique of passive acoustics in shrimp farming, considering its already established presence in the field [284]. It is imperative to broaden the scope of analysis beyond the assessment of feeding behavior alone [285]. Instead, it is crucial to emphasize the enhancement of estimations regarding feed [286]. This innovative approach holds the potential to yield not only direct advantages for farmers but also enduring benefits for researchers [287]. It opens avenues for conducting feed consumption trials that were previously limited to laboratory settings – typically in small indoor tanks where leftover feed could be retrieved. However, with this approach, such trials can now be conducted on the scale of commercial ponds [288]. This advancement is poised to address significant inquiries related to the impact of environmental factors on feed consumption under authentic pond conditions [289]. This insight can be gleaned through the comprehensive analysis of historical data obtained from acoustic recordings and water quality sensors [290]. Moreover, computer vision stands out as a viable tool for researchers aiming to extend their observations to pond environments when visibility conditions are conducive. This observational method carries the potential to furnish behavioral cues that aid in estimating feed intake [291]. By integrating these technologies, researchers can gain a more comprehensive understanding of shrimp feeding dynamics in real-world contexts [292]. The precise quantification of feeding activity is of essential importance, as stated by Norton and Berckmans (2017), and relies on the identification of feature variables. The extraction of these metrics from animal bio-responses can be achieved in a highly effective manner. This can be accomplished by either integrating them with passive acoustic monitoring, which serves as a surrogate for feeding activity, or by conducting thorough laboratory trials that enable the precise tracking of feed intake. The implementation of continuous monitoring of behavior in conjunction with water quality assessment can function as a proactive mechanism for detecting welfare-related issues at an early stage [293]. In addition to passive acoustics, computer vision systems provide the capability to extract valuable information regarding collective movements in relation to feeding zones, hence enhancing the comprehensive analysis [294]. Despite the challenges

associated with aquatic conditions, current advancements in machine learning have the potential to overcome these obstacles [295]. However, the consistent and accurate evaluation of feeding behavior for farmers using underwater observations remains a distant objective [296]. At now, there is a lack of a comprehensive system that adequately addresses the requirements of shrimp producers in this domain within the market [297]. Moreover, although mostly relevant in experimental pond environments, telemetry techniques offer a captivating opportunity for understanding extensive patterns of mobility and spatial utilization [298]. The utilization of PIT-tag telemetry, for example, can be easily employed to provide valuable insights for enhancing the timing and spatial allocation of feed, so enabling increased accessibility for a larger segment of the population [299].

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DISCLOSURE STATEMENT

The writers assert that they do not possess any conflicts of interest.

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