Precision Aquaculture: A way forward for sustainable Agriculture

Abstract:

The escalating demands for food, fiber, energy, and water due to swift population growth have underscored the necessity for the sustainable utilization of natural resources. The advent of precision farming tools and machinery since the 1990s has markedly enhanced productivity and optimized the employment of inputs in aquaculture. The burgeoning connectivity in rural regions and its improved integration with data from sensor systems, remote sensors, equipment, and smartphones have paved the way for innovative concepts in Digital Aquaculture.Automation is the most effective strategy to manage situations, augment productivity, and reduce manufacturing costs. Biosensors are deployed to control unidentified sensor-based remotely and guided aerial vehicles to apply chemicals or fertilizers while monitoring water quality. A sophisticated aeration system manages the concentration of dissolved oxygen. Another critical aspect is the administration of feeding and automatic biomass estimation. Robotics and automatic feeders are employed in ponds and cages to minimize feed wastage and the Feed Conversion Ratio (FCR), with these tools being dependent on the behaviour of the organisms and the water condition. Post-harvest, farmers acquire information on biomass estimation to attain optimal yield. The most vital element is the automatic monitoring of the health and welfare management of the organism to detect any challenging situations or early signs of anomalies. An underwater surveillance system, a camera-based visual system, collects data on water quality, organism activity, feeding, cage biofouling, and net cleaning. Automation is poised to shape the future of the aquaculture industry to make the nations agriculture sustainable.

Keywords: Aquaculture, technology, tools, Automatic, production,

1. Introduction:

Aquaculture involves cultivating fish, crustaceans, mollusks, aquatic plants, algae, and more. With a global annual growth rate of 7%, the significance of aquaculture in contributing to the overall production of animal proteins is on the rise[1]. As per the United Nations Food and Agriculture Organization, the advent of digital technology in agriculture presents a substantial prospect to address climate change, eradicate hunger and poverty, and mitigate environmental degradation[2]. Digitalization is set to transform every facet of the agri-food production chain. Connecting and rapidly processing vast volumes of data facilitates more efficient operations, increased economic returns, improved environmental impacts, and enhanced field working conditions[3]. However, to implement these transformations, governments must foster the development of rural societies and small businesses and establish infrastructure in rural areas[4]. This will enable them to accept and implement novel ideas.

In aquaculture, practitioners often view the field as a blend of art and science. The effectiveness of operations largely depends on the farm manager's instinct rather than an in-depth analysis of the cultivated species' physiology, ecology, and behavior[5]. Consequently, there has been a certain reluctance among farm owners to depend on automated crop management systems. Nonetheless, the evolution of aquaculture into a scientific discipline has been expedited by recent advancements in research and business practices, leading to the embrace of novel technology[6]. The real-time tracking of system parameters, managers now have unprecedented insights into their aquaculture facilities' physical and biological conditions [7]. From 1960 to 2020, the per capita consumption of fish products rose from 9-20kg/person. However, aquaculture encounters several challenges due to unforeseen climate variability, which leads to alterations in water quality parameters and the emergence of diseases[8]. Aquaculture practitioners’ resort to labor-intensive conventional manual testing techniques to assess the properties of water and identify and treat diseases. This approach could potentially yield unsatisfactory results[9]. Hence, it is more advantageous to have an automated monitoring system for the aquafarm. A variety of modern technologies can be employed to address these challenges[10]. Today, every life stage of fish, from broodstock and eggs to mature adults, is intensively cultivated. The hatchery stage is typically conducted in indoor tanks, allowing for control over environmental conditions and external factors that affect the fish[11]. In industrial farming, the majority of finfish species are transferred to open-air ponds or sea cages for their final growth phase, with the exception of those species that are exclusively raised in tanks[12]. The reason behind this is that the water quality requirements of a fish significantly fluctuate with its size. Consequently, it's more feasible to allow a consistent expansion of the production unit volume in ponds as the fish grow, compared to indoor tanks [13]. Moreover, fish cultivated in marine-based aquaculture are exposed to natural fluctuations in vital aspects of the production environment [14].

2. Precision Agriculture

Precision Agriculture (PA) involves the utilization of both near and remote sensing techniques through IoT based sensors to monitor crop conditions at various growthstages[15].This refers to collecting and examining data from sensors related to the aquatic environment and cultivated species, which could assist in decision-making processes for farm operations [16]. It encompasses the gathering and analysis of extensive data concerning crop health and other related parameters. Various factors contribute to plant health, such as water levels, temperature, and more. PA encourage farmers to accurately discern the specific parameters required for a healthy crop, their precise locations, and the optimal quantities needed at any given moment[15].

By 2050, India's agri-food sector will face a daunting task: providing sustenance for a population exceeding 1.7 billion, given the country's limited resources in terms of cultivable land, water, and energy [17]. The scope for expanding our net cultivated area is minimal, as it has almost plateaued at 140 million hectares[18]. The intensification of agriculture has led to the deterioration of natural resources, particularly soil and water. The present approach to input application is guided by standard protocols for a composite sample or visible crop symptoms, neglecting the variability within the field[19]. The mean values, which are seldom observed in a specific field and are used to formulate recommendations, indicate an improper or excessive use of inputs. This leads to environmental harm and a reduction in the efficiency of input usage [20]. Hence, the use of modern tools and methods to amplify agricultural practices is essential. Precision farming emerges as a viable approach for the sustainable development of agriculture. It advocates the use of suitable technologies or methods to apply the right inputs in the correct amounts at the right times and places[21].

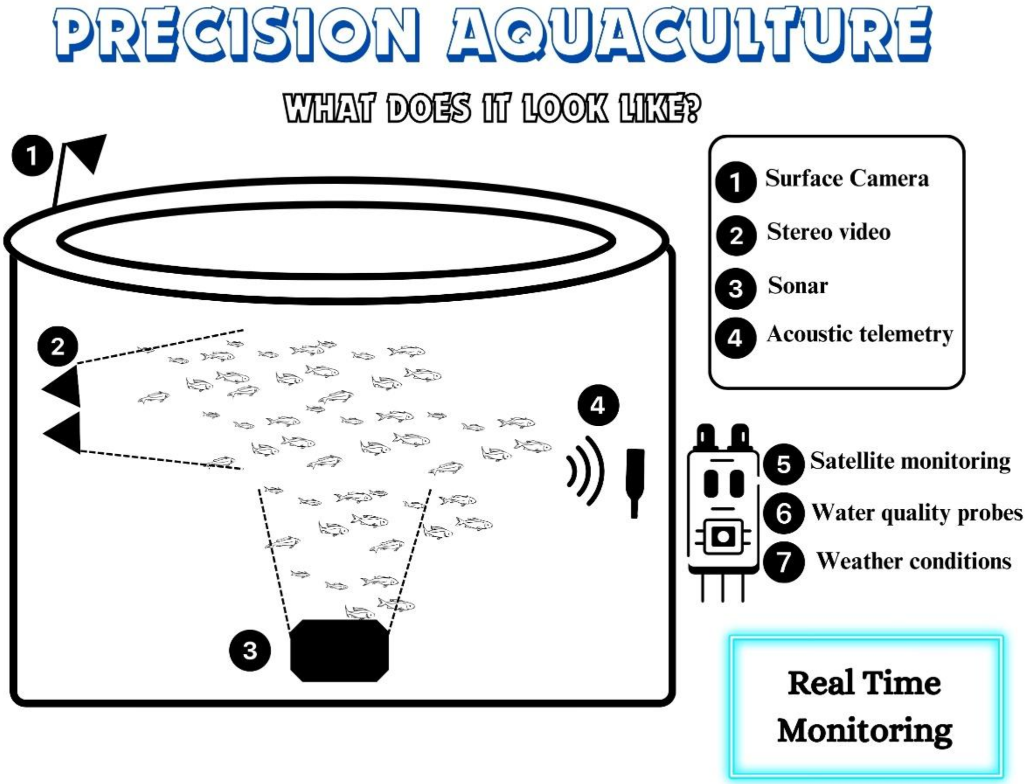

Fig. 1. Precision Aquaculture process [14]

3. What is Precision Aquaculture?

The recent surge in aquaculture has been likened to a "Blue Revolution", drawing parallels with the "Green Revolution" that saw a boost in wheat yields beginning in the 1950s. However, concerns have been raised about the swift expansion of this industry due to possible adverse environmental impacts, including the eutrophication of adjacent waters and alterations to habitats[22]. Due to market dynamics and stringent rules pertaining to sustainable development, the annual growth of aquaculture in Europe has declined, settling at 1%[23]. These factors have led to a significant focus on the ecological advancement of aquaculture in marine ecosystems, along with the endorsement of notions such as "ecological aquaculture" and "eco aquaculture"[24]. Precision aquaculture focuses on the application of modern technologies for the ecological intensification of aquaculture farms. This approach, coupled with the need for enhanced efficiencies and economies of scale, is crucial for fostering the sustainable growth of the industry[7]. Contemporary aquaculture farms produce data in a variety of formats[25].In-situ sensors measure a broad spectrum of environmental parameters, such as salinity, dissolved oxygen (DO), chlorophyll, and temperature as given in Fig. 1[26].

Environmental data, when remotely sensed, can cover considerably larger spatial domains. This data can be on a global scale when derived from a satellite-based monitoring system, or on a bay scale when obtained from terrestrial sensors such as CODAR-type HF radar [27]. Factors related to the animals, such as size, group behavior, and movement, need to be measured to gather information on farm operations. This is typically achieved using underwater technologies such as video surveillance, hydroacoustic technology, and images captured by aerial drones (Fig. 2)[28].

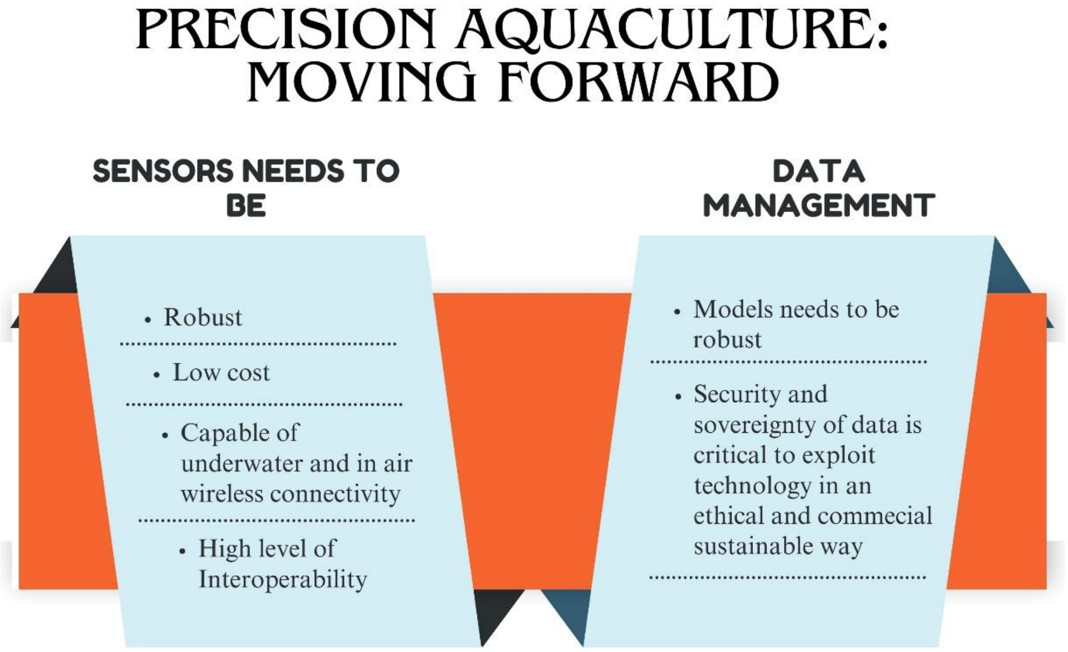

Figure 2. Precision aquaculture sensors and used [14]

4. Concept, Components, and Requirements of Precision Farming:

Dr. Pierre Roberts introduced the idea of Precision Farming as a solution to the issue of nutrient variability in expansive farms in the USA. The primary goal was to enhance production, reduce input expenses, and lessen negative effects on the environment[29]. The introduction of geo-referenced grid soil sampling has enabled the evaluation of field variability. Consequently, the need for a composite sample-based single recommendation for the entire farm may no longer be necessary[30]. The utilization of the Global Navigational

Satellite System (GNSS) has simplified the process of capturing crop yields while the harvester operates within the field[31]. The correlation between yield variation and nutrient levels obtained through grid sampling can be readily established [32]. As a result, the entire field could be subdivided into more manageable and uniform management units[33]. The development of a Variable Rate Applicator was spurred by the need to deliver nutrients according to the specific requirements of each site as mentioned in Fig. 3[34]. During the 1980s, advancements in soil nutrient management, particularly through the work of Dr. Roberts, laid the foundation for precision farming, initially termed as 'Site Specific Crop Management'[35]. The advancement of spectral and hyper-spectral sensors along with high-resolution satellite imagery has expedited the generation and collection of information[36]. In this context, the term "Satellite Farming" is occasionally used, while "Precision Farming" is also now referred to as "Climate Smart Agriculture"[37]. Hence Fig. 4 illustrated a Precision Farming Framework (PFF) cycle.

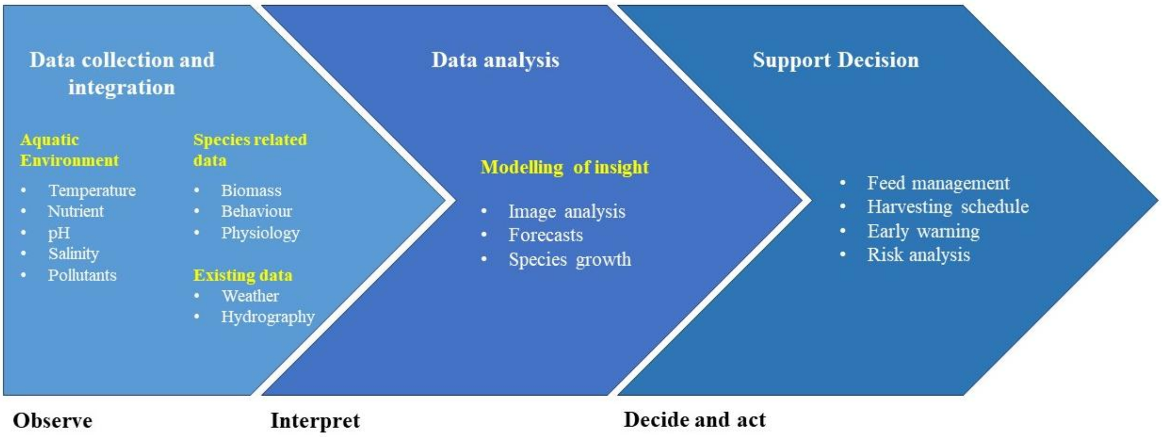

Fig. 3. Precision aquaculture Framework [14]

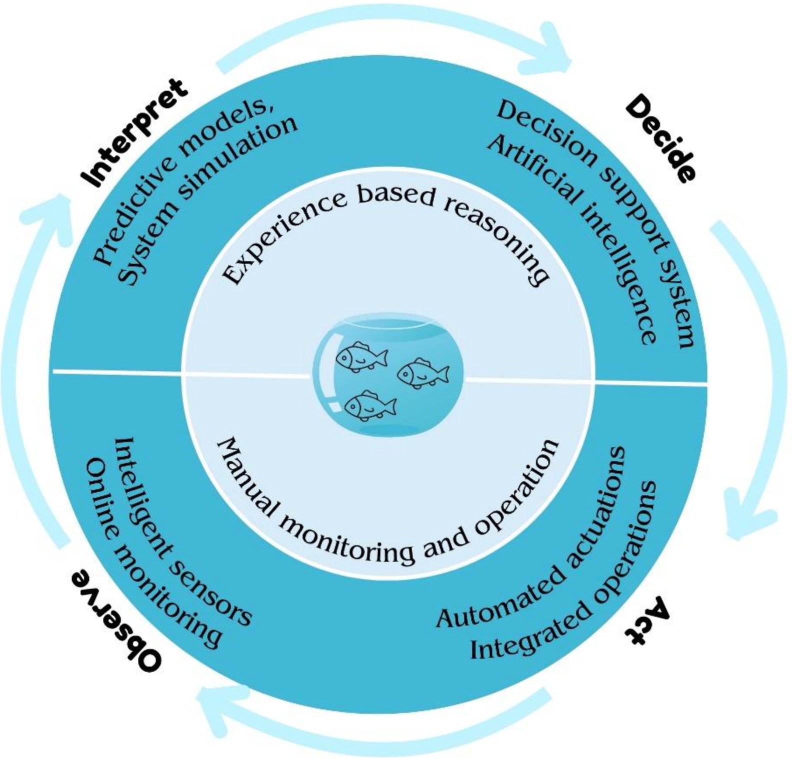

Fig. 4.A Precision Farming Framework (PFF) cycle[14].

5. The overarching aims of precision aquaculture have been defined as:

5. 1. Water Quality Monitoring:

In marine aquaculture, maintaining optimal water quality is crucial for achieving exceptional output performance, which often surpasses expectations with diligent monitoring and control (Fig. 5 and Fig. 6). Key physical and chemical variables such as temperature, dissolved oxygen levels, pH, turbidity, and ammonia concentration must be carefully managed to prevent significant losses and a reduction in production by 20% to 40% [38]. In shrimp cultivation facilities, significant setbacks can occur due to a substantial reduction in dissolved oxygen levels, particularly during periods of high production. There have been instances of severe aquatic life losses at the Marine Aquaculture Center of FURG (FURG-EMA)[39]. In certain instances, a delayed response from the user (exceeding 30 minutes) has significantly affected almost the entire shrimp production cycle[40]. Temperature fluctuation is a critical factor in implementing a rigorous monitoring control strategy. Various physiological activities such as respiration, digestion, and nourishment intake are among the processes directly related to the water temperature across all species[41]. As the temperature rises, so does the activity level of the animals. Consequently, their oxygen demand escalates as well[42]. Keeping a close eye on essential water quality parameters is a significant move towards boosting productivity in aquaculture. Here, 'performance' takes on a broader connotation, balancing environmentally friendly sustainable practices with production[1].

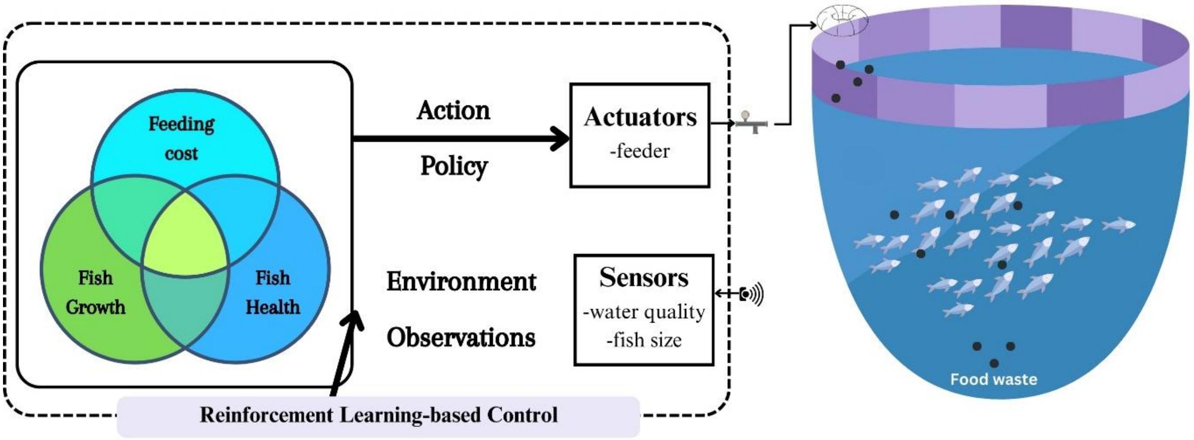

Figure 5. Precision Aquaculture[12]

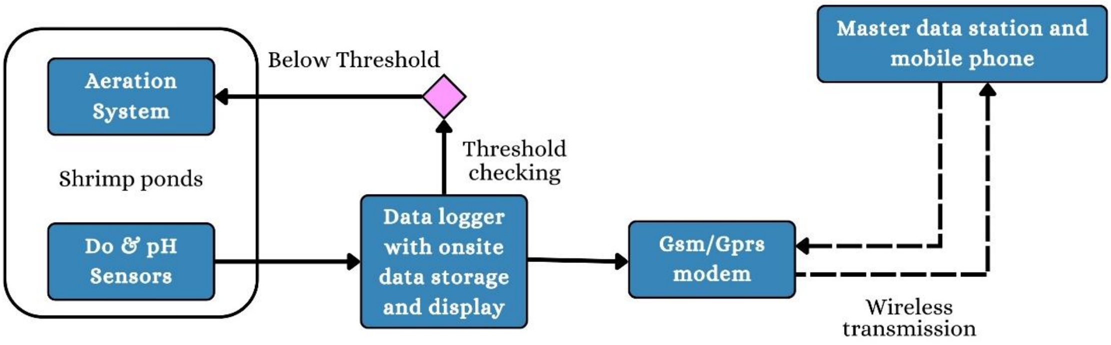

Figure 6. Flow chart of water quality monitoring [20]

5. 2. Food Feeding System:

Overfeeding fish leads to food wastage and water contamination. Additionally, undernourishment results in slower growth rates, both of which adversely affect the wellbeing of the fish[43]. Hence, the act of feeding holds paramount importance in aquaculture. Owing to time constraints, farmers and other aquaculture practitioners may not be able to adequately feed the fish. This could potentially result in instances of both overfeeding and underfeeding within their aquatic farms[11].We provide an automated feeding device (Fig. 7) that eliminates the need for manual feeding, thereby mitigating the adverse consequences of both overfeeding and underfeeding[44].

The feeder device will dispense food to the fish based on specific measurements and timings. By implementing an accurate feeding schedule with this device, it's possible to reduce the overall feeding expenses, contributing to savings in both time and labor costs[45]. Indeed, the design of a food feeder takes into account factors such as the size and species of the fish. This ensures that the feeder is tailored to meet the specific needs of the fish, promoting their health and well-being[46].

This apparatus is designed to distribute a set quantity of food within a specified time frame. The operation of this feeding mechanism is made possible by a motor and timer attached to the food dispensing unit[10].

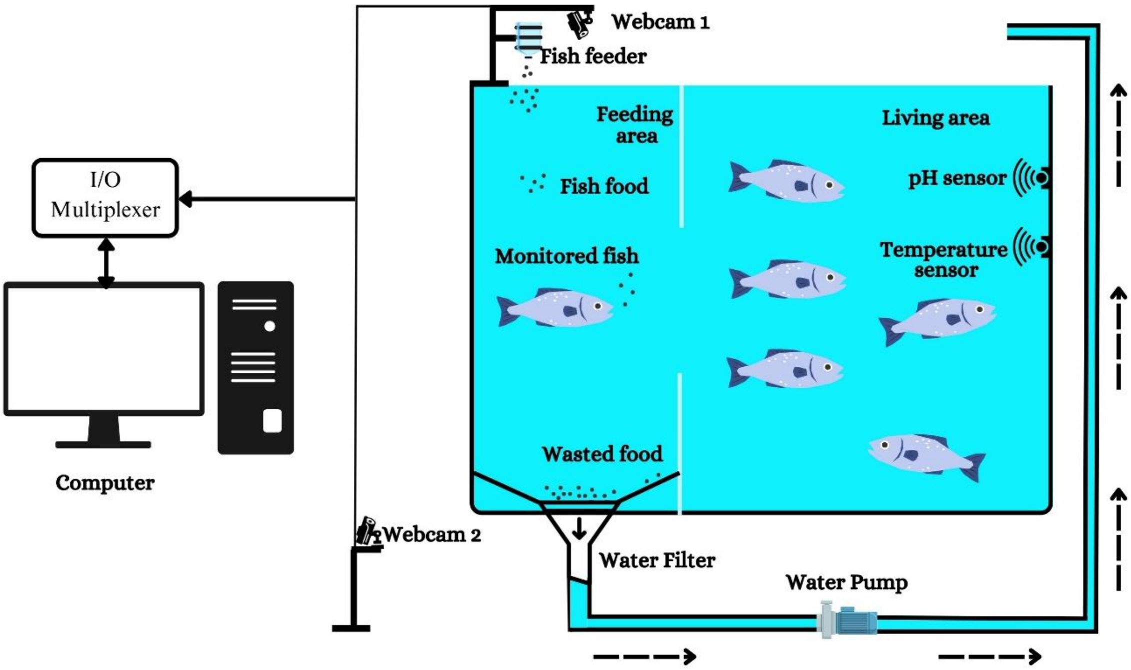

Figure 7. Automatic feeding device [47]

5. 3. Precision in the assessment of soil properties:

Identifying an efficient approach for assessing soil characteristics that minimizes the time and effort needed for soil sampling and analysis can be challenging[48]. Indeed, even with years of research dedicated to soil testing, the on-site evaluation of soil attributes in near real-time continues to be a complex endeavor[49]. A robust new approach is required for comprehensive and accurate mapping of soil parameters, taking into account spatial variations. Recent progress in methods based on remote sensing (RS), including proximal, airborne, and satellite-based RS, provides the capability to generate quantitative and predictive soil attribute maps with greater precision and resolution. Proximal sensing methods, such as visible-near-infrared, mid-infrared, X-ray fluorescence spectroscopy, among others, are particularly beneficial for studies at the field size or profile level. In contrast, airborne and satellite-based remote sensing techniques are more appropriate for characterizing soil properties[50]. The integration of data from multiple sensors and advancements in data mining methodologies have enhanced our comprehension of the dynamic characteristics of soil parameters, which are affected by a range of environmental factors (Fig. 8). The emergence of a novel and advanced method known as digital soil mapping (DSM) has been facilitated by progress in geo-information technology. This method allows for precise forecasting and spatial mapping at a chosen scale and high resolution, utilizing machine learning (ML) techniques and data mining algorithms[51]. Indeed, the utilization of pedometric methods, capable of predicting spatial and temporal changes in soil types and characteristics, constitutes the foundation of Digital Soil Mapping (DSM) [52].

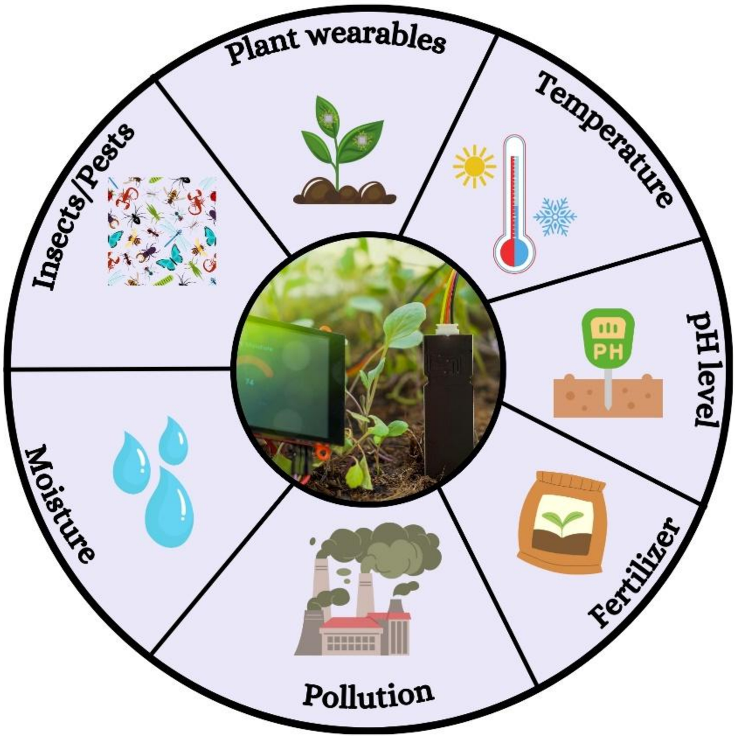

Figure 8. Soil sensors [24]

5. 4. Remote sensing in precision aquaculture:

Satellite-derived remote sensing methodologies are commonly employed to guide the operations of aquaculture, spanning from regional to international scales [53]. Numerous efforts have been made to utilize remote sensing for monitoring agricultural states and predicting yields, by incorporating indicators into models that simulate crop growth processes[54]. These methods, while time-consuming, are ideal for evaluations over extensive regions. However, they offer limited utility to small-scale farmers and pose challenges in achieving near real-time implementation[55]. In order to fulfill these requirements, India operates a number of satellites that offer diverse spatio-temporal and spectral resolutions[56]. Most remote sensing techniques are confined to multispectral wide bands, which encounter challenges in accurately and quantitatively determining soil and plant parameters due to their limited spectral resolution[57]. Hyperspectral remote sensing (Fig. 9) is fundamentally based on the examination of a multitude of continuous spectral channels with precise specifications[58]. Hyperspectral remote sensing is an emerging discipline that offers numerous advantages compared to conventional broadband multispectral remote sensing[59]. For a remote sensing technology to be commercially viable for precision agriculture in India, it needs to possess certain characteristics: a quick turnaround time (24-48 hours), affordable data cost (100 Rs./acre/season), high spatial resolution (minimum 2 m multi-spectral), and superior spectral resolution[60].

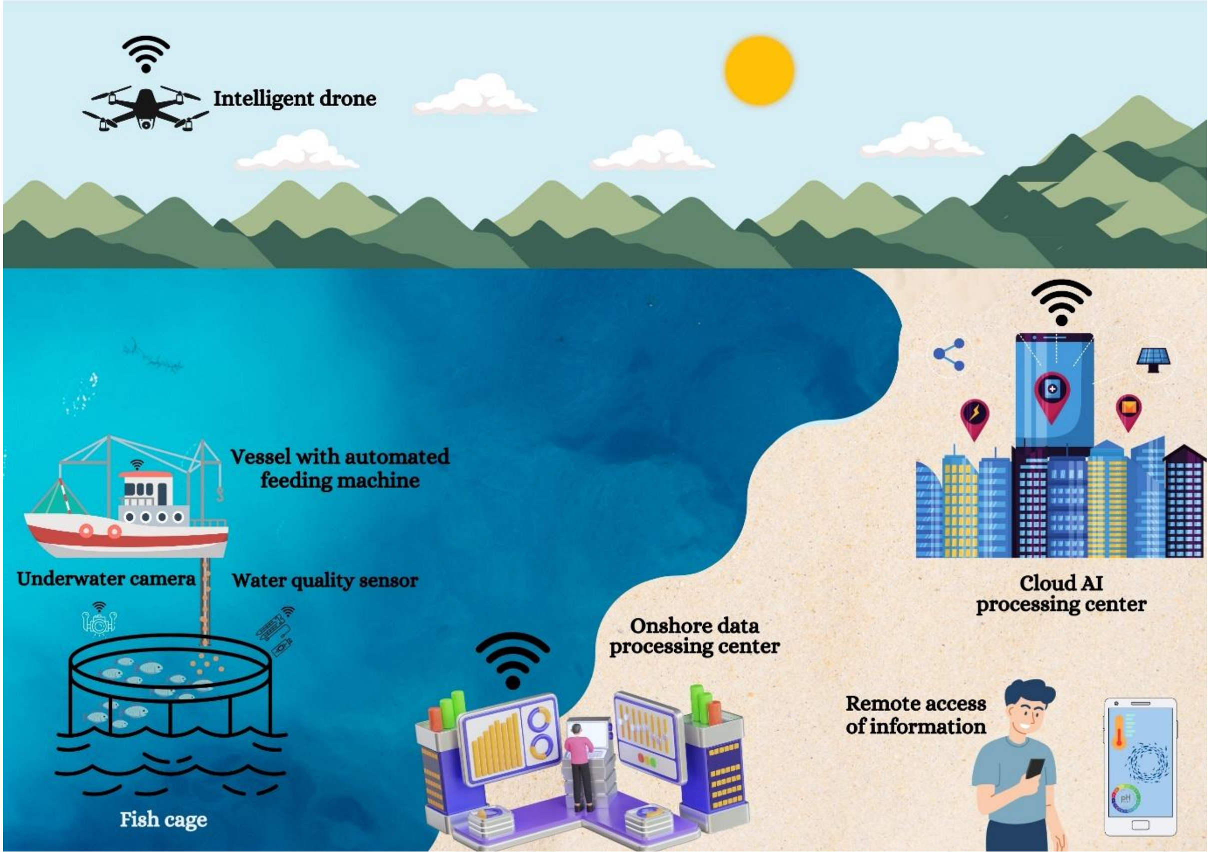

Figure 9. Remote sensing in aquaculture [61]

5. 5. Water Recirculating System:

Recirculation in aquaculture is a vital aspect of aquafarming technology (Fig 10). In this context, the recirculating system is employed, which circulates water from the fish tank and directs it through specially designed growth bags for filtration purposes[62]. Biochips are also utilized in the process of nitrification. By recirculating the water that has flowed through the plants back into the tank, the surplus nitrate levels and other impurities in the water are diminished[63]. The method of recirculating fish farming stands out as the most eco-friendly approach to yield high-quality fish[64]. The nutrients derived from fish farms are utilized for the production of biogas or serve as organic fertilizers for agricultural practices[65].

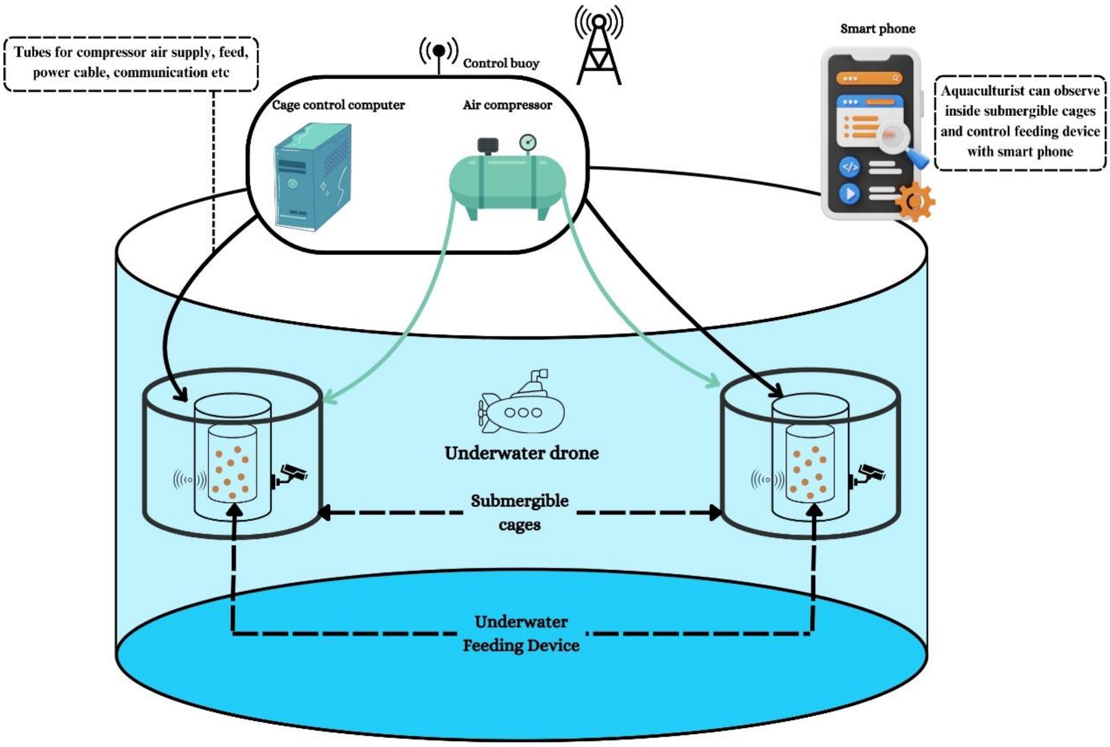

Figure 10. Water Recirculating System[21]

5. 6. Disease Detection Method:

Diseases affecting fish result in significant losses in aquaculture production. The rise in mortality rates within fish farms can be directly attributed to these infections [66]. As a consequence of escalating treatment expenses, loss of cultured species, and diminished yield both in terms of quantity and quality, there has been a noticeable rise in production costs [67]. Manystudy focuses on the main factors contributing to, the importance of, and strategies for managing fish infections in aquaculture production (Fig. 11). By imparting practical insights into diseases and health maintenance within aquaculture settings, it aims to enhance understanding and promote effective management of cultured fisheries and related practices[68]. Current fish diseases stem from various factors such as diminished fish resistance, the presence of pathogens, unfavorable water conditions, among others[69]. Within this system, following image acquisition, morphological processes such as image segmentation, noise reduction, and conversion to grayscale are implemented[70]. The feature extractor utilizes the FAST (Fast Segment Test) features to aid in extracting characteristic points[71]. Once the FAST features are obtained, the next step involves conducting dimensionality reduction through Principal Component Analysis (PCA). Subsequently, a neural network classifier is utilized in the training process to detect fish diseases[72]. Enhanced accuracy is observed when comparing the training dataset with the testing dataset[73]. Utilizing this technique accelerates the diagnosis of fish disease and streamlines the aquaculture process through automation[74].

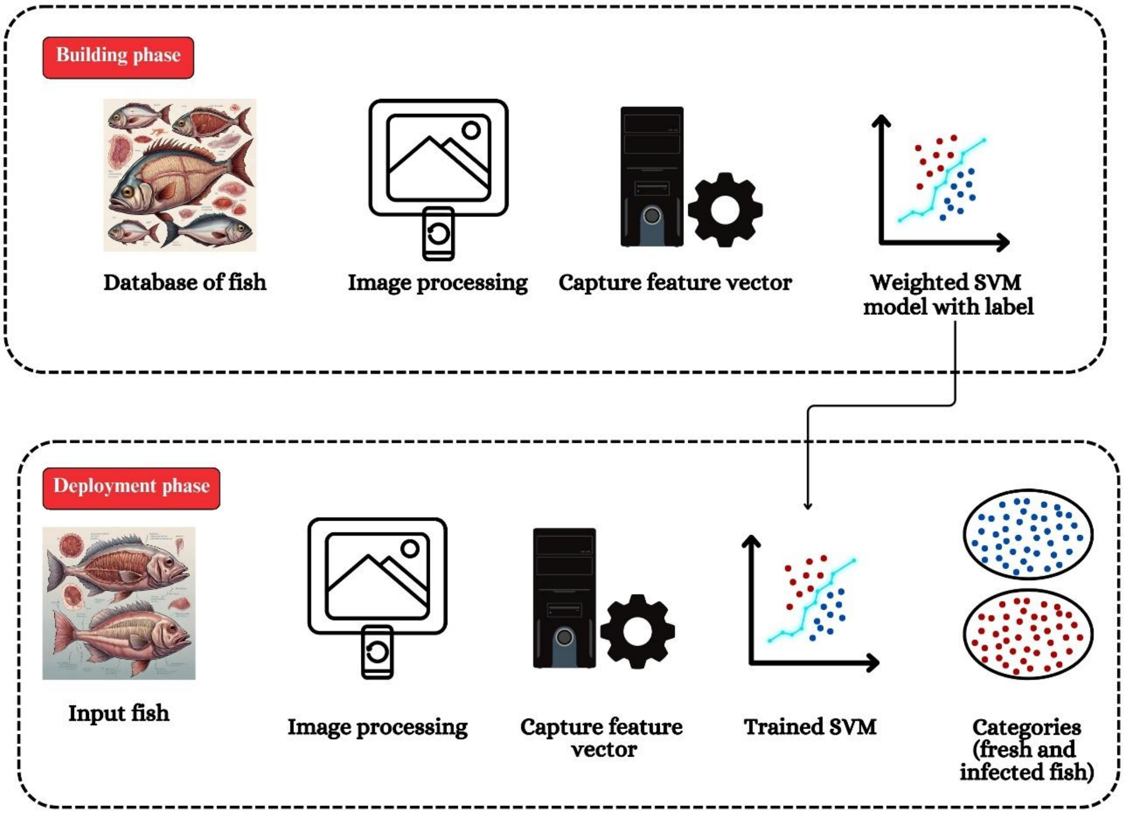

Figure 11. Automatic fish disease monitoring [75]

6. Limitations in Precision Aquaculture

Precision aquaculture, while promising in many aspects, also comes with its own set of disadvantages:

6.1 Cost: Implementing precision aquaculture systems can be expensive. This includes the initial setup costs for technology such as sensors, monitoring equipment, and data analysis tools, as well as ongoing maintenance expenses. This can be a barrier to entry for smaller-scale aquaculture operations.

6.2 Complexity: Precision aquaculture systems can be complex to set up and manage. They often require specialized knowledge in areas such as data analysis, technology integration, and system optimization. This complexity can be daunting for aquaculture farmers, particularly those with limited technical expertise.

6.3 Reliability: Precision aquaculture systems rely heavily on technology, including sensors and data networks. If any component of these systems fails or malfunctions, it can disrupt operations and potentially lead to financial losses. Ensuring the reliability and resilience of these systems can be challenging, especially in remote or harsh environments.

6.4 Data Privacy and Security: Precision aquaculture involves collecting and analyzing large amounts of data, including sensitive information about production processes, environmental conditions, and animal health. Ensuring the privacy and security of this data is crucial to prevent unauthorized access, data breaches, or misuse, which could have serious consequences for both the farm and the wider ecosystem.

6.5 Skill Requirements:Operating precision aquaculture systems requires specialized skills and training. Farmers and workers need to be proficient in areas such as data analysis, technology troubleshooting, and system optimization. Acquiring these skills can be time-consuming and costly, particularly for traditional aquaculture operations transitioning to precision methods.

6.6 Environmental Impact: While precision aquaculture aims to optimize resource utilization and minimize environmental impact, there is still potential for unintended consequences. For example, increased automation and intensification could lead to greater energy consumption, waste production, or habitat disturbance if not managed carefully. Balancing productivity with sustainability remains a challenge in precision aquaculture.

6.7 Dependency on Connectivity: Many precision aquaculture systems rely on stable internet connectivity for data transmission, monitoring, and control. However, in remote or rural areas with limited infrastructure, access to reliable internet service may be inconsistent or unavailable. This can hinder the effectiveness and reliability of precision aquaculture solutions in certain locations.

Overall, while precision aquaculture offers numerous benefits in terms of efficiency, productivity, and sustainability, it also presents challenges and limitations that need to be carefully considered and addressed by industry stakeholders.

6. Conclusion:

Industrial fish farming serves as a significant source of animal protein for human consumption, aiming to meet the increasing demand for nutrient richfood to global population growth. However, scaling up the fish production by volumes and quality and adhering to current production methods may not suffice to address this challenge. Factors such as the scarcity of feed raw materials, limited availability of suitable farming locations, environmental concerns, and conflicts with other industries underscore the need for a transition from experience-driven to knowledge-driven approaches in optimizing production.To meet these challenges, the industry must embrace more sophisticated and intelligent fish farming techniques. Current trends indicate a shift towards more production with minimum land, emphasizing the importance of monitoring and regulating the production process. Technical tools will play a crucial role in overcoming these obstacles, with Precision Fish Farming (PFF) emerging as a framework for implementing technologically driven approaches.

7. References:

[1] R.R. Teixeira, J.B. Puccinelli, L. Poersch, M.R. Pias, V.M. Oliveira, A. Janati, M. Paris, Towards Precision Aquaculture: A High Performance, Cost-effective IoT approach, ArXiv Prepr. ArXiv210511493 (2021).

[2] M.E. Mondejar, R. Avtar, H.L.B. Diaz, R.K. Dubey, J. Esteban, A. Gómez-Morales, B. Hallam, N.T. Mbungu, C.C. Okolo, K.A. Prasad, Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet, Sci. Total Environ. 794 (2021) 148539.

[3] É. Nicolétis, P. Caron, M. El Solh, M. Cole, L.O. Fresco, A. Godoy-Faúndez, M. Kadlecikoví, E. Kennedy, M. Khan, X. Li, Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, (2019).

[4] É.L. Bolfe, L.A. de C. Jorge, I.D. Sanches, A. Luchiari Júnior, C.C. da Costa, D. de C. Victoria, R.Y. Inamasu, C.R. Grego, V.R. Ferreira, A.R. Ramirez, Precision and digital

agriculture: Adoption of technologies and perception of Brazilian farmers, Agriculture 10 (2020) 653.

[5] D. An, J. Huang, Y. Wei, A survey of fish behaviour quantification indexes and methods in aquaculture, Rev. Aquac. 13 (2021) 2169–2189.

[6] J.W. Meade, Aquaculture management, Springer Science & Business Media, 2012.

[7] F. Antonucci, C. Costa, Precision aquaculture: a short review on engineering innovations, Aquac. Int. 28 (2020) 41–57.

[8] C. Boyd, A. McNevin, Aquaculture, resource use, and the environment, John Wiley & Sons, 2015.

[9] S.N. Zainurin, W.Z. Wan Ismail, S.N.I. Mahamud, I. Ismail, J. Jamaludin, K.N.Z. Ariffin, W.M. Wan Ahmad Kamil, Advancements in monitoring water quality based on various sensing methods: a systematic review, Int. J. Environ. Res. Public. Health 19 (2022) 14080.

[10] M. Manoj, R. Rajan, Precision aquaculture using iot & machine learning techniques, Agpe R. Gondwana Res. J. Hist. Sci. Econ. Polit. Soc. Sci. 2 (2020) 105–111.

[11] C. Somerville, M. Cohen, E. Pantanella, A. Stankus, A. Lovatelli, Small-scale aquaponic food production: integrated fish and plant farming, FAO Fish. Aquac. Tech. Pap. (2014) I.

[12] A. Chahid, I. N'Doye, J.E. Majoris, M.L. Berumen, T.M. Laleg-Kirati, Model predictive control paradigms for fish growth reference tracking in precision aquaculture, J. Process Control 105 (2021) 160–168.

[13] J.E. Bardach, J.H. Ryther, W.O. McLarney, Aquaculture: the farming and husbandry of freshwater and marine organisms, John Wiley & Sons, 1974.

[14] M. Føre, K. Frank, T. Norton, E. Svendsen, J.A. Alfredsen, T. Dempster, H. Eguiraun, W. Watson, A. Stahl, L.M. Sunde, Precision fish farming: A new framework to improve production in aquaculture, Biosyst. Eng. 173 (2018) 176–193.

[15] U. Shafi, R. Mumtaz, J. García-Nieto, S.A. Hassan, S.A.R. Zaidi, N. Iqbal, Precision agriculture techniques and practices: From considerations to applications, Sensors 19 (2019) 3796.

[16] F. O'Donncha, C.L. Stockwell, S.R. Planellas, G. Micallef, P. Palmes, C. Webb, R. Filgueira, J. Grant, Data driven insight into fish behaviour and their use for precision aquaculture, Front. Anim. Sci. 2 (2021) 695054.

[17] M.K. Jhariya, A. Banerjee, R.S. Meena, S. Kumar, A. Raj, Sustainable intensification for agroecosystem services and management: an overview, Sustain. Intensif. Agroecosystem Serv. Manag. (2021) 1–35.

[18] J. Gladju, B.S. Kamalam, A. Kanagaraj, Applications of data mining and machine learning framework in aquaculture and fisheries: A review, Smart Agric. Technol. 2 (2022) 100061.

[19] C. Wang, Z. Li, T. Wang, X. Xu, X. Zhang, D. Li, Intelligent fish farm—the future of aquaculture, Aquac. Int. (2021) 1–31.

[20] S. Zhao, S. Zhang, J. Liu, H. Wang, J. Zhu, D. Li, R. Zhao, Application of machine learning in intelligent fish aquaculture: A review, Aquaculture 540 (2021) 736724.

[21] T.T.E. Vo, H. Ko, J.-H. Huh, Y. Kim, Overview of smart aquaculture system: Focusing on applications of machine learning and computer vision, Electronics 10 (2021) 2882.

[22] K.K. Sharma, S.P. Wani, N.T. Yaduraju, S. Nedumaran, A. Rao, S.D. Mazumdar, A. Ashok Kumar, P. Bhatnagar-Mathur, S.M. Tripathi, S.M. Karuppanchetty, Second Green Revolution: Growth Engine for Transformation. The Associated Chambers of Commerce and Industry of India, (2011).

[23] F. O'Donncha, J. Grant, Precision aquaculture, IEEE Internet Things Mag. 2 (2019) 26–30.

[24] Y. Tian, Z. Yang, X. Yu, Z. Jia, M. Rosso, S. Dedman, J. Zhu, Y. Xia, G. Zhang, J. Yang, Can we quantify the aquatic environmental plastic load from aquaculture?, Water Res. 219 (2022) 118551.

[25] G.J. Meaden, J. Aguilar-Manjarrez, Advances in geographic information systems and remote sensing for fisheries and aquaculture, FAO Fish. Aquac. Tech. Pap. (2013) I.

[26] R.A. Bórquez López, L.R. Martinez Cordova, J.C. Gil Nuñez, J.R. Gonzalez Galaviz, J.C. Ibarra Gamez, R. Casillas Hernandez, Implementation and evaluation of open-source hardware to monitor water quality in precision aquaculture, Sensors 20 (2020) 6112.

[27] J.D. Paduan, L. Washburn, High-frequency radar observations of ocean surface currents, Annu. Rev. Mar. Sci. 5 (2013) 115–136.

[28] L. Parra, G. Lloret, J. Lloret, M. Rodilla, Physical sensors for precision aquaculture: A Review, IEEE Sens. J. 18 (2018) 3915–3923.

[29] X. Yang, S. Zhang, J. Liu, Q. Gao, S. Dong, C. Zhou, Deep learning for smart fish farming: applications, opportunities and challenges, Rev. Aquac. 13 (2021) 66–90.

[30] E. Aldana Jague, High resolution three dimensional spatial patterns of soil organic carbon storage in eroding agricultural landscapes, PhDdiss Univ. Cathol. Louvain (2017) 173.

[31] M. Pérez Ruiz, S. Upadhyaya, GNSS in precision agricultural operations, Intech, 2012.

[32] F. Mazzetto, R. Gallo, M. Riedl, P. Sacco, Proposal of an ontological approach to design and analyse farm information systems to support Precision Agriculture techniques, in: IOP Conf. Ser. Earth Environ. Sci., IOP Publishing, 2019: p. 012008.

[33] A. Castrignanò, G. Buttafuoco, R. Quarto, D. Parisi, R.V. Rossel, F. Terribile, G. Langella, A. Venezia, A geostatistical sensor data fusion approach for delineating homogeneous management zones in Precision Agriculture, Catena 167 (2018) 293–304.

[34] P.P. Pawase, S.M. Nalawade, G.B. Bhanage, A.A. Walunj, P.B. Kadam, A.G. Durgude, M.G. Patil, Variable rate fertilizer application technology for nutrient management: A review, Int. J. Agric. Biol. Eng. 16 (2023) 11–19.

[35] A. Dobermann, S. Blackmore, S.E. Cook, V.I. Adamchuk, Precision farming: challenges and future directions, in: Proc. 4th Int. Crop Sci. Congr., Brisbane Australia, 2004.

[36] Y. Zhong, X. Wang, S. Wang, L. Zhang, Advances in spaceborne hyperspectral remote sensing in China, Geo-Spat. Inf. Sci. 24 (2021) 95–120.

[37] R.P. Beluhova-Uzunova, D.M. Dunchev, Precision farming–concepts and perspectives, Zagadnienia Ekon. RolnejProblems Agric. Econ. (2019).

[38] P. Singh, A Survey on Water Quality Monitoring and Controlling Using Different Modality of Machine Learning Model, in: Mach. Learn. Healthc. Secur., CRC Press, 2024: pp. 25–51.

[39] G. Krantzberg, A. Tanik, J.S.A. do Carmo, A. Indarto, A. Ekdal, M. Gurel, E. pehlivanoglu Mantas, Z. Wang, G. Wang, C. Zhao, Advances in water quality control, Scientific Research Publishing, Inc. USA, 2010.

[40] T. Kompas, T.N. Che, R. Quentin Grafton*, Technical efficiency effects of input controls: evidence from Australia’s banana prawn fishery, Appl. Econ. 36 (2004) 1631–1641.

[41] E.N. Taylor, L.M. Diele- Viegas, E.J. Gangloff, J.M. Hall, B. Halpern, M.D. Massey, D. Rödder, N. Rollinson, S. Spears, B. Sun, The thermal ecology and physiology of reptiles and amphibians: A user’s guide, J. Exp. Zool. Part Ecol. Integr. Physiol. 335 (2021) 13–44.

[42] H. Pörtner, Climate change and temperature-dependent biogeography: oxygen limitation of thermal tolerance in animals, Naturwissenschaften 88 (2001) 137–146.
[43] O.J. Eriegha, P.A. Ekokotu, Factors affecting feed intake in cultured fish species: A review, Anim. Res. Int. 14 (2017) 2697-2709-2697–2709.
[44] O.-I. Lekang, Feeding equipment and feed control systems, in: Feed Feed. Pract. Aquac., Elsevier, 2022: pp. 399–425.
[45] C. Zhou, D. Xu, K. Lin, C. Sun, X. Yang, Intelligent feeding control methods in aquaculture with an emphasis on fish: a review, Rev. Aquac. 10 (2018) 975–993.
[46] M.H. Md Jamal, Modelling and control of the fish feeder system, Universiti Tun Hussein Onn Malaysia, 2013.
[47] M.M. Alammar, A. Al-Ataby, An Intelligent Approach of the Fish Feeding System, Dep. Electr. Eng. Electron. Univ. Liverp. UK (2018).
[48] A. Chatterjee, R. Lal, L. Wielopolski, M.Z. Martin, M.H. Ebinger, Evaluation of different soil carbon determination methods, Crit. Rev. Plant Sci. 28 (2009) 164–178.
[49] B. Kuang, H.S. Mahmood, M.Z. Quraishi, W.B. Hoogmoed, A.M. Mouazen, E.J. van Henten, Sensing soil properties in the laboratory, in situ, and on-line: a review, Adv. Agron. 114 (2012) 155–223.
[50] R.V. Rossel, V.I. Adamchuk, K.A. Sudduth, N.J. McKenzie, C. Lobsey, Proximal soil sensing: An effective approach for soil measurements in space and time, Adv. Agron. 113 (2011) 243–291.
[51] Y. Fan, X. Wang, T. Funk, I. Rashid, B. Herman, N. Bompoti, M.S. Mahmud, M. Chrysochoou, M. Yang, T.M. Vadas, A critical review for real-time continuous soil monitoring: Advantages, challenges, and perspectives, Environ. Sci. Technol. 56 (2022) 13546–13564.
[52] E.S. Mohamed, A.M. Saleh, A.B. Belal, A. Gad, Application of near-infrared reflectance for quantitative assessment of soil properties, Egypt. J. Remote Sens. Space Sci. 21 (2018) 1–14.
[53] M. Ottinger, K. Clauss, C. Kuenzer, Aquaculture: Relevance, distribution, impacts and spatial assessments–A review, Ocean Coast. Manag. 119 (2016) 244–266.
[54] D.A. Kasampalis, T.K. Alexandridis, C. Deva, A. Challinor, D. Moshou, G. Zalidis, Contribution of remote sensing on crop models: a review, J. Imaging 4 (2018) 52.
[55] P. Defourny, S. Bontemps, N. Bellemans, C. Cara, G. Dedieu, E. Guzzonato, O. Hagolle, J. Inglada, L. Nicola, T. Rabaute, Near real-time agriculture monitoring at national scale at parcel resolution: Performance assessment of the Sen2-Agri automated system in various cropping systems around the world, Remote Sens. Environ. 221 (2019) 551–568.
[56] P.S. Roy, M.D. Behera, S.K. Srivastav, Satellite remote sensing: sensors, applications and techniques, Proc. Natl. Acad. Sci. India Sect. Phys. Sci. 87 (2017) 465–472.
[57] T. Angelopoulou, N. Tziolas, A. Balafoutis, G. Zalidis, D. Bochtis, Remote sensing techniques for soil organic carbon estimation: A review, Remote Sens. 11 (2019) 676.
[58] J.M. Bioucas-Dias, A. Plaza, G. Camps-Valls, P. Scheunders, N. Nasrabadi, J. Chanussot, Hyperspectral remote sensing data analysis and future challenges, IEEE Geosci. Remote Sens. Mag. 1 (2013) 6–36.
[59] J.L. Hatfield, A.A. Gitelson, J.S. Schepers, C.L. Walthall, Application of spectral remote sensing for agronomic decisions, Agron. J. 100 (2008) S-117-S-131.
[60] R.P. Sishodia, R.L. Ray, S.K. Singh, Applications of remote sensing in precision agriculture: A review, Remote Sens. 12 (2020) 3136.
[61] P. Ruby, B. Ahilan, C. Antony, S. Selvaraj, RECENT TRENDS IN AQUACULTURE TECHNOLOGIES, J. Aquac. Trop. 37 (2022) 27–34.

[62] F. Murray, J. Bostock, D. Fletcher, Review of recirculation aquaculture system technologies and their commercial application, (2014).

[63] I. Bogárdi, R.D. Kuzelka, W.G. Ennenga, Nitrate contamination: exposure, consequence, and control, Springer Science & Business Media, 2013.

[64] J. Bregnballe, A guide to recirculation aquaculture: an introduction to the new environmentally friendly and highly productive closed fish farming systems, Food & Agriculture Org., 2022.

[65] Z. Svobodova, J. Machova, G. Poleszczuk, J. Hůda, J. Hamáčková, H. Kroupova, Nitrite poisoning of fish in aquaculture facilities with water-recirculating systems, Acta Vet. Brno 74 (2005) 129–137.

[66] M. Tavares-Dias, M.L. Martins, An overall estimation of losses caused by diseases in the Brazilian fish farms, J. Parasit. Dis. 41 (2017) 913–918.

[67] E.W. Low, H.A. Chase, Reducing production of excess biomass during wastewater treatment, Water Res. 33 (1999) 1119–1132.

[68] O. Alfred, A. Shaahu, D.A. Orban, M. Egwenomhe, An overview on understanding the basic concept of fish diseases in aquaculture, IRE J. 4 (2020) 83–91.

[69] J.R. Winton, Fish health management, Fish Hatch. Manag. 2nd Ed. Am. Fish. Soc. Bethesda Md. (2001) 559–640.

[70] G. Louverdis, M.I. Vardavoulia, I. Andreadis, P. Tsalides, A new approach to morphological color image processing, Pattern Recognit. 35 (2002) 1733–1741.

[71] G. Li, L. Yu, S. Fei, A deep-learning real-time visual SLAM system based on multi-task feature extraction network and self-supervised feature points, Measurement 168 (2021) 108403.

[72] M.J. Mia, R.B. Mahmud, M.S. Sadad, H. Al Asad, R. Hossain, An in-depth automated approach for fish disease recognition, J. King Saud Univ.-Comput. Inf. Sci. 34 (2022) 7174–7183.

[73] S. Gupta, K. Saluja, A. Goyal, A. Vajpayee, V. Tiwari, Comparing the performance of machine learning algorithms using estimated accuracy, Meas. Sens. 24 (2022) 100432.

[74] D. Li, X. Li, Q. Wang, Y. Hao, Advanced Techniques for the Intelligent Diagnosis of Fish Diseases: A Review, Animals 12 (2022) 2938.

[75] M.S. Ahmed, T.T. Aurpa, M.A.K. Azad, Fish disease detection using image based machine learning technique in aquaculture, J. King Saud Univ.-Comput. Inf. Sci. 34 (2022) 5170–5182.