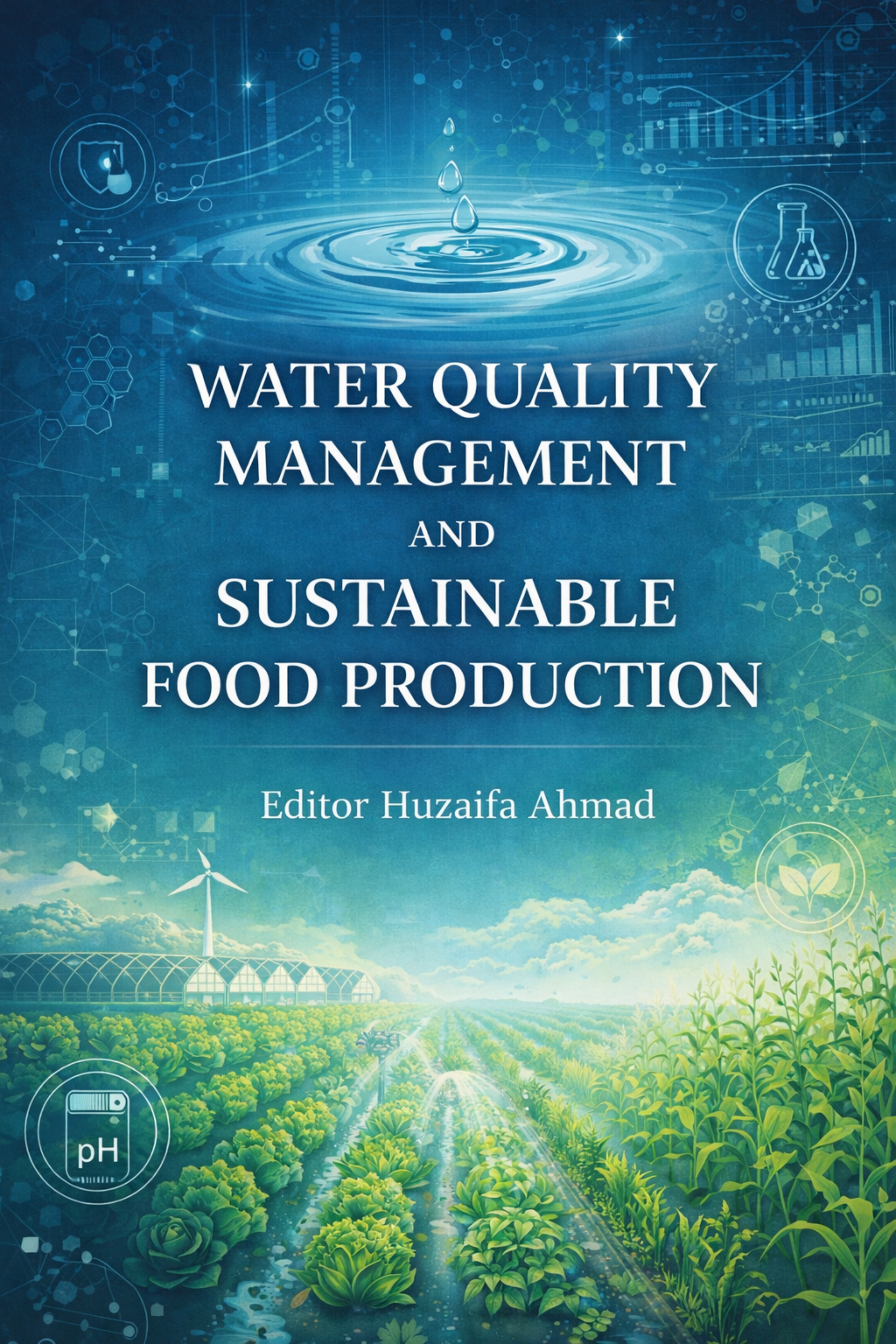
WATER QUALITY MANAGEMENT AND SUSTAINABLE FOOD PRODUCTION

Editor Huzaifa Ahmad



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PREFACE

This book brings together interdisciplinary perspectives that address sustainability in food production, agriculture, and environmental education. The chapters highlight how environmental engineering principles, agricultural efficiency, and ethical frameworks can collectively contribute to responsible resource management and long-term ecological balance.

The chapter Aquaculture Water Quality Management: Environmental Engineering Approaches for Sustainable Fish Production examines engineering strategies for maintaining optimal water conditions in aquaculture systems, emphasizing environmental protection alongside productivity. This is complemented by The Efficiency of Nitrogen Use in Cereal Agriculture in Algeria, which analyses nutrient management practices aimed at improving crop yields while reducing environmental impacts in arid and semi-arid agricultural contexts.

The final chapter, Islamic Eco-Theology in Environmental Engineering Education in Indonesia, introduces a value-based and educational dimension by exploring how ethical and theological perspectives can be integrated into engineering curricula. Together, these chapters offer a holistic view of sustainability that combines technical solutions, agricultural innovation, and cultural-ethical considerations, making the book a valuable resource for researchers, educators, and practitioners alike.

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CHAPTER 1
AQUACULTURE WATER QUALITY MANAGEMENT: ENVIRONMENTAL ENGINEERING APPROACHES FOR SUSTAINABLE FISH PRODUCTION

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INTRODUCTION

Aquaculture plays vital role as a crucial sector in global food security, by providing world's animal protein supply and supporting livelihoods, basically in poor countries. The rapid expansion of aquaculture, while increasing production, has presented significant challenges in water quality management. Inferior water quality may adversely affect fish health, growth, feed conversion efficiency, and overall productivity, while also intensifying environmental degradation via nutrient enrichment, toxic algal blooms, and the spread of diseases. This chapter explore the integration of environmentally friendly cut out basis to enhance sustainable aquaculture via effective water quality management. The main topics discussed include physical, chemical, and biological water quality parameters, monitoring and modeling techniques, pollution sources, recirculating aquaculture systems (RAS), biofloc technology, integrated multi-trophic aquaculture (IMTA), wastewater treatment, and sustainable management strategies. A holistic approach is emphasized, including technical solutions, ecological perspectives, and socio-economic and policy considerations to achieve resilient and sustainable production systems. Furthermore, emerging technologies such as IoT-based monitoring, AI-assisted predictive management, precision aquaculture, and circular economy techniques are analyzed as potential methods for improving water quality and overall system efficiency. By integrating scientific, technological, and administrative advancements, aquaculture can maintain high production levels, alleviate environmental issues, and provide a sustainable source of high-quality protein to meet rising global food demands. This chapter demonstrated a widespread framework for students, authorities, practitioners, and policymakers to perform environmentally friendly and economically benefited aquaculture systems.

1. GLOBAL TRENDS AND SOCIO-ECONOMIC SIGNIFICANCE

Over the course of the last several decades, there has been a significant increase in the degree to which the demand for aquaculture products has increased all over the globe (FAO, 2022).

The expansion of this business has been ascribed to a number of different factors, all of which are interconnected with one another. The Food and Agriculture Organization of the United Nations (FAO, 2024) and Troell et al., (2014) cite a number of factors that contribute to this phenomenon. These factors include rapid population growth, urbanization, the decline of wild fish populations, and an increasing demand for high-quality dietary protein (Naylor et al., 2021). It has been reported by the Food and Agriculture Organization (FAO, 2022) that aquaculture is now responsible for more than fifty percent of the total fish that is eaten all over the globe via eating.

As a consequence of this, it is one of the sectors of the food production business that is expanding at the rate that is the most rapid throughout the whole world. This growing trend is especially noticeable in Asia, which accounts for more than ninety percent of the total aquaculture output throughout the whole world. Specifically, the region of Asia is where this increase is most visible. Several countries, including China, India, Bangladesh, Vietnam, and Thailand, have greatly expanded their aquaculture businesses in order to satisfy the requirements of both the local production of protein and the requirements of the global market, as stated by (Belton and Thilsted, 2014).

By simultaneously satisfying both sets of requirements, they hope to achieve their aim. Aquaculture, which is an essential part of Bangladesh's agricultural sector, is also a significant contributor to the expansion of rural areas in Bangladesh, which in turn contributes to the nation's overall food security.

According to (Rahman et al., 2020), the industry makes a significant contribution to the economy by creating revenue for communities located both along the shore and in the interior of the nation. Additionally, it offers job opportunities to millions of smallholder farmers, which is a significant contribution to the economy. People living in low-income households are more likely to consume fish since it is an important source of animal protein. Additionally, high-value species of fish, such as tilapia, pangasius, and shrimp, add to the profits that are produced from exports. These fish are exported.

1.1 Environmental Challenges and Water Quality Management

The fast development of aquaculture in Bangladesh and other South Asian nations has resulted in substantial environmental and operational problems (Belton et al., 2018; Ahmed et al., 2019). This is despite the fact that aquaculture is important from an economic and nutritional standpoint. Even though aquaculture is a substantial business, this is the situation that has arisen. When it comes to aquaculture, one of the most significant issues that must be overcome is the regulation of water quality. This is the case because the quality of the water has a direct impact on the health, development, and survival of fish. This is the reason why this is the case. Poor water quality can lead to hypoxia, the accumulation of toxic nitrogenous compounds (ammonia and nitrite), pH fluctuations, harmful algal blooms, and the proliferation of pathogens, which can ultimately result in the outbreak of diseases, a reduction in the efficiency with which feed is converted, and significant economic losses (Boyd and McNevin, 2015). Untreated effluents from aquaculture operations contribute to nutrient loading and eutrophication in the water bodies that are located in the surrounding area, which in turn has an impact on the functioning of ecosystems and the biodiversity that they support (Troell et al., 2014; Boyd, 2019).. The management of water quality in a sustainable manner is vital for both the efficiency of production and the preservation of the environment. This is because it is anticipated that these difficulties will become more severe as the production of goods on a global scale increases (Verdegem, 2013a)**.**

1.2 Strategic Engineering and Technological Innovations

It is possible that a more strategic way to tackling these difficulties would be to make use of environmental engineering techniques. These approaches entail the application of scientific ideas and technical discoveries to the management of aquaculture water. The use of methods such as mechanical filtration, sedimentation, biofiltration, increased aeration, nutrient recycling, and effluent treatment are some of the strategies that farmers may employ in order to keep the water quality within the optimal limits for certain species (Martins et al., 2010). These are just some of the strategies that farmers may employ.

Furthermore, the integration of recirculating aquaculture systems (RAS), biofloc technology (BFT), and integrated multi-trophic aquaculture (IMTA) is an example of how environmental engineering can reduce the amount of water used, recycle nutrients, and lessen the amount of discharge into the environment, all while simultaneously improving fish growth and health (Chopin et al., 2012; Timmons et al., 2018).This is an example of how environmental engineering can be used to improve fish growth and health. This serves as an illustration of how environmental engineering may be used to enhance the general health and development of fish. In recent years, there have been significant developments in monitoring and modeling, which have made it possible to make more improvements in the management of water quality.

The use of real-time sensors, platforms that are founded on the Internet of Things (IoT), and predictive water quality models are all viable options for the purpose of carrying out proactive treatments. According to the Food and Agriculture Organization of the United Nations (FAO, 2022) and Boyd and McNevin, (2015), these treatments have the potential to enhance feed efficiency while concurrently decreasing stress levels and mortality rates in cultured species. These technologies, when combined with ecological knowledge, such as the dynamics of microbial communities, the interactions between plankton, and the cycling of nutrients, support adaptive and resilient aquaculture systems that are able to withstand environmental variability, climate fluctuations, and water scarcity (Ghose, 2014; Ahmed et al., 2019).

These systems are able to support the cultivation of aquatic organisms that are able to survive in their natural environments. The development of aquatic species that are able to thrive in their natural surroundings is something that can be supported by these systems to a certain extent. It is also essential to keep in mind that sustainable aquaculture is not only a technological task; rather, it necessitates the incorporation of social, economic, and regulatory concerns. According to Belton et al., (2018) and the Food and Agriculture Organization of the United Nations (FAO, 2022), regulatory frameworks, training programs, and community participation are essential components that must be present in order to guarantee the implementation of practices that are environmentally responsible and the fulfillment of effluent and water quality criteria.

These components are necessary in order to guarantee the implementation of practices that are environmentally responsible. Agricultural aquaculture systems are able to provide output that is robust, high-yielding, and ecologically sustainable. This production is able to meet the nutritional needs of populations on a global scale as well as those in the local community. For the purpose of accomplishing this aim, the way by which it may be accomplished is by integrating technical innovation with ecological and socio-economic factors. It is necessary to have a well-coordinated plan that takes into account environmental engineering, ecological knowledge, technological innovation, and the incorporation of socio-economic variables in order to guarantee the sustainability of aquaculture on a worldwide scale. In a nutshell, the sustainability of aquaculture is dependent on the effective control of water quality by the aquaculture industry. In a world that is undergoing fast transformation, it is not out of the question for aquaculture to continue to be a dependable supply of high-quality protein, to preserve rural livelihoods, and to make a contribution to environmental stewardship (Boyd and McNevin, 2015; Timmons et al., 2018; FAO, 2022).

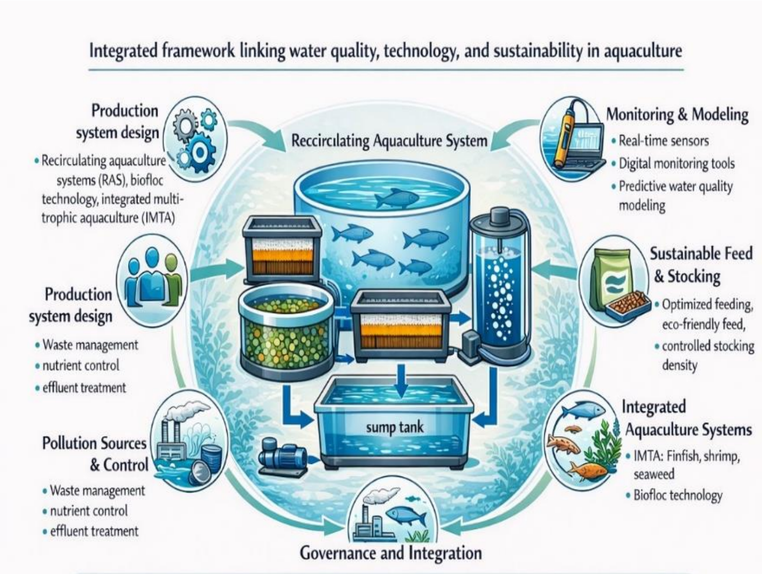

Figure 1. Integrated framework linking water quality, technology, and sustainability in aquaculture

2. WATER QUALITY PARAMETERS IN AQUACULTURE

It is the quality of the water that plays a key role in defining the overall efficacy of aquaculture, as well as the health of the fish, their development, and their overall development. The intricate interplay of physical, chemical, and biological components has the consequence of exerting a direct influence on the physiological processes of the species that have been grown. These components have a number of different ways in which they interact with one another. As a result, it is of the highest significance to make certain that these parameters are correctly controlled and monitored in order to keep the circumstances at their optimal state, decrease the danger of disease outbreaks, and guarantee that production is maintained (Boyd & Tucker, 2012; FAO, 2022).

2.1 Physical Parameters

Temperature

Temperature directly affects fish metabolism, including how they eat, digest food, and grow. Each fish species has a specific temperature range that is ideal for it; if the temperature strays too far from this range, it can cause stress, weaken the immune system, and make it harder to convert feed into energy, as (El-Sayed, 2006; Abdel-Tawwab and Wafeek, 2014; Boyd and McNevin, 2015). Sudden temperature fluctuations, often seen in shallow ponds or open tanks, causes thermal shock, which enhance fish more susceptible to disease. Also, temperature affects how much oxygen is dissolved in the water and how microbes behave, which then impacts water quality. Dissolved oxygen (DO) is crucial for fishes' physiological activities.

Dissolved Oxygen (DO)

dissolved oxygen (DO) concentrations less than 3 mg/L responsible for Hypoxia, stunted growth, lower feed conversion and can also induced mass mortality (Timmons et al., 2018). DO levels are subject to influence from various factors, including stocking density, water temperature, photosynthetic activity, and the breakdown of organic materials. Therefore, the maintenance of DO within optimal ranges necessitates both aeration and sufficient water circulation (Abdel-Tawwab et al., 2015; Cheng et al., 2022).

Turbidity and Transparency

Elevated turbidity levels obstruct light penetration, which in turn limits the photosynthetic activity of aquatic plants and phytoplankton, disrupting oxygen production and nutrient recycling, basically within semi-intensive and extensive aquaculture systems (FAO, 2022).Therefore, turbidity negatively affects visual feeders such as tilapia and carp, by reducing their feeding efficiency and disturbing their growth. The resuspension of sediment, frequently accumulated by storms or excessive feeding, exacerbates turbidity issues (Uys and Hecht, 1985).

Suspended Solids

Suspended solids, which include particulate organic matter, contribute to sedimentation processes and influence microbial dynamics within the aquatic environment. An excess of these solids can result in the clogging of fish gills, the promotion of anaerobic zones within sediments, and an acceleration of decomposition, which releases ammonia and hydrogen sulfide (Ebeling et al., 2006;Bilotta and Brazier, 2008) Therefore, consistent sediment management and filtration practices are crucial for maintaining optimal water quality.

2.2 Chemical Parameters

pH

The pH level of water affects metabolic processes, enzyme activity, and the overall health of fish. The predominant freshwater species thrive within a pH range of 6.5–9; however, values beyond this range may induce stress or impede growth (Boyd & Tucker, 2012). The pH is influenced by photosynthesis, respiration, organic decomposition, and the buffering capability of the water (Parra et al., 2018).

Nitrogenous Compounds: Ammonia, Nitrite, and Nitrate

Excessive feeding and accumulation of waste lead to elevated concentrations of ammonia (NH_3/NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). Unionized ammonia is very toxic at minimal doses, causing gill damage, osmoregulatory disruption, and mortality (Hargreaves, 2013).

Nitrite impairs oxygen transport by forming methemoglobin, but increased nitrate concentrations may indicate sustained nutrient enrichment and potential eutrophication. Effective water exchange, biofiltration, and microbial control are crucial for the management of nitrogenous compounds (Camargo et al., 2005; Kroupova et al., 2005).

Salinity

Salinity is particularly important in brackish and marine ecosystems. Fluctuations resulting from tidal incursion, evaporation, or freshwater intake may exert stress on euryhaline species, affecting osmoregulation and growth (Boyd, 2019). Stable salinity levels are crucial for the development of larvae and the survival of post-larvae in shrimp farming (Bœuf and Payan, 2001).

Hardness and Alkalinity

Water hardness, defined as the accumulation of calcium and magnesium, mixed with alkalinity, influences buffering capacity, pH stability, and gill functioning. Low alkalinity reduces tolerance to pH fluctuations caused by photosynthesis, respiration, and microbial decomposition (Timmons et al., 2018). Effective alkalinity management ensures a stable environment that fosters fish growth and improves disease resistance.

Heavy Metals and Contaminants

Heavy metals (lead, cadmium, arsenic) and chemical contaminants derive from feed, water, and surrounding agricultural runoff (Malik et al., 2010). The accumulation of these compounds in water and fish tissues poses risks to human health and may disrupt aquatic microbial communities (Kumar et al., 2022). Regular supervision and use of approved feed and water sources are essential for safe aquaculture production.

2.3 Biological Parameters

Microbial Load

The health of fish is significantly influenced by the presence of bacterial, viral, and fungal populations.

The proliferation of pathogens, which can precipitate disease outbreaks and economic setbacks, is often exacerbated by suboptimal water conditions, especially those characterized by elevated organic loads (FAO, 2022). A balanced microbial community, which can be cultivated through biofloc systems, recirculating aquaculture systems (RAS), or probiotic application, can improve both water quality and the immune responses of fish (De Schryver et al., 2008; Defoirdt et al., 2011).

Plankton Density

Furthermore, phytoplankton and zooplankton are crucial for nutrient cycling, oxygen production, and the provision of natural food sources for fish. Conversely, excessive plankton growth can instigate algal blooms, which subsequently diminish dissolved oxygen levels at night and contribute to eutrophication (DiTullio et al., 2003). Balanced plankton populations are sustained by appropriate fertilization, water exchange, and stocking practices.

The water quality within aquaculture systems is fundamentally determined by a complex interplay of physical, chemical, and biological factors, each of which directly impacts fish metabolism, growth, and overall survival. A comprehensive understanding of these parameters, coupled with consistent monitoring and management strategies, is crucial for achieving sustainable and high-yield aquaculture operations. According to Boyd & Tucker, (2012) and the FAO, (2022), profitable and ecologically sound fish farming systems may be achieved via the use of interventions such as temperature regulation, aeration methods, nutrient management protocols, sediment handling processes, and microbial control measures (Heisler et al., 2008).

Table 1. Summary Of Critical Water Quality Parameters and Their Recommended Ranges for Freshwater Aquaculture

Parameter	**Optimal Range**	**Effect of Deviation**	**Reference**
Temperature (°C)	24–30	Stress, reduced growth, mortality	(Boyd and McNevin, 2015)
Dissolved Oxygen (mg/L)	>5	Hypoxia, death, low feed efficiency	(Timmons et al., 2018)

pH	6.5–9	Metabolic disorders, mortality	Boyd & Tucker, (2012)
Ammonia (mg/L)	<0.02	Gill damage, toxicity	(Hargreaves, 2013)
Nitrite (mg/L)	<0.1	Methemoglobinemia, stress	(Boyd, 2019)
Nitrate (mg/L)	<50	Chronic toxicity, growth inhibition	(Kumar et al., 2022)

3. SOURCES OF WATER POLLUTION IN AQUACULTURE

Aquaculture systems, which are crucial for meeting the world's growing need for fish, both contribute to and are affected by water pollution. Poor management in aquaculture, especially as it becomes more intensive, can lead to the buildup of organic waste, nutrients, chemicals, and sediments (Piedrahita, 2003). This buildup then worsens water quality and threatens the health of aquatic ecosystems. Therefore, understanding where water pollution comes from and how it behaves is essential for managing aquaculture sustainably (Boyd & Tucker, 2012; FAO, 2022).

Organic Waste

Organic waste produced from uneaten fish feed and fish waste in aquaculture ponds and tanks. In intensive farming, 30-40% of the feed remain uneaten. This leftover feed then breaks down in the water or in the sediment (Boyd & Tucker, 2012).The breakdown of this organic material by microbes uses up dissolved oxygen, releases ammonia and nitrite, and can also produce harmful gases like hydrogen sulfide (Avnimelech and Ritvo, 2003). Elevated concentrations of these substances can induce stress in cultured organisms, impede their growth, and heighten their vulnerability to disease. Furthermore, the accumulation of organic matter on pond bottoms can engender anaerobic conditions, thereby intensifying the decline in water quality. To alleviate these consequences, consistent monitoring, sediment removal, and the implementation of controlled feeding protocols are indispensable (Crab et al., 2012).

Nutrient Loading

The practice of aquaculture frequently necessitates the use of antibiotics, pesticides, and other chemical agents to mitigate disease and manage parasitic infestations. Nevertheless, the overapplication or improper utilization of these substances can result in their accumulation within pond water, sediment, and fish tissues (Sapkota et al., 2008). Contaminated water sources, fertilizers, or feed components are the main suppliers of heavy metals, including cadmium, lead, and arsenic in aquaculture ponds (Kumar et al., 2022). Human health hazards via bioaccumulation within the tissues of consumable fish through Long-term accumulation of pollutants and it can also destroy normal aquatic microbial communities, by disturbing nutrient cycling and water quality. To mitigate chemical pollution, the implementation of eco-friendly chemicals, routine water quality assessments, and integrated disease management strategies is essential (Varol and Sünbül, 2020).

Chemical Contaminants

Accumulation of inorganic nutrient such as nitrogen (N) and phosphorus (P) compounds, may results from excessive feeding, over-fertilization, or the inappropriate application of high-protein feeds, causes algal blooms, which initially enhance primary productivity of ponds, frequently induced eutrophication and enhance oxygen depletion, and the production of harmful algal toxins (Hargreaves, 2013). In intensive aquaculture systems, such as those cultivating carp or tilapia, the application of high-protein feeds, coupled with insufficient water exchange, can precipitate frequent oxygen depletion events. These events, which occur during the nocturnal respiration of dense phytoplankton populations, compromise fish health and, furthermore, affect the quality of adjacent aquatic environments upon the release of effluents (Smith and Schindler, 2009; Verdegem, 2013).

Sedimentation and Erosion

Runoff originating from adjacent agricultural fields, construction sites, or deforested regions can introduce substantial quantities of sediments, organic matter, and agrochemicals into aquaculture ponds and cages (FAO, 2022).

Sedimentation diminishes water transparency, impedes light penetration, disrupts the photosynthetic processes of aquatic flora, and can obstruct fish gills. Consequently, it may, over an extended period, modify pond morphology, diminish habitat suitability, and ultimately reduce overall productivity. To lessen the effects of sedimentation, it is recommended to choose sites carefully, use vegetative buffer zones, and implement erosion control methods (Bilotta and Brazier, 2008; Verdegem, 2013b)

Combined Effects and Environmental Implications

These sources of pollution often interact in ways that make their effects stronger. For example, when nutrients increase and organic waste builds up, this can worsen low oxygen levels and create conditions that help harmful microbes grow (Burford et al., 2003). If these problems aren't managed well, they can lead to large fish kills, economic losses, and environmental damage downstream. Therefore, sustainable aquaculture requires water quality management practices that address organic matter, nutrient control, chemical use, and sedimentation at the same time (Boyd & Tucker, 2012; Hargreaves, 2013; FAO, 2022).

4. ENVIRONMENTAL ENGINEERING APPROACHES TO WATER QUALITY MANAGEMENT

Maintaining the highest level of water quality at all times is crucial for ecologically conscious aquaculture since water parameters have a direct impact on fish health, growth, and productivity. Environmental engineering offers a wide range of technological solutions that may be used to reduce pollution, control water quality, and increase the efficiency of management systems. By combining physical, chemical, and biological management strategies, aquaculture operations may provide increased sustainability, reduced environmental impact, and improved financial returns (Boyd and McNevin, 2015; Timmons et al., 2018). This is because aquaculture companies have the opportunity to develop more ecologically friendly practices.

Water Exchange and Circulation

Regular water swapping is one of the easiest and most effective methods to keep a pond or tank's water quality stable. This is because it enables more frequent water swapping. Nitrogenous compounds (ammonia, nitrite, and nitrate) are diluted, metabolic waste is eliminated, and dissolved oxygen (DO) is restored by water exchange. According to Boyd and McNevin, (2015) continual circulation in intensive systems-which may be accomplished using pumps or paddlewheels-prevents water from getting stagnant, ensures constant temperature and oxygen distribution, and promotes improved microbial populations. In deeper ponds, circulation systems also help avoid stratification, which may lead to hypoxic zones (Cripps and Bergheim, 2000). This is particularly true during the hot summer months or at night when the rate of respiration is higher than the rate of oxygen generation. Automated water flow controls may be a feature of increasingly sophisticated circulation systems due to their advanced nature. These controls would alter exchange rates based on the characteristics of water quality that they evaluate in real time.

Aeration and Oxygenation

In high-density aquaculture systems, aeration is essential because dissolved oxygen (DO) levels may drop as rapidly as is practical. The use of mechanical aerators, such as diffused aeration systems, airlifts, and paddlewheels, is said to enhance water circulation and boost oxygen transfer (Timmons et al., 2018). Microbubble aeration is one of the more recent discoveries that has significantly improved the effectiveness of oxygen transport due to technical developments. By creating smaller bubbles with a larger surface area, this is achieved. These bubbles are more effective in dissolving oxygen. Aeration not only helps fish grow and digest, but it also inhibits harmful gasses like hydrogen sulfide from accumulating in the sediments of the pond, helps oxidize ammonia to less harmful nitrate, and regulates pH. The aeration process alone is the cause of all these advantages (Ebina et al., 2013).

Filtration and Sediment Removal

Particulate debris and suspended particles may obstruct fish gills and prevent photosynthesis in addition to decreasing water clarity. Additionally, they reduce the purity of the water. To keep these items out of recirculating or flow-through systems, filtration devices including settling basins, screen filters, and sand filters are used. harmful systems remove harmful contaminants. Sediment traps and regular pond sludge removal are two effective strategies that may be employed in pond culture to prevent nutrient buildup, reduce the development of organic load, and maintain the stability of the benthic ecology that occurs in the pond. Among other things, these treatments limit the growth of anaerobic bacteria and lessen the production of potentially dangerous compounds in sediments (Cripps and Bergheim, 2000).

Recirculating Aquaculture Systems (RAS)

As part of its abbreviation, "RAS" stands for "recirculating aquaculture systems." A kind of fish farming known as "recirculating aquaculture systems" (RAS) is characterized by a high level of control and labor intensity. Water is continuously purified and reused using this technique. Among the crucial components of RAS are protein skimmers, mechanical filters, UV sterilizers, and biofilters. Other components include protein skimmers. According to Martins et al., (2010) each of these components helps to eliminate solids, organic substances, nitrogenous wastes, and pathogens. Temperature, dissolved oxygen, pH, and salinity are just a few of the water quality factors that can now be carefully controlled because to the RAS. As a consequence, the system generates less effluent, which lessens the need for freshwater. RAS has several benefits, including year-round production, less disease risk, and efficient use of land and water resources. To achieve this, however, a substantial amount of financial resources and a high level of technical expertise are required (Dalsgaard et al., 201; Alam et al., 2023)

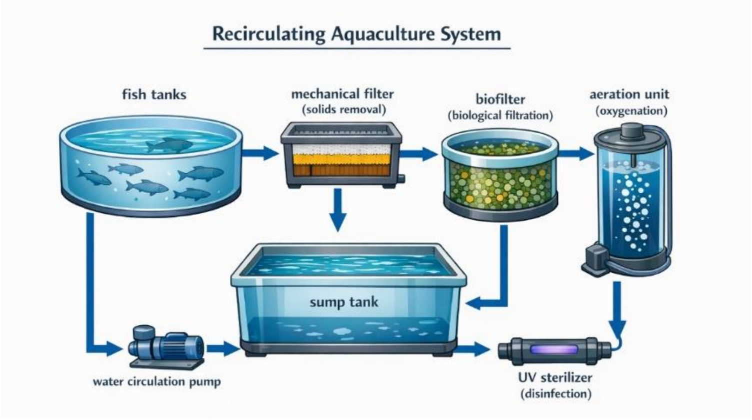

Figure 2. Schematic of a Recirculating Aquaculture System.
(Diagram showing tanks, mechanical filters, biofilters, aeration units, and water circulation pumps.)

Biofloc Technology

Biofloc technology (BFT), a recent and environmentally friendly method, uses bacterial colonies to improve water quality and increase nutrient levels. In BFT systems, adding carbon sources like sugars helps convert nitrogenous waste into microbial biomass. This process then encourages the growth of heterotrophic bacteria (Avnimelech, 2009; Crab et al., 2012). The resulting microbial waste, called biofloc, then becomes an additional food source for the species being cultured.

The benefits of biofloc technology include:

- **Ammonia control:** Microorganisms break down harmful nitrogenous compounds in the water, which reduces ammonia levels. Biofloc technology reduce feed cost and provides supplementary nutrition for shrimp and fish
- **Improved growth and immunity:** Bioflocs bolster disease resistance and foster gut health.
- **Sustainable nitrogen recycling:** This approach lessens the environmental consequences of wastewater and sewage release.

In tropical regions, biofloc-based aquaculture has proven effective in shrimp and tilapia production, leading to diminished water usage and operational costs while sustaining vigorous growth rates (AftabUddin et al., 2020).

Figure 3. Biofloc Technology

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) seeks to create a self-sustaining, healthy ecosystem through the co-cultivation of organisms at different trophic levels. Secondary species, encompassing various fish and plant types, consume the waste produced by primary species, such as finfish, within Integrated Multi-Trophic Aquaculture (IMTA) systems (Chopin et al., 2012b). This approach enhances overall system productivity, facilitates nutrient recycling, and diminishes the discharge of nitrogen and phosphorus. Besides, IMTA contributes to economic diversification by production and marketing of multiple species in a single culture system. Successful IMTA cultivation requires selection of specific species, optimum stocking densities, and approach to optimize nutrient utilization (Troell et al., 2009).

Wastewater Treatment and Effluent Management

The discharge of aquaculture system effluents, which contain chemicals, fine particulates, and nutrients, into adjacent water bodies poses environmental risks and can trigger eutrophication.

Environmental engineering offers several methods for wastewater treatment, including constructed marshes, sedimentation ponds, and biofilters (Boyd & Tucker, 2012).Particles are settled before water enter in a sedimentation pond, in the same time, constructed marshes remove harmful pollutants through microbial and plant activity. These processes facilitates sustainable aquaculture by ensuring adherence to regulatory frameworks and environmental accountability (Liu and Han, 2004; Vymazal and Vymazal, 2010).

Integration of Approaches for Sustainability

Integrated approaches are preferable for sustainable aquaculture practices, notwithstanding the potential benefits of individual treatments such as aeration, recirculating aquaculture systems (RAS), biofloc technology (BFT), or integrated multi-trophic aquaculture (IMTA) in enhancing water quality. The optimal water quality, reduced environmental impact, and improved economic viability are achieved through the integration of aeration, filtration, nutrient recycling, and wastewater treatment (Verdegem, 2013a). Furthermore, predictive models and monitoring tools facilitate effective management by enabling farmers to implement timely adjustments based on real-time water quality data (Boyd and McNevin, 2015; Timmons et al., 2018).

5. MONITORING AND MODELING OF WATER QUALITY

Monitoring and modeling water quality are essential for effective aquaculture water quality management. Continuous monitoring ensures that water parameters stay within the ideal ranges for fish health and growth. At the same time, modeling allows farmers and managers to predict future problems and take preventive steps.

5.1 Water Quality Monitoring Techniques

Manual Sampling

Manual sampling is a key method in aquaculture for assessing important water quality indicators. These include pH, ammonia, nitrite, nitrate, dissolved oxygen (DO), temperature, and turbidity. Samples are routinely gathered and subsequently analyzed in laboratories, adhering to established protocols.

Manual sampling yields precise and comprehensive data, thereby proving especially effective in identifying chemical contaminants, heavy metals, and microbial concentrations that automated sensors might overlook (Boyd & Tucker, 2012; Rice et al., 2012). Nevertheless, this method is labor-intensive and does not provide real-time responsiveness.

Online Sensors

Automated water quality sensors facilitate continuous, real-time surveillance of essential parameters, including dissolved oxygen, pH, temperature, conductivity, and turbidity. These sensors are strategically positioned within ponds or tanks, functioning in concert with automated control systems-such as aerators, pumps, and alarms-to identify any fluctuations in water quality. As a result, real-time monitoring enables the swift execution of corrective actions, thereby mitigating the risks associated with hypoxia, ammonia toxicity, and other stressors that can negatively impact fish physiological functions (Parra et al., 2018).

Remote Sensing and IoT-based Platforms

The integration of innovative technologies, specifically the Internet of Things (IoT) and remote sensing platforms, facilitates the remote assessment of water quality parameters within extensive aquaculture ventures. IoT-equipped devices gather data from a multitude of sensors, subsequently transmitting this information to cloud-based dashboards. This enables managers to remotely monitor trends, scrutinize patterns, and formulate data-informed decisions. Furthermore, remote sensing offers comprehensive environmental data, including surface temperature readings and algal bloom identification, thereby enhancing predictive accuracy and management effectiveness (Ali, 2021; FAO, 2022; Rastegari et al., 2023).

5.2 Modeling Approaches

Water Quality Models

Mathematical water quality models represent the dynamic behavior of physicochemical factors such as dissolved oxygen, ammonia, nitrite, nitrate, temperature, and salinity in aquaculture systems.

Models are used to assess how feeding practices, stocking density, aeration, and water exchange affect water quality over time. These models help farmers predict potential stressors or oxygen shortages, which allows for the proactive implementation of preventative measures and improves system performance (Iqbal et al., 2018; Mladenović-Ranisavljević and Žerajić, 2018).

Ecosystem Models

Ecosystem-level modeling helps evaluate the long-term sustainability of aquaculture systems by considering both living (like fish, plankton, and microbes) and non-living (like temperature, nutrients, and dissolved gases) factors. These models analyze nutrient cycles, algal blooms, and ecological interactions, assisting decision-makers in balancing productivity with environmental protection. Ecosystem models are especially important for integrated multi-trophic aquaculture (IMTA) systems, which involve the interaction of different species in a shared environment (Nobre et al., 2010).

6. SUSTAINABLE STRATEGIES FOR WATER QUALITY MANAGEMENT

Sustainable aquaculture requires an all-encompassing approach that integrates environmental, economic, and social dimensions. Ensuring optimal water quality is essential for maximizing productivity, protecting ecosystem health, complying with laws, and improving resilience to environmental changes.

Feed Management

Feed Administration Feed serves as the primary source of nutrients in aquaculture systems. Optimizing feed quantity, frequency, and composition reduces waste, decreases organic loading, and manages nitrogen and phosphorus levels in water (Hargreaves, 2013). The use of high-quality, digestible feed and the implementation of feeding techniques, such as demand feeders or split-meal schedules, may reduce uneaten feed and nutrient loss. Furthermore, alternative protein sources, such insect meal and plant-based proteins, may enhance sustainability and mitigate environmental impacts (Henry et al., 2015; Hua et al., 2019).

Stocking Density Control

Maintaining optimal stocking densities for fish or shrimp is crucial for both water quality and the well-being of the animals. Higher densities can quickly reduce oxygen levels, cause the buildup of ammonia and nitrite, and increase stress. Consequently, this stressor increases the animals' vulnerability to illness (Boyd & Tucker, 2012). By aligning livestock density with system capacity, farmers can potentially achieve optimal growth rates and maintain stable water quality. The implementation of recirculating aquaculture systems (RAS), aeration, and biofloc technologies allows for moderately increased densities while also protecting environmental integrity (Moniruzzaman et al., 2015; Aura et al., 2025)

Pond and Tank Design

The proficient design of ponds and tanks significantly influences water circulation, sedimentation, and aeration. Features such as sloped pond bottoms, drainage channels, and modular tank designs provide effective silt removal and water circulation (Lawson, 1995). The use of aeration sites and appropriately situated inflow and outflow structures ensures uniform water quality throughout the system. Sophisticated designs may include multi-chamber biofilters, sedimentation basins, or integrated wetlands to enhance water quality management (Lekang, 2013).

Policy and Regulatory Framework

Legislation and regulations are essential for promoting sustainable aquaculture practices. Establishing standards for effluent discharge, water quality, chemical use, and habitat conservation is essential for ensuring that aquaculture practices meet environmental safety regulations (FAO, 2022). Farmers are supported in using the best management practices through incentives, training programs, and monitoring, which helps to reduce environmental impacts while maintaining productivity (Alexander et al., 2015).

Climate Resilience Consideration

Aquaculture systems are increasingly vulnerable to climate-induced stressors, encompassing shifts in temperature, saltwater intrusion, flooding, drought, and severe weather events. Resilience may be bolstered through adaptive management approaches, such as recirculating aquaculture systems (RAS), shaded ponds, polyculture systems, and integrated water management techniques (Boyd and McNevin, 2015). Shaded pond systems are designed to lessen temperature variability, while polyculture methods foster increased resistance to disease and environmental stressors through the diversification of species. Moreover, the incorporation of forecasting tools with climate models allows farmers to proactively predict and manage environmental shifts, thus safeguarding agricultural output and water quality (Osmundsen et al., 2020).

Integrated Sustainable Practices

Effective water quality management requires combining several strategies. These include optimizing feed, controlling stocking density, designing ponds, using aeration and filtration, implementing biofloc systems, and following regulations. Using these methods together is essential for maximizing production efficiency, maintaining ecological balance, and ensuring economic viability, which is the foundation of sustainable aquaculture. Moreover, ongoing monitoring, modeling, and the use of advanced technologies like the Internet of Things (IoT), artificial intelligence (AI), and precision aquaculture significantly improve system efficiency and long-term sustainability ((Timmons et al., 2018;Føre et al., 2018; FAO, 2022).

7. CASE STUDIES

Recirculating Aquaculture Systems (RAS) in Bangladesh

In Bangladesh, the escalating demand for intensive and high-value fish production, particularly tilapia (Oreochromis niloticus) and pangasius (*Pangasianodon hypophthalmus*), has spurred a heightened interest in Recirculating Aquaculture Systems (RAS). These systems offer the advantage of continuous water filtration, treatment, and recirculation, which, in turn, minimizes the necessity for frequent water exchanges.

Intensive RAS units operating in Bangladesh have shown considerable advancements in water quality management, successfully maintaining dissolved oxygen, pH, and ammonia concentrations within ideal parameters (Roy et al., 2025). In addition, RAS improves biosecurity, thus mitigating the prevalence of bacterial and viral infections commonly found in open pond systems. Accelerated growth rates, better feed conversion ratios, and higher survival rates are observed by farmers in this system than the conventional pond culture. The system also promotes efficient resource utilization, a crucial factor in highly populated areas with restricted land resources. Despite these advantages, challenges persist, including substantial initial capital outlays and the necessity for specialized technical knowledge; nevertheless, research indicates that appropriate training and local adaptation can render RAS a viable model for intensive aquaculture in Bangladesh (Arifa et al., 2021).

Biofloc Technology in Thailand

Biofloc technology (BFT) has emerged as a transformative method in shrimp aquaculture, especially within Thailand, a leading global shrimp producer. BFT systems facilitate the proliferation of microbial aggregates, or bioflocs, which utilize nitrogenous wastes, thereby converting them into microbial protein that functions as supplementary feed (Krummenauer et al., 2011).

The implementation of BFT in Thai shrimp farms has resulted in a reduction of water exchange by up to 90%, thereby substantially mitigating the environmental consequences of nutrient discharge. Therefore, biofloc integration functions as a supplementary nutrient source, which enhance 20% in feed conversion rates. Furthermore, research demonstrated that biofloc technology boost shrimp immune responses and disease resistance, thereby reduce dependence on antibiotics and pesticides (Hargreaves, 2013; Emerenciano et al., 2013). Furthermore, biofloc technology (BFT) is consistent with circular economy principles, recycling nutrients within the system and reduce dependence on freshwater resources. Maintenance of optimal carbon-to-nitrogen ratios and aeration needs, exist, biofloc technology presents a potentially sustainable solution for intensive aquaculture in tropical environments.

Integrated Multi-Trophic Aquaculture (IMTA) in China

Integrated Multi-Trophic Aquaculture (IMTA) is gaining traction in China's coastal areas, integrating species from various trophic levels to establish a balanced and sustainable ecosystem. In IMTA systems, the waste generated by fed species, such as finfish, serves as nutrients for filter feeders (e.g., mussels or oysters) and primary producers (e.g., seaweeds), thereby diminishing nutrient loading and lessening environmental consequences (Chopin et al., 2012c; Fang et al., 2016). Chinese integrated multi-trophic aquaculture (IMTA) farms have demonstrably mitigated nitrogen and phosphorus effluent loads, thereby addressing a significant obstacle within coastal aquaculture. Simultaneously, farmers experience advantages stemming from diversified revenue sources, given the harvesting and marketing of multiple species. Research findings suggest that IMTA not only improves water quality but also bolsters ecosystem resilience by stabilizing microbial communities and diminishing the occurrence of harmful algal blooms(Troell et al., 2009; Chopin et al., 2012b; Buck et al., 2018).

IMTA systems necessitate meticulous species selection, stocking ratios, and spatial planning to ensure compatibility and optimize nutrient recycling. Despite the increased complexity of management compared to monoculture practices, the enduring environmental and economic advantages render IMTA a potentially advantageous approach for sustainable coastal aquaculture.

8. FUTURE PERSPECTIVES

Sustainable aquaculture is increasingly recognized as a crucial element in securing global food supplies and fostering economic advancement in rural areas. Nevertheless, the rapid growth of aquaculture presents significant challenges related to environmental and resource management, particularly concerning water quality, nutrient enrichment, disease occurrences, and the effects on surrounding ecosystems. The future of aquaculture relies on the implementation of innovative environmental engineering solutions, digital technologies, sustainable resource utilization, and robust policy frameworks to establish productive and resilient systems (Boyd and McNevin, 2015; FAO, 2022).

Advanced Sensors and AI-Based Monitoring

The forthcoming era of aquaculture administration will substantially depend on sophisticated sensor networks integrated with artificial intelligence (AI) and machine learning algorithms. High-precision sensors are capable of continuously monitoring water quality parameters, including dissolved oxygen, pH, temperature, ammonia, nitrate, turbidity, and microbial burden (Saberioon and Cisar, 2016). AI systems are capable of analyzing these data streams to detect anomalies, predict potential stress events, and autonomously optimize operational parameters. For example, machine learning models can forecast hypoxia risks or ammonia surges by examining historical data and present water conditions, enabling producers to adopt proactive strategies (Timmons et al., 2018). This predictive monitoring method reduces the likelihood of widespread mortality, improves feed efficiency, and supports the overall sustainability of the system (Zhao et al., 2021).

Precision Aquaculture

Precision aquaculture represents a pioneering approach that amalgamates environmental, nutritional, and health data to enable enhanced decision-making. IoT sensors integration perform automated feeders, cameras, and disease monitoring instruments, thereby farmers can simultaneously sustain optimal livestock densities, feeding schedules, and water quality. Precision aquaculture enhances production efficiency while concurrently reducing resource waste and nutrient discharge, thereby mitigating environmental impacts (Boyd & Tucker, 2012). Automated feeding systems, which adjust feed quantities based on real-time evaluations of fish behavior and biomass, exemplify this approach; they can substantially reduce uneaten feed and nitrogenous waste, thereby mitigating a major source of water pollution.

Sustainable Feed Alternatives

The nutrient inputs resulting from aquaculture feed remain a continual challenge. Future strategies emphasize the development and adoption of sustainable feed alternatives, such as insect meal, microbial protein, algae-based feeds, and plant-derived constituents.

These alternatives not only decrease dependence on fishmeal and fish oil but also lower nitrogen and phosphorus excretion, thereby enhancing water quality (Hargreaves, 2013; FAO, 2022).Furthermore, feed formulations enhanced with probiotics and functional additives possess the potential to enhance gastrointestinal health, bolster immune responses, and reduce dependence on antibiotics, thereby promoting sustainable aquaculture practices (Hua et al., 2019).

Circular Economy Approaches

The circular economy model is becoming increasingly important in aquaculture, where waste materials are converted into valuable resources. Biogas, a nutrient-rich byproduct of aquaculture, is utilized for crop fertilization, growing algae, and producing bioenergy(Chopin et al., 2012b). Biofloc and integrated multi-trophic aquaculture (IMTA) systems exemplify early models of circular nutrient recycling, converting waste into microbial biomass or utilizing multi-trophic species to absorb leftover nutrients. Consequently, the potential integration of waste valorization technologies can diminish environmental emissions, improve farm profitability, and foster ecosystem-based management, thus aligning aquaculture with wider sustainability objectives (Verdegem, 2013b; Gephart et al., 2021).

Policy Integration and Ecosystem-Based Management

To ensure the long-term sustainability of solutions, the adoption of innovative technological advancements necessitates the development of appropriate legal and regulatory frameworks. Future plans should incorporate ecosystem-based aquaculture management (EBAM), acknowledging the interconnectedness among farms, local ecosystems, and socio-economic networks. This guidance aligns with the standards set by the Food and Agriculture Organization of the United Nations as of 2022. The release of effluent, water usage, chemical application, and environmental regulation must adhere to these standards, which should encompass binding restrictions. These regulations should define standards for environmental monitoring and offer incentives for the adoption of sustainable management practices and technologies.

Achieving a balance between aquaculture production and environmental conservation requires collaborative governance involving stakeholders, scientists, and local communities. This will constitute the crucial stage in attaining this state of harmony.

Climate-Resilient Aquaculture

The aquaculture method known as climate-sensitive agriculture. The effects of climate change may be classified into various categories of challenges. The variations in temperature, the application of salt, the occurrence of extreme weather events, and the scarcity of accessible water exemplify these challenges. All of these issues influence both the purity of water and the quantity of fish yield (Boyd and McNevin, 2015). Future aquaculture systems must incorporate adaptive management strategies, such as polyculture, shaded ponds, recirculating aquaculture systems (RAS), and integrated water management approaches. These exemplify only a limited selection of cases. This is just a small part of the possible strategies. Advances in climate modeling could help with proactive decisions about climate change. These examples are not exhaustive (Barange et al., 2018).

Integration of Emerging Technologies

Blockchain technology might enhance food safety and traceability, but robots can handle feeding, harvesting, and upkeep without human interaction. Multi-technology agricultural management will optimize water quality, feed efficacy, health, and environmental effect. This will enable the efficient management of agricultural activities. This will facilitate the development of a comprehensive farm management strategy. The future of sustainable aquaculture relies on progress in environmental engineering, digital technologies, sustainable feed development, circular economy strategies, and environmentally responsible legislation. Timmons et al., (2018); Boyd, (2019) and FAO, (2022) concur that aquaculture represents a viable and sustainable strategy for securing the global food supply. Aquaculture considers each of these commercial techniques. By implementing these strategies, one can ensure the efficient utilization of resources, minimize environmental impact, enhance productivity, and promote resilience to climate variability.

CONCLUSION

Maintaining ideal physical, chemical, and biological conditions in the aquatic environment is essential for disease prevention, stress reduction, and the advancement of sustainable aquaculture. Considering the increasing global demand for aquaculture products and the resulting pressures on freshwater and coastal ecosystems, effective water quality management is crucial for environmentally and economically sound fish production. Environmental engineering provides various tools, methodologies, and technologies to maintain and improve water quality.

Aeration and oxygenation, in conjunction with water circulation, filtration, sediment removal, and wastewater treatment, represent fundamental components. Advanced technological applications, such as Recirculating Aquaculture Systems (RAS), biofloc technology (BFT), and Integrated Multi-Trophic Aquaculture (IMTA), exemplify methods that facilitate high-density aquaculture production while concurrently reducing environmental impacts. These strategies enhance the efficacy of water and fertilizer utilization, thereby reducing the discharge of pollutants into adjacent ecosystems. In accordance with this premise, they highlight the prospects for sustainable growth within the aquaculture industry.

Furthermore, monitoring and modeling are essential for the implementation of these technological solutions. Proactive management is enabled through real-time sensor monitoring, IoT platforms, and predictive water quality models, allowing farmers to swiftly address variations in dissolved oxygen, pH, temperature, or nitrogenous compounds.

These strategies contribute to a reduction in the likelihood of mass mortality incidents, enhance feed conversion efficiencies, and refine overall system functionality. Through the incorporation of these methodologies with ecological considerations-including planktonic dynamics, microbial community stability, and nutrient cycling-aquaculture practitioners can potentially formulate a comprehensive water quality management plan that harmonizes productivity with environmental responsibility. Furthermore, sustainable aquaculture necessitates an assessment of socio-economic and policy dimensions.

Effective governance, regulatory structures, and capacity-building initiatives promote responsible practices, support the implementation of novel technologies, and encourage environmentally conscious production methods. Collaboration among academics, engineers, policymakers, and agricultural specialists is crucial for developing context-specific solutions that effectively address both local and global challenges.

The future implementation of innovative technologies, precision aquaculture methods, climate-resilient designs, and circular economy principles will enhance the sustainability of aquaculture systems. The adoption of these strategies will result in increased productivity and profitability, while also bolstering resilience to climate variability, the impacts of climate change, and resource limitations. Consequently, an integrated approach, incorporating environmental engineering, ecological perspectives, technological advancements, and collaborative governance, is essential for achieving global sustainable fish production, thereby strengthening food security, livelihoods, and ecosystem health.

REFERENCES

Abdel-Tawwab, M., Wafeek, M., 2014. Influence of water temperature and waterborne cadmium toxicity on growth performance and metallothionein-cadmium distribution in different organs of Nile tilapia, Oreochromis niloticus (L.). J. Therm. Biol. 45, 157–162. https://doi.org/10.1016/j.jtherbio.2014.09.002

Abdel-Tawwab, Mohsen, Hagras, Ahmed E, Heba, •, Elbaghdady, A.M., Monier, M.N., Abdel-Tawwab, M, Monier, Á.M.N., Hagras, A E, Elbaghdady, H.A.M., 2015. Effects of dissolved oxygen and fish size on Nile tilapia, Oreochromis niloticus (L.): growth performance, whole-body composition, and innate immunity. Aquac. Int. 2015 235 23, 1261–1274. https://doi.org/10.1007/S10499-015-9882-Y

AftabUddin, S., Siddique, M.A.M., Sein, A., Dey, P.K., Rashed-Un-Nabi, M., Haque, M.A., 2020. First use of biofloc technology for Penaeus monodon culture in Bangladesh: Effects of stocking density on growth performance of shrimp, water quality and bacterial growth. Aquac. Reports 18, 100518. https://doi.org/10.1016/J.AQREP.2020.100518

Ahmed, N., Thompson, S., Glaser, M., 2019. Global Aquaculture Productivity, Environmental Sustainability, and Climate Change Adaptability. Environ. Manage. 63, 159–172. https://doi.org/10.1007/S00267-018-1117-3

Alam, M.J., Shammi, M., Tareq, S.M., 2023. Distribution of microplastics in shoreline water and sediment of the Ganges River Basin to Meghna Estuary in Bangladesh. Ecotoxicol. Environ. Saf. 266, 115537. https://doi.org/10.1016/J.ECOENV.2023.115537

Alexander, K.A., Potts, T.P., Freeman, S., Israel, D., Johansen, J., Kletou, D., Meland, M., Pecorino, D., Rebours, C., Shorten, M., Angel, D.L., 2015. The implications of aquaculture policy and regulation for the development of integrated multi-trophic aquaculture in Europe. Aquaculture 443, 16–23. https://doi.org/10.1016/J.AQUACULTURE.2015.03.005

Ali, I., 2021. Data Collection in Studies on Internet of Things (IoT), Wireless Sensor Networks (WSNs), and Sensor Cloud (SC): Similarities and Differences. https://doi.org/10.36227/TECHRXIV.14039486.V1

Arifa, Begum, M.K., Lalon, R.M., Alam, A.S., Rahman, M.S., 2021. Economic feasibility of Pabda and stinging catfish culture in recirculating aquaculture systems (RAS) in Bangladesh. Aquac. Int. 2021 301 30, 445–465. https://doi.org/10.1007/S10499-021-00807-1

Aura, C.M., Awandu, H., Mziri, V., Awuor, F.J., Nyamweya, C.S., Musa, S., 2025. Optimizing stocking density for enhanced fish yield in lacustrine cage aquaculture. Sci. African 28, e02721. https://doi.org/10.1016/J.SCIAF.2025.E02721

Avnimelech, Y., Ritvo, G., 2003. Shrimp and fish pond soils: processes and management. Aquaculture 220, 549–567. https://doi.org/10.1016/S0044-8486(02)00641-5

Barange, M. (ed. ., Bahri, T. (ed. ., Beveridge, M.C.M. (ed. ., Cochrane, K.L. (ed. ., Funge-Smith, S. (ed. ., Poulain, F. (ed. ., 2018. Impacts of climate change on fisheries and aquaculture : synthesis of current knowledge, adaptation and mitigation options. Impacts Clim. Chang. Fish. Aquac. Synth. Curr. knowledge, Adapt. Mitig. options 347–362.

Belton, B., Bush, S.R., Little, D.C., 2018. Not just for the wealthy: Rethinking farmed fish consumption in the Global South. Glob. Food Sec. 16, 85–92. https://doi.org/10.1016/J.GFS.2017.10.005

Belton, B., Thilsted, S.H., 2014. Fisheries in transition: Food and nutrition security implications for the global South. Glob. Food Sec. 3, 59–66. https://doi.org/10.1016/J.GFS.2013.10.001

Bilotta, G.S., Brazier, R.E., 2008. Understanding the influence of suspended solids on water quality and aquatic biota. Water Res. 42, 2849–2861. https://doi.org/10.1016/J.WATRES.2008.03.018

Bœuf, G., Payan, P., 2001. How should salinity influence fish growth? Comp. Biochem. Physiol. - C Toxicol. Pharmacol. 130, 411–423. https://doi.org/10.1016/S1532-0456(01)00268-X

Boyd, C.E., 2019. Water quality: an introduction. Springer Nature. 1–711.

Boyd, C.E., McNevin, A.A., 2015. Aquaculture, Resource Use, and the Environment. Aquac. Resour. Use, Environ. 9780470959190, 1–337. https://doi.org/10.1002/9781118857915

Buck, B.H., Troell, M.F., Krause, G., Angel, D.L., Grote, B., Chopin, T., 2018. State of the art and challenges for offshore Integrated multi-trophic aquaculture (IMTA). Front. Mar. Sci. 5, 345988. https://doi.org/10.3389/FMARS.2018.00165/BIBTEX

Burford, M.A., Thompson, P.J., Mcintosh, R.P., Bauman, R.H., Pearson, D.C., 2003. Nutrient and microbial dynamics in high-intensity, zero-exchange shrimp ponds in Belize.

Camargo, J.A., Alonso, A., Salamanca, A., 2005. Nitrate toxicity to aquatic animals: a review with new data for freshwater invertebrates. Chemosphere 58, 1255–1267. https://doi.org/10.1016/J.CHEMOSPHERE.2004.10.044

Cheng, C., Liu, J., Ma, Z., 2022. Effects of aquaculture on the maintenance of waterbird populations. Conserv. Biol. 36, e13913. https://doi.org/10.1111/COBI.13913;REQUESTEDJOURNAL:JOURNAL:15231739;WGROUP:STRING:PUBLICATION

Chopin, T., Cooper, J.A., Reid, G., Cross, S., Moore, C., 2012a. Open-water integrated multi-trophic aquaculture: Environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Rev. Aquac. 4, 209–220. https://doi.org/10.1111/J.1753-5131.2012.01074.X;SUBPAGE:STRING:ABSTRACT;WEBSITE:WEBSITE:PERICLES;REQUESTEDJOURNAL:JOURNAL:17535131;ISSUE:ISSUE:DOI

Chopin, T., Cooper, J.A., Reid, G., Cross, S., Moore, C., 2012b. Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Rev. Aquac. 4, 209–220. https://doi.org/10.1111/J.1753-5131.2012.01074.X

Chopin, T., Cooper, J.A., Reid, G., Cross, S., Moore, C., 2012c. Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Rev. Aquac. 4, 209–220. https://doi.org/10.1111/J.1753-5131.2012.01074.X

Crab, R., Defoirdt, T., Bossier, P., Verstraete, W., 2012. Biofloc technology in aquaculture: Beneficial effects and future challenges. Aquaculture 356–357, 351–356. https://doi.org/10.1016/J.AQUACULTURE.2012.04.046

Cripps, S.J., Bergheim, A., 2000. Solids management and removal for intensive land-based aquaculture production systems. Aquac. Eng. 22, 33–56. https://doi.org/10.1016/S0144-8609(00)00031-5

Dalsgaard, J., Lund, I., Thorarinsdottir, R., Drengstig, A., Arvonen, K., Pedersen, P.B., 2013. Farming different species in RAS in Nordic countries: Current status and future perspectives. Aquac. Eng. 53, 2–13. https://doi.org/10.1016/J.AQUAENG.2012.11.008

De Schryver, P., Crab, R., Defoirdt, T., Boon, N., Verstraete, W., 2008. The basics of bio-flocs technology: The added value for aquaculture. Aquaculture 277, 125–137. https://doi.org/10.1016/J.AQUACULTURE.2008.02.019

Defoirdt, T., Sorgeloos, P., Bossier, P., 2011. Alternatives to antibiotics for the control of bacterial disease in aquaculture. Curr. Opin. Microbiol. 14, 251–258. https://doi.org/10.1016/J.MIB.2011.03.004

DiTullio, G.R., Geesey, M.E., Jones, D.R., Daly, K.L., Campbell, L., Smith, W.O., 2003. Phytoplankton assemblage structure and primary productivity along 170°W in the South Pacific Ocean. Mar. Ecol. Prog. Ser. 255, 55–80. https://doi.org/10.3354/MEPS255055

Ebeling, J.M., Timmons, M.B., Bisogni, J.J., 2006. Engineering analysis of the stoichiometry of photoautotrophic, autotrophic, and heterotrophic removal of ammonia–nitrogen in aquaculture systems. Aquaculture 257, 346–358. https://doi.org/10.1016/J.AQUACULTURE.2006.03.019

Ebina, K., Shi, K., Hirao, M., Hashimoto, J., Kawato, Y., Kaneshiro, S., Morimoto, T., Koizumi, K., Yoshikawa, H., 2013. Oxygen and Air Nanobubble Water Solution Promote the Growth of Plants, Fishes, and Mice. PLoS One 8. https://doi.org/10.1371/JOURNAL.PONE.0065339

Effects of Stocking Density on Growth, Body Composition, Yield and Economic Returns of Monosex Tilapia (Oreochromis niloticus L.) under Cage Culture System in Kaptai Lake of Bangladesh, 2015. https://doi.org/10.4172/2155-9546.1000357

El-Sayed, A.F.M., 2006. Tilapia culture. Tilapia Cult. 1–277. https://doi.org/10.1079/9780851990149.0000

Emerenciano, M., Gaxiola, G., Cuzo, G., 2013. Biofloc Technology (BFT): A Review for Aquaculture Application and Animal Food Industry. Biomass Now - Cultiv. Util. https://doi.org/10.5772/53902

Fang, J., Zhang, J., Xiao, T., Huang, D., Liu, S., 2016. Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China. Aquac. Environ. Interact. 8, 201–205. https://doi.org/10.3354/AEI00179

Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J.A., Dempster, T., Eguiraun, H., Watson, W., Stahl, A., Sunde, L.M., Schellewald, C., Skøien, K.R., Alver, M.O., Berckmans, D., 2018. Precision fish farming: A new framework to improve production in aquaculture. Biosyst. Eng. 173, 176–193. https://doi.org/10.1016/J.BIOSYSTEMSENG.2017.10.014

Gephart, J.A., Henriksson, P.J.G., Parker, R.W.R., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., Troell, M., 2021. Environmental performance of blue foods. Nat. 2021 5977876 597, 360–365. https://doi.org/10.1038/s41586-021-03889-2

Ghose, B., 2014. Fisheries and Aquaculture in Bangladesh:Challenges and Opportunities. Ann. Aquac. Res. 1, 1–5. https://doi.org/10.47739/2379-0881.AQUACULTURE.1001

Hargreaves, J., 2013. Biofloc production systems for aquaculture.

Heisler, J., Glibert, P.M., Burkholder, J.M., Anderson, D.M., Cochlan, W., Dennison, W.C., Dortch, Q., Gobler, C.J., Heil, C.A., Humphries, E., Lewitus, A., Magnien, R., Marshall, H.G., Sellner, K., Stockwell, D.A., Stoecker, D.K., Suddleson, M., 2008. Eutrophication and Harmful Algal Blooms: A Scientific Consensus. Harmful Algae 8, 3–13. https://doi.org/10.1016/J.HAL.2008.08.006

Henry, M., Gasco, L., Piccolo, G., Fountoulaki, E., 2015. Review on the use of insects in the diet of farmed fish: Past and future. Anim. Feed Sci. Technol. 203, 1–22. https://doi.org/10.1016/J.ANIFEEDSCI.2015.03.001

Hua, K., Cobcroft, J.M., Cole, A., Condon, K., Jerry, D.R., Mangott, A., Praeger, C., Vucko, M.J., Zeng, C., Zenger, K., Strugnell, J.M., 2019.

The Future of Aquatic Protein: Implications for Protein Sources in Aquaculture Diets. One Earth 1, 316–329. https://doi.org/10.1016/J.ONEEAR.2019.10.018

Iqbal, M.M., Shoaib, M., Farid, H.U., Lee, J.L., 2018. Assessment of Water Quality Profile Using Numerical Modeling Approach in Major Climate Classes of Asia. Int. J. Environ. Res. Public Heal. 2018, Vol. 15, 15. https://doi.org/10.3390/IJERPH15102258

Kroupova, H., Machova, J., Svobodova, Z., 2005. Nitrite influence on fish: A review. Vet. Med. (Praha). 50, 461–471. https://doi.org/10.17221/5650-VETMED

Krummenauer, D., Peixoto, S., Cavalli, R.O., Poersch, L.H., Wasielesky, W., 2011. Superintensive culture of white shrimp, Litopenaeus vannamei, in a biofloc technology system in Southern Brazil at different stocking densities. J. World Aquac. Soc. 42, 726–733. https://doi.org/10.1111/J.1749-7345.2011.00507.X

Kumar, R., Sinha, R., Refat Jahan Rakib, M., Padha, S., Ivy, N., Bhattacharya, S., Dhar, A., Sharma, P., 2022. Microplastics pollution load in Sundarban delta of Bay of Bengal. J. Hazard. Mater. Adv. 7, 100099. https://doi.org/10.1016/J.HAZADV.2022.100099

Lawson, T.B., 1995. Aquaculture in Ponds, Raceways, and Tanks. Fundam. Aquac. Eng. 157–191. https://doi.org/10.1007/978-1-4613-0479-1_9

Lekang, O.I., 2013. Aquaculture Engineering: Second Edition. Aquac. Eng. Second Ed. https://doi.org/10.1002/9781118496077

Liu, F., Han, W., 2004. Reuse strategy of wastewater in prawn nursery by microbial remediation. Aquaculture 230, 281–296. https://doi.org/10.1016/J.AQUACULTURE.2003.09.033

Malik, N., Biswas, A.K., Qureshi, T.A., Borana, K., Virha, R., 2010. Bioaccumulation of heavy metals in fish tissues of a freshwater lake of Bhopal. Environ. Monit. Assess. 160, 267–276. https://doi.org/10.1007/S10661-008-0693-8

Martins, A., Ramalho, N., Morin, E., 2010. A comprehensive meta-analysis of the relationship between Emotional Intelligence and health q. https://doi.org/10.1016/j.paid.2010.05.029

Mladenović-Ranisavljević, I.I., Žerajić, S.A., 2018. Comparison of different models of water quality index in the assessment of surface water quality. Int. J. Environ. Sci. Technol. 15, 665–674. https://doi.org/10.1007/S13762-017-1426-8

Naylor, R.L., Hardy, R.W., Buschmann, A.H., Bush, S.R., Cao, L., Klinger, D.H., Little, D.C., Lubchenco, J., Shumway, S.E., Troell, M., 2021. A 20-year retrospective review of global aquaculture. Nat. 2021 5917851 591, 551–563. https://doi.org/10.1038/s41586-021-03308-6

Nobre, A.M., Robertson-Andersson, D., Neori, A., Sankar, K., 2010. Ecological–economic assessment of aquaculture options: Comparison between abalone monoculture and integrated multi-trophic aquaculture of abalone and seaweeds. Aquaculture 306, 116–126. https://doi.org/10.1016/J.AQUACULTURE.2010.06.002

Osmundsen, T.C., Amundsen, V.S., Alexander, K.A., Asche, F., Bailey, J., Finstad, B., Olsen, M.S., Hernández, K., Salgado, H., 2020. The operationalisation of sustainability: Sustainable aquaculture production as defined by certification schemes. Glob. Environ. Chang. 60, 102025. https://doi.org/10.1016/J.GLOENVCHA.2019.102025

Parra, L., García, L., Sendra, S., Lloret, J., 2018. The use of sensors for monitoring the feeding process and adjusting the feed supply velocity in fish farms. J. Sensors 2018. https://doi.org/10.1155/2018/1060987

Piedrahita, R.H., 2003. Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation. Aquaculture 226, 35–44. https://doi.org/10.1016/S0044-8486(03)00465-4

Pond Aquaculture Water Quality Management - Claude E. Boyd, C.S. Tucker - Google Books [WWW Document], 2012. URL https://books.google.com.bd/books?hl=en&lr=&id=2r8GCAAAQBAJ&oi=fnd&pg=PR11&dq=Boyd+%26+Tucker,+2012&ots=pKD41w_7Go&sig=MxqsuFuFPZOCxgOZIShlXL1a28o&redir_esc=y#v=onepage&q&f=false (accessed 12.20.25).

Rahman, M.T., Nielsen, R., Khan, M.A., Ankamah-Yeboah, I., 2020. Impact of management practices and managerial ability on the financial performance of aquaculture farms in Bangladesh. Aquac. Econ. Manag. 24, 79–101. https://doi.org/10.1080/13657305.2019.1647578

Rastegari, H., Nadi, F., Lam, S.S., Ikhwanuddin, M., Kasan, N.A., Rahmat, R.F., Mahari, W.A.W., 2023. Internet of Things in aquaculture: A review of the challenges and potential solutions based on current and future trends. Smart Agric. Technol. 4, 100187. https://doi.org/10.1016/J.ATECH.2023.100187

Rice, E.W. editor, Baird, R.B. editor/a, Eaton, A.D. editor/a, Clesceri, L.S. editor/a, Bridgewater, L. editor/a, 2012. Standard methods for the examination of water and wastewater.

Roy, D., Saha, P.K., Sarker, S., Parves, M.A., Zavyalov, A.P., Latifa, G.A., 2025. Culture practice of Oreochromis niloticus through recirculating aquaculture system (RAS): a modern and growth-optimized approach of fish culture by maintaining water quality with proper fish stocking density in Bangladesh. Environ. Sci. Pollut. Res. 2025 3218 32, 11749–11766. https://doi.org/10.1007/S11356-025-36386-4

Saberioon, M.M., Cisar, P., 2016. Automated multiple fish tracking in three-Dimension using a Structured Light Sensor. Comput. Electron. Agric. 121, 215–221. https://doi.org/10.1016/J.COMPAG.2015.12.014

Sapkota, A., Sapkota, A.R., Kucharski, M., Burke, J., McKenzie, S., Walker, P., Lawrence, R., 2008. Aquaculture practices and potential human health risks: current knowledge and future priorities. Environ. Int. 34, 1215–1226. https://doi.org/10.1016/J.ENVINT.2008.04.009

Smith, V.H., Schindler, D.W., 2009. Eutrophication science: where do we go from here? Trends Ecol. Evol. 24, 201–207. https://doi.org/10.1016/J.TREE.2008.11.009

The State of World Fisheries and Aquaculture 2022, 2022. . State World Fish. Aquac. 2022. https://doi.org/10.4060/CC0461EN

The State of World Fisheries and Aquaculture 2024, 2024. . State World Fish. Aquac. 2024. https://doi.org/10.4060/CD0683EN

Timmons, M.B.., Guerdat, T., Vinci, B.J.., 2018. Recirculating aquaculture 779.

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H., Fang, J.G., 2009. Ecological engineering in aquaculture — Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture 297, 1–9. https://doi.org/10.1016/J.AQUACULTURE.2009.09.010

Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmers, P.H., Folke, C., Arrow, K.J., Barrett, S., Crépin, A.S., Ehrlich, P.R., Gren, Å., Kautsky, N., Levin, S.A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B.H., Xepapadeas, T., De Zeeuw, A., 2014. Does aquaculture add resilience to the global food system? Proc. Natl. Acad. Sci. U. S. A. 111, 13257–13263. https://doi.org/10.1073/PNAS.1404067111/ASSET/5E012B24-A474-4468-AE46-B2BA891230D3/ASSETS/GRAPHIC/PNAS.1404067111FIG04.JPEG

Uys, W., Hecht, T., 1985. Evaluation and preparation of an optimal dry feed for the primary nursing of Clarias gariepinus larvae (Pisces: Clariidae). Aquaculture 47, 173–183. https://doi.org/10.1016/0044-8486(85)90063-8

Varol, M., Sünbül, M.R., 2020. Macroelements and toxic trace elements in muscle and liver of fish species from the largest three reservoirs in Turkey and human risk assessment based on the worst-case scenarios. Environ. Res. 184. https://doi.org/10.1016/J.ENVRES.2020.109298

Verdegem, M.C.J., 2013a. Nutrient discharge from aquaculture operations in function of system design and production environment. Rev. Aquac. 5, 158–171. https://doi.org/10.1111/RAQ.12011;REQUESTEDJOURNAL:JOURNAL:17535131;WGROUP:STRING:PUBLICATION

Verdegem, M.C.J., 2013b. Nutrient discharge from aquaculture operations in function of system design and production environment. Rev. Aquac. 5, 158–171. https://doi.org/10.1111/RAQ.12011

Vymazal, J., Vymazal, J., 2010. Constructed Wetlands for Wastewater Treatment. Water 2010, Vol. 2, Pages 530-549 2, 530–549. https://doi.org/10.3390/W2030530

Zhao, S., Zhang, S., Liu, J., Wang, H., Zhu, J., Li, D., Zhao, R., 2021. Application of machine learning in intelligent fish aquaculture: A review. Aquaculture 540, 736724. https://doi.org/10.1016/J.AQUACULTURE.2021.736724

(PDF) Biofloc technology. A practical guide book. The World Aquaculture Society [WWW Document], 2009. URL https://www.researchgate.net/publication/308052605_Biofloc_technology_A_practical_guide_book_The_World_Aquaculture_Society (accessed 12.21.25).

CHAPTER 2
THE EFFICIENCY OF NITROGEN USE IN CEREAL AGRICULTURE IN ALGERIA

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INTRODUCTION

Nitrogen Use Efficiency (NUE) in cereals is an important issue in the case of Algeria, because agri-culture is essential not only for ensuring the country's food security but also for its development. For Algeria, which has an average rainfall ranging from 195 to 450 mm'a year and high temperatures, efficiency in the usage of nitrogen fertilizer is essential because it influences both the production potential and the sustainability of the environment. Improving the overall efficiency of nitrogen use in Algeria from the current 14,77 kg kg–1 to the Mediterranean average efficiency of 25–30 kg kg–1 may potentially improve overall domestic production of cereals by 40–70%.

Nitrogen is a critical macronutrient for plant nutrition and primarily impacts protein and chlorophyll production in cereals (Fageria and Baligar, 2005). In the context of Algeria, where cereals form the backbone of the agricultural sector, the efficient management of nitrogen is paramount to maximize productivity and qualify as highly nutritious. However, the overdependence on nitrogen fertilizers has often led to inefficient outcomes. Mismanagement of nitrogen fertilizers has led to the contamination of water sources and the resultant acidic soil (Boufekane et al., 2021).

Climate variability has also made the efficient management of nitrogen even more difficult (Kourat et al., 2022). The amount of rainfall has directly impacted the flow of nitrogen to plants. This has often led to an increased amount of fertilizing to compensate for the productivity losses. Such an economic burden on farmers has often generated concerns over the resultant effects on the environment. It should be noted that this chapter emphasizes the efficacy of nitrogen management, along with associated advantages and difficulties, as specifically related to cereal crops in Algeria, with a view to improving efficiency and protecting the environment as well.

1. STRATEGIC ROLE OF CEREALS IN THE ALGERIAN AGRICULTURAL SECTOR

Cereals production is one of the most important sectors in Algerian agriculture, as it is the base of food security in the country.

Crops area vary between 3 and 3.5 million hectares, and per capita cereal consumption equals 205 kg per year, which is among the highest in the world (Food and Agriculture Organization of the United Nations, 2018. The main cereal productions in the country include durum wheat, soft wheat, and barley. Nonetheless, production area covers only 24% to 55% of domestic demand in a year, with significant irregularity, requiring massive importation to cover the gap (Ministère de l'Agriculture et du Développement Rural, 2015).

This fact represents a challenge in the matter of sovereignty, thus the need for increased efforts in improving cereal productivity through approaches like the optimisation of nitrogen fertilization. Durum wheat (<i>Triticum durum Desf. </i>) is the predominant species in the Algerian cereal crop, representing 46% of the country's entire cereal production and occupying 41% of the cropped area (Benbelkacem & Kellou, 2000).

This can be attributed to its comparable tolerance to semi-arid conditions and the cultural role it plays in traditional meals such as couscous, pasta, and bread. Moreover, the productiveness, which averages merely 8-15 quintals per hectare compared with the international average of 30-40 q/ha, remains lower than the potential outputs achievable by such a critical crop for the subsistence agricultural economy, primarily due to the difficult climate and inefficient use of agricultural inputs such as nitrogen fertilizer applications.

The major climate-related drawbacks are large rainfall spatial and temporal variations, high temperatures at the end of the season promoting maturity, short grain filling seasons with low yield potentials, and low nitrogen transfer to the grains (Bheemanahalli et al., 2019).

The soil conditions are also unsupportive, with clayey soil texture and alkaline nature (>8), low organic matter content (1-2%), low available nitrogen content (<25 mg/kg soil), high active lime values (20-40%), higher hazards of ammonium volatilization, and ammonium fixation on the clay- humus complex (Halitim, 1988). The above adverse factors require the use of fertilizers for acceptable crop yields. On the contrary, the use of nitrogen is inefficient due to the ped conditions.

2. DECIHERING NITROGEN USE EFFICIENCY

NUE can be calculated as the ratio of grain yield (in kg/ha) to available nitrogen, which is a sum of both soil nitrogen and nitrogen applied via fertilizer, and can be measured as kg grain/kg N (Moll et al., 1982). The above concept of nitrogen use efficiency can be broken down into two sub-components, that is, nitrogen uptake efficiency and nitrogen use efficiency, and can be expressed as NUE = NUpE × NUtE, where nitrogen uptake efficiency measures the potential of the plant to uptake nitrogen from the soil, while nitrogen use efficiency measures how effective it is to convert nitrogen into grain.

Understanding these elements is crucial for pinpointing where improvements can be made. In the Algerian environment, the values of NUE vary between 7.95-19,87 kg kg-1, averaging 14,77 kg kg-1, way below the optimal value of 30-40 kg kg-1 (Boulelouah et al., 2022). This value accounts for less than 50% of the average global value that stands at 33 kg kg-1. Nitrogen uptake efficiency values stand between 0.29-0,74 kg kg-1, below the optimal value that exceeds 0,70 kg kg-1, though nitrogen utilization efficiency values stand between 24-27 kg kg-1, in the normal range of 20-30 kg kg-1 in the Mediterranean region (Lupini et al., 2021).

Therefore, it is evident that the values of NUpE are the major limiting factor, especially in drought years, though values of NUtE are in the normal physiological range. Other performance measures help deliver a broader perspective of nitrogen use.

Agronomic efficiency (AE), which expresses the additional yield per unit of N fertilizers, differs from a high of 30,57 kg of grain per kg of N fertilizers used in rainy years to a range of 3.4–6,63 kg of grain per kg of N fertilizers used in drought years, thereby demonstrating the important role of nitrogen-water interactions (Ayadi et al., 2022). The apparent recovery efficiency (ARE) of N, which defines the percentage of nitrogen actually assimilated by the crop, reaches a maximum of 81% but drops lower than 30% during drought, averaging between 50% and 60%, which therefore suggests that between 40% and 50% is lost or, rather, retained by the soil (Davies et al., 2020).

The nitrogen harvest index (NHI), which defines the proportion of nitrogen assimilated that is attributed to grain production, varies from a minimum of 0.66 to a maximum of 0.73, with higher values being recorded in drought years due to nitrogen mobilization, whereby approximately 70% of nitrogen assimilation is mobilized into the grain (Havé et al., 2017). The main determinants which influence NUE in Algeria are presented Rainfall is seen as the most influential factor for NUE in Algeria. In arid conditions (<200 mm rainfall per year), NUE is on average 7,95 kg kg-1, meaning that only 24% of the global mean is attained. In regular conditions (200-400 mm rainfall per year), NUE is higher, amounting to 14,77 kg kg-1 NUE, or 45% of the global mean, while in wet conditions (>400 mm rainfall per year), NUE goes up to 19,87 kg kg-1, meaning that 60% of the global mean is attained, with a global mean of 33 kg kg-1 (Mrad et al., 2019). Water is a crucial factor for N uptake because N uptake needs water for three functions: solubilization of mineral N in the soil solution, transport of ions from the soil to roots by water-driven mass flow and diffusion, and uptake by transporters, which need respiration and energy from water.

Temperature plays an essential but often underestimated role in NUE. High-end-of-cycle temperatures hasten leaf senescence, shorten the grain-filling period, limit N remobilisation from vegetative parts to grains, and decrease NUtE efficiency (Xu et al., 2022). The optimal temperature for grain filling is 20-22°C; above this range, N remobilisation is disrupted, and NHI decreases with heat stress. Climate change is increasing the frequency of damaging heat waves. Conversely, cool spring temperatures prolong the vegetative phase, allow better N accumulation in aerial parts, and increase tillering potential. Soil type substantially affects NUE in Algeria. Algerian soils typically exhibit pH values of 7.98.4, creating a high ammonia volatilisation risk. Active lime content of 20-40% reduces N availability, while low organic matter of 1-2% limits N mineralisation (Halitim, 1988). The clay- silt texture leads to ammonium fixation on clay, and available N below 25 mg/kg necessitates fertiliser inputs. The mechanisms limiting N absorption include ammonium fixation on the clay- humus complex, reducing plant availability; significant ammonia volatilisation favoured by high pH; and denitrification under temporary waterlogging in poorly structured clay soils (Li et al., 2017).

Experimental studies show soil type can induce yield variations of 25% for soft wheat and over 50% for durum wheat and barley in response to N fertilisation, justifying differentiated fertilisation approaches based on pedological characteristics. Genotypic variability offers significant opportunities to improve NUE. Modern high-performing genotypes exhibit distinct characteristics in their nitrogen-use efficiency components (Gouis et al., 2000). Tall varieties such as MBB and Megress show NUpE of 0.54-0,62 kg/kg and NUtE of 27.55 and 24,73 kg/kg, respectively, with better uptake traits resulting from more developed root systems and faster N absorption kinetics. Modern short varieties like GTAdur show NUpE of 0.50-0,60 kg/kg but superior NUtE of 27,66 kg/kg, with an average NUE of 27,66 kg/kg, representing the best overall performance through better N translocation to grains, high performance steadiness across environments, exceptional drought tolerance, and optimised resource allocation between vegetative and reproductive growth (Boulelouah et al., 2022). These results indicate that selecting and disseminating high-performing, locally adapted genotypes represents a promising, cost-effective strategy for improving national NUE.

3. CURRENT STATE OF NITROGEN USE IN ALGERIA

National fertiliser consumption figures reveal a complex picture of nitrogen use in Algeria. In 2009, consumption averaged only 7,8 kg per hectare of arable land, well below the 100-150 kg/ha used in Mediterranean countries (International Fertiliser Industry Association, 2013). From 2002 to 2010, consumption increased from 0.7 to 1,1 kg N/ha, representing a 57% increase. This differs dramatically from the developed. Mediterranean countries have been decreasing their consumption due to environmental policies. However, these statistics mask significant heterogeneity in field practices, with applied doses ranging from 0 to 150 kg N/ha, compared to the recommended dose of 100-120 kg N/ha for durum wheat under rainfed conditions. Some farmers apply no fertiliser due to budgetary restrictions, while others apply excessive doses to maximise yield. Experimental studies in the Sétif region offer clear proof of nitrogen response patterns. Increasing N doses from 40 to 80 to 120 kg N/ha increases N absorption and grain N content, but the marginal efficiency decreases beyond 120 kg N/ha (Boulelouah et al., 2022).

The economic and agronomic optimum is rarely achieved in practice, highlighting the discrepancy between research recommendations and farmer implementation.

4. CURRENT NITROGEN FERTILISATION PRACTICES AND THEIR LIMITATIONS

The international "4Rs" framework for optimal nitrogen management provides a useful structure for evaluating current practices: Right Source, Right Rate, Right Time, and Right Place. In terms of source selection, urea containing 46% N predominates in Algeria due to its relatively low cost, market availability, and support from the subsidy system. However, this demonstrates considerable problems in Algerian conditions, particularly very high ammonia volatilisation risk on alkaline calcareous soils with pH exceeding 8 (Li et al., 2017). Losses are particularly severe without rain immediately after application, with up to 30-40% N loss in dry conditions. Better alternatives include ammonium nitrate with lower volatilisation risk and stabilised fertilisers containing urease or nitrification inhibitors, but these are more expensive and have limited local market availability. Mechanical incorporation of urea immediately after spreading limits volatilisation but is rarely practised due to time, equipment, and labour constraints (Woodley et al., 2020).

Regarding the right rate, current practices reveal highly problematic dose-management patterns. When N dose increases from 40 to 120 kg/ha, NUE decreases drastically by 43% from 19.06 to 10,91 kg/kg, while NUpE drops 21% at 80 kg/ha and 43% at 120 kg/ha compared to the 40 kg/ha baseline (Boulelouah et al., 2022). Beyond 120 kg N/ha, there is no significant yield gain in rainy conditions due to progressive saturation of plant absorption capacity and proportional increase in environmental losses through volatilisation, leaching, and denitrification. Current problems include many farmers applying insufficient doses due to budgetary restrictions or drought anticipation, while others apply excessive doses hoping to maximise yield, and rarely accounting for predictable rainfall, initial soil N, or previous crop effects. The timing and fractionation of applications represent another major limitation. Traditional practice involves either a single massive application at tillering or two applications without agronomic reasoning at tillering and stem elongation.

The optimal split application strategy should allocate 33% at the beginning of tillering for good crop establishment and vigorous early growth, 67% at the 1 cm spike stage during early stem elongation to support yield component formation, and an optional third application at the last leaf stage to improve protein content without penalising yield (Belete et al., 2018). The benefits of proper fractionation include better synchronisation with crop physiological needs, substantially reduced volatilisation and leaching losses, avoidance of massive single inputs, and improvement of all agronomic parameters, including biomass, grain weight, yield, and protein content. Applications should be timed just before predicted rain or immediately followed by irrigation to promote rapid dissolution and infiltration.

Finally, the right place principle is largely violated in current practice. Surface broadcast without incorporation is the dominant method, leading to maximum exposure to volatilisation, uneven distribution, and poor root-zone contact. Improved methods include immediate incorporation by burying urea after spreading with a tool pass, and banding by applying it locally in bands near seed rows, both of which offer substantially improved efficiency and drastically reduced losses (Woodley et al., 2020).

The Nitrogen Nutrition Index (NNI) is an important diagnostic tool that compares the actual plant nitrogen concentration with a theoretical critical concentration that corresponds to nitrogen- limited growth. An NNI lower than 1 indicates nitrogen deficiency and nitrogen-limited growth, an NNI = 1 indicates optimal nitrogen nutrition, and an NNI higher than 1 indicates toxic or non- limiting nitrogen. In the case of Algeria, it has been found that the typical values of NNI are usually lower than 1, thus confirming that plants are nitrogen-limited, and there are large variations according to genotype and climatic year (Lupini et al. 2021).

Soil testing and management of input application data also entail opportunities that remain underexploited regarding the improvement of nitrogen use efficiency (NUE). At present, pre- planting soil testing is rarely practiced by Algerian agricultural producers, although the nitrogen availability contents show distinct spatial heterogeneity across Algerian soils, which vary between 11 and 37 mg/kg.

Also, appropriate adjustments of nitrogen application according to initial soil nutrient contents can help avoid excessive and insufficient nitrogen application. Other testing opportunities involve the analysis of crop residues at harvest time, previous to the current crop, where a preceding legume crop cycle or fallowed fields release relatively higher amounts of residual nitrogen compared to cereal-based crop rotation cycles. The development of supportive decision-making infrastructure rooted in modern testing opportunities is a fundamental chance for enhancing NUE within agricultural production practices.

Practical instruments for making a diagnosis differ in how easily and effectively they can be applied. Chlorophyll SPAD meters are utilized for assessing, in a real-time manner and under nondestructive conditions, the nitrogen status expressed in leaves and are cost-effective and portable (Chowdhury et al., 2024). The tissue test allows for plant nitrogen concentration determination and comparison with critical levels at successive growth phases. Remote sensing with NDVI and plant health parameters has a great application for diagnosing nitrogen status but is poorly utilized in Algeria. Each of these instruments holds a great ability to change nitrogen management practices into a precision level focused on crop peculiarities.

5. NUE PERFORMANCES DE BLÉ DUR EN ALGÉRIE

International comparisons also relate Algeria to the Mediterranean region. Algeria's average NUE value of 14,77 kg/kg is only 45% compared with the global average. This performance is further split with regard to dry years at 7,95 kg/kg, which is only 24% compared with the global average, and for wet years at 7,95 kg/kg, which is 60% compared with the global average. In similar semi-arid regions, Tunisia's performance is comparable at around 14.35-19.06 kg/kg, which corresponds to 43-58% compared with the global average. Morocco's performance is marginally better at around 20-30 kg/kg, which corresponds to 61-91% compared with the global average but is dependent on variable conditions. Southern European countries like Spain, Italy, or Greece perform better at around 25-35 kg/kg, which corresponds to 76-106% compared with the global average due to favorable conditions in the Mediterranean climate regions through efficient irrigation practices.

The global average NUE is 33 kg/kg (Ayadi et al., 2022; Lupini et al., 2021). These comparisons made in regards to NUE levels indicate that Algeria's performance is at the lower end among regions that belong to the Mediterranean climate The Mediterranean area offers large potential for the creation of added value, especially with reference to the management of water scarcity. Component analysis pinpoints where the bottleneck lies. Nitrogen Uptake Efficiency (NUpE) values vary from 0,29 kg/kg during dry years to 0,74 kg/kg during wet years, but are all substandard at values below 0,29 kg/kg, indicating that nitrogen uptake is the main constraining factor. Conversely, Nitrogen Utilisation Efficiency (NUtE) values vary from 24 to 27 kg/kg, which is within the Mediterranean limits of 20 to 30 kg/kg for Mediterranean environments, and indicates that varieties have good physiological efficiency (Boulelouah et al., 2022). It is therefore obvious that improving NUpE, as opposed to other factors, is crucial to maximize growth and production.

5.1 Effect of Nitrogen Dose on NUE Components

The relationship between nitrogen dose and capability demonstrates a clear inverse pattern. As N dose increases from 0 to 120 kg/ha, total N absorbed increases from 64.68 to 91,08 kg/ha (41% increase) and grain N increases from 46.12 to 60,96 kg/ha (32% increase). However, this increase is not proportional to the dose applied. NUpE decreases by 29% from 0.66 to 0,47 kg/kg when the dose increases from 40 to 120 kg/ha. NUE decreases drastically by 43% from 19.06 to 10,91 kg/kg. NUtE also declines by 15% from 28.22 to 24,00 kg/kg, and NHI decreases from 0.71 to 0.67 (Boulelouah et al., 2022).

This pattern reflects the law of diminishing returns. The first 40 kg N/ha produces a very high efficiency of 19,06 kg grain per kg N. The next 40 kg N/ha yields a moderate efficiency of 14,99 kg grain per kg N. The final 40 kg N/ha delivers a low efficiency of 10,91 kg grain per kg N. Beyond 120 kg N/ha, there is minimal or no yield increase. The declining efficiency results from progressive saturation of root absorption capacity, increased losses to the environment, and excessive N accumulation in vegetative parts that is not fully remobilised to grains (Dhakal et al., 2021).

The optimal plan includes moderate, well-considered N fertilisation at 100- 120 kg N/ha, representing the best compromise between acceptable yield, satisfactory protein quality, economic efficiency, and environmental protection.

5.2 The Critical Nitrogen × Rainfall Interaction

Nitrogen absorption by roots is directly and entirely dependent on soil moisture. Without sufficient water, nitrates and ammonium remain immobilised in concentrated soil solution, cannot be transported to roots by mass flow and diffusion, and cannot be effectively absorbed by membrane transporters that require metabolic energy from respiration. Evidence for this critical relationship comes from NUpE values ranging from single to almost triple, from 0.29 to 0,74 kg/kg between dry and wet years, highlighting an essential reliance on water availability (Lupini et al., 2021).

Water stress also affects nitrogen remobilisation during grain filling. Nitrogen absorbed early in vegetative parts, including stems and leaves, must be efficiently remobilised to grains during filling to ensure high yield and high protein quality. Water stress severely reduces photosynthesis, accelerates leaf senescence, disrupts orderly N remobilisation, and reduces both NUtE and NHI. Paradoxically, NHI sometimes reaches a maximum of 0.73 in dry years, explained by forced, accelerated mobilisation under acute stress, where vegetative biomass is "sacrificed," though this is not a desirable outcome despite the high NHI (Havé et al., 2017).

Practical management implications require an adaptive decision framework based on rainfall assessment. During the autumn-winter period from October to February, if cumulative rainfall is significantly below normal (less than 150 mm), the nitrogen dose should be reduced to 60-80 kg N/ha due to a high risk of poor utilisation and a high potential for loss. The normal rainfall range of 150-300 mm warrants a standard application of 100-120 kg N/ha, with balanced risk and reward. Above- normal rainfall exceeding 300 mm allows increased application of 120-140 kg N/ha, with a high probability of good utilisation and profitability. Spring monitoring from March to May should guide adjustments to the second and third applications based on actual rainfall received, crop N status as assessed by SPAD or visual assessment, and weather forecasts for the grain-filling period (Kourat et al., 2022).

Fixed, uniform N recommendations are inappropriate; the approach must integrate seasonal climate forecasts, regular precipitation monitoring during the season, and remain agile and adjustable.

6. IMPACT OF NITROGEN FERTILISATION ON YIELD AND QUALITY

Nitrogen fertilisation significantly affects biomass production and yield components. Biomass production increases significantly with N inputs through stimulated tillering and increased leaf area, for example, increasing from 4,070 to 4,582 kg/ha (12.6% gain) from 0 to 120 kg N/ha. The number of spikes represents the most responsive component to early N at tillering, likely boosted by 15% with N fertilisation, for example, from 238 to 279 spikes per square meter (Boulelouah et al., 2022).

Yield response varies highly with rainfall conditions. In wet years exceeding 400 mm, nitrogen effects are highly significant with yield gains up to 1.97 t/ha (40-50% increase) from 0 to 120 kg N/ha. Normal years with 250-400 mm show moderate effects, with a gain of 0.8-1.2 t/ha (20-30% increase). Dry years below 250 mm yield result in non-significant or even negative effects, with minimal or no yield response. Thousand-grain weight (TGW), determined during the final grain filling phase, is more influenced by water and temperature than N alone and can actually decrease with high N dose in dry conditions, for example, declining from 40.43 to 35.66 grams due to excessively high grain number versus available resources (Rharrabti et al., 2001).

Protein content shows a strong nitrogen response pattern. Grain protein content increases linearly with N inputs. In wet year examples, protein increases from 9.76% at 0 kg N/ha to 12.14% at 120 kg N/ha, representing a 24.4% increase. In dry years, protein increases from 12.4% to 17.5%, a dramatic 41% increase. The higher protein in dry years results from a concentration effect: low yields due to water stress mean absorbed N is concentrated in reduced grain mass, mechanically increasing the percentage (De Santis et al., 2021). Protein accumulation, which combines both yield and quality, provides a better quality metric, more relevant to nutrition and economics, that determines market value.

Protein accumulation increases from 243 kg/ha at 0 kg N/ha to 339 kg/ha at 120 kg N/ha, representing a 40% increase, with best conditions exceeding 900 kg/ha. Semolina and pasta industries prioritise and pay premiums for protein content exceeding 12% due to better pasta cooking quality and a more intense amber-yellow colour (Blandino et al., 2015).

The classic yield-protein antagonism presents a physiological trade-off: dry years produce very high protein (14-15%) but low yield (below 20 q/ha), while wet years achieve high yield (above 40 q/ha) but moderate protein (11-12%). Overcoming this antagonism requires a late N application strategy, applied at the last leaf stage or early heading. Although little is absorbed in absolute terms as growth slows, nitrogen is very efficiently directed to developing grains, significantly increasing protein without penalising yield, though this strategy faces additional costs and the technical difficulty of late-season field intervention (Blandino et al., 2015).

7. ECONOMIC PROFITABILITY OF NITROGEN FERTILISATION

Net marginal return (NMR) analysis shows dramatic variability by climatic conditions. Unfavourable dry years with less than 250 mm rainfall yield NMR of 236.67 €/t as a baseline. In normal years with 250-400 mm, yields reach approximately 470 €/t, representing a 98% increase. Favourable wet years exceeding 400 mm produce 745.03 €/t, a remarkable 215% increase over dry years. This high interannual variability, with single- to triple-year variations, represents a major economic risk for farmers who must decide on fertilisation before knowing actual rainfall patterns (Ierna & Mauromicale, 2019).

Paradoxically, increasing the dose from 0 to 120 kg N/ha results in a 13% reduction in net income from €606.55 to €529.48 per ton. This happens because the high additional cost of fertiliser at high doses is not compensated by sufficient yield gain, particularly in frequent unfavourable rainfall years. The marginal rate of return ranges from 1.64 to 2.36, meaning each €1 invested in N generates €1.64- 2.36 additional net income, which generally continues to be positive, indicating N fertilisation is profitable overall (Euclides et al., 2022). The economic optimum recommends 100-120 kg N/ha for durum wheat under rainfed conditions.

This optimum achieves a yield close to the maximum achievable, acceptable and valuable protein content of 11-12 % in normal years, and optimised economic profitability. Lower doses of 40-60 kg N/ha significantly limit yield potential and fail to reach minimum protein levels for optimal industrial valorisation. Higher doses exceeding 150 kg N/ha produce no significant yield increase in rainy conditions, increased lodging risk, especially in wet years, degraded net economic profitability, and higher costs without proportional benefit. These average recommendations must be adjusted for seasonal climate forecasts, fluctuating relative prices among inputs and products, and variable initial soil N content, strengthening the need for personalised, situation-specific advice (Boulelouah et al., 2022).

8. NITROGEN LOSSES AND ENVIRONMENTAL IMPACTS

The fate of applied nitrogen shows considerable inefficiencies. Recovery efficiency reaches 81% in the best conditions with a wet year, optimal fractionation, and moderate dose, but drops below 30% in poor conditions with a dry year and high dose. The average recovery of 50-60% means that 40-50% of applied N is lost or immobilised, representing both meaningful economic loss for farmers and major environmental risk (Davies et al., 2020).

Major nitrogen loss pathways in Algerian conditions include ammonia volatilisation, which accounts for 30-40% of applied N. This occurs under conditions of high pH (>8), urea use, the absence of rain, and high temperatures, leading to air pollution and the formation of PM2.5 (Li et al., 2017). Nitrate leaching varies with conditions, being particularly problematic in sandy soils and under intense rainfall, leading to groundwater contamination (Lakhdari et al., 2025).

Denitrification occurs moderately under waterlogged clay soils, producing N_2O emissions as a powerful greenhouse gas (Rabbai et al., 2024). Runoff represents low to moderate losses during intense rainfall and on slopes, leading to surface water eutrophication. Ammonia volatilisation is particularly significant in Algeria due to characteristic alkaline soils with pH exceeding 8, where urea is quickly hydrolysed to ammonium, which then volatilises as gaseous ammonia.

High temperatures and drying winds accelerate loss, with up to 30-40% loss without rain after application. Reduction approaches include immediate mechanical incorporation into soil and application just before predicted rainfall, though these practices are rarely implemented due to practical challenges (Woodley et al., 2020).

Nitrate leaching in Algeria occurs under conditions where generally limited precipitation reduces leaching risk, but occasional intense Mediterranean rainfall episodes pose problems, particularly in light sandy soils and irrigated areas. Hydrogeochemical studies show nitrate concentrations in groundwater locally exceed potability standards of 50 mg NO_3^-/L, posing public health problems (Boufekane et al., 2021). Denitrification involves the biological conversion of nitrates to N_2O, a powerful greenhouse gas, and N_2, which is inert but represents N loss. This occurs in heavy clay soils that are poorly drained and temporarily waterlogged. The importance resides in

N_2O has a global warming potential 298 times that of CO_2 over 100 years (Rabbai et al., 2024). Environmental impacts manifest in multiple ways. Eutrophication of surface waters occurs through runoff of nitrogen-laden water into rivers, lakes, and reservoirs, leading to excessive algal growth and blooms that degrade water quality. In Algeria, intensive cereal regions, including the Sétif plain and Mitidja, experience recurrent algal blooms during heavy rainfall, compromising water supply for drinking and agricultural irrigation (Schmale et al., 2019).

Groundwater pollution represents an emerging public health problem, with intensive cultivation areas showing elevated nitrate levels in wells and boreholes that often exceed the 50 mg NO_3^-/L standard, posing health risks, including methemoglobinemia in infants and potential hazards for other groups. The long-term concern is that groundwater recharge is very slow in a semi-arid context, so accumulated pollution persists for decades even after reducing surface N inputs (Lakhdari et al., 2025). Greenhouse gas emissions include direct N_2O emissions, primarily from microbial denitrification, with agricultural soils representing roughly 75% of total N_2O emissions in Algeria. Since N_2O has a global warming potential 298 times that of CO_2 over 100 years, this constitutes a major contribution to climate change.

Indirect emissions arise from industrial N fertiliser production through the energy-intensive Haber-Bosch process contributing significant fossil CO_2. Ammonia volatilisation contributes to fine particulate matter (PM2.5), acidification of terrestrial and aquatic ecosystems, and negative impacts on air quality and biodiversity (Rabbai et al., 2024).

8.1 Toward Sustainable Nitrogen Management

The international "4R" concept provides a relevant and operational framework for optimising nitrogen use. The Right Source principle recommends choosing the N fertiliser form most suitable for local pedoclimatic conditions. Currently, urea dominates due to its low cost and availability, but ammonium nitrate or stabilised fertilisers with urease or nitrification inhibitors would be better, though they are more expensive. The method consists of differentiated public subsidy policies favouring more efficient forms (Woodley et al., 2020).

The Right Rate principle requires adjusting the N dose to actual crop requirements and circumstances through decision-making tools adapted to the Algerian context, combined with soil analysis, rainfall monitoring, and foliar diagnostics, including SPAD and NNI. Recommendation grids should account for initial soil N, previous crop, soil type, region, and forecasts. Tools needed include calibrated crop simulation models for dynamic N need simulation and optimised fertilisation strategies for changing conditions (Liu et al., 2022).

The Right Time principle aims to maximise crop N uptake while minimising losses. Optimal fractionation for Algeria allocates 33% at the beginning of tillering to ensure good establishment and vigour, 50% at 1 cm spike stage during early stem elongation to support yield component formation, and an optional 17% at the last leaf stage to improve protein content specifically. Critical timing requires application just before predicted rainfall or immediately after irrigation (Belete et al., 2018).

The Right Place principle entails placing N near active roots to optimise absorption, using methods such as burying urea immediately after spreading and applying it locally in bands near seed rows. These methods substantially improve efficiency and drastically reduce losses (Woodley et al., 2020).

Decision support tools are available at varying levels in Algeria. Soil analysis to determine initial N status before sowing is limited in availability and needs expansion. SPAD meters for instantaneous leaf N assessment during the season are in limited supply. NNI for diagnosing N nutrition status during the season remains in research use only. Weather forecasts for timing applications are improving throughout the season. Crop models for dynamically simulating N requirements during the planning stage are still in research use only. Mobile apps and SMS for delivering personalised advice throughout the season represent emerging capabilities (Ding et al., 2022).

8.2 Strategies for Improving NUE

Genetic improvement through exploiting genetic variability shows that modern high-performing genotypes, such as Megress and GTAdur, demonstrate high productivity, good NUE, and stability across contrasting environments, and act as important sources of favourable traits (Gouis et al., 2000). Selection criteria should include traditional grain yield, as well as explicit NUpE and NUtE, and performance steadiness across dry versus wet years and poor versus rich soils, with multi-environment selection for the most stable and resilient genotypes.

Priority traits for improvement should focus on better NUpE through deeper, denser, and more efficient root systems that explore larger soil volumes and access N and water at depth, which is critical in semi-arid conditions. The difficulty lies in root phenotyping under field conditions, which is technically challenging and costly, and the solution involves using molecular markers linked to quantitative trait loci (QTLs) controlling root architecture (Karunarathne et al., 2020). For better NUTE, priorities include improved N remobilisation from vegetative organs to grains, a high and stable NHI, progressive and orderly foliar senescence, and prolonged grain-filling duration. Modern tools, including genomics and marker-assisted selection, can pyramid multiple favourable complex traits and significantly accelerate genetic progress (Liang et al., 2025). Optimisation of cultural practices begins with sowing management. Early sowing in October- November, depending on region and altitude, promotes deeper autumn rooting and better utilisation of autumn and winter rains.

Optimal seeding density of 300-350 viable grains per square meter for durum wheat under rainfed conditions provides a good compromise between competition and resource utilisation (Porker et al., 2020). Previous crop and residue management provide considerable opportunities. Legume preceding crops, including fava bean, chickpea, and lentil, can provide 30-60 kg N/ha through symbiotic N fixation and mineralisation of N-rich residues. The traditional cereal-long fallow system could evolve into a cereal-legume rotation, with benefits including improved NUE, biological sustainability, and economic broadening (Venkatesh et al., 2017; Smith et al., 2023). Residue incorporation post-harvest via systematic incorporation gradually builds organic matter stocks, with mineralisation providing N to subsequent crops.

Simplified cultivation techniques (SCT), particularly direct seeding, offer multiple benefits, including maintaining permanent residue cover on the soil surface, decreasing direct evaporation, improving water infiltration and retention, decreasing runoff and erosion risks, thereby reducing N losses, and limiting abrupt organic matter mineralisation (Kumar et al., 2023). Experimental trials in Algeria show that direct seeding can improve yields by 33-34 q/ha compared with conventional ploughing in semi-arid areas, largely due to better water conservation, which enhances N utilisation.

Improved water management is a critical integration, given NUE's strong dependence on water availability. Water management must be integrated with N management through strategies such as supplementary irrigation at crucial periods (if available), water-harvesting techniques, soil moisture conservation through mulching and reduced tillage, and matching N application to water availability. Irrigation timing should be coordinated with N applications for maximum efficiency (Saggaï & Bachi, 2018).

8.3 Public Policies and Economic Incentives

Change in the subsidy regime requires consideration of the current state where general fertilizer subsidies lower production cost but can lead to overuse or inappropriate use irrespective of efficiency. An efficient fertilizer subsidy regime will require progressive improvements to effectively direct subsidies toward more efficient types of fertilizer, namely stabilized fertilizers and ammonium nitrate, and not urea.

Subsidized financial support will be required to encourage farmers to adopt methods that can increase Nitrogen Use Efficiency (NUE) related to soil testing, optimal split application, modern testing methods, and simplified farming practices (Noor, 2017). Remunerative quality standards must respond to the current problem that the institutional purchase price of durum wheat does not adequately take into account protein levels. This has the consequence of discouraging optimal N fertilization.

The proposed method would consist of a transparent pricing system according to protein levels and the introduction of a bonus-malus system to adequately reward farmers and promote step-by-step optimization of agricultural practices to favor the right compromise between production levels and respect for the environment (Blandino et al., 2015).

Regulations on the environment and strict conditions concerning the maximum rate of N applied in sensitive areas would reduce diffuse contamination and promote greater efficiency (Vasile Scăețeanu & Madjar, 2025). R&D funding is relevant to meeting major long-run needs for research and development on nutrition related to N, particularly concerning semi-arid environments, whereby it seeks to develop specific research-oriented knowledge that can provide Algerian settings with innovative solutions geared to meet local challenges.

Among various research thrusts are those related to climate change, greater efficacy for diagnosis specific to Algeria, economic assessments related to better methodologies, research that encourages farmer involvement, and those studying geographical variations (Kourat et al., 2022).

Case Study: Applied Implementation

An example farm in the Sétif region demonstrates the potential for improvement. Baseline conditions before optimisation included 20 hectares of durum wheat using the older Bousselam variety with 150 kg/ha N application as a single application at tillering using urea fertiliser, achieving an average yield of 18 q/ha, protein content of 11.5 %, NUE of 9,2 kg/kg, and net income of €450/ha.

After implementing recommendations including switching to the improved GTAdur variety, reducing N application to 110kg/ha split between 37 kg at tillering and 73 kg at stem elongation, using ammonium nitrate fertilizer, conducting soil tests, and SPAD monitoring during season, results improved dramatically to average yield of 26 q/ha (44% increase), protein content of 12.8% (11 % increase), NUE of 16,3 kg/kg (77% increase), and net income of €680/ha (51% increase). Key success factors included reduced total N dose but improved placement and timing, better variety selection, more efficient N source, diagnostic tool use, and split application strategy (Boulelouah et al., 2022).

Conclusions and Perspectives

Evaluation of the current state reveals that nitrogen use efficiency (NUE) in cereal production in Algeria is a worrying factor, which is yet to reach a satisfactory level. The existing NUE level of 14,77 kg of grain per unit of nitrogen with a percentage of 50% compared to the world average (33 kg/kg) also indicates a dramatic situation with great fluctuations varying from 7.95 to 19,87 kg/kg depending upon the rain regime, which comes as a major limitation due to the critical nitrogen-water interaction typical of a semi-arid region, leading to a condition of recurrent vulnerability to natural risks (Lupini et al., 2021).

Levers for change act on various timescales. Short-term levers (change period: 1-2 years) are: Split application (expected NUE effect: 15-25%, low level of difficulty), use of SPAD (impact: 10-15%, low level of difficulty), supplementation for soil testing (impact: 10-20%, medium level of difficulty), and public awareness programs for farmers (impact: 5-10%, low level of difficulty). The medium-term levers for change (change period: 3-5 years) are: Improvement in subsidy schemes (impact: 20-30%, high level of difficulty), development of agricultural advisory services (impact: 25-35%, medium level of difficulty), quality-based pricing (impact: 15-25%, medium level of difficulty), and demonstration sites (impact: 10-20%, low level of difficulty).

The long-term levers for change (change period: 5-10 years) are: Use of improved crop varieties (impact: 30-50%, medium level of difficulty), simplification/modification of crop production practices (impact: 25-40%, medium level of difficulty), adoption of legume crop rotations (impact: 20-35%, low level of difficulty), Problems and constraints requiring attention include climate change, with projections on rising temperatures and lower precipitation, which may accentuate existing conditions, further degrade NUE, and add uncertainty (Kourat et al., 2022). Financial barriers, such as the high cost of efficient fertilizer and technology, act as a hindrance, especially for smaller farmers, which demands financial assistance. Inadequacies in the institutional capabilities related to agricultural advisory systems and inefficient use of best practices demand considerable outlays. Financial motivations are inadequate, which stems from poor valuations related to poor quality, which does not favor optimal fertilizer use for quality, requiring a change in financial policies. Knowledge- related problems include poor comprehension related to geographic variation, the need for more location-specific studies, and poor awareness by the farmer. Nevertheless, there exist some challenges which, if met, would help improve the present scenario. Climate service provision with proper season-long forecasting can help farmers make fertilization policies appropriate for their region (Kourat et al., 2022). Information technology, like mobile phone applications and text messages, can help in sharing appropriate advices and weather notifications (Ding et al., 2022). National agricultural research and international collaboration can help develop region-specific knowledge and innovation (Reddy et al., 2024). Encouragement for sustainable and efficient agricultural practices can help create a favorable environment, and increased awareness can accelerate adoption of more sustainable practices.

Final recommendations for the various stakeholders are specific and provide direct instructions to follow. Farmers, to mention, must do the following among others: split applications of nitrogen with one-third and two-thirds of total applied at tillering and stem elongation, respectively; apply nitrogen based on seasonal rainfall forecasts; test soils before sowing; use SPAD meters or visual diagnosis; practice superior varieties like GTAdur and Megress; and take part in trainings and demonstrations (Boulelouah et al., 2022).

Recommendations for decision-makers include: gradual subsidy reform to benefit efficient N forms; implementation of quality-based prices for durum wheat; agri-advice service development; research and development, environmental regulations in at-risk areas; development of a high-quality climate forecast service (Vasile Scăețeanu & Madjar, 2025).

Among the priorities for researchers are the continuation of knowledge development for the local conditions, the development of local diagnosis tools and the economic analysis of improved practices, participatory research with growers, regional analysis, and the effects of climate change on NUE (Kourat et al. 2022; Reddy et al. 2024).

Regarding Extension Services, the crucial activities are developing the network of demonstration plots, offering tailored information according to the season, conducting training on advanced diagnostics, facilitating farmer-to-farmer knowledge sharing, and sharing success stories and case studies (Ding et al., 2022). For the stakeholders in the industry, the recommendations include the production and promotion of efficient N fertilizers, promotion of training programs for farmers, adoption of quality-oriented purchase systems, infrastructure for better N forms, and coordination on R&D (Blandino et al., 2015). "The way ahead is an imperative.

Improving NUE in Algerian agriculture is a major challenge as well as a huge opportunity for improving agricultural production, food security, the economic profitability of farmers, and environment management simultaneously (Coggins et al., 2025). This requires a joint and coordinated effort on the part of scientists, advisors, farmers, policymakers, and representatives from the cereal sector as a whole. The knowledge and technologies for the use of improved NUE are available, and the only issue is the use and adoption of the knowledge and the technologies on a wider scale. Algeria can change its cereal agriculture system into a productive and profitable system for ensuring future generations' food security and environmental integrity.

REFERENCES

Abeledo, L. G., Savin, R., & Slafer, G. A. (2008). Wheat productivity in the Mediterranean Ebro Valley: Analyzing the gap between attainable and potential yield with a simulation model. European Journal of Agronomy, 28(4), 541-550. https://doi.org/10.1016/j.eja.2007.12.001

Ayadi, S., Trifa, Y., Zouari, I., Esposito, S., Hammami, Z., Landi, S., Baraket, M., Jallouli, S., Ben Azaiez, F., & Chamekh, Z. (2022). Variation of grain yield, grain protein content and nitrogen use efficiency components under different nitrogen rates in Mediterranean durum wheat genotypes. Agriculture, 12(7), Article 916. https://doi.org/10.3390/agriculture12070916

Belete, F., Molla, A., Tana, T., & Dechassa, N. (2018). Effect of split application of different N rates on productivity and nitrogen use efficiency of bread wheat (Triticum aestivum L.). Agriculture & Food Security, 7(1), Article 92. https://doi.org/10.1186/s40066-018-0242-9

Benbelkacem, A., & Kellou, K. (2000). Évaluation des variétés de céréales dans différents environnements et diagnostic sur les potentialités et les contraintes des zones de production [Evaluation of cereal varieties in different environments and diagnosis of the potential and constraints of production areas]. Recherche Agronomique, 7, 21-36.

Bheemanahalli, R., Balyan, H. S., Saripalli, G., Gill, K. S., Gupta, P. K., Sunoj, V. S. J., Grant, N., Jagadish, S. V. K., & Prasad, P. V. V. (2019). Quantifying the impact of heat stress on pollen germination, seed set, and grain filling in spring wheat. Crop Science, 59(2), 684-696. https://doi.org/10.2135/cropsci2018.05.0292

Blandino, M., Vaccino, P., & Reyneri, A. (2015). Late-season nitrogen increases improver common and durum wheat quality. Agronomy Journal, 107(2), 680-690. https://doi.org/10.2134/agronj14.0405

Boufekane, A., Yahiaoui, S., Meddi, H., Meddi, M., & Busico, G. (2021). Modified DRASTIC index model for groundwater vulnerability mapping using geostatistic methods and GIS in the Mitidja plain area (Algeria). Environmental Forensics, 23(5-6), 539-556. https://doi.org/10.1080/15275922.2021.1913674

Boulelouah, N., Berbache, M., Rebouh, N., Bedjaoui, H., & Selama, N. (2022). Influence of nitrogen fertilizer rate on yield, grain quality and nitrogen use efficiency of durum wheat (Triticum durum Desf) under Algerian semiarid conditions. Agriculture, 12(11), Article 1937. https://doi.org/10.3390/agriculture12111937

Chowdhury, M., Kumar Khura, T., Ahmad Parray, R., Kushwaha, H. L., Upadhyay, P. K., Jha, A., Patra, K., Kushwah, A., & Kumar Prajapati, V. (2024). The use of destructive and nondestructive techniques in concrete nitrogen assessment in plants. Journal of Plant Nutrition, 47(14), 2271- 2294.https://doi.org/10.1080/01904167.2024.2342353

Coggins, S., Urfels, A., Sherpa, S. R., Jat, M. L., Kumar, V., Jat, H. S., McDonald, A. J., Silva, J. V., Sapkota, T. B., Malik, R. K., Krupnik, T., Nayak, A. K., Craufurd, P., & Nayak, H. S. (2025). Data- driven strategies to improve nitrogen use efficiency of rice farming in South Asia. Nature Sustainability, 8(1), 22-33. https://doi.org/10.1038/s41893-024-01496-3

Davies, B., Coulter, J. A., & Pagliari, P. H. (2020). Timing and rate of nitrogen fertilization influence maize yield and nitrogen use efficiency. PLoS ONE, 15(5), Article e0233674. https://doi.org/10.1371/journal.pone.0233674

De Santis, M. A., Flagella, Z., Laus, M. N., & Soccio, M. (2021). Influence of drought and salt stress on durum wheat grain quality and composition: A review. Plants, 10(12), Article 2599. https://doi.org/10.3390/plants10122599

Dhakal, K., Pandit, N. R., Vista, S. P., Baral, B. R., Pokhrel, K. R., & Gaihre, Y. K. (2021). Optimizing N fertilization for increasing yield and profits of rainfed maize grown under sandy loam soil. Nitrogen, 2(3), 359- 377. https://doi.org/10.3390/nitrogen2030025

Ding, J., Jia, X., Zhang, W., & Klerkx, L. (2022). The effects of combined digital and human advisory services on reducing nitrogen fertilizer use: Lessons from China's national research programs on low carbon agriculture. International Journal ofAgricultural Sustainability, 20(6), 1136-1149. https://doi.org/10.1080/14735903.2022.2057643

Euclides, V. P. B., Montagner, D. B., De Araújo, A. R., De Aragão Pereira, M., Dos Santos Difante, G., De Araújo, I. M. M., Barbosa, L. F., Barbosa, R. A., & Gurgel, A. L. C. (2022). Biological and economic responses to increasing nitrogen rates in Mombaça guinea grass pastures. Scientific Reports, 12(1), Article 1230. https://doi.org/10.1038/s41598-022-05796-6

Fageria, N. K., & Baligar, V. C. (2005). Enhancing nitrogen use efficiency in crop plants. Advances in Agronomy, 88, 97-185. https://doi.org/10.1016/S0065-2113(05)88004-6 Food and Agriculture Organization of the United Nations. (2018). FAOSTAT: Statistical database. https://www.fao.org/faostat/en/

Food & Agriculture, 3(1), Article 1348214. https://doi.org/10.1080/23311932.2017.1348214

Gouis, J. L., Béghin, D., Heumez, E., & Pluchard, P. (2000). Genetic differences for nitrogen uptake and nitrogen utilisation efficiencies in winter wheat. European Journal ofAgronomy, 12(3-4), 163-173. https://doi.org/10.1016/S1161-0301(00)00045-9

Halitim, A. (1988). Sols des régions arides d'Algérie [Soils of the arid regions ofAlgeria]. Office des Publications Universitaires.

Havé, M., Marmagne, A., Chardon, F., & Masclaux-Daubresse, C. (2017). Nitrogen remobilization during leaf senescence: Lessons from Arabidopsis to crops. Journal of Experimental Botany, 68(10), 2513-2529. https://doi.org/10.1093/jxb/erw365

Ierna, A., & Mauromicale, G. (2019). Sustainable and profitable nitrogen fertilization management of potato. Agronomy, 9(10), Article 582. https://doi.org/10.3390/agronomy9100582 International Fertilizer Industry Association. (2013). Assessment of fertilizer use by crop at the global level 2010-2010/11. IFA. https://www.fertilizer.org

Karunarathne, S. D., Han, Y., Li, C., & Zhang, X.-Q. (2020). Advances in understanding the molecular mechanisms and potential genetic improvement for nitrogen use efficiency in barley. Agronomy, 10(5), Article 662. https://doi.org/10.3390/agronomy10050662

Kourat, T., Smadhi, D., & Madani, A. (2022). Modeling the impact of future climate change impacts on rainfed durum wheat production in Algeria. Climate, 10(4), Article 50. https://doi.org/10.3390/cli10040050

Kumar, R., Meena, P., Kumar, A., Dhandapani, A., Yashavanth, B., Kumar, S., & Venu, N. (2023). Natural farming practices for chemical-free agriculture: Implications for crop yield and profitability. Agriculture, 13(3), Article 647. https://doi.org/10.3390/agriculture13030647

Lakhdari, A. S., Bouselsal, B., Saibi, H., & Ouarekh, M. (2025). Assessment of groundwater quality and hydrogeochemical properties in the Adrar Continental Intercalaire aquifer of the Algerian Sahara. Applied Water Science, 15(7), Article 150. https://doi.org/10.1007/s13201-025-02552-9

Li, Y., Huang, L., Liang, Z., Zhang, H., & Wang, M. (2017). Assessment of ammonia volatilization losses and nitrogen utilization during the rice growing season in alkaline salt-affected soils. Sustainability, 9(1), Article 132. https://doi.org/10.3390/su9010132

Liang, Y. L., Yan, P. S., Li, W. X., Ding, W. N., Li, G. X., Xu, J. M., Ding, Z. J., & Zheng, S. J. (2025). Bridging genomic insights to agricultural practice: GWAS applications in mining nutrient utilization efficiency genes for crop improvement. Plant, Cell & Environment, 48(10), 3145-3162. https://doi.org/10.1111/pce.70027

Liu, Q., Zhong, N., Fu, X., Song, W., Wu, Y., & Wu, K. (2022). Improving crop nitrogen use efficiency toward sustainable green revolution. Annual Review of Plant Biology, 73(1), 523-551. https://doi.org/10.1146/annurevarplant-070121-015752

Lupini, A., Bacchi, M., Sunseri, F., Badagliacca, G., Abenavoli, M. R., Preiti, G., & Monti, M. (2021). Nitrogen use efficiency in durum wheat under different nitrogen and water regimes in the Mediterranean basin. Frontiers in Plant Science, 11, Article 607226. https://doi.org/10.3389/fpls.2020.607226

Mekhlouf, A., Benderradji, L., Chenafi, H., Bouzerzour, H., & Fellahi, Z. (2006). Étude comparative de quelques variétés de blé dur (Triticum durum Desf.) cultivées en Algérie [Comparative study of some durum wheat varieties (Triticum durum Desf.) cultivated in Algeria]. Courrier du Savoir, 7, 63- 68.

Ministère de l'Agriculture et du Développement Rural. (2015). Statistiques agricoles: Superficies et productions [Agricultural statistics: Areas and production] (Series B). MADR.

Moll, R. H., Kamprath, E. J., & Jackson, W. A. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agronomy Journal, 74(3), 562-564. https://doi.org/10.2134/agronj1982.00021962007400030037x

Mrad, D., Djebbar, Y., Dairi, S., & Boukhari, S. (2019). Applied multivariate analysis on annual rainfall in the northeast ofAlgeria. Journal of Water and Climate Change, 11(4), 1165-1176. https://doi.org/10.2166/wcc.2019.272

Noor, M. A. (2017). Nitrogen management and regulation for optimum NUE in maize -- A mini review. Cogent

Porker, K., Straight, M., & Hunt, J. R. (2020). Evaluation of G × E × M interactions to increase harvest index and yield of early sown wheat. Frontiers in Plant Science, 11, Article 994. https://doi.org/10.3389/fpls.2020.00994

Rabbai, A., Barba, J., Canducci, M., Hart, K. M., Mackenzie, A. R., Kettridge, N., Curioni, G., Ullah, S., & Krause, S. (2024). Fertilization-induced greenhouse gas emissions partially offset carbon sequestration during afforestation. Soil Biology and Biochemistry, 199, Article 109577. https://doi.org/10.1016/j.soilbio.2024.109577

Reddy, M. B., Sravani, P., Kumar, S., Rajawat, M. V. S., Jaiswal, D. K., Dhar, S., Azman, E. A., Garg, K., & Kumar, S. (2024). Nitrogen use efficiency reimagined: Advancements in agronomic, ecophysiological, and molecular strategies. Journal of Plant Nutrition, 48(9), 1577-1603. https://doi.org/10.1080/01904167.2024.2447840

Rharrabti, Y., Villegas, D., García del Moral, L. F., Aparicio, N., Elhani, S., & Royo, C. (2001). Environmental and genetic determination of protein content and grain yield in durum wheat under Mediterranean conditions. Plant Breeding, 120(5), 381-388. https://doi.org/10.1046/j.1439-0523.2001.00628.x

Saggaï, S., & Bachi, O. E. K. (2018). Evaporation reduction from water reservoirs in arid lands using monolayers: Algerian experience. Water Resources, 45(2), 280-288.https://doi.org/10.1134/S009780781802015X

Schmale, D. G., Ault, A. P., Saad, W., Scott, D. T., & Westrick, J. A. (2019). Perspectives on harmful algal blooms (HABs) and the cyberbiosecurity of freshwater systems. Frontiers in Bioengineering and Biotechnology, 7, Article 128. https://doi.org/10.3389/fbioe.2019.00128

Smith, M. E., Onofri, A., Stalenga, J., Bommarco, R., García-Díaz, A., Schmer, M. R., Lehman, R. M., SantínMontanyá, I., Berti, A., Morari, F., Costa, A., Drury, C. F., Sandström, B., Plaza, E. H., Osborne, S. L., Blecharczyk, A., Calderon, F. J., Strock, J., Culman, S., ... Jäck, O. (2023). Increasing crop rotational diversity can enhance cereal yields. Communications Earth & Environment, 4(1), Article 82. https://doi.org/10.1038/s43247-023-00746-0

Vasile Scăețeanu, G., & Madjar, R. M. (2025). The control of nitrogen in farmlands for sustainability in agriculture. Sustainability, 17(12), Article 5619. https://doi.org/10.3390/su17125619

Venkatesh, M. S., Hazra, K. K., Ghosh, P. K., Khuswah, B. L., Ganeshamurthy, A. N., Ali, M., Singh, J., & Mathur, R. S. (2017). Long-term effect of crop rotation and nutrient management on soil- plant nutrient cycling and nutrient budgeting in Indo-Gangetic plains of India. Archives ofAgronomy and Soil Science, 63(14), 2007- 2022. https://doi.org/10.1080/03650340.2017.1320392

Woodley, A. L., Calder, W., Oloya, T. O., Phillips, L. A., Yang, X. Y., Drury, C. F., & Reynolds, D. W. (2020). Ammonia volatilization, nitrous oxide emissions, and corn yields as influenced by nitrogen placement and enhanced efficiency fertilizers. Soil Science Society ofAmerica Journal, 84(4), 1327-1341. https://doi.org/10.1002/saj2.20079

Xu, Z., Jiang, Y., & Zhou, G. (2022). Temperature effects on crop productivity. In G. Zhou & Y. Wang (Eds.), Plant responses to climate change (pp. 45-78). Academic Press.

CHAPTER 3
ISLAMIC ECO-THEOLOGY IN ENVIRONMENTAL ENGINEERING EDUCATION IN INDONESIA

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INTRODUCTION

Environmental degradation has emerged as one of the most pressing global challenges of the twenty-first century, affecting ecological stability, public health, economic resilience, and social justice (Yao et al., 2024). Climate change, water pollution, biodiversity loss, and unsustainable resource exploitation increasingly demand integrated solutions that transcend purely technical approaches (Jianing et al., 2024). Environmental engineering, as a discipline, plays a critical role in addressing these challenges through the design of sustainable systems, technologies, and infrastructures. However, growing evidence suggests that technical competence alone is insufficient to ensure long-term environmental sustainability. Ethical frameworks, cultural values, and moral responsibility significantly influence the application of ecological knowledge in real-world studies. In this regard, higher education institutions are increasingly called upon to cultivate not only technical expertise but also environmental ethics and ecological consciousness among future engineers (H. Huang et al., 2024).

Indonesia presents a particularly compelling study for this discourse. As one of the world's most biodiverse countries and the largest Muslim-majority nation, Indonesia faces severe environmental challenges, including deforestation, water contamination, coastal degradation, and urban waste management problems (Surur et al., 2025). These issues are exacerbated by rapid industrialisation, population growth, and uneven environmental governance. At the same time, Indonesian society is profoundly shaped by religious values, particularly Islamic teachings that emphasise the stewardship of the Earth. This intersection between environmental urgency and religious worldview creates a unique opportunity to integrate Islamic eco-theology into environmental engineering education as a value-based framework for sustainable development (Adinugraha, Solehuddin, et al., 2025).

Islamic eco-theology is rooted in Qur'anic principles and prophetic traditions that articulate a holistic relationship between humans, nature, and the Creator. Concepts such as *khalifah* (stewardship), *amanah* (trust), *mizan* (balance), and *fasad* (corruption of the Earth) offer a comprehensive ethical foundation for environmental responsibility.

These principles frame environmental care not merely as a technical obligation but as a moral and spiritual duty. Despite their relevance, Islamic eco-theological values remain underutilised in formal engineering education, which often prioritises positivistic and technocratic paradigms detached from ethical and spiritual dimensions (Adinugraha, Sholehuddin, et al., 2025).

The dominant paradigm in environmental engineering education globally has been shaped by Western scientific traditions that emphasise efficiency, optimisation, and technological innovation. While these approaches have produced significant advancements, they often marginalise local wisdom, religious ethics, and socio-cultural studies. In Indonesia, this epistemological gap becomes more pronounced as engineering curricula frequently adopt global standards without sufficient local adaptation. As a result, graduates may possess advanced technical skills yet lack the ethical orientation and cultural sensitivity needed to address environmental problems in a socially responsible and sustainable manner (Haque & Sharif, 2021).

Integrating Islamic eco-theology into environmental engineering education can enrich the epistemological foundation of the discipline by embedding ethical reasoning, moral accountability, and spiritual awareness into technical learning processes. Such integration does not seek to replace scientific rigour but to complement it by fostering environmentally responsible engineers who internalise sustainability as a moral imperative (Latuapo & Farid, 2024). By aligning engineering education with Islamic ethical values, institutions can produce graduates who are not only problem solvers but also guardians of ecological balance.

Recent scholarly works have increasingly explored the relationship between religion and environmentalism. Studies in environmental ethics underscore the influence of faith-based values on shaping pro-environmental behaviour and policy advocacy. Islamic studies scholars have developed eco-theological interpretations of the Qur'an and Sunnah, emphasising environmental stewardship as a crucial component of the Islamic worldview. Meanwhile, research in engineering education has begun to acknowledge the importance of ethics, sustainability, and social responsibility in curriculum design (Rohman et al., 2024). However, these bodies of literature often develop in isolation, with limited interdisciplinary synthesis.

In the Indonesian study, existing studies primarily focus on Islamic environmental ethics at the community level, environmental education in Islamic schools, or general sustainability education in higher education. Research on ecological engineering education tends to emphasise technical competencies, accreditation standards, and industry alignment, with minimal attention given to the integration of religious or ethical considerations (Romdloni et al., 2024). Few studies systematically examine how Islamic eco-theological principles can be conceptually and pedagogically embedded within environmental engineering curricula. This lack of integration reflects a broader state of the art in which ecological engineering education remains largely secular and technocratic, even in societies with a religious foundation.

The absence of a coherent framework for integrating Islamic eco-theology into environmental engineering education constitutes a significant research gap. Current curricula rarely articulate how Islamic values can inform engineering decision-making, project design, or environmental impact assessment. There is limited empirical and conceptual research addressing how such integration can be operationalised at the curriculum, instructional, and institutional levels. Moreover, there is a lack of analysis on how students and educators perceive the relevance of Islamic eco-theology to engineering practice (Arofah et al., 2025).

This chapter identifies several interrelated problems arising from this gap. Environmental engineering education in Indonesia often lacks a value-based orientation that resonates with students' religious identities. Ethical instruction, when present, tends to be generic and detached from Islamic moral frameworks. Consequently, graduates may approach environmental problems with a narrow technical mindset that overlooks ethical consequences and long-term ecological balance. This disconnect undermines the transformative potential of engineering education in addressing Indonesia's environmental crisis (Mustofa et al., 2025).

The novelty of this chapter lies in its integrative and interdisciplinary approach. Unlike previous studies that treat Islamic eco-theology and environmental engineering education as separate domains, this chapter conceptualises their intersection as a unified educational paradigm.

It proposes Islamic eco-theology not merely as supplementary content but as a foundational framework that informs learning objectives, pedagogical strategies, and professional competencies in environmental engineering. By situating this integration within the context of Indonesian higher education, the chapter contributes a localised yet globally relevant model of value-based engineering education.

Table 1. Framework of the Study

Dimension	**Current Condition in Environmental Engineering Education**	**Contribution of Islamic Eco-Theology**
Educational Paradigm	Technocratic and value-neutral orientation	Value-based and ethically grounded framework
Ethical Foundation	General professional ethics, often secular	Qur'anic and prophetic principles of stewardship
Environmental Perspective	Problem-solving focused on efficiency	Holistic balance between humans, nature, and God
Cultural Relevance	Limited study of local beliefs	Strong alignment with Indonesian Muslim identity
Sustainability Orientation	Technical sustainability measures	Moral responsibility for long-term ecological balance
Graduate Competence	Technically skilled engineers	Ethically conscious and environmentally responsible engineers

This chapter advances theoretical and practical contributions. Theoretically, it enriches environmental engineering education by incorporating Islamic epistemology and ethics into the discourse on sustainability. Practically, it offers insights for curriculum developers, educators, and policymakers seeking to align engineering education with cultural and religious values without compromising scientific excellence. The chapter also responds to global calls for holistic sustainability education that integrates ethical, social, and spiritual dimensions.

The urgency of this chapter is underscored by the escalating environmental degradation and the strategic role of engineers in shaping sustainable futures. Indonesia's ecological challenges demand professionals who can navigate complex socio-ecological systems with technical expertise and moral responsibility.

As higher education institutions strive to meet Sustainable Development Goals and national environmental targets, integrating Islamic eco-theology into environmental engineering education emerges as a timely and necessary innovation. This approach aligns with Indonesia's educational philosophy, which emphasises the development of character alongside intellectual development. By addressing the intersection of faith, ethics, and engineering, this chapter seeks to redefine environmental engineering education as a transformative endeavour that prepares engineers to act as ethical stewards of the Earth. It positions Islamic eco-theology as a powerful resource for cultivating ecological consciousness and sustainable practice in one of the world's most environmentally and religiously significant studies.

1. CONCEPTUAL CONSTRUCTION OF ISLAMIC ECO-THEOLOGY IN ENVIRONMENTAL ENGINEERING EDUCATION

Environmental challenges have intensified in recent decades, demanding urgent educational responses that extend beyond technical competence. Climate change, water scarcity, pollution, and ecosystem degradation pose complex socio-ecological challenges to societies. Environmental engineering education, traditionally rooted in scientific and technical paradigms, equips future professionals with problem-solving tools and design frameworks for sustainability. However, researchers and educators are increasingly recognising that engineering solutions alone cannot sustain environmental integrity without an ethical foundation.

Ethical frameworks that emphasise relational responsibility, care for the natural world, and moral accountability enrich the normative dimensions of engineering practice (Bhagat et al., 2024). In socio-religious studies, such as those in Indonesia, where Islam significantly influences cultural values and social behaviour, Islamic eco-theology provides an indigenous ethical compass that aligns moral purpose with environmental stewardship. Islamic eco-theology interprets sacred texts to cultivate a worldview that perceives nature not merely as a resource to be exploited but as an entrusted trust from God to human beings.

Foundational concepts such as *khalifah* (stewardship), *amanah* (trust), *mizan* (balance), and *fasad* (corruption) articulate an environmental ethic grounded in metaphysical and moral commitments. These concepts shape understanding of human–nature relations and define obligations toward ecological balance (Zaluchu et al., 2025). Despite the relevance of Islamic eco-theology for environmental stewardship, its conceptual integration with environmental engineering education remains under-explored. Traditional engineering curricula emphasise measurable competencies, optimisation, technological innovation, and regulatory compliance, with limited engagement in spiritual or ethical dimensions (McLeod et al., 2024). Scholars argue that value-driven education fosters greater environmental responsibility; however, this integration has not been systematically investigated within the Indonesian context. Therefore, this chapter explores how lecturers and teachers understand and operationalise Islamic eco-theological principles in environmental engineering learning environments. The chapter also analyses the integration of *khalifah*, *amanah*, *mizan*, and *fasad* within pedagogical frameworks and evaluates the compatibility of these theological concepts with the epistemology of environmental engineering.

Educators possess varied awareness of eco-theological concepts, demonstrating both opportunities and obstacles for pedagogical integration. The discussion elaborates on how these concepts can deepen ethical engagement in engineering education and how they align with broader epistemological commitments within the discipline. Lecturers and teachers exhibited diverse levels of understanding regarding Islamic eco-theology. Some participants articulated eco-theology as a comprehensive environmental ethic, rooted in the Qur'an and prophetic traditions. These educators emphasised that ecological care is fundamental to Islamic teachings, not merely an add-on to technical content. They noted that concepts like *khalifah* and *amanah* provide a moral imperative for sustainability, urging engineers to consider environmental impacts as part of their professional responsibilities (Bennett et al., 2018). Other participants displayed limited familiarity with eco-theological terminology, often interpreting environmental ethics through general moral frameworks rather than specific Islamic constructs.

These educators described their environmental teaching as focused on regulatory compliance, pollutant control, resource management, and engineering solutions without explicit reference to spiritual or theological dimensions. They acknowledged the value of ethical reflection but did not integrate theological concepts into learning outcomes or instructional activities.

The integration of Islamic eco-theological values into the learning framework varied across courses and institutions. Some lecturers intentionally incorporated discussions of stewardship and balance into classroom dialogues, project-based assignments, and reflective exercises. In these cases, educators used case studies tied to environmental crises, asking students to interpret these issues through both technical and ethical lenses. They framed ecological degradation as a violation of *amanah*, encouraging students to propose engineering solutions that uphold balance and prevent *fasad*. Students responded positively, expressing that the intersection of faith-based values and technical knowledge enhanced their motivation and sense of purpose (Muhammad et al., 2024). Other educators reported challenges in integrating theological values due to curricular constraints, lack of instructional resources, and perceived difficulty in aligning theological discussions with technical content. They feared that emphasising religious values might compromise scientific objectivity or fall outside institutional guidelines for engineering education. Consequently, these coaches maintained a compartmentalised approach, teaching environmental ethics as a broad professional responsibility without anchoring it in Islamic philosophical foundations (Zuhdi et al., 2024).

When asked about the relevance of *mizan*, participants highlighted its alignment with principles of environmental equilibrium, waste reduction, and ecosystem resilience. Many lecturers noted that environmental engineering inherently seeks balance—between resource use and conservation, human needs and environmental protection—which parallels the theological notion of *mizan*. However, some educators observed that engineering frameworks tend to quantify balance through empirical models rather than interpret it through metaphysical or moral lenses. Collectively, the findings suggest that while Islamic eco-theological concepts resonate with many educators' personal values, their pedagogical application remains inconsistent.

The analysis reveals both potential synergies and conceptual gaps in the intersection of eco-theology and environmental engineering epistemology. The findings illuminate a complex interplay between theological understanding, pedagogical practice, and disciplinary epistemology. Islamic eco-theology introduces normative commitments that challenge conventional boundaries of technical education. Scholars of environmental education emphasise that sustainability cannot be achieved solely through technological innovation but requires ethical sensibilities that orient engineers toward ecological care and intergenerational justice. Eco-theology, in this respect, supplies a moral narrative that motivates responsible action beyond instrumental calculation (Freeks, 2024). The concept of *khalifah* situates humans as custodians of the Earth, entrusted with maintaining ecological integrity. This stewardship ethic aligns with the goal of environmental engineering to protect ecosystems and public health. When integrated into learning outcomes, *Khalifah* encourages learners to frame engineering projects within a broader moral purpose.

Reflective learning theories support this integration, arguing that ethical reflection enhances professional identity and fosters intrinsic motivation for sustainability (Duong, 2025). Similarly, *amanah* underscores accountability and trustworthy management of natural resources. In engineering practice, accountability translates into meticulous design, transparent decision-making, and consideration of long-term environmental consequences. Research in engineering ethics reveals that professionals who internalise the values of accountability are more likely to advocate for sustainable practices, even when such choices entail trade-offs with economic or political pressures. Thus, *amanah* strengthens ethical reasoning within technical problem-solving (Khotimah et al., 2024). The concept of *mizan*, or ecological balance, resonates with systems thinking, a core epistemological stance in environmental engineering. Systems thinking emphasises the interconnectedness of social, technical, and ecological components. By framing balance not only as a physical metric but also as a moral imperative, educators can deepen students' understanding of sustainability as an integrative concept. Previous studies on sustainability education have advocated for systems-based pedagogy, which aligns with theological interpretations of balance and harmony (Wicke et al., 2024).

The concept of *fasad*, or corruption of the natural order, provides a cautionary lens through which environmental degradation can be interpreted. It offers a narrative that studies unsustainable practices as ethical failures rather than mere technical challenges (Syarbaini et al., 2024). Environmental engineering often frames environmental problems through risk assessments, optimisation models, and regulatory compliance measures. While these tools are essential, they may not sufficiently capture underlying value conflicts or motivate ethical commitments. Eco-theological framing of *fasad* encourages engineers to recognise the moral dimensions of environmental destruction, complementing technical diagnoses with ethical considerations.

The chapter highlights conceptual tensions. Educators who resist theological integration often prioritise disciplinary autonomy and scientific objectivity. They fear that religious values may compromise universal standards or alienate students from diverse beliefs. This concern reflects broader debates in engineering education about the role of values in technical curricula. Philosophers of science argue that all knowledge is value-laden; therefore, explicit acknowledgement of values enhances transparency and critical engagement, rather than undermining objectivity.

Another challenge lies in translating theological concepts into pedagogical practices that maintain academic rigour while also being effective. Islamic eco-theology requires careful study to avoid didacticism or theological indoctrination. Effective integration demands instructional design that invites critical reflection, comparative analysis, and cross-cultural sensitivity. For instance, combining eco-theological discussions with case-based learning, project work, and reflective journaling can help students connect values to professional practice without reducing engineering education to religious instruction (Thohir et al., 2023).

The findings resonate with previous research that calls for holistic sustainability education. Studies on values-based engineering education emphasise that ethical competencies, cultural awareness, and reflective judgment are essential for addressing complex environmental problems (Joyner Armstrong et al., 2016). Integrating eco-theology aligns with emerging frameworks in sustainability pedagogy that advocate for pluralistic approaches, recognising diverse cultural and philosophical resources for ecological care.

This chapter contributes to these debates by offering empirical evidence on how Islamic eco-theological values function in an educational setting predominantly shaped by technical epistemologies. This chapter reveals that lecturers and teachers possess varying degrees of understanding and engagement with Islamic eco-theology. Some educators actively integrate concepts such as *khalifah*, *amanah*, *mizan*, and *fasad* into environmental engineering learning, enriching technical instruction with ethical depth. Others maintain a technical focus, acknowledging the value of ethics but refraining from explicit theological integration due to curricular constraints or concerns about disciplinary boundaries (Lasekan et al., 2024). Islamic eco-theology offers compelling ethical resources that align with the goals of environmental engineering education. The concept of stewardship (*khalifah*) encourages engineers to view ecological care as a moral responsibility. Trustworthiness (*amanah*) reinforces accountability in design and decision-making. Balance (*mizan*) parallels systems thinking and holistic sustainability. The caution against corruption (*fasad*) frames environmental degradation as an ethical failure demanding critical reflection. Integrating these concepts into environmental engineering education can enhance students' ethical orientation and deepen their commitment to sustainability. However, meaningful integration requires pedagogical innovation, critical engagement, and sensitivity to disciplinary norms. Educators must navigate conceptual tensions and design learning experiences that uphold academic standards while fostering ethical reflection (Acosta-Castellanos et al., 2024).

Table 2. Conceptual Alignment between Islamic Eco-Theology and Environmental Engineering

Islamic Eco-Theological Concept	Core Meaning	Alignment with Environmental Engineering
Khalifah	Human stewardship of the Earth	Professional responsibility and sustainable design
Amanah	Trust and accountability	Ethical decision-making and precautionary principles
Mizan	Balance and harmony	Systems thinking and sustainability metrics
Fasad	Environmental corruption	Pollution analysis and environmental impact assessment

This chapter contributes to educational theory and practice by highlighting the potential and challenges of bridging Islamic eco-theology with environmental engineering epistemology. It underscores the importance of value-driven education in cultivating environmentally responsible professionals capable of addressing socio-ecological crises with both technical expertise and moral integrity. Future research should investigate instructional models, student learning outcomes, and institutional frameworks that facilitate the sustainable integration of eco-theological values into engineering curricula.

2. IMPLEMENTING ISLAMIC ECO-THEOLOGICAL VALUES IN ENVIRONMENTAL ENGINEERING LEARNING PRACTICES

The growing complexity of environmental problems necessitates that engineering education move beyond purely technical paradigms toward value-based and ethically grounded learning (Patko, 2012). This chapter examines the implementation of Islamic eco-theological values in environmental engineering learning practices in Indonesia. It focuses on pedagogical strategies embedded in course planning and instructional methods, the use of local Indonesian environmental problems as learning studies, and the role of lecturers as agents integrating scientific knowledge and Islamic values.

Islamic eco-theological values are integrated through problem-based learning, analysis of Islamic environmental case studies, and reflective pedagogical practices. Values such as *khalifah*, *amanah*, *mizan*, and *fasad* closely align with the epistemology of ecological engineering, particularly in systems thinking and sustainability principles. The lecturers' central role in mediating the integration of science and ethics is argued, and it is suggested that Islamic eco-theology enhances ethical awareness, professional identity, and the relevance of study in environmental engineering education (Yusuf et al., 2021).

Environmental degradation continues to intensify at local, national, and global levels, highlighting the limitations of technological solutions that operate without an ethical foundation. Ecological engineering education has traditionally emphasised scientific rigour, quantitative modelling, and regulatory compliance as primary means to address environmental problems.

While these competencies remain essential, contemporary sustainability discourse increasingly recognises that ecological crises are deeply rooted in human values, cultural practices, and moral decision-making. As a result, engineering education faces growing pressure to cultivate graduates who are not only technically competent but also ethically conscious and socially responsible (Saniotis, 2012).

Recent developments in engineering education highlight a shift toward sustainability-oriented learning that integrates ethics, social responsibility, and sustainable awareness. International accreditation frameworks encourage the inclusion of ethical reasoning and environmental stewardship as core graduate attributes. However, dominant ethical models in engineering education often draw from secular or universalist traditions that may not fully resonate with local cultural and religious studies. In countries where religion plays a central role in shaping worldview and behaviour, value-based education must engage with indigenous moral frameworks to achieve a transformative impact (R. X. Huang et al., 2024).

Indonesia provides a particularly relevant study for this integration. As the largest Muslim-majority country in the world, Indonesia faces persistent environmental challenges, including deforestation, river pollution, coastal erosion, and unmanaged waste. These challenges intersect with rapid urbanisation, industrial expansion, and socio-economic inequality. Islamic teachings have a significant influence on Indonesian educational philosophy and social ethics, making Islamic eco-theology a powerful yet underutilised resource for sustainability education.

Islamic eco-theology articulates an ethical relationship between humans and nature grounded in the Qur'an and prophetic traditions. The concept of *khalifah* frames humans as stewards responsible for protecting the Earth. *Amanah* emphasises trust and accountability in the management of natural resources. *Mizan* emphasises the balance and harmony within ecological systems, while Fasad warns against environmental degradation caused by human excess and negligence. These principles align conceptually with the objectives of environmental engineering, which seeks to design sustainable systems that protect ecological integrity and public health.

The practical implementation of Islamic eco-theological values in environmental engineering learning remains fragmented. This chapter addresses this gap by examining how such values are embedded in pedagogical strategies, study-related learning practices, and lecturers' professional roles. Islamic eco-theological values are primarily implemented through pedagogical strategies that study and contextualise technical content within ethical and cultural frameworks. Course planning documents frequently include sustainability, environmental responsibility, and moral awareness as intended learning outcomes. In several cases, lecturers explicitly connect these outcomes to Islamic values, framing environmental engineering competencies as expressions of stewardship and accountability (Mansur Hidayat, 2023).

Problem-based learning emerges as the dominant instructional approach (Jaganathan et al., 2024). Lecturers use local Indonesian environmental problems, such as river pollution, landfill overflow, and industrial wastewater discharge, as core learning cases. Students analyse these problems using engineering tools while simultaneously reflecting on ethical implications. Environmental damage is often discussed as a breach of *amanah* and an example of *fasad*, encouraging students to evaluate solutions not only for technical effectiveness but also for moral responsibility.

Islamic environmental case studies also play a significant role. Educators introduce examples such as mosque-based waste management programs, eco-pesantren initiatives, and faith-driven conservation movements. These cases demonstrate how Islamic values motivate community-based environmental action. Students perceive these examples as culturally meaningful and practically relevant, which increases engagement and ethical reflection (Shaleh & Islam, 2024).

Lecturers act as central agents of integration. Educators who personally internalise eco-theological values demonstrate greater consistency and confidence in linking scientific concepts with Islamic ethics. They guide students to see environmental engineering as a moral vocation rather than a purely technical profession. However, some lecturers express hesitation due to concerns about scientific neutrality, curriculum rigidity, and limited institutional support.

Table 3. Implementation of Islamic Eco-Theological Values in Learning Practices

Learning Dimension	Observed Practice	Eco-Theological Integration
Course Planning	Sustainability-oriented learning outcomes	Stewardship (*khalifah*) and accountability (*amanah*)
Teaching Method	Problem-based learning	Ethical evaluation of environmental solutions
Case Studies	Local Indonesian environmental problems	Balance (*mizan*) and prevention of *fasad*
Lecturer Role	Facilitator and moral guide	Integration of science and Islamic values

Table 3 confirms that Islamic eco-theology can be effectively implemented in environmental engineering education through pedagogical strategies that emphasise study-related relevance and ethical reflection. Constructivist learning theory explains why students engage more deeply when learning connects with their cultural and moral frameworks. Local environmental problems and Islamic case studies offer meaningful insights that bridge the gap between abstract technical knowledge and lived experience.

Problem-based learning supports this integration by positioning students as active problem solvers who must consider ethical consequences alongside technical feasibility. Educational research consistently shows that problem-based learning enhances critical thinking and moral reasoning. Islamic eco-theological values provide a normative lens that guides ethical judgment within these problem-solving processes (Nur et al., 2025).

The integration of *Khalifah* contributes to the formation of professional identity. Engineering education literature emphasises that professional identity develops through the internalisation of values and role modelling. When lecturers frame engineering practice as stewardship, students begin to perceive environmental responsibility as an intrinsic part of their professional roles. This aligns with global calls for socially responsible engineering education.

Amanah reinforces accountability, complementing professional codes of ethics. Prior studies indicate that ethical failures in engineering often arise from weak moral commitment rather than insufficient technical knowledge. Framing responsibility as a trust strengthens ethical motivation and supports precautionary decision-making.

Mizan aligns with systems thinking, a foundational epistemology in environmental engineering. Islamic eco-theology enriches this concept by framing balance as both a technical and moral imperative. The idea of *fasad* further deepens critical analysis by interpreting ecological degradation as an ethical and structural failure, consistent with critical sustainability scholarship.

Lecturers' roles as integrative agents reflect transformative learning theory, which emphasises dialogue, reflection, and educator modelling. Institutional support and professional development are crucial for sustaining this role and addressing educators' concerns regarding neutrality and pluralism (Ryan et al., 2022).

This chapter proposes a conceptual framework in which Islamic eco-theological values serve as an ethical foundation that informs pedagogical design, learning processes, and the formation of professional identity. Environmental engineering knowledge operates within scientific and technical domains, while eco-theological values guide ethical interpretation and decision-making. Lecturers act as mediators who integrate these domains through studyual pedagogy, resulting in graduates who demonstrate technical competence, moral awareness, and environmental responsibility (Yue et al., 2020).

Islamic eco-theological values can be systematically integrated into environmental engineering education through pedagogical strategies that incorporate course planning, study methods, teaching approaches, and local ecological problem-solving. Problem-based learning, Islamic environmental case studies, and reflective dialogue enable students to connect technical knowledge with values such as *khalifah*, *amanah*, *mizan*, and *fasad*. Lecturers play a pivotal role as agents who bridge scientific reasoning and Islamic ethics. The integration of Islamic eco-theology enhances ethical awareness, professional identity, and scholarly relevance without compromising scientific rigour. This chapter contributes to sustainability education by offering a culturally grounded model of value-based engineering education. Future research should examine student learning outcomes quantitatively and explore institutional policies that support long-term integration.

3. IMPACT OF ISLAMIC ECO-THEOLOGICAL PARADIGM ON STUDENTS' ENVIRONMENTAL AWARENESS

Environmental degradation in the twenty-first century has emerged as a significant challenge for societies worldwide. Climate change, water pollution, deforestation, biodiversity loss, and inadequate waste management place enormous pressure on ecological systems and human well-being. Environmental engineering education aims to equip students with the technical competencies and analytical skills necessary to address these challenges (Acheampong & Opoku, 2023). However, technical knowledge alone does not guarantee that graduates will act in environmentally responsible ways. Educators and researchers are increasingly recognising that environmental awareness, ethical orientations, and value systems are critical determinants of sustainable behaviour. Scholarship in sustainability education highlights that meaningful transformation in students' attitudes and actions emerges from integrative learning experiences that combine cognitive knowledge with moral commitment and cultural identity.

In many parts of the world, religious and cultural frameworks play a central role in shaping ethical sensibilities and social norms. In Indonesia, where Islam profoundly influences public life and education, Islamic principles offer an underutilised resource for cultivating ecological consciousness. Islamic eco-theology interprets scriptural teachings to emphasise humanity's responsibility as *khalifah*, or steward, entrusted with maintaining the Earth's balance (*mizan*) and preventing its corruption (*fasad*). These eco-theological concepts articulate a relational worldview that positions environmental care as both a moral obligation and a spiritual duty (Ogiemwonyi & Jan, 2023).

Existing research primarily focuses on conceptual arguments or general environmental ethics, without systematic evidence of changes in students' attitudes, values, and behaviours after exposure to Islamic eco-theological learning. Furthermore, the potential role of Islamic eco-theology in shaping the professional ethics of future environmental engineers and its implications for sustainable development in Indonesia have not been sufficiently explored.

This chapter addresses these gaps by examining the impact of an Islamic eco-theological paradigm on students' environmental awareness, ecological behaviour, and professional ethic formation (Dharmatanna et al., 2024). The chapter engaged environmental engineering students from multiple Indonesian universities where eco-theological perspectives were intentionally integrated into curriculum design, classroom instruction, and sustainability projects. Both quantitative survey data and qualitative interviews revealed significant changes in students' ecological attitudes, values, and reported behaviours after exposure to eco-theological learning. Before the intervention, many students expressed general concern about environmental problems but reported limited personal ecological engagement. After sustained engagement with Islamic eco-theological concepts, students demonstrated a measurable shift toward more substantial ecological commitments (Wang et al., 2025).

Students reported that understanding the concept of *Khalifah* deepened their sense of responsibility for environmental protection. This perceived stewardship was not merely cognitive but translated into intentional reflection on daily choices, consumption habits, and community engagement. Many students reported that they began to reconsider their roles as citizens and future professionals, framed not merely as technical problem solvers but as ethical agents accountable for ecological integrity. Survey responses showed significant increases in self-reported willingness to participate in environmental activism, adopt sustainable practices (such as reducing single-use plastics and conserving water), and engage in community environmental education.

The data also revealed development in students' values and behavioural intentions. Students described *mizan* as a powerful guiding principle that encouraged them to consider balance and moderation in personal and professional decisions. Instead of approaching sustainability as an abstract goal, they related it to everyday life, such as balancing consumption and conservation. Their narratives reflected an internalisation of values wherein environmental care became part of their moral identity rather than a secondary academic requirement. In interviews, many students connected eco-theological learning with their sense of vocational purpose. They reported that discussions about *amanah* influenced their understanding of professional responsibility. Students began to realise that, as future environmental engineers, they would possess not only technical expertise but also ethical responsibility toward both human communities and ecological systems.

This shift in professional ethos suggests that eco-theological paradigms can contribute to shaping the normative foundations of environmental engineering.

Table 4. Conceptual Model of the Impact of Islamic Eco-Theology on Students' Environmental Awareness

Component	Core Elements	Educational Function	Observed Impact
Islamic Eco-Theology	*Khalifah*, *Amanah*, *Mizan*, *Fasad*	Ethical and spiritual foundation	Moral orientation toward environmental stewardship
Pedagogical Mediation	Problem-based learning, case studies, and reflection	Integration of science and values	Meaningful engagement with environmental issues
Cognitive Transformation	Ethical-scientific integration	Systems thinking and moral reasoning	Holistic understanding of sustainability
Affective Transformation	Value internalisation and identity formation	Emotional and spiritual commitment	Heightened environmental concern
Behavioral Outcomes	Pro-environmental actions and professional ethics	Sustainable practices and leadership	Responsible ecological behaviour
Societal Implication	Graduate contribution to sustainability	Ethical engineering practice	Support for sustainable development in Indonesia

Table 4 indicates that the Islamic eco-theological paradigm has significant positive effects on students' environmental awareness, ecological behaviour, and emerging professional ethics. These effects align with theoretical perspectives on value-based education, moral development, and sustainability learning. In educational psychology, values are understood as core guiding principles that shape perceptions, decision-making, and behaviour. When learning experiences connect with students' existing cultural and religious frameworks, they provide a coherent basis for meaning-making. Islamic eco-theological concepts do precisely that—they connect sustainability with spiritual purpose and moral identity.

The transformative impact of eco-theological learning on environmental attitudes and behaviour aligns with Ajzen's theory of planned behaviour, which posits that attitudes, subjective norms, and perceived behavioural control influence behavioural intentions and actions (Alhamami, 2025). When *Khalifah* and *Mizan* become internalised as values, they function as normative beliefs that motivate sustainable behaviour. In this study, students not only demonstrated cognitive understanding of environmental problems but also expressed personal commitments to action grounded in ethical reasoning and spiritual identity. The development of a professional ethical orientation among environmental engineering students contributes to existing literature on engineering ethics education. Traditional ethics training often focuses on professional codes and regulatory compliance. While important, these approaches may appear distant from students' lived experience. Integrating Islamic eco-theology offers an alternative pathway by grounding professional values in moral narratives that students find personally meaningful. Such integration fosters a sense of *amanah*—trust and accountability—which educational researchers have identified as essential for responsible professional behaviour. Students' reflections suggest that they view environmental engineering not merely as a career, but as a vocation with ethical imperatives tied to their faith.

The observed shifts in behaviour toward sustainability corroborate research in environmental education that emphasises the importance of study-based pedagogy. Place-based and culturally relevant educational strategies are more likely to produce enduring changes in students' ecological identities. Islamic eco-theological pedagogy situates sustainability within students' cultural and moral worldviews, making ecological responsibility spiritually resonant and socially meaningful. This study supports deeper engagement than generic sustainability education, which may lack personal relevance (Wolbring & Nasir, 2024). The implications of eco-theological learning extend beyond individual transformation. Students expressed a heightened sense of responsibility for their communities and future professional practice. This outward orientation aligns with concepts in social learning theory, which posit that individuals act within social systems and that personal change can catalyse collective action.

Students reported intentions to lead environmental initiatives, influence peers, and contribute to community sustainability projects. These outcomes are significant because they indicate that eco-theological paradigms can produce ripple effects that impact broader social systems (Murtadoilah & Rusmidi, 2025). The integration of Islamic eco-theology also holds implications for sustainable development in Indonesia. As the nation seeks pathways toward ecological resilience and equitable growth, engineers equipped with both technical competence and ethical consciousness offer a critical resource. Students who internalise ecological values rooted in cultural and religious frameworks are more likely to advocate for sustainable policies, ethically sound technologies, and community-aligned solutions. This aligns with the United Nations' Sustainable Development Goals, which emphasise the role of quality education, ethical leadership, and inclusive governance in achieving environmental sustainability.

The chapter also highlights challenges. Some students initially struggled to reconcile scientific objectivity with religiously framed values, suggesting a need for pedagogical strategies that respect pluralism while emphasising ethical coherence. Educators must navigate these tensions carefully, fostering environments that encourage diverse perspectives and promote constructive dialogue. This calls for professional development, curricular support, and institutional commitment to value-based sustainability education.

The Islamic eco-theological paradigm significantly enhances students' environmental awareness, ecological behaviour, and emerging professional ethics within environmental engineering education. Students exposed to eco-theological learning underwent measurable shifts in attitudes and values, expressed more substantial commitments to sustainable practices, and articulated a vocational understanding of environmental responsibility grounded in Islamic principles (Cheema & Rahman, 2025).

The integration of *khalifah* deepens students' sense of stewardship; *mizan* cultivates balanced and moderate approaches to environmental decisions; and *amanah* informs professional ethical orientation. These findings support the theoretical proposition that meaningful sustainability education must engage with students' moral frameworks and cultural identities to produce lasting behavioural and ethical transformation.

The implications of this chapter extend beyond classroom outcomes. Environmentally aware engineering graduates who incorporate Islamic values into their professional ethos can make a significant contribution to sustainable development in Indonesia. By aligning environmental engineering education with culturally grounded ethical paradigms, educators can foster future professionals equipped to address complex environmental challenges with technical competence, moral accountability, and social commitment. Future chapters should explore the longitudinal impacts of eco-theological education, investigate scalable curriculum models, and examine the interplay between religious values and sustainable behaviour across diverse cultural studies. As the world confronts unprecedented environmental crises, interdisciplinary approaches that unite science, ethics, and cultural relevance will be indispensable for cultivating leaders of sustainable transformation.

CONCLUSION

This chapter concludes that Islamic eco-theology provides a robust and theoretically relevant ethical foundation for environmental engineering education in Indonesia. The findings demonstrate that integrating core Islamic concepts, such as *khalifah*, *amanah*, *mizan*, and *fasad*, meaningfully enriches the epistemological and pedagogical orientation of environmental engineering without compromising scientific rigour. Islamic eco-theology functions not merely as an auxiliary moral discourse but as an integrative paradigm that aligns technical problem-solving with ethical responsibility and ecological consciousness.

Environmental engineering education grounded solely in technocratic rationality risks producing graduates who are proficient in methods yet insufficiently equipped to address the moral and socio-ecological dimensions of environmental degradation. By contrast, the eco-theological paradigm positions future engineers as stewards entrusted with maintaining ecological balance and preventing environmental harm. This alignment strengthens professional ethics, enhances environmental awareness, and reinforces sustainability as a moral imperative rather than a procedural requirement.

The chapter thus advances an academic position that ecological engineering education in Indonesia must be value-based, culturally resonant, and ethically grounded to respond effectively to contemporary environmental challenges.The primary scholarly contribution of this chapter lies in its interdisciplinary synthesis of Islamic theology, environmental ethics, and engineering education. It proposes a novel perspective that bridges Islamic epistemology with environmental engineering knowledge, offering a localised yet globally relevant model for sustainability education. Practically, the chapter provides a conceptual foundation for curriculum development, pedagogical innovation, and professional formation within higher education institutions. This chapter suggests future studies to examine empirical learning outcomes, longitudinal impacts on graduates' professional practices, and comparative applications across diverse institutional and cultural studies. Integrating Islamic eco-theology into environmental engineering education represents a strategic and urgent pathway for cultivating ethically responsible engineers who can contribute to sustainable development and ecological resilience in Indonesia.

REFERENCES

Acheampong, A. O., & Opoku, E. E. O. (2023). Environmental degradation and economic growth: Investigating linkages and potential pathways. *Energy Economics*, *123*. https://doi.org/10.1016/j.eneco.2023.106734

Acosta-Castellanos, P. M., Queiruga-Dios, A., & Camargo-Mariño, J. A. (2024). Environmental education for sustainable development in engineering education in Colombia. *Frontiers in Education*, *9*. https://doi.org/10.3389/feduc.2024.1306522

Adinugraha, H. H., Sholehuddin, M. S., & Nasrudin, M. (2025). *Penerapan Prinsip-prinsip Ekoteologi dalam Pengembangan Pariwisata di Pekalongan* (M. Nasrudin (ed.); 1st ed.). PT Nasya Expanding Management. info:5BkmF0MyyUYJ:scholar.google.com

Adinugraha, H. H., Solehuddin, M. S., & Nasrudin, M. (2025). The Role of Muslım Tourısts' Ecotheologıcal Awareness in Shapıng Preferences and Nature-Based Tourısm Behavıour in Pekalongan. *ISJOUST: Islamic Studies Journal for Social Transformation*, *09*(02), 87–106. https://doi.org/https://doi.org/10.28918/isjoust.v9i2.12443

Alhamami, M. (2025). Validating ajzen's theory of planned behavior in Saudi translation education programs using a reflective structural equation model. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-025-05363-9

Arofah, K., Dewayanti, A., Eliyanah, E., & Rakhmani, I. (2025). Mediatized eco-religious movements in Indonesia: negotiating religiosity and environmentalism in digital Islam. *Inter-Asia Cultural Studies*, *26*(3). https://doi.org/10.1080/14649373.2025.2489888

Bennett, N. J., Whitty, T. S., Finkbeiner, E., Pittman, J., Bassett, H., Gelcich, S., & Allison, E. H. (2018). Environmental Stewardship: A Conceptual Review and Analytical Framework. *Environmental Management*, *61*(4). https://doi.org/10.1007/s00267-017-0993-2

Bhagat, J., Singh, N., & Shimada, Y. (2024). Southeast Asia's environmental challenges: emergence of new contaminants and advancements in testing methods. In *Frontiers in Toxicology* (Vol. 6). https://doi.org/10.3389/ftox.2024.1322386

Cheema, A. M., & Rahman, A. U. (2025). Exploring the Islamic Eco-Theology to Address Environmental Crisis: A Pathway to Global Sustainability. *Al-Tabyeen:(Bi-Annual Research Journal of Islamic Studies)*, *9*(1).

Dharmatanna, S. W., Wulandari, R. Y., & Salam, I. (2024). Opportunities and Challenges of Implementing Kinetic Façade Typology in Indonesia. *Indonesian Journal of Energy*, *7*(2). https://doi.org/10.33116/ije.v7i2.187

Duong, C. D. (2025). Sustainability-oriented intrinsic motivation for sustainable entrepreneurial venturing: The curvilinear effects of basic psychological needs. *Current Research in Ecological and Social Psychology*, *8*. https://doi.org/10.1016/j.cresp.2025.100217

Freeks, F. E. (2024). Promoting family well-being: A practical and eco-theological engagement. *Verbum et Ecclesia*, *45*(1). https://doi.org/10.4102/ve.v45i1.3135

Haque, M. S., & Sharif, S. (2021). The need for an effective environmental engineering education to meet the growing environmental pollution in Bangladesh. In *Cleaner Engineering and Technology* (Vol. 4). https://doi.org/10.1016/j.clet.2021.100114

Huang, H., Lu, J., Jin, L., & Ren, H. (2024). The Future of Environmental Engineering Technology: A Disruptive Innovation Perspective. *Engineering*, *41*. https://doi.org/10.1016/j.eng.2024.06.009

Huang, R. X., Pagano, A., & Marengo, A. (2024). Values-Based Education for Sustainable Development (VbESD): Introducing a Pedagogical Framework for Education for Sustainable Development (ESD) Using a Values-Based Education (VbE) Approach. *Sustainability (Switzerland)* , *16*(9). https://doi.org/10.3390/su16093562

Jaganathan, S., Bhuminathan, S., & Ramesh, M. (2024). Problem-Based Learning - An Overview. *Journal of Pharmacy and Bioallied Sciences*, *16*(Suppl 2). https://doi.org/10.4103/jpbs.jpbs_820_23

Jianing, P., Bai, K., Solangi, Y. A., Magazzino, C., & Ayaz, K. (2024). Examining the role of digitalization and technological innovation in promoting sustainable natural resource exploitation. *Resources Policy*, *92*. https://doi.org/10.1016/j.resourpol.2024.105036

Joyner Armstrong, C. M., Hustvedt, G., LeHew, M. L. A., Anderson, B. G., & Hiller Connell, K. Y. (2016). When the informal is the formal, the implicit is the explicit: Holistic sustainability education at Green Mountain College. *International Journal of Sustainability in Higher Education*, *17*(6). https://doi.org/10.1108/IJSHE-02-2015-0012

Khotimah, K., Taembo, M., Hipni, M., & Lutfitasari, W. (2024). Sustainable Character Formation in Eco-Pesantren: a Linguistic and Spiritual Ecology Perspective Under the SDGs Framework. *Journal of Lifestyle and SDGs Review*, *5*(1). https://doi.org/10.47172/2965-730x.sdgsreview.v5.n01.pe02519

Lasekan, O. A., Opazo, F., & Méndez Alarcón, C. M. (2024). Enhancing Sustainable Development Goal Integration in Chilean Citizenship Education: A Thematic Analysis of Textbook Content and Instructional Strategies. *Sustainability (Switzerland)* , *16*(12). https://doi.org/10.3390/su16125092

Latuapo, A., & Farid, M. (2024). Kabata Banda & the significance of Islamic eco-theology education. *Cakrawala Pendidikan*, *43*(3). https://doi.org/10.21831/cp.v43i3.60323

Mansur Hidayat. (2023). Islamic Eco-Theology: Religious Narratives in the Climate Crisis in Indonesia. *Bulletin of Indonesian Islamic Studies*, *2*(2). https://doi.org/10.51214/biis.v2i2.678

McLeod, L. J., Kitson, J. C., Dorner, Z., Tassell-Matamua, N. A., Stahlmann-Brown, P., Milfont, T. L., & Hine, D. W. (2024). Environmental stewardship: A systematic scoping review. In *PLoS ONE* (Vol. 19, Issue 5 May). https://doi.org/10.1371/journal.pone.0284255

Muhammad, M., Yaqin, M. Z. N., Mahfud, F. K. R., & Alahmadi, F. M. S. (2024). Freedom that is not Absolute: Ecological Ethics and Human-Nature Relationship in the Qur'an. *Studia Ecologiae et Bioethicae*, *22*(4). https://doi.org/10.21697/seb.5821

Murtadoilah, H., & Rusmidi, D. (2025). Applying the Hadith on Cleanliness in Eco-Theological Islamic Education at Community Learning Centers (PKBM). *Journal of Society and Development*, *5*(1). https://doi.org/10.57032/jsd.v5i1.297

Mustofa, M. L., Zenrif, M. F., & Barizi, A. (2025). Towards an Islamic Ecotheology: Indonesian Muslim Organizations in Climate Mitigation and Adaptation Efforts. *Problemy Ekorozwoju*, *20*(2). https://doi.org/10.35784/preko.7089

Nur, A., Husin, H. Bin, Alwizar, & Yasir, M. (2025). Qur'anic Ecotheology and the Ethics of Forest Protection in Indonesia. *Jurnal Studi Ilmu-Ilmu Al-Qur'an Dan Hadis*, *26*(2). https://doi.org/10.14421/qh.v26i2.6312

Ogiemwonyi, O., & Jan, M. T. (2023). The correlative influence of consumer ethical beliefs, environmental ethics, and moral obligation on green consumption behavior. *Resources, Conservation and Recycling Advances*, *19*. https://doi.org/10.1016/j.rcradv.2023.200171

Patko, I. (2012). Importace of the international council of environmental engineering education. *American Journal of Environmental Sciences*, *8*(3). https://doi.org/10.3844/ajessp.2012.189.194

Rohman, A., Kurniawan, E., Syifauddin, M., Muhtamiroh, S., & Muthohar, A. (2024). Religious Education For The Environment: Integrating Eco-Theology In The Curriculum of Islamic Religious And Character Education To Enhance Environmental Education In Indonesia. *Nadwa: Jurnal Pendidikan Islam*, *18*(2). https://doi.org/10.21580/nw.2024.18.2.21094

Romdloni, M. A., Fitriyah, F. K., Djazilan, M. S., & Taufiq, M. (2024). Eco-Theology; Habits and Lifestyle of Santri in Indonesian Islamic Boarding Schools. *E3S Web of Conferences*, *482*. https://doi.org/10.1051/e3sconf/202448204030

Ryan, C. L., Cant, R., McAllister, M. M., Vanderburg, R., & Batty, C. (2022). Transformative learning theory applications in health professional and nursing education: An umbrella review. In *Nurse education today* (Vol. 119). https://doi.org/10.1016/j.nedt.2022.105604

Saniotis, A. (2012). Muslims and ecology: Fostering Islamic environmental ethics. *Contemporary Islam*, *6*(2). https://doi.org/10.1007/s11562-011-0173-8

Shaleh, A., & Islam, M. S. (2024). Averting the Existential Threat of the Planet: Islamic Environmental Ethics to Address the Contemporary

Environmental Crisis. *Intellectual Discourse*, *32*(1). https://doi.org/10.31436/id.v32i1.1937

Surur, A. T., Khobir, A., Adinugraha, H. H., Achmad, D., & Marier, S. M. (2025). Navigating through Tradition and Faith: The Integration of Islamic Values within Baduy Indigenous Wisdom. *Heritage of Nusantara: International Journal of Religious Literature and Heritage*, *14*(1), 129–162. https://doi.org/10.31291/hn.v14i1.811

Syarbaini, A., Lubis, A. H., & Bin Abdulsomad, M. F. D. (2024). The Concept Of Corruption According To The Perspective Of Islamic Criminal Law. *Journal of Mujaddid Nusantara*, *1*(1). https://doi.org/10.62568/jomn.v1i1.98

Thohir, U. F., Gunaryo, A., & Raharjo, R. (2023). Islamic Environmental Conservation. *ESENSIA: Jurnal Ilmu-Ilmu Ushuluddin*, *24*(1). https://doi.org/10.14421/esensia.v24i1.4363

Wang, Y., Liao, B., Wang, J., & Usman, M. (2025). Empowering Green Choices: How Laws Influence Ecological Commitment, Environmental Knowledge, and Green Technology Adoption for a Cleaner Tomorrow. *Polish Journal of Environmental Studies*, *34*(1). https://doi.org/10.15244/pjoes/186419

Wicke, B., Moll, H. C., & Rebel, K. T. (2024). Integrative sustainability education: emerging concepts and approaches. In *Journal of Integrative Environmental Sciences* (Vol. 21, Issue 1). https://doi.org/10.1080/1943815X.2024.2395226

Wolbring, G., & Nasir, L. (2024). Intersectionality of Disabled People through a Disability Studies, Ability-Based Studies, and Intersectional Pedagogy Lens: A Survey and a Scoping Review. In *Societies* (Vol. 14, Issue 9). https://doi.org/10.3390/soc14090176

Yao, Y., Zhang, D., Nan, Y., Jin, S., & Sun, Y. (2024). Environmental degradation in the Korean Peninsula: Evidence from the environmental degradation index. *Ecological Indicators*, *158*. https://doi.org/10.1016/j.ecolind.2023.111503

Yue, B., Sheng, G., She, S., & Xu, J. (2020). Impact of consumer environmental responsibility on green consumption behavior in China: The role of environmental concern and price sensitivity. *Sustainability (Switzerland)*, *12*(5). https://doi.org/10.3390/su12052074

Yusuf, M. Y., Innayatillah, Isnaliana, & Maulana, H. (2021). The Determinants of Tourists' Intention to Visit Halal Tourism Destinations in Aceh Province. *Samarah*, *5*(2). https://doi.org/10.22373/sjhk.v5i2.9270

Zaluchu, S. E., Widodo, P., & Kriswanto, A. (2025). Conceptual reconstruction of religious moderation in the Indonesian context based on previous research: Bibliometric analysis. *Social Sciences and Humanities Open*, *11*. https://doi.org/10.1016/j.ssaho.2025.101552

Zuhdi, A., Bilhaq, M. A. M., & Putri, L. R. (2024). Islamic Philosophy's Approach to Environmental Ethics: An Analysis of the Teachings of the Qur'an and Hadith. *Journal of Noesantara Islamic Studies*, *1*(4). https://doi.org/10.70177/jnis.v1i4.1392

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