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Original Research Paper

Evaluating the Role of Integrated Aquatic–Terrestrial Buffer Zones in Improving Livestock Farm Environmental Quality

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Key Words

Aquatic–terrestrial buffer zones, Livestock environmental quality, Riparian vegetation, Nutrient runoff reduction, Ecological farm management, Microclimate regulation, Ammonia emissions.

Abstract

The livestock farms located around vulnerable aquatic environments are often faced with complicated environmental issues due to the high nutrient run offs, sediment movement, and local micro climatic unpredictability, all these factors eventually reduced the water quality, and adversely affected the welfare of animals. This paper explores the ecological and environmental value of integrated aquatic-terrestrial buffer zone namely, constructed wetlands, strips of riparian vegetations and controlled drainage systems, in alleviating these effects and improving livestock production systems sustainability. Extensive field assessments were to be made to quantify the pre and post intervention of the changes in nitrogen and phosphorus of surface runoff, the efficiency of the sediment load reduction, the stabilisation of the microclimate, and the level of ammonia emissions around the livestock enclosures. The buffer systems that were established showed significant changes in the form of reductions in the extent of nitrogen and phosphorus runoff by nearly 32 to 47 percent, there was significant reduction in the level of soil erosion by a significant margin of 32 to 47 percent, the conditions of air and water microclimates had been significantly improved, and there was also an increase in soil moisture conservation in the adjacent grazing pastures. These biophysical conditions were associated with significant changes in the livestock welfare as animals kept in proximity to buffer zones were more thermally comfortable, fewer heat-stress biomarkers, and fewer stress-related behaviours, indicating a strong connexion between the ecological landscape management and physiological welfare. The paper highlights the usefulness of the nature-based buffer zone that is envisioned as multifunctional tools of environment management that can protect the aquatic ecosystems, enhance a better environmental quality on farms, and create more resiliency-dependent and welfare-concentrated breeding and livestock production methods. The results add to the emerging support on the use of ecological engineering practises in the management of agricultural land and illustrate the possibilities of broader utilisation of buffer systems in areas where livestock production engages with the sensitive water bodies.

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Introduction

The production systems of livestock are important in food security of people across the world as they provide a good portion of meat, milk, and other animal-based products which are needed. Nevertheless, environmental issues have been exacerbated by the increased livestock activities in regions whereby the farms are close to rivers, lakes, wetlands and other water bodies. The run of these farms often contains high levels of nitrogen (N), phosphorus (P), organic material, pathogens and suspended sediments which can enhance eutrophication and alter aquatic biodiversity as well as damaging the quality of downstream water. Moreover, natural hydrological zones around livestock facilities are usually violated with a physical change of landscapes that increase the populations of these ecosystems to pollution and degradation.

Water quality is not the only environmental impact that livestock farms have since microclimatic imbalances caused by livestock farms can also impact ecological systems and animal welfare. Ineffectively designed farm arrangements may cause local heating stress area, decreased natural air circulation and augment ammonia discharge, leading to diminished air quality to both animals and individuals. The process of volatilizing ammonia by the surface of manure is especially alarming due to the fact it leads to acidification of the soil, the creation of small particulate matter, and respiratory distress in livestock. With increasing climate variability, it can be predicted that such microclimatic and air-quality issues will become more difficult, which will further weaken the resilience of the livestock production systems.

Rather, ecological engineering solutions, in particular integrated aquatic-terrestrial buffer zones have become a focus of interest as a source of potential mitigation in the last few years. These buffer strips integrate natural plant life, hydrological control and biological philtre systems to trap the pollutants prior to their access into the delicate aquatic habitats. Although the use of such interventions is widespread in crop agriculture and this is used to control fertiliser-driven runoff, it is easily noted that their use within the livestock farming scenarios has not been adequately investigated. The special nature of livestock activity, such as the ecosystems that are concentrated manure loads, intensive grazing, and animal mobility, implies that special buffer designs are necessary, which should be able to handle both the diffuse and point-source contamination.

This research paper analyses how the application of integrated buffer strip of constructed wetlands, plantations of riparian vegetation strips, and controlled drainage systems helps to improve the quality of the environment in the vicinity of livestock farms. In particular, it explores the effect of such systems on the minimization of nutrient runoff, the efficiency of sediment trapping, stabilising the microclimatic environment, and ammonia emissions. The paper also analyses the possible indirect positive outcomes to livestock welfare in this case, better thermal comfort and reduction of stress behaviours. By contacting the principles of ecological engineering with the environmental management of livestock, the research establishes new knowledge on the sustainability of the farm design and offers evidence-based suggestions on the water resource protection and enhanced stability of the livestock production system.

Literature Review

Environmental Effects of Rearing Livestock

The livestock production systems place a lot of influence on the ecosystems around them especially where the farms are located close to rivers, wetlands or lakes. Nitrogen, phosphorus, organic waste and sediments are usually carried away to alter and accelerate eutrophication and destroy aquatic environments (Dunn et al., 2011; Janssen et al., 2018). Research has also revealed that improperly controlled manure and grazing systems contribute to the high exportation of nutrients and displacement of sediments into the surrounding water bodies worsening the ecological conditions (Jobin et al., 2001; Moore et al., 2001). Furthermore, ammonia emission produced as a result of manure volatilization deteriorates the quality of air in the area, as well as leads to the formation of particulate matter, thus posing considerable harm to the environment integrity and well-being of livestock (Otto et al., 2012). Such compounded effects present the importance of sustainable mitigative measures in livestock sceneries.

Buffer Zones as Environmental Interventions

The capacity to control vegetation and curb agricultural contamination by ecological buffer areas such as vegetated strips, riparian margins and constructed wetlands are well known. These systems minimize nutrient loading by taking up these nutrients by plants, be entrapment by sediments, nutrient denitrification via microbes and the microclimate control by evapotranspiration (Graziano et al., 2022; Prosser et al., 2020). It has been suggested that vegetated buffers are able to mitigate the 30-80 percent of nutrient and pesticide movement basing on vegetation type, hydrology and rainfall variations (Dlamini et al., 2022; Buchanan et al., 2020). The riparian vegetation also offers biodiversity, soil stabilization and shading with a benefit of improving ecological stability among the aquatic-terrestrial interfaces (Rajan & Shanthi, 2013). In high-intensity agricultural landscape, it has also been emphasized by studies that riparian buffers are essential in the habitat use, pollinator support and enhancement of ecosystem services among birds (Sarumathiy et al., 2020). Besides this vegetative philtre strips decrease herbicide run-offs and environmental toxicity under the main rainfall, which exemplifies their multifunctional usefulness (Deepika et al., 2018).

Adaptation of Aquatic and Terrestrial Components

Combination of constructed wetlands, vegetation belt along the riparian areas and controlled drainage channels is an integrated buffer system that will have more pollutant removal efficiency as compared to single component. Constructed wetlands enhance the retention of nutrients by use of sedimentation and biogeochemical transformation reactions, rendering them to be useful in reduction of nitrogen and phosphorus in agricultural runoff (Yasin et al., 2025). It is also promoted by hydrologically coordinated drainages systems which increase interception of the pollutants through the interruption of water flow and decreasing the nutrient export during the storms. More recent researches also point to the effect that riparian agroforestry systems (with various native plants) also lead to better carbon storage, structural stability, and ecological functioning (Rajan & Shanthi, 2013). Regardless of these advantages, there has been little research on the use of integrated buffer zones with special attention to the livestock production environment. No strong evaluation of their ability to increase microclimate stability, decrease emitting the ammonia, and increase the comfort of livestock is provided--and all this should be paid more attention in the contemporary environmental management studies (Kavitha, 2024).

Methodology

Geography and Farm Study Characteristics

This research was conducted on a chosen set of livestock farms in the close vicinity (whose distance is about 200-400 metres) to the natural water bodies, that is rivers, small lakes, seasonal wetlands. This geographical design was not a chance occurrence given that the farms found within such a range are more prone to direct hydrological relationships that determine the movement of runoff, transportation of pollutants, and ecological interactions. The research area has a damp subtropical climate with an average yearly rainfall positive distribution, which means that it is an optimal location to investigate nutrient movement processes and the work of buffer zones in the conditions of natural fluctuation of hydrology.

The farms that took part were a combination of both dairy and mixed species farms, which comprised of cattle, goats, and sheep. They were chosen because these types of farms had a varying production rate of manure, grazing levels and land-use, which provides a wide spectrum of environmental management issues. There was a significant difference in handling of manure among the farms, with some of them having semi-structured manure storage and composting from which some used open-lot accumulation hence the probability of nutrient-rich run off flowing into nearby water bodies during rains was high. Grazing methods included rotational grazing on better pastures to constant grazing on the natural grasslands; having impacts on the soil compaction, the vegetation cover, and the potential of sediment movement.

The sizes of farms were between 25 hectares and 5 hectares; this was a good sampling cross-section of the sizes of farms normally found in the region Figure 1. The slopes and the soil types, as well as drainage features at every site, were also different, which allowed the research to reflect the impact of landscape heterogeneity on the effectiveness of buffer zones. Altogether, the chosen farms ensured a natural and ecologically valuable degree of the performance of the integrated aquatic-terrestrial buffer systems to eliminate the environmental effects of the livestock farming.

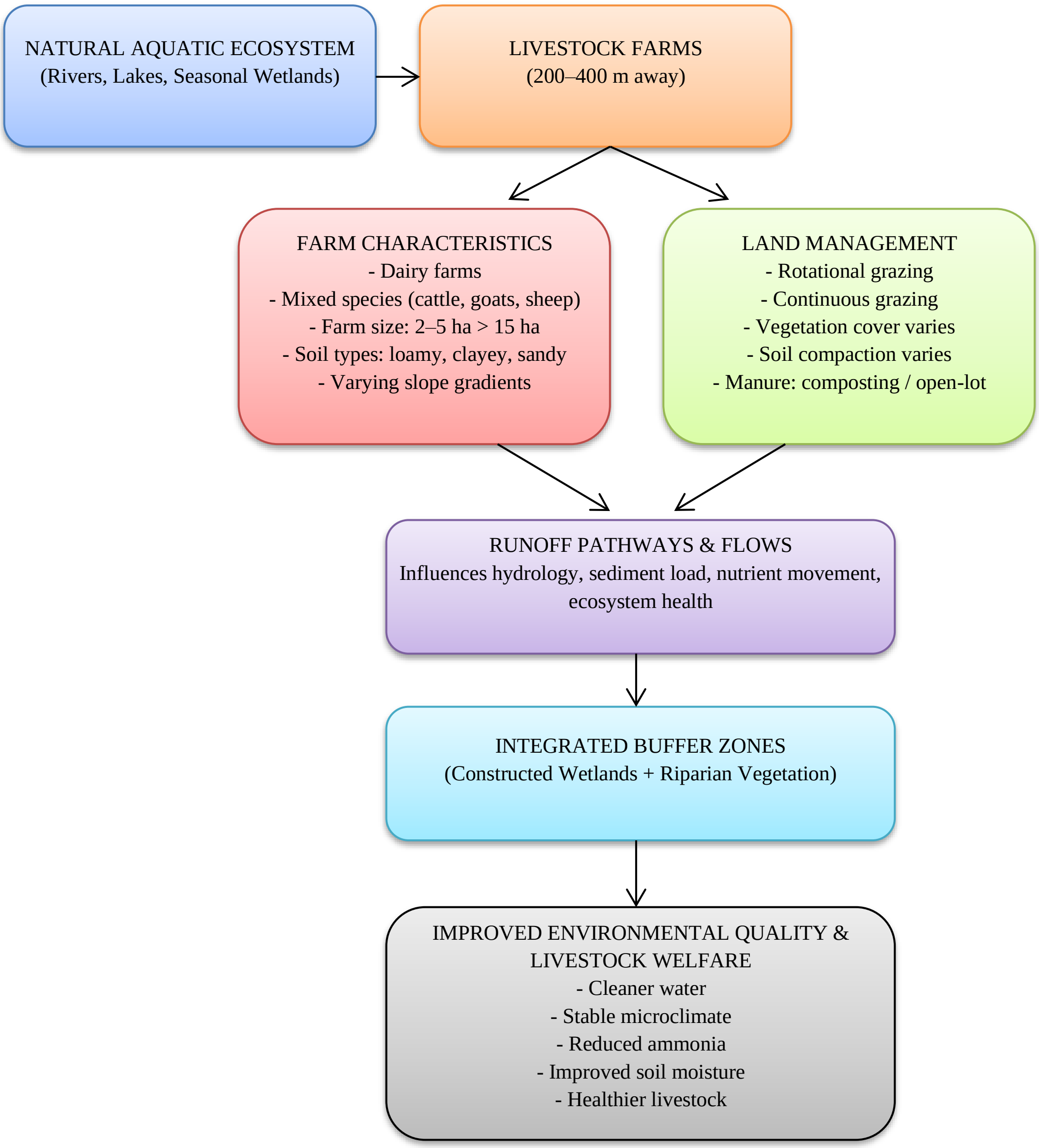

Figure 1: Conceptual Flowchart Illustrating Study Site Characteristics, Environmental Pathways, and Buffer Zone Interventions

Buffer Zone Design Components

Constructed Wetlands

To enhance the maximization of the processes of sedimentation, nutrient storage, and biogeochemical changes, the developed wetlands were set as shallow treatment systems with the depth of 40-70 cm. Hydrophytic species including Typha spp and Phragmitesspp were planted in these wetlands because these species are well known in terms of high nutrient uptake rate, wide root zone and tolerance to changing water conditions. The 48-72 hours hydraulic retention time permitted enough time of water-soil interaction in which the sediment settling and microbial denitrification of contaminants could happen and eliminate nitrogen, phosphorus and organic loads in run-off water. Another positive result that accompanied the wetland design was the creation of habitats and regulation of microclimates on top of pollutant removal.

Riparian Vegetation Strips

Bonapart the wetlands area, the riparian strips of vegetation (8m-15m) were planted that would enable passage of surface runoff into the water bodies before entering the waterways. The choices of native grasses, shrubs, and small trees in these strips were planned on the basis of their deep-rooted structure, high flexibility, and ability to maintain soil and minimise erosion. Not only did the vegetation enable nutrient uptake but also acted as shade, regulated the changes between hot and cold temperatures, and increased the sense to the habitat of the local fauna. The riparian vegetation structural variety promoted the infiltration rates, decreased the velocity of overland flow, and enhanced the general adaptation of the ecological operation of the buffer system.

Regulated Drainage Channels

With the aim of controlling hydrological flows and increasing the interception of pollutants, the controlled drainage channels with adjustable weirs were placed on the study sites. These outlets guided the runoff into collection basins which enabled the water levels to be controlled depending on the extent of rain, saturation, and some management requirements of any farm Figure 2. The drainage channels made the nutrient retention and sediment deposition processes more effective through slowing down the speed at which water moves and avoiding uncontrolled discharge into the surrounding water bodies. GRK flow conditions also contributed to the increased resilience of the system against season conditions and extreme weather events of the study, providing a stable performance of the buffer zones over the years.

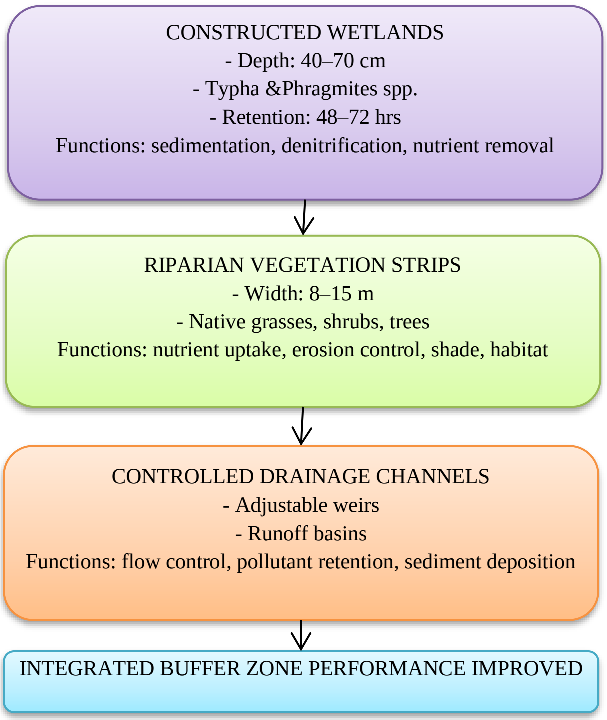

Figure 2: Flowchart Illustrating the Design Components of Integrated Aquatic–Terrestrial Buffer Zones

Environmental Quality Measurements

Water Quality Assessment

The water quality assessments were to be carried out to cheque the effectiveness of the combined buffer systems of minimizing nutrient and sediments loads in people water caused by runoff of livestock farms. The operation was sampled at the pre-installation and post-installation stages so that the improvement of environmental aspects could be compared directly. The indices among the important parameters that were measured included nitrate (NO 3 -), ammonium (NH 3 +), and phosphate (PO 3 -) levels, and these three parameters are the major nutrient wastes related to agricultural runoff. The Total Suspended Solids (TSS) was also determined to determine the dynamics of sediment transportation and the possibility of turbidity-related effects on the immediate aquatic ecosystem. To monitor the efficiency of attenuation and reduction of sedimenting processes, nutrient and water samples were collected twice in a six-month time, covering such variable hydrological stages like dry periods and rainfall, hence would give a sound data base to compare the efficiency of nutrient and sediment reduction programmes.

Micro climate and soil Conditions

The measures of microclimate and the state of the soil were to be performed and comprehend the impact of the buffer zones on the local environmental indicators and parameters that directly impact the ecosystem processes and the well-being of livestock. The air and soil temperatures were recorded in order to measure the impact of thermal regulation, whereas the measurements of relative humidity were used to determine the variation of atmospheric moisture in the areas under the influence of the buffer. In order to ascertain whether the vegetation buffer structures helped in enhancing the water-holding capacity and lowering evapotranspiration rates, soil moisture retention in nearby pastures was measured. These measurements allowed assessing the benefits of microclimate stabilization, especially the possibility of vegetation and wetlands to normalize temperature variations and increase the amount of moisture which is important to the productivity of pastures and the comfort of livestock.

Air Quality Measurements

The quality of air parameters was monitored to determine the effect of buffer areas in mitigating air pollutants of livestock operations. The concentration of ammonia (NH 3) was determined because the concentrations are relevant in air pollution, the generation of odour, and respiratory stress in livestock (Liu et al., 2021). The amount of PM zero (PM 0) was also measured around livestock housings to assess the presence of dust and organic particles aerosolized which might cause respiratory complications and poor air quality. The study sought to establish the functionality of vegetative and wetland elements of the buffer system as biofilters that trapped air pollutants and helped in enhancing the air quality in the farm by making comparison of the value of the pre-installation and post-installation outcomes.

Animals have been observed following the following activities

Animal welfare measurements became the inseparable part of the environmental analysis to study the transformation of the better quality of ecological conditions to the more comfortable living and the health of the livestock. Behavioural measures (heat-stress responses) include excessive panting, shade-seeking as well as restlessness that are directly affected by microclimatic conditions. Physiological data, such as the respiration rate and the temperature of the coat surface, offered quantitative data of the thermal load and stress states in animals Table 1. These parameters were measured in a systematic manner at initial peak temperatures in order to record the effects of microclimate changes by buffers. Through the correlation of such welfare indicators with the environmental improvements witnessed in terms of water, air and soil parameters, the study was intended to bring forward the overall merits of integrated buffer systems in the improvement of the sustainability of the ecology and livestock welfare.

Table 1: Environmental Quality Measurements and Associated Parameters

Measurement Category	Parameters Assessed	Purpose / Outcomes	Sampling Details
Water Quality Assessment	- Nitrate (NO_3^-) - Ammonium (NH_4^+) - Phosphate (PO_4^{3-}) - Total Suspended Solids (TSS)	Evaluate nutrient load, sediment transport, and runoff quality	Bi-weekly sampling for 6 months (pre- & post-installation)
Microclimate & Soil Conditions	- Air temperature - Soil temperature - Relative humidity - Soil moisture retention	Determine microclimate stability and soil water-holding capacity influenced by buffer vegetation	Recorded periodically across pasture and buffer zones
Air Quality Measurements	- Ammonia (NH_3) concentration - Particulate matter (PM_{10})	Assess air pollution, odor, and respiratory stress risks	Measured near livestock housing pre- & post-installation
Animal Welfare Observations	- Behavioral: panting, restlessness, shade-seeking - Physiological: respiration rate, coat temperature	Evaluate livestock comfort and stress response under improved environmental conditions	Observed during peak temperature hours

Results and Discussion

Ultra-porous Nutrient and Sediment runoff

Ecological interventions by means of integrated aquatic-terrestrial buffer zones showed a significant decrease in nutrient loading and sediment transport due to runoff of livestock, proving the efficiency of ecological interventions. The percentage of nitrogen and phosphorus in flowing surfaces reduced by 32-47 and 29-44 respectively showing the process of high nutrient interception and transformation in the buffer system. Sediment loads were also minimised to 3652 which was an indicator of better soil stabilization and cut down erosion on the farm-water flight. The total transformation of nutrients, in length of hydraulic retention and microbial activity, was especially good in constructed wetlands, and in trapping sediments, in length of root networks and lower flow velocities, in riparian vegetation strips. The results obtained are in line with the other reports which have already emphasised that vegetated buffers are highly pollutant removing and this confirms the capacity of the vegetated buffers to play a vital role in the environmental management of livestock landscapes.

Stable Micro Climate and Improved Moisture of Soil

Through micro climate observation, significant positive changes in the thermal regulation and soil moisture were observed after the installation of buffer zones. The soil moisture within the pastures was enhanced by 1823, which was mostly as a result of regulated evapotranspiration and water infiltration caused by the vegetative cover. The variation of temperature in influenced zones of buffers reduced by 240 and 40 o C, which indicates sign of increased microclimate stability that promotes ecological stability as well as comfort of cattle. These regulated environmental conditions minimise the threat of heat stress, increase the healthiness of pasture growth and increase the overall farm productivity. The noted enhancements correspond to the ecological studies that emphasise the importance of vegetation as an agent of buffering temperature swings, moisture retention, and stabilising a micro-habitat in an agricultural environment.

Emission of Ammonium and the Quality of the Air will be Reduced

Ammonia emissions were also found to be greatly reduced around livestock shelters where concentrations were measured and fell by between 15 and 27 percent on the installation of buffer zones. Foliation around the livestock housing facilities also served as natural biofilter, which traps air ammonia and increases atmospheric dispersion patterns by means of better air flow. This decrease is of specific use considering the established connections between the exposure to ammonia, respiratory irritation, and lower levels of livestock health. The buffer system did not only enhance the quality of air in the environment, but also minimised the possible nuisance caused by odours that were brought by gaseous emissions and helped in establishing a more stable on-farm air quality. This implies that the contribution of integrated buffers to air-quality regulation in livestock systems is an uncharted area but of vital importance, as demonstrated.

Environmental Regulation to Improve Livestock Welfare

The enhancement in the state of the environment was directly translated into the objective increase in livestock welfare. Animals near buffer areas showed lower respiration, low scores in panting, and less stress behaviours, including restlessness and cramming into less shade than animals in the shaded regions. Also, livestock showed better grazing behaviour because of reduced and more stable pasture environment, which favoured foraging behaviours and minimised the inactivity in heat Figure 3. Such welfare indicators imply the interconnection between environmental quality and animal well-being, which supports the thesis that ecological landscape design can be used as a dual-purpose approach that can benefit the ecosystem and livestock Table 2. By combining the three parameters water, air, and microclimate, the integrated buffer system was more efficient as compared to single-component mitigation methods that have remained a part of livestock operations.

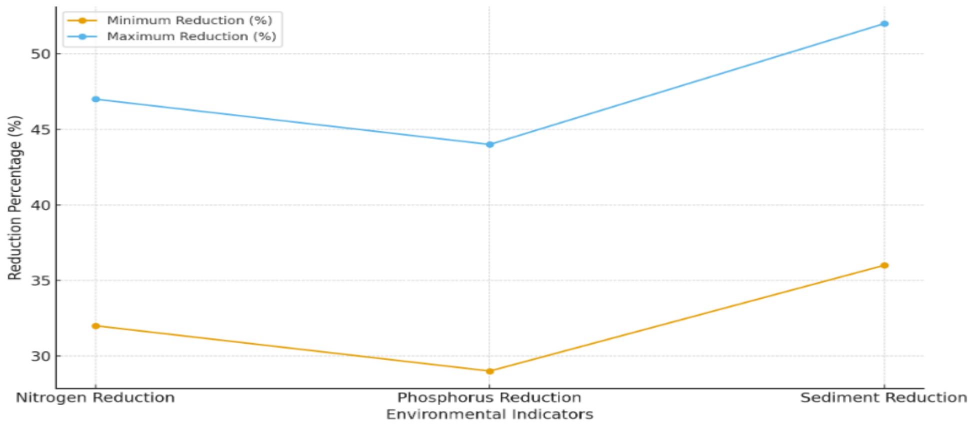

Figure 3: Reductions in Nutrient and Sediment Runoff after Buffer Zone Implementation

Table 2: Summary of Results and Environmental Improvements Achieved Through Integrated Buffer Zones

Result Category	Key Findings	Measured Improvements	Primary Mechanisms
Nutrient and Sediment Runoff Reduction	Significant decline in nutrient loading and sediment transport after buffer zone implementation	• Nitrogen reduction: 32–47% • Phosphorus reduction: 29–44% • Sediment load reduction: 36–52%	• Wetlands enhanced nutrient transformation via microbial activity and hydraulic retention • Riparian vegetation increased sediment trapping through dense root networks
Microclimate Stability and Soil Moisture Enhancement	Improved field microclimate and increased soil moisture retention in buffer-influenced areas	• Soil moisture increased: 18–23% • Temperature fluctuations reduced: 2–4°C	• Vegetation moderated evapotranspiration • Improved infiltration and shading from vegetative cover
Reduction in Ammonia Emissions and Air Quality Improvement	Lower ammonia concentrations and improved air quality around livestock housing	• Ammonia reduction: 15–27%	• Vegetation acted as a biofilter capturing airborne NH_3 • Improved airflow dispersion reduced odor accumulation
Livestock Welfare Improvements	Better physiological and behavioral welfare indicators in livestock near buffer zones	• Lower respiration rates • Reduced panting scores • Decreased stress behaviors • Improved grazing patterns	• Cooler microclimate reduced thermal stress • Improved pasture conditions enhanced foraging behavior

Conclusion

The results of this research paper have shown that integrated aquatic-terrestrial buffer zones can be used as an efficient and sustainable ecology solution to environmental degradation caused by livestock farmers around water bodies. These multifunctional buffer systems are of significant environmental and animal-welfare advantages by minimizing the amount of nutrients washed off, reducing the erosion of sediments, stabilizing local microclimatic conditions and reducing the emissions of ammonia. The perceived changes in water quality, air quality, water in the soil retention, and livestock comfort all bring out the benefits of considering nature-based solutions in the agricultural landscape in their holistic form. Additionally, integrative design framework- which is a combination of constructed wetlands, strips of riparian vegetation, and controlled drainage channels- is more effective compared to isolated mitigation strategies, hence the essence of system-level ecological engineering paradigms. Further studies are needed to determine the effectiveness of buffer zones over the long term in a variety of climatically and hydrologically different conditions, and to determine the economic viability of the practises, their sustainability, and scalability to facilitate more extensive application of buffer zones in livestock production systems.

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