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Review

A Review on Nitrogen Flows and Obstacles to Sustainable Nitrogen Management within the Lake Victoria Basin, East Africa

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Abstract: The Lake Victoria Basin (LVB) is located in the upper reaches of the Nile River Basin and is shared by five East-African countries. The population in the catchment is growing rapidly and the lake is facing several environmental problems. During the past few decades, numerous efforts have been made across the five countries, with the coordination of the Lake Victoria Basin Commission (LVBC) to reduce the loading of reactive nitrogen (Nr) into the lake and Lake Watershed. However, most of the measures envisaged to ensure long-term sustainable N management are not as easily adopted as planned. This paper reports on a review study on N flows and obstacles in achieving sustainable N management in the LVB, with the objectives of improving the understanding of the N cycle and examining the N management practices and policies that can help reduce the loss of Nr in the region. The scientific literature related to a range of N flows, N management obstacles, and options to overcome obstacles has been analyzed using N prospects developed at the global level for their potential applicability across the LVB. The study showed that an unbalanced use of N input is a serious threat to agricultural productivity leading to extreme soil N mining and degradation, with the majority of LVB farms operating within negative N balances and above the safe operating boundary for N in production systems. From the projections in N input as recommended by various stakeholders, there would likely be changes in both current yield and N use efficiency (NUE) values; however, most small-scale farmers will continue to experience low yields, which remains a challenge for food security in the area. These results suggest that scientists as well as those involved in decision-making and policymaking processes should formulate new targets for fertilizer increment to reduce the yield gap for sustainability, focusing on more integrated soil fertility as a package for nutrient management in cropping systems.

Keywords: Lake Victoria Basin; reactive nitrogen; obstacles to N management; N budget; N management practices and policies; N use efficiency

1. Introduction

The cycling of bioavailable nitrogen (N) in Earth's biogeochemical system is influenced by food, feed and fiber production, food consumption, and food waste and loss [1–3]. As a major yield-determining nutrient in most farming systems, adequate amounts of N are required to sustain yields and ensure long-term sustainable land management across the Earth system [4,5]. However, the current state of N fertilizer use is very different in various regions of the world [6]. Nitrogen is in low supply and used sparingly in some parts of the world, such as Sub-Saharan Africa, whereas it is used in excess in most developed countries, which has implications for agricultural production, food security, economy, human health, and ecosystems. In both situations (high and low N fertilizer use), it is vital to optimize the efficiency of N inputs [7]. Furthermore, nitrogen management should be handled using an integrated and multidisciplinary approach through strong collaboration between various stakeholders and sectors such as agriculture, wastewater, transport and industry.

The Lake Victoria Basin (LVB) in East Africa is located in the upper reaches of the Nile River Basin and is shared by five countries: Burundi, Kenya, Rwanda, Tanzania, and Uganda. The basin receives 80% of its water from direct rainfall, and 20% is sourced from rivers [8]. Over the last 50 years, the LVB has undergone rapid population growth and urbanization [9] with a growing population rate of more than 3%. Since the livelihood of this population is mainly based on the exploitation of land resources, the acceleration of anthropogenic activities (farming, overfishing, deforestation, biomass burning, urban development, and industrialization) has exerted increasing pressure on natural resources [10]. Furthermore, the discharge into the lake of untreated wastewater from diverse municipalities and industries is a major source of pollution [11].

During the past few decades, numerous efforts have been made across countries sharing the LVB, with the coordination of the Lake Victoria Basin Commission (LVBC), to reduce the reactive nitrogen (Nr) loading into the lake by improving the nitrogen use efficiency (NUE) of various crops, wastewater management interventions, Nr recovery from wastewater, sustainable land management practices, policy interventions to increase N fertilizer use in the regions, strengthening extension systems, and collaborating with various stakeholders [10]. However, N management remains a challenging issue in the basin because most measures envisaged to ensure long-term sustainable N management are often not easily adopted as planned. Thus, better achievement of such intervention measures requires a better understanding of the potential bottlenecks or obstacles that could hamper the success of interventions.

Sub-Saharan Africa (SSA) is characterized by low application of mineral N inputs compared to other regions with sufficient use of N in cropping systems [12,13]. As one of the most characteristic sites in SSA, the Lake Victoria Basin was selected as one of the demonstration sites of a worldwide project launched by the UNEP, with financial support from the Global Environment Facility (GEF), entitled "Targeted research for improving understanding of the global nitrogen cycle towards the establishment of an International Nitrogen Management System (INMS)" [14]. Recent studies [8,10,11,15,16] have shown that the nitrogen load in lakes includes significant sources of municipal and industrial waste, atmospheric deposition, agriculture, and the natural sector. The contribution of each source is not well understood, and there is a need to determine the best approach to assess N use efficiency in the basin and the best interventions to improve it.

This paper reports on a review study on N flows and obstacles in achieving sustainable nitrogen management in the LVB with the objectives of improving the understanding of the N cycle and examining the N management practices and policies that can help to reduce losses of reactive nitrogen in the region and enhance its sustainable management in food systems. The scientific literature related to a range of N flows, N management obstacles, and options to overcome obstacles has been analyzed and synthesized using N prospects developed at the global level [17–19] for their potential applicability across the LVB.

2. Methodology

2.1. The Study Site

The study was carried out in the Lake Victoria Basin, which straddles five East African (Burundi (7%), Rwanda (11%), Uganda (16%), Kenya (22%) and Tanzania (44%)), covering an approximate area of 194,200 km^2 (Figure 1A) [8,20]. The basin plays a major ecological, social, and economic role and is central to the development and regional integration of the East African Community. The basin is inhabited by some of the most impoverished Eastern

African rural populations (Figure 1B), with an approximate population of 30 million and a projected annual increase of 6% [10,20].

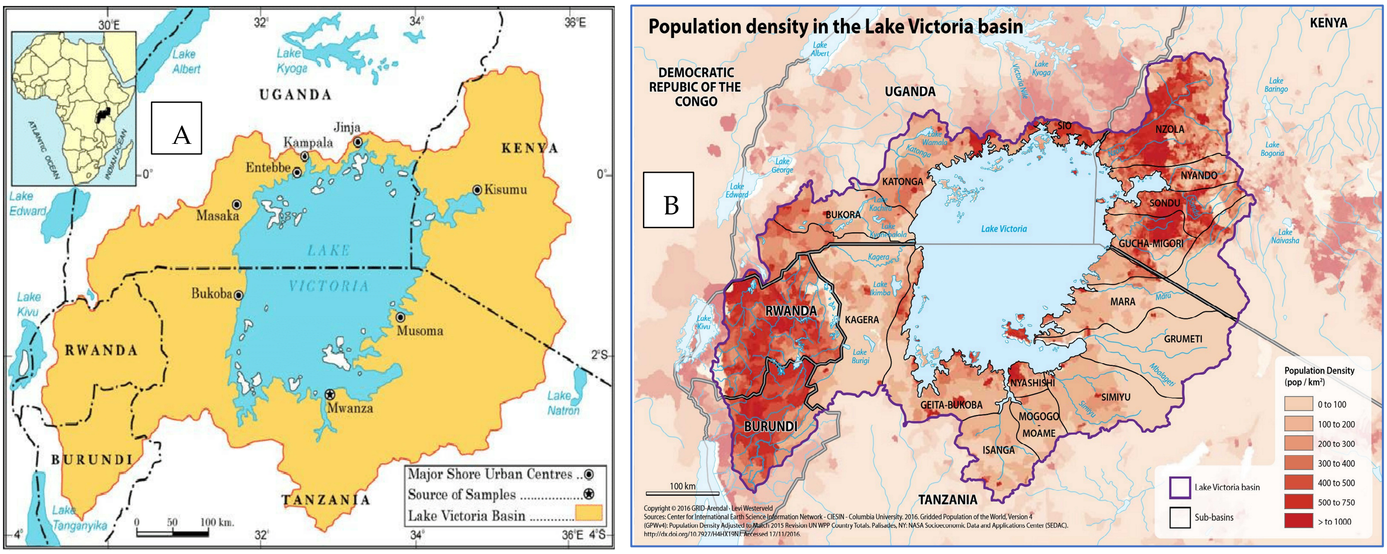

Figure 1. Map showing the East Africa Lake Victoria catchment (**A**) and the population density in the LVB (**B**).

Land and water resources in the region facilitate dense farming and fishing activities involving more than 70% of the population. Rice and maize are the predominant crops in the basin. The climate is equatorial humid, with the temperature controlled by the high elevation (from 1135 to 2700 m above sea level) of the lakes and surrounding mountains. The temperatures (20–32 °C) are lower than those in typical tropical conditions. The region experiences bimodal rainfall, with short rains occurring between mid-March and the end of May and long rains occurring from mid-October to the end of December. The annual rainfall ranges from 1000 to 1500 mm. Rainfall is controlled by the movement of the inter-tropical convergence zone (ITCZ) [15].

Soil types include Ferralsols, Vertisols, Nitisols, Cambisols, and Acricsols [21]. Owing to the insufficient application of N fertilizer in croplands, agriculture in the region mainly depends on soil nutrient mining, leading to significant losses of N to the ecosystem owing to unsustainable agricultural management practices [10,22]. As a consequence of unsustainable agricultural practices (deforestation, erosion, encroachment of marginal lands due to population pressure and low crop productivity per unit area) and nutrient inputs from municipal wastewater, the eutrophication of Lake Victoria has been related to the high loading of nutrients, mainly N and P.

2.2. Approach for the Assessment

The approach to the study was based on a literature review using the report entitled "Our nutrient world" [13] as a starting point to identify N sources and budget in the Lake Victoria Basin and to detail the potential obstacles and options for overcoming obstacles to change, using the definition of the agri-food chain as a reference to assess the different steps and processes driving the agri-food sector in the area. This study builds on lessons learned from previous studies and other initiatives to identify past and current initiatives to maximize the effectiveness and efficiency of N management in the area. Kanter et al. [3] provided the foundation for specific N policy interventions differentiated by ambition level to represent a broad spectrum of possible N prospects and grouped them into air quality controls, crop NUE improvement, livestock NUE improvement, manure recycling increase, dietary change, food loss and waste reduction and wastewater treatment and recycling. Sutton et al. [13] also showed that the value of N saved by reducing losses is typically greater than the business cost of saving it. If the benefits of improved nitrogen management outweigh the costs, what are the obstacles preventing change? This study focused on addressing such obstacles to sustainable nitrogen management and issues related to a lack of awareness, dominant priorities for regional food and energy sufficiency and economic growth.

3. Nitrogen Flows in the Lake Victoria Basin

3.1. Some Nitrogen Sources and Budgets in the LVB

Atmospheric N deposition: According to several authors [20,23–26], anthropogenic activities (bush fires, charcoal and crop residue burning, and intensification of land use), driven by population pressure, have significantly contributed to the high atmospheric deposition in the LVB to the level of 273 Gg N year^{-1} (about 70%) of wet N in the lake and 104 Gg N year^{-1} (30%) of dry N in the catchment area. The wet N deposition into the lake (59 Gg N year^{-1}) comprises 14% of oxidized compounds, 27% of dissolved organic N, and 59% of reduced compounds [23].

Nitrogen fixation (natural and agricultural): In areas with limited availability and access to synthetic fertilizers, biological nitrogen fixation (BNF) is a substantial source of N for crop production [27], and the use of Rhizobium inoculants in leguminous crops, such as soybean and cowpea, significantly contributes to enhancing symbiotic N fixation and soil fertility [28]. Nitrogen fixation in the basin is diverse and varies according to Mugidde et al. [29], ranging from 18 to 231 Gg N ha^{-1} year^{-1}. Zhou et al. [10] reported a value of 64.8 Gg N year^{-1} from farmlands in the whole catchment and a value of 98.2 Gg Nyear^{-1} from non-agricultural lands and pastures. However, these values might not be easy to control in the field because of the dynamic fragmentation of this landscape owing to anthropic pressures.

N from fertilizers and manure: Several authors have reported the low level of fertilizers (12–15 kg N ha^{-1}) used for crop production in Sub-Sahara Africa [12,30–32]. Some of the reasons that justify this are the affordability, availability, and poor quality of available fertilizers in the markets. Although it has been reported [33] that some commercial farms in the LVB (floriculture and tea) use more than 150 kg N ha^{-1}, smallholder farmers use a low rate of fertilizer and N from animal manure, leading to N losses to the ecosystem of the catchment and the lake [12,33,34]. In general, N consumption is higher than N production from crops and livestock in the LVB [10]. Therefore, agricultural production is at the expense of the soil N stock (soil N mining), which is estimated to be 14.17 kg N ha^{-1} yr^{-1} or 276.28 Gg N year^{-1} in the LVB [10]. According to UNECA [31], the five countries (Kenya, 620,700 t; Tanzania, 289,700 t; Uganda, 64,300 t; Burundi, 46,500 t; Rwanda, 39,500 t) sharing the LVB are among the least consumers of fertilizers in sub-Saharan Africa. However, Kayombo and Jorgensen [20] reported that the total N imported into the Lake between 2000 and 2004 was approximately 3.9 kg N ha^{-1} year^{-1}, 1.5 kg N ha^{-1} year^{-1}, and 0.7 kg N ha^{-1} year^{-1}, respectively, from the Kenyan, Tanzanian, and Ugandan sub-basins.

Other sources: There are many other sources that contribute to N dynamics in the LVB such as (i) reactive nitrogen (Nr) pollution into the lake [35] from wastewater (3.5 Gg N) and farming activities (52 Gg N); (ii) emissions of N compounds (N_2, N_2O, NO, NH_3), which are estimated to be 124.91 Gg N year^{-1} from pasture, 106.34 Gg N year^{-1} from agriculture and 90.82 Gg N year^{-1} from others [36]; (iii) N exported from fisheries and the Nile River at a rate of 4 Gg N yr^{-1} and 40 Gg N year^{-1}, respectively [10]; (iv) nitrogen emission from the transport sector, estimated to approximately 8% of the total N footprint [37]; (v) and nitrogen emission from the energy sector, contributing approximately 4% of the total N footprint [37].

Nitrogen budget in the LVB: Table 1 summarizes the trends in the N budget for Lake Victoria and its catchment based on reports from several authors [10,23,34,35,37,38]. There is a negative balance (about −80 Gg N.year^{-1}) between input and output in the terrestrial system and a highly excessive balance in the lake system.

Table 1. N budget for Lake Victoria and the Lake Victoria Basin (Gg N year^{-1}).

Action Area	Actions	Input	Output	Balance
Terrestrial system in the LVB	Atmospheric N deposition	273		
	Livestock Manure	97–453		
	Natural N2 fixation	96		
	Agricultural N2 fixation	27–65		
	N fertilizers	15–154		
	N emissions from soils and biomass burning		401	
	N-Harvest		278	
	N emissions from Urban/Energy sector		36	
	N export		87–110	
	Sub-total	508–1041	802–825	−294–+216
Lake system	Natural N3 fixation	963		
	Atmospheric N deposition	96–102		
	Nile river N export		40	
	Fishery N export		4	
	Sub-total	1059–1065	44	+1015–+1021

3.2. Potential Threats to Natural Resource Management in the LVB

Water quality: Groundwater resources are important sources of drinking water for rural and peri-urban areas and support a diverse range of livelihood activities. However, owing to poor waste management practices, groundwater resources below many peri-urban and urban areas are at a high risk of nitrate (NO_3^-) pollution [39,40]. Nyilitya et al. [35] indicated that in part of the LVB, the NO_3^- concentration ranged from <0.04 to 90.6 mg L^{-1}, with approximately 75% of the shallow wells and 63% of the boreholes exceeding the drinking water threshold for NO_3^- and nitrite (NO_2).

Over the last few decades, the eutrophication of Lake Victoria has caused considerable hardship to the livelihood of the population around the LVB. This has reduced the biodiversity of the lake in terms of fish and phytoplankton [41]. The N and P concentrations in the lake have facilitated algal blooms, proliferation of water hyacinth, depletion of dissolved oxygen and death of fish, creating a dead zone in the deeper areas of the lake [41,42]. Unfortunately, increasing erosion and runoff due to deforestation, fish filleting, and tanneries around the area continue to increase the N load on the lake.

Soil quality: In the LVB, there is an acute problem of soil nutrient depletion, mainly of N [12,34], varying from 32 to 60 kg ha^{-1} year^{-1}. The major factors driving the depletion of nutrient stocks (including N) are inappropriate land use, unsustainable agricultural management practices, and low nutrient use. Several studies have shown that land-use change in the LVB contributes significantly to the dynamics of soil nutrients and soil properties [34,43,44]. There were also great variations in soil nutrients as a function of land use type, but only slight variation among the sites. For example, Figure 2 shows the variation in soil nitrogen at various sites in the upper Mara River. There were no significant differences between the sites, although the mean values varied from 2.1 ± 2.2% in Silibwet to 3.5 ± 4.7% in Kirumi [43].

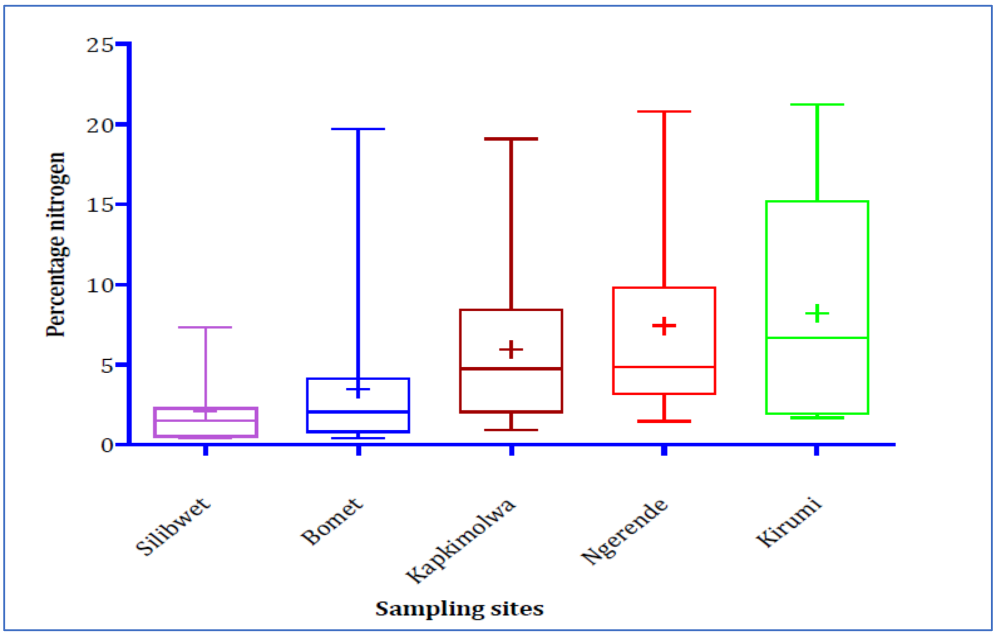

Figure 2. Variation in soil nitrogen at various sites in the upper Mara River catchment [43].

4. Challenges and Obstacles to Better N Management within the Food Production and Consumption System

According to Kanter et al. [19], the most relevant and common actors throughout the agri-food chain are fertilizer-producing companies, farmers, farm inputs/food traders, food processing companies, retailers, consumers, and wastewater facilities. Each actor in this chain plays a key role, and inefficiency can lead to N pollution and negative impacts on NUEs throughout the full supply chain [45]. An analysis of the literature is summarized in Table 2, which shows the main drivers and obstacles for better N management in the LVB in each segment of the chain. The farmers segment appears to be the most vulnerable to pressure from all the drivers. The relevant obstacles are presented in the following sections.

Table 2. Main obstacles in the agri-food chain systems in the LVB.

Type of Obstacles	Agri-Food Chain Actors					
	Fertilizer Industry	**Farmers**	**Traders/Processors**	**Retailers**	**Consumers**	**Wastewater**
Structural Obstacles	Lack of or limited Fertilizer Industries	Infrastructural deficiencies	Infrastructural deficiencies	Infrastructure and dependence on consumers	Knowledges	Poor technology
Economic Obstacles	Poor economic priority	Poor economic incentives	Poor access to markets	Prices	Lifestyle	Lack of Investment
Sector-level Obstacles	na	Poor access to inputs and knowledges	ni	ni	na	na
Policy-related Obstacles	Unsuitable political control	Land grabbing and insecure land tenure	Poor quality standard	Need of Policies	Need of policies	Policies needs
Societal and cultural Obstacles	na	Various sociocultural obstacles	ni	Various preferences	Culture	Culture
Behavioral and cognitive Obstacles	na	Various cognitive hindrances	ni	Various preferences	Willingness	Willingness
Environmental Obstacles	na	Land degradation	Need of policies	Need of policies	Need of policies	Policies needs

N.B: na: not applied; ni: not investigated.

Fertilizer use: In the densely congested area of the LVB (Figure 1B), land is intensively cultivated, leading to soil degradation and severe limitations into crop production because of the effects of soil mining on soil fertility [46] (environmental obstacles). Furthermore, unavailability and inaccessibility to correct fertilizer formulation, inaccessibility to N fertilizers in rural areas due to poor transportation by roads and poor fertilizer distribution systems (structural obstacles), and low-quality fertilizers in local markets are among the major reasons for the low usage of N fertilizers in the region [12,47] (sector-level, policy-related obstacles). Financial obstacles such as financial shortage, uncertainty about price profitability, high cost of fertilizer, lack of, low or poorly structured subsidies for fertilizers, and the low purchasing power of smallholder farmers also contribute to the low usage of N fertilizers in the LVB [12,48] (economic, policy-related obstacles). For example, in 2006, the average application of fertilizers for arable crops in LVB countries was estimated to be 1 kg ha^{-1} $year^{-1}$ in Uganda, 5 kg ha^{-1} $year^{-1}$ in Tanzania and 30 kg ha^{-1} $year^{-1}$ in Kenya, which are far below the global average (100 kg ha^{-1} $year^{-1}$) [49]. Moreover, soil quality faces strong pressure from soil organic matter depletion, which promotes soil erosion and the associated N losses. Most farmers are smallholders who cannot afford expensive and rarely available inorganic fertilizers. The yield response is low due to low levels of organic matter in soils (environmental, social and cultural, behavioral and cognitive obstacles).

Guidelines for smallholder farming: Several other factors limit N efficiency in food production systems in the LVB. There is a lack of clear and adaptive guidelines for smallholder farmers, absence of policies governing N fertilizer use, lack of know-how to change farm management practices, low awareness on environmental impacts of nitrogen pollution and weak extension services [12,47,50,51] (policy-related, sector-level, behavioral and cognitive obstacles). Due to a lack of assistance and cultural obstacles, a significant number of farmers in the LVB believe that the use of chemical fertilizers can contribute to negative effects on their soils and subsequent long-term reduction in crop productivity [52,53]. Poor fertilizer management practices (rate, amount, placement, and timing), a lack of knowledge on the benefits of fertilizer and a lack of labor for manure application are also among the obstacles in food production [52,53] (social and cultural, behavioral and cognitive, and structural obstacles). Furthermore, collaboration between private and public partners and the linkage between extension, research, and capacity-building services are weak, with negative implications for soil nutrient management and crop productivity [49,53]. Some countries (Kenya and Tanzania) use low amounts of organic inputs due to a lack of alternative energy and fuel sources, lack of livestock feed, limited production and supply of bio-fertilizers, lack of scientific data on integrated crop–livestock–natural resource research, and low availability and access to organic source of N [52].

With the establishment of the East African Community, agriculture has now shifted to a priority on the agenda of the region. Efforts are now being made through fertilizer policy to reduce taxes on N fertilizer inputs, with the aim of increasing fertilizer use among small-scale farmers with low purchasing power for inputs [54]. Governments are also recognizing their failure in the excessive focus on input subsidy programs, which often fail to reach low-income farmers [55], rather than agronomic practices to guide farmers towards better actions [56] and in the improvement of on- and off-farm infrastructure (policy-related, structural obstacles). However, the high cost of low-quality inputs derived from the relatively poor development of the market and road infrastructures (structural obstacles) and reduced access to credit facilities in smallholder communities (economic obstacles) remain the main challenges of the agricultural sector [47,51].

Seed quality: Seed availability and the existence of counterfeit seeds, among other agricultural products, impose a major limitation on achieving higher crop NUE in East Africa in general and in the LVB [57] (social and cultural, economic, and structural obstacles). The region has been identified as having one of the largest yield gaps in the world [58,59]. The diversity of cropping systems is constrained by the lack of reliable large-scale infrastructure [60,61]; hence, farmers must carefully consider what to plant. Additionally, there is a lack of supportive facilities, such as organic agro-vets and shops, which hinder the adoption of organic production systems [62].

The use of machinery: The use of modern machinery increases the acreage covered by farmers, which is of key importance because LVB agricultural production growth is a consequence of surface expansion rather than improved crop yields [63]. However, the adoption of new agricultural practices and modern machinery/equipment is limited by land fragmentation into small parcels and the inability to access global markets and obtain affordable credit (structural, social and cultural, behavioral and cognitive obstacles). There is also a lack of affordable and small-scale mechanization that fits small and/or fragmented land-holdings [52].

Low financial support on agriculture: Low public expenditure in the agricultural sector and a lack of formal access to credit negatively affect farming operations and the natural resource management capability of smallholder farmers (economic, sector-level obstacles) [49]. Education is positively correlated with financial income level; thus, less-educated farmers are less likely to be financially secure [64]. Therefore, the labor is mostly manual, and 60–80% is performed by women [65].

Gender issues: The empowerment of women was identified as a priority in the 2030 Agenda for Sustainable Development Goals [66]; despite their important role in agricultural trade and marketing in smallholder communities, women are generally excluded from financial activities and have limited access to land and capital, greatly impacting the quantity of fertilizer use and N soil mining [67,68]. The existing gender inequality in land tenure is a consequence of patriarchal societal systems, as well as women's perceived gender roles [69,70] (social and cultural obstacles). Only about 19–26% of household heads are female [71,72] in the LVB, so most farm decisions are made by men [57]. Nonetheless, social and cultural norms in East Africa are evolving [69], and efforts are being made towards a more gender-egalitarian agrarian society [73,74].

Land grabbing and insecure land tenure: Land grabbing is another highly controversial and recurrent problem in the region, and it has been identified as a significant obstacle for long-term sustainable agriculture [75]. International organizations, foreign investors/financiers, and agribusiness actors have shifted their attention to Africa [76], where weak policies and one-sided contracts allow the exploitation of land in vulnerable communities without fair compensation for the loss of land (environmental, structural, economic, policy-related). Local communities displaced from their own lands, women, and youth are particularly vulnerable to land grabbing [76,77]. However, Kumeh and Omulo [76] highlighted the existing knowledge gap regarding the impact of land grabbing on the livelihoods of young farmers in the region. This is a key issue to tackle given that Africa has the youngest population in the world (the median age is 18 years), which is expected to remain so in the future [78].

In East Africa in general, the insecurity of land tenure, inadequate access to land, lack of mechanisms to transfer rights of plots, and inequitable distribution of available lands among rural communities have resulted in severe land degradation and declining soil fertility [49,52], especially in grasslands (40% of the total area), forests (26%) and croplands (12%) [79], mainly because of overgrazing, deforestation or inadequate agricultural management practices [80]. Waterlogging in the highland vertisols and inherent soil conditions (e.g., texture, sloping, and erodibility) are some of the soil management issues identified as obstacles to N management [52] (environmental, structural, economic, and policy-related obstacles).

Food losses: Post-harvest yield losses are significant because of on-farm infrastructure problems. Although there is no consensus regarding the magnitude of food losses in East Africa (4–50% of grains are lost throughout the agri-food chain), it is agreed that most cereal/grain losses occur during post-harvest and on-farm storage, whereas vegetable and meat-based product losses occur mostly in processing, packaging, and distribution [60,81] (structural obstacles). The food industry faces the problem of power concentration among large retailers [82]. For instance, large food processing companies in the dairy industry can afford large investment costs and can find a "niche" market to avoid competition, while small dairy producers (e.g., yoghurts) find the market overly saturated [83] (economic, policy-related obstacles). Other existing obstacles in the food industry include the high fluctuation of commodity prices, lack of capital to invest in modern food processing technologies, unreasonable food standards (e.g., in packaging), and food quality issues from farmers' inadequate practices (e.g., feeding pineapples to dairy cattle resulting in low-quality milk) (policy-related, economic, and sector-level obstacles).

Climate change: East Africa is considered one of the regions that is most vulnerable to climate change, presenting additional obstacles for land use and agricultural policies to surpass. Projected increases in temperature and aridity, as well as reductions in precipitation, negatively impact water availability [84]. Groundwater, the main and safest drinking water source, is estimated to have a 30% reduction in recharge rates [85], except in areas with already negligible precipitation. The mostly rain-fed agriculture will face significant risks, with yield gaps that will be considerably harder, showing projected yield reductions of 27–32% for warming of 2 °C [86]. Livestock productivity is reduced or even impaired by the likely scarcity of drinking water for livestock and reduced amount of fodder produced. Thus, food security will become increasingly difficult to achieve, thus increasing the number of malnourished people and hygiene-related deaths [87], leading to social unrest [88].

Wastewater treatment: Conversely, highly densely populated areas around waterbodies, such as the Lake Victoria watershed (500–1000 people km^{-2}; [11]), have excessive Nr derived from insufficient wastewater treatment and sewage line connectivity between informal settlements. This lack of infrastructure considerably affects the management of N loading into surface waters [10], which negatively impacts the biodiversity and livelihoods of inhabitants [20] (structural and environmental obstacles). The lack or absence of wastewater treatment plants in the region, solid waste, domestic and industrial water, and agricultural waste are the major N sources in the lake (structural obstacles). Current environmental policies also fail to include recycling, nutrient recovery and agricultural application of organic wastes (e.g., biosolids; [12]), which could provide valuable sources of agricultural N (policy-related, sector-level obstacles).

5. Options to Overcome N Management Obstacles in the LVB and Regional Efforts

5.1. Lessons from Selected Success Stories in Sub-Saharan Africa for LVB to Overcome N Management Obstacles

Following a study on the challenges of producing more food and energy with less pollution, Sutton et al. [13] identified key actions as pivotal to an overall improvement in societal N management, some of which address a variety of obstacles and can be applied in the context of LVB, including the following: improving nutrient use efficiency in crop and animal production, increasing the fertilizer equivalence value of animal manure, improving nutrient use efficiency in fertilizer and food supply, reducing waste, lowering emissions through energy-efficient systems such as renewable sources, development of technology for NO_x capture and utilization, recycling of N and P from wastewater systems in cities, agriculture and technology, and spatial and temporal optimization of nutrient flows. Aiming to optimize nutrient flows from the farm to the continental scale, Sutton et al. [13] highlighted the need to take a global approach to overcoming obstacles in achieving a more efficient use of N, not only because nutrient flows are not confined to administrative boundaries but also because commodity trade occurs globally. Some actions undertaken in one area could have important spillover effects for other locations, and even multiplicative effects at the regional or global level. Therefore, establishing a common framework to overcome obstacles in the implementation of N management strategies is a valuable tool for policymakers and stakeholders [89]. The foremost measures required to overcome these obstacles are grouped into three main categories: (i) public awareness campaigns, because public perception is a major obstacle in wastewater reuse (behavioral/cognitive, social and cultural, and sector-level obstacles); (ii) positive environmental and societal policies to promote the recycling of wastewater and biosolids (policy-related, sector-level obstacles); and (iii) economic/financial incentives and government subsidies (economic, sector-level obstacles). Specific cases of success stories are reported below.

Deployment of appropriate policy and investment to increase the access and availability of fertilizers: Fertilizer-targeted or universal subsidy policies have contributed to increased fertilizer consumption and application rates in many SSA countries [30,56]. Table 3 indicates the growth rate of fertilizer consumption and application rate as well as the type of subsidy adopted in selected SSA countries, including the LVB.

Table 3. Fertilizer use growth rates and fertilizer subsidy policies in selected SSA and LVB countries [90].

Type of Fertilizer Subsidy	Country	Share of Fertilizer Subsidy as a Share of Agricultural Spending (%)	Average Growth Rate of Fertilizer Consumption (% 2006–2017)	Average Growth Rate of Fertilizer Application Rate (% 2006–2017)
Targeted subsidy	Tanzania	12.8	13.0	10.0
	Kenya	16.1	0.0	−1.0
	Zambia	19.9	14.0	12.0
	Malawi	44.5	1.0	0.0
Universal subsidy	Nigeria	9.2	30.0	27.0
	Mali	9.0	25.0	24.0
	Ghana	NA	11.0	10.0
	Burkina Faso	13.8	6.0	4.0

The fertilizer production capacity in SSA is the main challenge, owing to the lack of low-cost raw materials for fertilizer production, high capital requirement for investment, and low domestic demand [31]. However, in some African countries, the local capacity for fertilizer production has shown good progress, as shown in Figure 3.

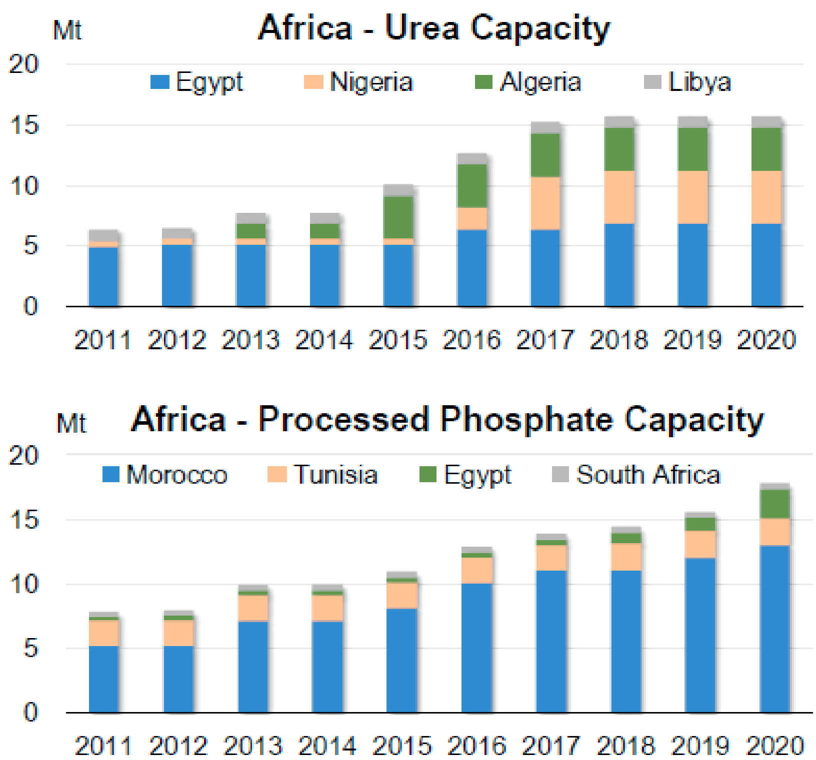

Figure 3. Urea and phosphate fertilizers production capacity development between 2011 and 2020 in major producing countries within Africa [31].

Improvement of crop responses to fertilizers: It is very important to educate farmers on the balanced application of nutrients (e.g., 4R stewardship: the right source, at the right rate, time, and place). Investing in extension services to educate farmers about integrated soil fertility management (ISFM) practices, crop breeding, and agronomic programs is also essential [91,92]. Many African countries have implemented ISFM practices [93] and have obtained results in terms of increased yield and improved returns (Table 4).

Table 4. Effect of ISFM practices on crop yield and benefit–cost ratio in selected SSA and LVB countries [93].

Country	Crop	ISFM Practices	Yield Change (t/ha)	* Benefit-Cost Ratio
Ghana	Soybean	Maize-legume rotations + improved seeds + fertilizer	+1.5 (150%)	2.3–2.7
West Kenya	Maize	Maize-Legume intercrop	+4 (300%)	1.8–2.2
South Tanzania	Maize	Improved seeds + fertilizer + Maize-legume rotation	+4.5 (300%)	2.1–2.5
Uganda (Isingiro)	Soybean	Improved seeds + fertilizer + crop rotation	+1 (100%)	2.0–2.3

N.B: * Yield Change (t/ha) is the difference of yields between the control plot and ISFM plot.

It is evident that overuse or underuse of N fertilizer is very harmful economically (e.g., reduction in crop yield and marginal profit) and environmentally (reactive nitrogen (N_r) pollutes water, air, soil, and ecosystems); however, in most SSA countries, including the LVB, "blanket" fertilizer recommendation without considering the spatial variability in soil properties is very common, which has negative implications for profitability [91]. It is important to invest in soil testing infrastructure to develop site-specific information and recommendations that recognize the local context to improve crop responses to N fertilizers [91,92]. Site-specific nutrient management is important for improving N fertilizer use efficiency (NUE), crop response rates, crop yield, maximizing marginal returns, and ensuring the sustainable intensification of SSA agriculture. Nutrient Expert (NE) has been implemented in some SSA countries including some LVB countries, and it is very useful for applying NPK nutrients properly [92]. A summary of site-specific nutrient management decision tools with direct implications for N management is presented in Table 5.

Table 5. Example of site-specific nutrient management (SSNM) in selected SSA and LVB countries [92].

Country	Crop Production System	Decision Tools	N Rate (Kg N ha^{-1})	P Rate (Kg N ha^{-1})	K Rate (Kg N ha^{-1})	Grain Yield (Mg ha^{-1})
Nigeria	Maize, rainfed	Nutrient Expert	110	15	12	3.9
Tanzania	Maize, rainfed	Nutrient Expert	100	12	12	2.7
South Africa	Maize, rainfed	SPAD Chlorophyll meter	26	42	-	
Burkina Faso	Rice, irrigated	FERRIZ + RIDEV	139	21	20	6.6
Senegal	Rice, irrigated	Nutrient Expert	141	18	34	6.9
Ghana	Rice, irrigated	Rice Advise	126	19	37	4.9
Mali	Rice, irrigated	FERRIZ + RIDEV	121	16	17	6.0

Decision tools are SSNM-based tools that provide fertilizer recommendations; RIDEV is used to simulate optimal timing of agronomic management actions; FERRIZ is based on the QUEFTS model together with on-farm data; SPAD is the SPAD chlorophyll meter; NE is Nutrient Expert; RA is Rice Advise.

Recognition and respect of tenure rights and consolidation of fragmented lands: Security of land is an incentive, particularly for smallholder farmers, to invest in their land and borrow money for agricultural inputs. Examples from Rwanda, Tsakok and Guedegbe [94] reported that the Land Use Consolidation (LUC) program increased access to agricultural inputs (seeds and fertilizers) as well as crop productivity and production, whereas the Crop Intensification Program (CIP) contributed to increasing the nutrient use efficiency (NUE) of crops.

Infrastructure improvement: Although it is still insufficient to connect the rural population with local and regional markets, efforts have been made to improve the infrastructure in rural areas in many countries in SSA. For example, the northern road corridor from the Mombasa seaport to inland Bujumbura is an important link between Burundi, Democratic Republic of Congo, Rwanda, Kenya, Tanzania, and Uganda [95,96]. Therefore, the construction of more infrastructures (road networks) is important for improving the availability and accessibility of fertilizer in the region.

Strengthening the agricultural extension services and increasing investment in agricultural research for development: Pardey et al. [97] reported that investment in agricultural research and extension and a positive correlation between research, extension systems, and farmers could accelerate the dissemination of good agricultural practices that could improve nutrient management in farmlands. Many countries within SSA did not achieve the Maputo Declaration target of spending 10% of total government expenditure on agriculture; however, some of the East African countries such as Kenya, Tanzania, and Uganda are showing a promising trend, which will help to improve N management in the region [95].

Promotion of sustainable land management practices: It is evident that sustainable land management practices (e.g., improved plant cover, intercropping, fallowing, mulching, combined application of green and animal manure, soil and water conservation practices, trapping sediments and nutrients through structural or vegetative barriers and bunds agroforestry, conservation agriculture, and land restoration) are vital for solving the problems of low soil organic matter (SOM), soil fertility, soil compaction, water infiltration, water scarcity and biodiversity reduction [98,99]. In collaboration with other stakeholders, the LVBC has implemented a basin-wide sustainable land management strategy that helps reduce nutrient losses to the environment, enhance crop productivity, restore ecosystems, and conserve the environment. For example, in Kenya, planting maize and beans in association with *Grevillea robusta* is a common agroforestry practice that helps activate nutrient cycling due to its deep rooting. Contour strip farming, integrated mulching and contour trenches are among the major soil and water conservation practices in the basin [100] that have been implemented in Kenya, Uganda and Tanzania (e.g., the Marebe catchment and Kagera River Basin).

Wastewater management: The LVBC and its stakeholders have implemented many projects to improve environmental management of polluted hotspots in the basin [8]. Planting trees to prevent sedimentation, protecting the function of the buffer zone of wetlands, and promoting the use of organic manure to increase soil organic matter are the key activities that help to control and prevent non-point source pollution. The major interventions to control point and non-point sources of pollution include the facilitation of cleaner production processes in industry, provision of sanitation facilities, and improvements in wastewater treatment facilities. Furthermore, the East African Community has developed an effluent discharge standard that can help mitigate the pollution caused by the discharge of untreated industrial effluent [8].

5.2. Efforts in Wastewater Management, Reactive Nitrogen (N_r) Removal and Recovery from Wastewater

As in other SSA countries, the growing LVB population continues to surpass the provision of sanitation services. Most of the urban centers around the lake (Kampala/Entebbe, Mwanza, and Kisumu) discharge significant amounts of wastewater into Lake Victoria, with few or no facilities for fecal sludge and wastewater collection and treatment [101]. These conditions exacerbate N and P loading in water bodies and alter the environment, ecosystems, and aquatic biodiversity [101]. The water quality of Lake Victoria has deteriorated over time, threatened by annual N discharge of 33 t year^{-1}, 57 t year^{-1} and 324 t year^{-1} in Uganda, Kenya, and Tanzania, respectively.

The LVBC, in collaboration with other stakeholders, implemented the Lake Victoria Environment Management Plan (LVEMP II) addressing (i) non-point sources of pollution through renovating the existing wastewater treatment plants and (ii) new wastewater treatment plants and (iii) industrial pollution, particularly in "hotspot" areas. The project has contributed significantly to the capacity building (training) of local administrators, communities, and the wider public, particularly in project planning, implementation, monitoring, and evaluation [8]. The European Union (EU)-funded project that was implemented in 2003–2015 increased sanitation coverage to 80%, increased water coverage, and developed the wastewater master plan of Kisumu City [102]. There are limited wastewater plants in the LVB with different efficiencies and capacities in terms of N_r removal, although they are not sufficient for the treatment of the large amounts of wastewater produced in the basin [103].

The Nyalenda (Kisumu, Kenya) wastewater stabilization ponds have low N removal efficiency with mean levels of reductions in total N, Organic N, nitrite (NO_2^-) and nitrate (NO_3^-) of 7.8%, 16.6%, 50% and 10.4%, respectively, indicating that the wastewater treatment system did not significantly contribute to the water quality of Lake Victoria [104]. According to Zhang et al. [105], biodegradation processes such as volatilization of ammonia (NH_4^+) gas nutrient consumption by weeds and autotrophic oxidation by nitrifying bacteria, Nitrobacter and Nitrosomonas are the major factors for the reduction in NO_3, NO_2, organic N and total N. Similarly, Kisat wastewater treatment plants in Kisumu have low N removal efficiency, and the analyzed nutrients ranged from 2.82 to 41.30%. However, both Kisat and Nyalenda wastewater treatment plants reduced the total phosphorus (TP) by 10% and 31%, respectively, whereas the wastewater treatment plant in Homa Bay reduced both the total nitrogen (TN) and total phosphorus (TP) by 11% [106]. The wastewater treatment facilities of Nyalenda, Kisat and Homa Bay are not sufficiently endowed to remove reactive nitrogen (N_r); as a result, their contribution to the water quality of Winam Gulf is insignificant.

Producing ammonium sulfate ($(NH_4)_2SO_4$) from urine via ion exchange is feasible for source-separated excreta collection and treatment services and has been implemented in Nairobi, Kenya. This is feasible and vital for SSA countries, including Kenya, as it can help alleviate soil nutrient depletion resulting from the low use of N fertilizers and unsustainable farm management practices [107]. Separation of human excreta and decentralized treatment plants can serve more households with low cost and energy as compared to the conventional waterborne sewers and treatment of urine by ion exchange, which is 40% less expensive compared to disposal of human waste without treatment. Ion exchange for nitrogen recovery from source-separated urine has an adsorption capacity of 4.02–4.21 mmol N/g resin and regeneration efficiency of >90% [107].

6. Summary of Lessons Learnt

N load: Nitrogen loading into the LVB includes biological N fixation, atmospheric deposition, municipal and industrial waste and erosion, with excessive nutrient load into river systems leading to eutrophication at selected locations and massive growth of algae and other invasive aquatic weeds. Thus, ecosystem equilibrium is disrupted by oxygen depletion, which affects fish breeding and other aquatic biota. The situation is worsening owing to population pressure and lack of alternative livelihood sources.

N use: In the LVB, there is too little nitrogen for crop, animal and human nutrition because of low application of reactive nitrogen (Nr) for crop production, while there is too much in water bodies such as Lake Victoria, with the nitrate levels (NO_3-N) in selected sections being as high as 16.2–87.9 $\mu g\ L^{-1}$ because of Nr losses through excessive soil erosion, atmospheric deposition, poor management of crop–livestock systems, and municipal and industrial wastewater, among others.

Low productivity: With the low use of N in production, most farmers are unable to meet the target of 50 kg of nutrients per ha set by the Abuja Declaration of 2006 [12,108]. Unbalanced N input to soils has led to excessive depletion and widespread yield gaps compared with other parts of the world. Poor quality fertilizers are also used as N sources (for example, urea containing 31% less N than the required amount in authentic urea).

Supporting services: There is a poor linkage between research and policy makers in the management of N input within the smallholder farming system, leading to a lack of policies to address the adoption of good agricultural practices and poor coordination of N input and management, particularly for organic sources that could create a better and more favorable means of sustainability [109,110]. The weak linkage between researchers, policymakers, extension services and farmers does not facilitate the transfer of new technologies to farmers' innovation [34].

Obstacles to better N management: There have been some challenges or obstacles (structural, economic, environmental, policy-related, societal/cultural, behavioral, and cognitive) in the adoption of selected technologies such as fertilizers, mainly because of acquisition costs, accessibility, and the need to apply fertilizers across several seasons to induce significant increases in yields due to poor soil retention capacity and carbon stocks. Inadequate investment in infrastructure such as effective wastewater treatment facilities, erosion control structures, and better distribution networks of technologies has also contributed to the lack of sustainability or scalability of proven technologies.

Overcoming obstacles: As for the opportunities for improving N management in the LVB in the farmers segment, which appeared to be the most vulnerable and likely to face the pressure of all the drivers, there is a need to increase the use of N input and NUE in cropping systems to improve agricultural productivity with cheap, sustainable, and environmentally friendly products. Alternative sources such as animal manure, crop residues, and biological nitrogen fixation should be explored by scientists and encouraged for use by farmers, combined with awareness of the use of 4R (right source, right rate, right time, and right place) stewardship of nutrient management, as well as using crop varieties that are well adapted to local conditions. The development of crop- and site-specific N applications to improve food production and minimize N loss to the environment is also a good opportunity for scientists and extension services. Governments should offer subsidies for farm inputs to promote N use and create efficient public–private partnerships for easier access to fertilizer products [110]. Regulatory bodies should assess the quality of fertilizer inputs to ensure their effectiveness and low impact on food contamination and environmental pollution. In general, the foremost measures required to overcome most obstacles are (i) public awareness campaigns, (ii) positive environmental and societal policies to promote recycling, (iii) economic and financial incentives, and government subsidies.

Areas of future research and policy perspectives: The population in the LVB is projected to reach 113–165 million people by 2050 [8,111], a 3–4-fold increase within the next three decades. Meeting the need for more food and feed will require significant N input to enhance crop and livestock production beyond the reported average of 18 kg ha^{-1} N based on the analysis of the 2006 Abuja Declaration (but falls short of the targeted 50 kg ha^{-1} N). It is therefore important for multi-stakeholder partnerships in implementing key N interventions, as shown in Figure 4. In the future, there will be a need not only for higher N input but also a balanced and integrated approach to avoid losses, on the one hand, and enhance the capacity of farmers to apply recommended amount to avoid soil mining and soil degradation, on the other hand. This can be achieved through future investment and engagement in research with the aim of achieving recommended NUEs and N balances within the region over time by taking into consideration 4R stewardship (Figure 4). This calls for a common policy approach by different countries regarding fertilizer access, research, application and management to avoid loading into the lake. Policy interventions by affected countries should also consider common approaches towards waste management within/into the lake basin/lake.

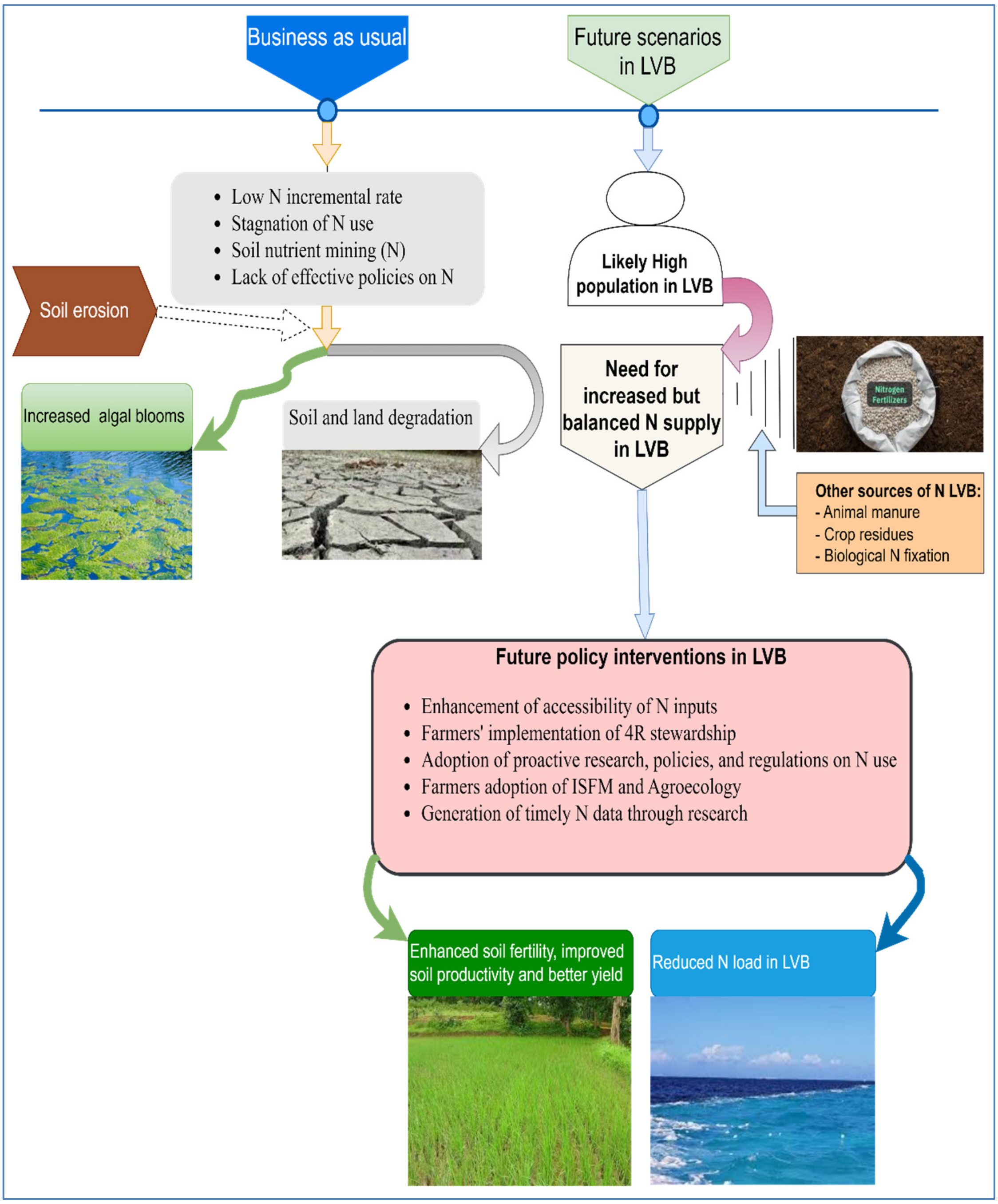

Figure 4. Framework depicting present condition and most likely areas of plausible future research and policies/scenarios in Lake Victoria Basin (LVB) and surrounding countries for sustainable N use, crop productive and environmental safety.

7. Conclusions

Unbalanced use of N input is a serious threat to agricultural productivity leading to extreme soil N mining. The majority of Lake Victoria Basin farms operate within negative N balances and above the safe operating boundary for N in production systems, although there is a lack of specialized systems to accurately monitor N flow at smaller spatial scales. From the projected changes by the recent East African Community in N input as recommended by various policies and stakeholders, there are likely to be changes in both the current yield and NUE values in the future; however, most small-scale farmers will continue to experience low yields, specifically in maize with less than 5 t ha^{-1}, which implies an overall challenge of food security for the rapidly growing population. The suggested fertilizer increment to 50 kg (NPK) ha^{-1} as spelt out in the Abuja Declaration will slightly improve the growth and yield of maize but is not sufficient to overcome the soil fertility decline compared to other regions with plausible nitrogen management strategies coupled with strong policies. Negative N balances were also evident from this analysis, with higher N removal than N input, indicating the presence of a low N status, leading to soil N mining and degradation of the overall fertility and quality of the soil.

The study revealed a gap or data limitation in the actual N flows in cropping. More research is required to close the gap for the development of effective policies that aim to improve the current scenario of low-to-zero N input by increasing the availability of fertilizers and affordable prices and encouraging the use of organic sources of N to increase sustainability in farms.

These results could be instrumental in informing policies on changes in N management, particularly concerning sustainability and food security, and the need for better recommendations. Therefore, decision-makers should focus on more integrated approaches to provide alternative tools and opportunities, such as increasing access to controlled-release fertilizers, nitrification inhibitors, manure, and composting, to improve soil fertility and increase crop productivity while simultaneously optimizing NUE. The findings of this study may be helpful in formulating new targets for fertilizers, particularly N input, to optimize NUE and reduce the yield gap for sustainability. The focus should also be on integrated soil fertility as a package for nutrient management in cropping systems. A reduction in nitrogen losses in Lake Victoria would benefit all Nile partner states, contributing to better water quality, reducing conflicts among countries, and addressing regional agreements and conventions related to transboundary water resource and nutrient and biodiversity management.

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