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Review

Assessment of Reactive Nitrogen Flows in Bangladesh's Agriculture Sector

Md. Mizanur Rahman [1,*], Jatish Chandra Biswas [2], Mark A. Sutton [3], Julia Drewer [3] and Tapan Kumar Adhya [4]

1 Department of Soil Science, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh
2 Krishi Gobeshona Foundation, Farmgate, Dhaka 1215, Bangladesh; jatishb@yahoo.com
3 UK Centre for Ecology & Hydrology, Penicuik EH26 0QB, UK; ms@ceh.ac.uk (M.A.S.); juew@ceh.ac.uk (J.D.)
4 Kalinga Institute of Industrial Technology, Bhubaneswar 751024, Odisha, India; adhyas@yahoo.com
* Correspondence: mizan@bsmrau.edu.bd; Tel.: +880-29205310-14 (ext. 2169) or +880-1710659303; Fax: +880-29205333

Abstract: To assess the status of and trends in agricultural nitrogen (N) flows and their wider consequences for Bangladesh, in this study, we analyzed data from national and international bodies. The increased rates of N fertilizer applied for increased food production leaves behind a huge amount of unutilized reactive N (Nr). N fertilizer use is the largest in the crop sector, an important sector, where current annual consumption is 1190 Gg. The present combined annual Nr production from crop, fishery, and livestock sectors is ~600 Gg, while emissions of nitrous oxide (N_2O), a potent greenhouse gas, are ~200 Gg. Poor N management results in Nr leaking into the environment, which has increased approximately 16-fold since 1961. One potential consequence is the disruption of ecosystem functioning. The balanced tradeoff between food production and reducing Nr input needs to be achieved. One solution to reducing Nr may be a holistic approach that optimizes N application rates and incorporates waste of one subsector as an input to another applying the principle of the circular economy.

Keywords: fisheries; livestock sectors; N_2O; manure; sustainable N management; nitrous oxide; South Asia

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1. Introduction

Nitrogen (N) is an essential nutrient for all life forms and the ultimate resource for food production. Molecular nitrogen (N_2) is plentiful in the atmosphere but is unreactive [1]. To make it available for plants and animals, it needs to be transformed into reactive forms such as ammonia (NH_3), nitrate (NO_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), amines, and other organic forms of N [2]. During the green revolution, the dramatic advances in inorganic fertilizer production and application to crop fields have contributed to increasing agricultural productivity, ensuring food security for the ever-expanding global population [3,4]. However, the excessive use of inorganic N fertilizer in agriculture, accompanied by reactive N (Nr) production, is threatening the sustainability of both crop production and the environment [5–7]. Nr is produced in the environment by lightning, wildfires, biological N_2 fixation (BNF), and use of applied organic and inorganic fertilizers to crop fields. It is also produced through the burning of fossil fuels, which leads to the formation of NO_x in the atmosphere. UNEP and WHRC [8] reported that in the last 150 years, the contribution of Nr from the agriculture, industry, and transport sectors to the atmosphere, soils, and water bodies has increased more than 10-fold annually. N fertilizer is applied to fields to increase crop yields. However, a considerable amount of Nr is not used by the crops and is instead lost from soil through different biological and abiotic processes.

Bangladesh's economy is largely dependent on agriculture; the share of agriculture in Bangladesh's gross domestic product (GDP) was 12.65% in 2020 [9]. In Bangladesh, agricultural land occupies 70.6% of the total land area, with total cultivable land covering 8.5 million ha [10]. As agricultural growth is essential to feed its huge population, Bangladesh is one of the most climate-vulnerable countries in the world [11]. Hence, increasing production from different agricultural sectors under a changing climate has become a serious challenge for Bangladesh. About 82,900 ha of agricultural land is lost every year because of new settlements, industrialization, road construction, and other developmental works, exerting tremendous pressure on limited land resources to produce more food for the increasing population [12]. In 1971, the population of Bangladesh was only 75 million, which increased to 81.36 million in 1980, and the current population stands at 166.01 million [13]. In 1980–1981, the food grain production in Bangladesh was only 15 Mt; by 2016–17, it increased to 55 Mt [10], representing a 267% increase and indicating a significant positive effect of modern technologies, including high N-fertilizer use, on increasing production from 0.20 Mt in 1960–1961 to 1.12 Mt in 2018–2019.

The fisheries sector plays a vital role in Bangladesh in terms of nutritional security, supplying over 60% of animal protein contributing 3.8% to the country's GDP [14]. The country has diverse and extensive fisheries resources, comprising capture fishery and aquaculture, both freshwater and marine. Inland aquaculture contributes 83.7% of the total fishery production in Bangladesh [15]. Bangladesh is the fifth largest aquaculture producer in the world, and the country's farmed fish production increased 1.78 times from 0.79 Mt in 2001–2002 to 2.2 Mt in 2017–2018 [10,16]. This increased fish production is largely supported by the applications of fertilizer and supplementary feed as inputs to the pond systems in freshwater aquaculture. Reportedly, only 10–30% of the applied feed N is utilized by fish and the residual 70–90% remains in the pond systems, becoming a potential source of gaseous losses to the environment in the form of NH_3 and nitrogen dioxide (NO_2) [17].

Livestock is another vital sector of the rural economy in Bangladesh. It accounts for 14.1% of the agricultural GDP and 2.6% of the country's GDP [18,19]. Chemical N fertilizer and animal manure are used for fodder production. Animal manure contains a large amount of N [20]. The annual fresh manure production in Bangladesh from ruminants and poultry is 151.3 and 4.5 Mt, respectively, which contribute a total of 0.296 Mt of N [21]. Animal manure may release substantial amounts of NH_3, N_2O, and NO to the environment during manure management and application to crop fields [22]. Conversely, animal manure, if applied to agricultural fields, might improve soil health and crop productivity. However, manure management in Bangladesh is traditional (mainly without manure treatment) and manure heaps might therefore act as a hotspot source of Nr in the environment.

Intensive cultivation practices with inorganic fertilizers cause environmental pollution and soil health degradation [23]. Globally, the N use efficiency, expressed as the ratio of N uptake to N applied, also called the apparent recovery efficiency, is only around ~20%, so 80% of the N in applied fertilizer is lost to the environment, equating to an annual loss of USD 200 billion [24]. In Bangladesh, traditionally, N fertilizer is broadcasted, an about 65–70% of the applied N is lost [25]. Such excess Nr reduces the quality of soil, water, and air; increases GHG emissions; degrades the ecosystems; and reduces biodiversity, significantly altering the global N budget, and ultimately affecting the global climate [1,26,27]. Among different forms of Nr, in the present study, we attempted to quantify release of NH_3, N_2O, and nitric oxide (NO), as well as non-CO_2 GHG emissions from the agricultural sectors in Bangladesh. High-input agriculture can contribute up to 60% N_2O emission globally, and N_2O is the most potent GHG, with a global warming potential (GWP) of 298 times that of CO_2 on a 100 year time horizon, i.e., N_2O absorbs 298 times more heat compared to CO_2 on a per-molecule basis [28]. NO and NO_2 can have serious negative impacts on the environment and human health. These include damage to the ozone (O_3) layer; reactions with volatile organic compounds (VOCs) to produce ground level O_3, which in turn can damage crops and is harmful to humans; and links to fine particulate matter ($PM_{2.5}$), which can cause respiratory diseases [29]. Nr can also negatively affect human health through occupational exposure to NO_2, which damages lung functions, and by causing methemoglobinemia through drinking NO_3^--contaminated ground water and consumption of excess NO_3^- containing leafy vegetables [30,31]. Unionized NH_3 can enter a fish's body through breathing, ingestion, and contact. It reacts with water and produces ammonium hydroxide, which damages fish cells. In addition, atmospheric NH_3 is known to damage plants, and contributes to the eutrophication and acidification of ecosystems [32].

Therefore, it is crucial to reduce Nr losses through sustainable N management that encompasses policy guidelines, social awareness, and execution in farmers' fields. To reach this goal, information is required on how much Nr is produced in Bangladesh from field agriculture, aquaculture, and livestock sectors, which is currently not available in the scientific literature. Moreover, to develop strategies for the effective use of N fertilizers in agricultural sectors, it is crucial to quantify the extent of Nr losses. In this study, we collated Nr use patterns in the crops, fisheries, and livestock sectors and associated Nr release as a first step to providing available data in one place, which might help guide policy formulation for the better management of N fertilizer.

2. Materials and Methods

In this study, we analyzed the information collected from different published sources including peer-reviewed journals and books as well as grey literature such as websites and reports. However, some of the information on agriculture, fishery, and livestock production systems in Bangladesh needed further conversion using different accepted equations and factors, which are summarized in this section. Definitions of different activities according to the FAO are briefly described, and include manure management, inorganic fertilizers, manure applied to soils, use of crop residues, cultivation of organic soils, and burning crop residues and grasses [33]. The term manure management includes aerobic and anaerobic decomposition of manure at the farm prior to being applied to the field. In the context of pasture, it usually means manure left in the fields as directly excreted by the livestock. Inorganic fertilizers are chemical fertilizers that are industrially produced. Manure applied to soils means manure N added to agricultural soils by farmers. Crop residues are, for example, straw left on agricultural fields. Organic soils used for agriculture decompose and release plant available N (NH_4^+, and NO_3^-) to the soil and ultimately release N_2O to the atmosphere. Burning crop residues, grasses, and biomass is the combustion of a specific material on-site.

2.1. Data Sources and Nr Production from Agriculture

Data on inorganic N fertilizer production, import, and consumption in Bangladesh from 1960–2019 were collected from various sources [20,33–35].

Excess (+) or deficit (−) N fertilizer was calculated using Equation (1).

$$\text{Excess } (+) \text{ or deficit } (-) = \text{Production} + \text{Import} - \text{Consumption} \tag{1}$$

Data on present status and future projections of N demand by rice and rice yields (during different cropping seasons, viz. aus, aman, and boro rice) were collected from different sources [20,36–38]. N uptake by rice was calculated considering a grain yield of 18 kg N t^{-1} [10]. Apparent recovery efficiency (RE) of N was calculated using Equation (2).

$$\text{RE } (\%) = \frac{\text{N uptake}}{\text{N applied}} \times 0.4 \times 100 \tag{2}$$

N uptake data from a zero N plot (nonfertilized control plot) was not available; therefore, the contribution of applied inorganic N fertilizer was generalized and considered to be 40% of total N recovery according to available literature data [39–41]. Therefore, RE was multiplied by 0.4 to find an overall estimation of N recovery in rice cultivation in Bangladesh.

Emissions of different Nr from inorganic fertilizer applied to crop fields were calculated using Equation (3).

$$\text{Emission of } NH_3, N_2O, \text{ and NO } \left(\text{kg y}^{-1}\right) = \text{N on cropland} \times \text{Emission factor} \quad (3)$$

Emission factors for N_2O and NO from inorganic N fertilizer in the South Asian region are 3.4% and 1.4%, respectively [42], and 22.4% for NH_3 in Bangladesh [43]. Data on N_2O emissions from manure applied to soils, use of crop residues, cultivation of organic soils, burning crop residues and grasses in Bangladesh for the period of 1961–2016 were obtained from FAOSTAT [33]. Activity data were categorized and are expressed as gigagrams of NH_3, N_2O, and NO. Furthermore, N_2O emissions in CO_2 equivalents (Mt CO_2e) from agriculture comprising crop and livestock production and management for the period of 1990–2018 were obtained from the Climatewatch website [44]. Values were divided by 298 for the conversion from CO_2e to N_2O as the GWP of N_2O is 298 times higher than that of CO_2.

2.2. Data Sources and Nr Production from Aquaculture

Fish feed production and consumption data in Bangladesh during 2008 to 2017 were collated from different sources [45–47] that were subjected to several conversions to derive Nr production.

Total N in fish feed was calculated based on available published data; specifically, feed contains 35% protein, with 16% N content in protein [17]. Lost N from feed was calculated considering a feed use efficiency of 30% [48]. The total ammonia nitrogen (TAN) in fish ponds includes both NH_4^+ in solution and gaseous NH_3 at equilibrium and was calculated using Equation (4) [49], where 0.092 is the model constant coefficient.

$$\text{TAN (t)} = \text{Feed (t)} \times \text{Protein fraction in feed} \times 0.092 \quad (4)$$

The conversion of the fraction from fish feed N to N_2O emission is 0.018 [17]; the amount of cultured fish production in ponds were 1.8 and 1.9 Mt in 2016 and 2017, respectively [46]; and the average feed conversion ratio (FCR) was found to be 1.4 [50]. Therefore, the calculated amount of feed required for growing fish was found to be 2.38 and 2.66 Mt in 2016 and 2017, respectively.

$$\text{Feed requirement (Mt)} = \text{FCR} \times \text{Fresh weight of fish (Mt)} \quad (5)$$

2.3. Data Sources and Nr Production from Livestock

The carcass weight of animals (livestock and poultry) of Bangladesh for the period of 1961–2017 was extracted from FAOSTAT [33], and manure N and Nr production were calculated using different conversion values as detailed below.

NH_3, N_2O, and NO emission data from livestock production in Bangladesh for the period of 1961–2017 were obtained from FAOSTAT [33]. The dressing percentages of beef cattle exotic, beef cattle indigenous, buffalo, swine, goat, sheep, turkey, broiler, and duck were 62%, 51%, 45%, 70%, 45%, 50%, 79%, 71% and 89%, respectively [51]. Slaughter weights of different animals were calculated using the dressing percentage (Equations (6)–(8)).

$$\text{Dressing percentage (DP)} = \frac{\text{Carcass weight}}{\text{Live weight}} \times 100 \quad (6)$$

$$\text{Total carcass weight or production (t)} = \frac{\text{Yield}}{\text{Carcass weight}} \times \text{Head} \quad (7)$$

$$\text{Live weight or slaughter weight (ton)} = \text{Carcass weight} \times \text{Dressing percentage (DP)} \quad (8)$$

Slaughter weights (kg) of all animal categories were multiplied by a specific emission factor (cattle 0.2, goat 0.83, sheep 0.67, poultry 0.3, and horse 0.18) in order to obtain N excretion in kilograms per animal per year as provided by Sheldrick et al. [52]. Total N (TN) was calculated using Equation (9) provided by Raza et al. [53]. N in manure was calculated by multiplying the fractions of TN excretion provided by Sheldrick et al. [52] for each type of animal (cattle 0.4586, goat 0.3145, sheep 0.995, poultry 0.6987, and horse 0.343) with the amount of manure (Equation (10)). It was then summed to obtain the total N as manure from livestock and poultry of Bangladesh. Volatilization loss of N from manure was calculated using Equation (11). Volatilization rates of N for cattle and poultry manure were 36%, and 28% for buffaloes, sheep, and goats [54]. N from manure applied to cropland was calculated using Equation (12) provided by Liu et al. [55]. Production of Nr (NH_3, N_2O, and NO) was calculated using Equation (13). The ammonia (NH_3) emission factor from manure N was 25% [56], and 4.56% and 0.13% for N_2O and NO, respectively [42]. The same factors were applied for deriving Nr from bioslurry, a semisolid byproduct from biogas plants after anaerobic digestion of manure.

$$\text{TN excretion} \left(\text{kg y}^{-1}\right) = \text{Slaughter weight (kg)} \times \text{Emission factor} \quad (9)$$

$$\text{N as manure} = \text{TN excretion (kg y}^{-1}) \times \text{Fraction of TN excretion} \quad (10)$$

$$\text{N loss} = \text{N in manure} \times \text{\% volatilization rates of different livestock manure} \quad (11)$$

$$\text{N on cropland} = \text{N as manure} - \text{N loss} \quad (12)$$

$$\text{Emission of Nr (kg y}^{-1}) = \text{Manure N on cropland} \times \text{Regional emission factor} \quad (13)$$

Nitrous oxide (N_2O) emission from manure management in Bangladesh for the period of 1961–2016 was obtained from FAOSTAT [33].

3. Results and Discussion

3.1. Nitrogen Fertilizer Consumption, Production, and Import in Bangladesh

Nitrogen consumption in Bangladesh was only 20,000 t in 1961, increasing to 1.27 Mt in 2008, and then decreasing to 1.19 Mt in 2019 (Figure 1). However, N fertilizer consumption in the country increased from 1961 to 2019 to increase food production (Figure 1). N production also increased over time until 1994, with a peak production of 1 Mt, and declined thereafter until 2019. To meet the N requirements, import of inorganic fertilizer (urea, DAP, etc.) started from 1991 and increased rapidly. There was an excess of urea N during 1985–2007, whereas a deficit existed before and after this period. The deficit in available fertilizer was balanced using di-ammonium phosphate (DAP) and different organic fertilizers as well. From DAP, 7512 t of N was used during 1980–1981, which increased rapidly to 109,620 t of N in 2016–2017 [20]. Consumption of N fertilizer in Bangladesh increased during the green revolution to increase food grain production, which began with the introduction of the IR-8 rice variety from IRRI, Philippines, in 1967. The spread of the green revolution and the resulting increase in food production were visible after the country's independence in 1971; since then, N consumption has increased linearly.

The major crops of Bangladesh are rice, wheat, maize, and potato. Rice was grown on 11.05 Mha of land in 2016–1207, and the total cropped area was 15.44 Mha [10] (Figure 2). This appears to be the maximum use of the country's agricultural land available for rice production, which ultimately contributed to a significant increase in rice production of about 34 Mt (Figure 2). This increased crop production resulted in an increase in N consumption (Figure 1). Furthermore, N fertilizer is also used in other crops, fodder production, semen preservation, and fishponds, but these data are not available. To increase food production, cropping has been intensified with high-yielding modern varieties that consume mainly large amounts of inorganic fertilizers, and, to a lesser extent, organic fertilizers. In the last decade, N constituted about 75% of the total plant nutrients applied as fertilizers in Bangladesh [57]. However, farmers' awareness of balanced fertilization and technology dissemination have contributed to reducing the share of chemical N fertilizer to 55% of the total nutrients applied to crop fields [58].

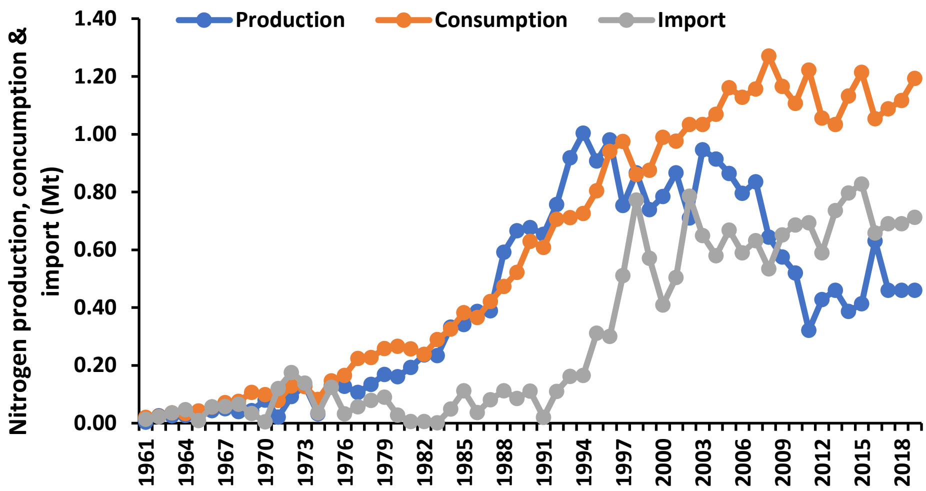

Figure 1. Trends in N production, consumption, import, and excess or deficit in Bangladesh since 1960–1965 to 2015–2019. Data compiled from different sources [20,33–35].

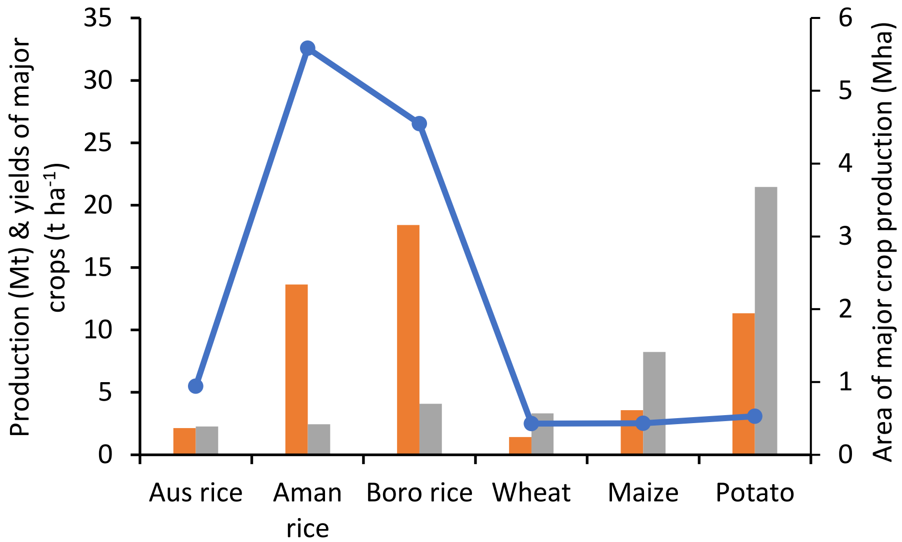

Figure 2. Major crops, area, production, and their yields in 2016–2017 in Bangladesh [10].

Rice production might have to be increased further to meet the increasing food demand of the growing population by using higher rates of N, P, K, and other fertilizers, and adopting pest management practices. According to the Bangladesh Unnayan Onneshan think-tank [38], the present requirement of urea for rice is 2.45 Mt; in 2050, the projected urea fertilizer requirement is 3.92 Mt (Figure 3a). The projected N demand for rice from 2007 to 2050 follows a linear trend. Among the three types of rice, urea consumption is the lowest in aus rice (pre-monsoon summer rice) and the highest in boro (dry season irrigated rice), whereas for the transplanted aman rice (monsoon rice), the requirement is almost as high as for boro rice [20]. The global N use as a percentage of N fertilizer demand was 9.5% in 2018 [59]. The N content in most of the soils of Bangladesh is low to medium [20]. Therefore, a large amount of inorganic N fertilizer is applied to bridge the gap between existing levels and the plants' requirements to increase crop production. The amount of ammonium N (NH_4^+-N) and nitrate N (NO_3^--N) in agricultural soils in Bangladesh varies from 5.1–21.2 and 2.6–5.6 mg kg^{-1}, respectively, [60], necessitating replenishing these nutrients from other sources such as inorganic fertilizers and manure. However, N undergoes several transformations in the soil and crop environments that result in loss of the N that cannot be taken up by the crop via the hydrosphere, atmosphere, and soil [61]. The loss of N from agricultural land is high in tropical and subtropical countries such as

Bangladesh [62]. Hence, despite intensive cropping with modern crop varieties and the use of mostly inorganic fertilizers, N use efficiency in Bangladesh is declining. The apparent recovery efficiency of N in rice in the country remains almost constant, ranging from 25–30%, with marginally higher rates in boro rice since 2007 to date and for predictions for 2050 (Figure 3b). Due to intensive cropping and the associated mining of nutrients, the contribution of the soil to the nutrients supply or crop productivity is also declining. Such plateauing of yield is of concern for future food security in Bangladesh. As a result, a higher amount of N fertilizers is being used by the farmers in order to maintain similar rice yields. Application of inorganic N fertilizer in agriculture is essential to meet global food, feed, and fiber needs [63]. At the same time, fertilizer efficiency also needs to be increased by adopting various soil and crop management activities. In various research stations in Bangladesh, the apparent recovery efficiencies of N for the major crops, viz. rice, wheat, maize, and potato, are 48%, 62%, 26%, and 58%, respectively, and agronomic efficiencies are 37, 40, 17, and 110 kg kg^{-1}, respectively (Figure 4). However, N use efficiencies are generally much lower in the farmers' fields because of poor N management and the imbalanced use of fertilizers (Figure 3b). Therefore, there is room to increase N use efficiency, particularly in farmers' fields.

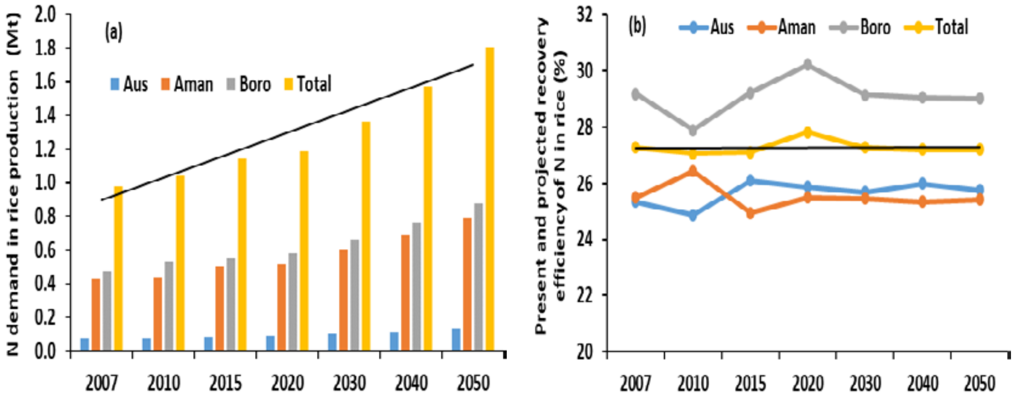

Figure 3. Present and future N demand (**a**), and its apparent recovery efficiency (**b**) in rice production in Bangladesh. Produced using data from different sources [20,36–38].

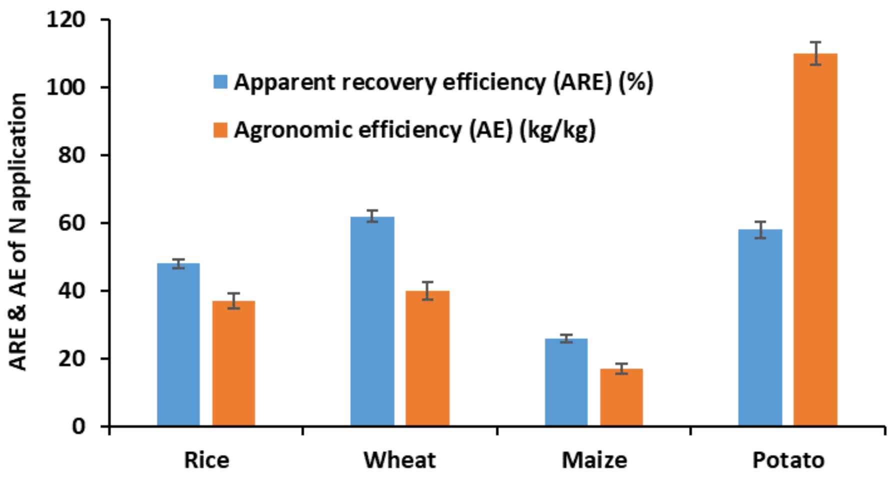

Figure 4. Apparent recovery and agronomic efficiency of N fertilizer of major crops in Bangladesh.

3.2. Reactive N (Nr) Production in Bangladesh's Agriculture

Significant proportions of N fertilizer applied for crop production are subject to loss to the atmosphere. The release of Nr from N fertilizer as NH_3, N_2O, and NO in Bangladesh since 1961 to 2019 has increased dramatically (Figure 5a). From 1961 to 2019, emissions of NH_3, N_2O, and NO from N fertilizer increased from 4.72 to 263.45, 0.68 to 37.95, and from

0.28 to 15.65 Gg, respectively. This magnitude of loss of Nr from inorganic N fertilizer is of serious concern for agricultural and environmental sustainability. Production of Nr and its losses to the environment have increased in recent years mostly because of higher rates of N fertilizer application coupled with low use efficiency. Losses occur through processes such as ammonia volatilization and nitrification-denitrification [64]. Surface run-off and leaching of Nr also occur in the form of NO_3^- and NH_4^+ from rice fields. NH_4^+-N loss is usually higher than NO_3^--N loss in wetland paddy fields in Bangladesh [65].

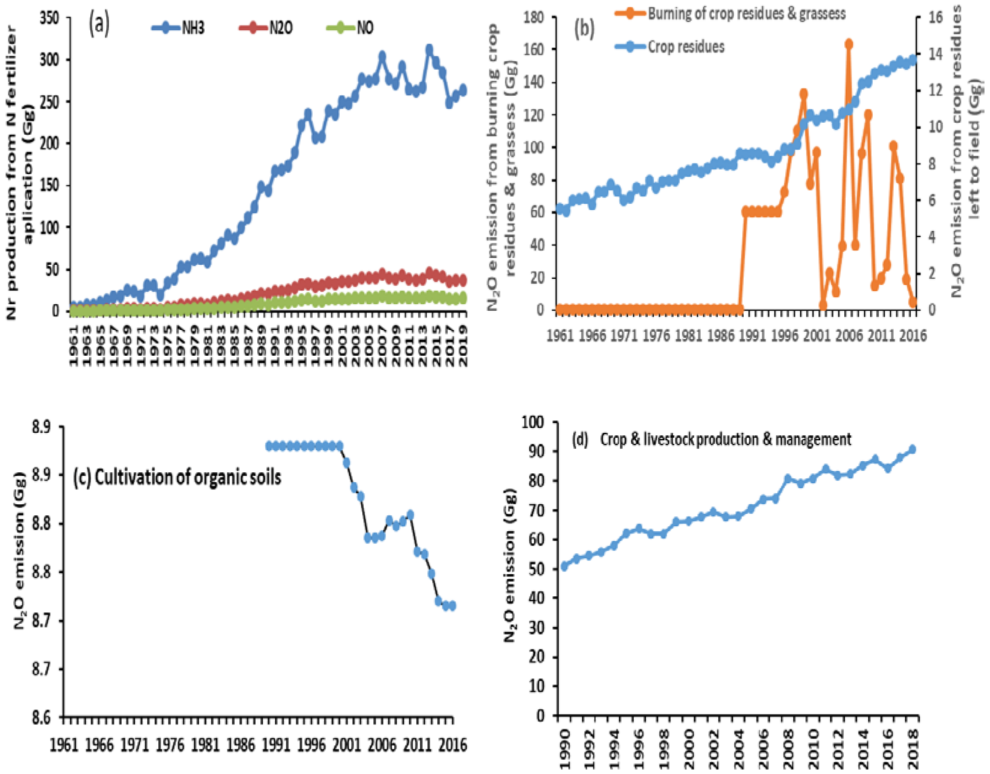

Figure 5. Reactive N (Nr) production in Bangladesh: (**a**) N fertilizer application, (**b**) crop residues, burning crop residues and grasses, (**c**) cultivation of organic soils, and (**d**) crop and livestock production and management. Raw data for (**a**–**c**) were taken from FAOSTAT [33] and IFASTAT [35], and for (**d**) from Climatewatch [44].

There was a noticeable loss of N_2O because of crop residue management and burning of crop residues and grasses in Bangladesh from 1961 to 2016 (Figure 5b). Residues incorporation into crop fields contributed to 5.56 and 13.70 Gg of N_2O in 1961 and 2016, respectively. On-site burning of crop residues and grasses showed similar emission rates of N_2O from 1961 to 1989 (0.35 to 0.44 Gg), then increased to a peak of 163.64 Gg in 2006, and decreased to 5.24 Gg in 2016 (Figure 5b). The likely reason for this is higher rates of burning during 1990 to 2006, before an awareness program was launched encouraging farmers not to burn residues. Cultivation of organic soils decreased N_2O emissions in croplands from 8.88 Gg in 1990 to 8.71 Gg in 2016 (Figure 5c). Better management of organic matter, soils, and crops might be the cause of slowing rates of N_2O emissions from the cultivation of organic soils. Furthermore, decomposition of organic soil might have reduced as N was taken up by microorganisms. N lost as N_2O from most of the agricultural activities increased substantially from 1961 to 2016. Data obtained from Climatewatch showed that N_2O emissions from crop and livestock production and management activities almost doubled from 50.97 to 90.73 Gg during the period of 1990 to 2018 (Figure 5d).

Losses of Nr as NH_3, N_2O, and NO from inorganic fertilizers, management of crop residues, and burning of crop residues and grasses are based on various assumptions and factors; however, the available numbers confirm a substantial release of Nr from crop agriculture. The agriculture sector of Bangladesh, comprising crop and livestock production and management, contributed 88.5 Mt CO_2e of non-CO_2 GHG emissions in 2018 and contributed the most (44.49%) compared to the energy, waste, and industrial process sectors (Figure 6). N fertilizers are necessary to feed the population, but excess Nr from agriculture can severely pollute the environment, as discussed above.

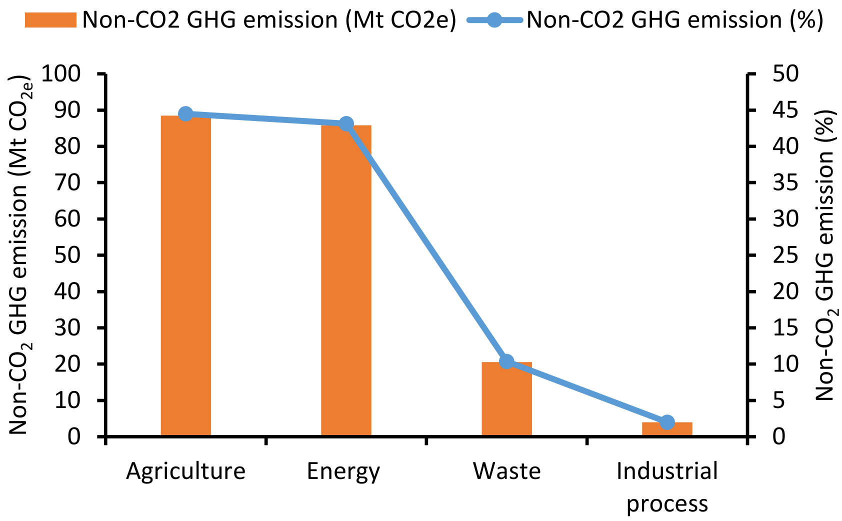

Figure 6. Non-CO_2 GHG emission from crop and livestock production and management in Bangladesh in 2018. Raw data were obtained from Climatewatch [44].

3.3. Nitrogen Use and Nr Production in Aquaculture

Fish provide 60% of the animal protein to the people of Bangladesh [46]. During the recent decades, aquaculture ventures have increased and intensified. The shift from low-input, extensive systems to high-input, intensive aquaculture systems has resulted in a huge demand for fish feed. Total feed production for pond aquaculture in 2008 was only 0.67 Mt, which increased 400 times to 2.66 Mt in 2017 (Figure 7a). Total feed comprises sinking, floating, and farm-made feeds, which contributed a total of 37,520 t of N in 2008, increasing to 148,960 t in 2017. Mamun-Ur-Rashid et al. [45] reported that the production and sale of fish feed in Bangladesh's aquaculture have increased radically in the last decade, where about 1.04 Mt of feed was produced commercially and between 0.3 and 0.4 Mt was produced at th village level with additional imports needed. Actual feed requirements are higher than local production. Raw unformulated feeds such as rice bran and mustard oil cake are applied to fishponds. Farmers in Bangladesh apply 1000 t of raw and unprocessed feed in their ponds annually [66]. This is included in farm-made feed in Figure 7a. Mamun-Ur-Rashid et al. [45] also reported that, since 2008, feed production has increased by 32% annually to approximately 3.0 Mt in 2017. Other data led to a fish feed requirement estimation of 2.65 Mt in 2017 in Bangladesh [47]. Fish feed serves as an important input of Nr in the aquaculture sector of the country, and cultured fish ponds released 675 t of N_2O in 2008 and 2681 tons in 2017 (Figure 7b). Total ammonia (NH_4^+ and NH_3) production in fish ponds was 21,574 and 85,652 t in 2008 and 2017, respectively (Figure 7b). Unaccounted-for loss of N was calculated to be 4014 t in 2008 and 20,587 t in 2017.

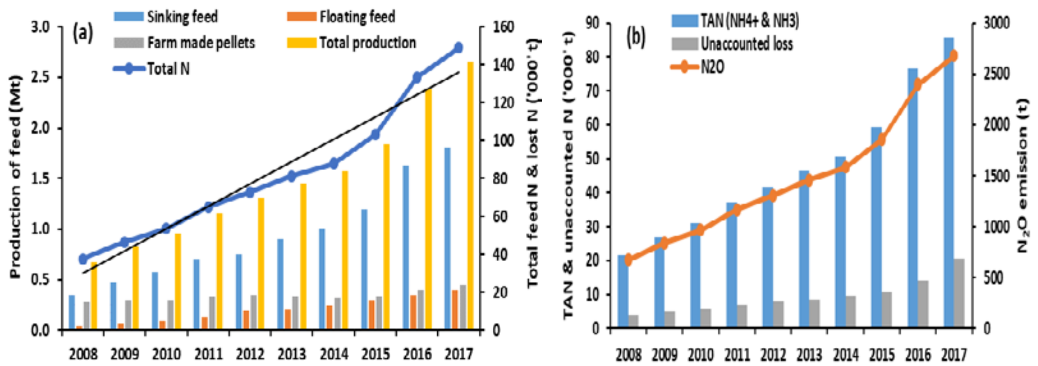

Figure 7. Fish feed and nitrogen in pond aquaculture: (**a**) Production of total feed, and (**b**) Nr production upon application to ponds in Bangladesh during 2008 to 2017 (modified from Mamun-Ur-Rashid et al. [45] and DoF [46]).

The application of improved feeds and fertilizers and best management approaches, has contributed to higher production of major fish species in Bangladesh [46]. Inorganic N is applied to fishponds at variable rates for different fish species, which enhances the phytoplankton production in pond environments and ultimately increases fish productivity. Nitrogen loss from aquaculture ponds is very high but rarely quantified or reported. In semi-intensive tilapia ponds, the fish utilize only 9–22% of the applied N from different organic and inorganic sources, so 78–91% remains unutilized (Table 1). Research revealed that in carp polyculture systems, about 40–50 kg organic manure is needed to produce 1 kg of fresh fish [67]. The food conversion ratio (FCR) in semi-intensive and intensive tilapia production systems varies between 0.75 and 2.5. Hence, the production of 100 t of fish biomass requires 75–250 t of feed, which is equivalent to 4.2–14.0 t of N.

Table 1. Nitrogen budget in tilapia ponds under different inputs in Bangladesh.

Parameter	N Input/Output in Tilapia Ponds (kg)		
	Urea	Urea + Poultry Manure	Feed
Inputs:			
Fertilizers	10.00	10.00	10.00
Feed	-	-	3.53
Manure	-	3.22	-
Outputs:			
Fish	0.89	1.45	2.95
Recovery (%)	8.90	10.97	21.80

Culture of *Pangasius* and other catfish is widespread in Bangladesh and accounted for about 15% of total fish production in 2012–2013 [16]. *Pangasius* farming in Bangladesh is characterized by high stocking densities, where the intensive supply of pellet feed is necessary for high yields [68]. A large amount of uneaten feed accumulates in *Pangasius* ponds, which contain high levels of N, P, and organic carbon. Nitrogen loss from commercial pellet feed under *Pangasius* pond culture systems was estimated/calculated to be 30% [69]. Researchers have reported that in *Pangasius* and other fish farming, only 10–30% of the applied nutrients supplied through organic and inorganic fertilizers and pellet feeds are used by fish, and the remaining 70–90% is dispersed in the environment, acting as a potential source of pollution [70,71]. Intensive aquaculture solely depends on feed supply, whreas semi-intensive types of fish culture require the combined application of feed, N fertilizer, and manure in ponds. Unutilized N in fishponds produces a large amount of NH_3, N_2O, and other Nr species such as NO_3^- and NO_2^-. According to Yuan et al. [72], the top 21 fish-producing countries in the world released 36.7 Gg of N_2O from freshwater aquaculture systems in 2014. It was reported that aquaculture can be a potential source of atmospheric N_2O formed during nitrification [17]. High levels of NH_3 production are toxic to aquatic animals, especially fish. It is obvious that the resultant negative effect of Nr produced from the aquaculture sector on the environment is a matter of serious concern.

3.4. Manure N and Nr Production from Livestock and Poultry

The number of livestock of different categories in Bangladesh increased at high rates from 1949 to 2017 (Table 2). The number of bovine animals plateaued from 2008 onward. This lower growth rate of 0.53% is likely because of the replacement of animals with machines in agriculture. However, the numbers of sheep and goats (2.31%) and poultry (2.39%) increased at higher rates. These huge numbers of livestock and poultry require a large amount of nutrients supplied through fodder and feed. For the quality production of milk and meat, quality fodder and nutrient supply is a necessity. Huque and Sarker [73] reported a large deficit in the quality of animal feed in Bangladesh.

Table 2. Livestock resources (million) in Bangladesh (1949–2017).

Livestock Resources	Year								Growth Rate (%)
	1949	1960	1977	1984	1996	2008	2011	2017	
Bovine (cattle, buffaloes, horses)	16.37	21.105	20.58	22.06	22.29	26.22	25.80	25.40	0.53
Sheep, goats	4.27	6.14	9.155	14.22	14.61	17.62	17.32	29.33	2.31
Poultry (fowls and ducks)	25.22	20.10	47.52	73.71	126.67	137.24	135.10	329.20	2.39

Source: AIS [10], Rahman et al. [70], and BBS [74].

Better management options, i.e., application of all required fertilizer elements including N, are required to overcome the shortfall in fodder production. Urea is used in cultivation of fodder crops, e.g., napier, maize, alfalfa, and *Moringa oliefera*, and other feed production. Even though recommended rates of fertilizer for fodder crops exist, they are basically ignored by most farmers. Animals are fed not only these fodder crops, but also about 27.32 Mt of fibrous biomass and 14,530 t of oilcakes as animal feed [74]. From all these activities, it is likely that a significant amount of reactive N leaks to the environment; however, data on the magnitudes of these losses are missing, which is a concern.

Livestock manure annually contributed 295,913 t of N, where the shares of ruminants and poultry were 234,515 and 61,398 t, respectively (ILMM, 2015). According to FAOSTAT [33], manure N was 80.66 Gg in 1961, which increased to 229.62 Gg in 2017 (Figure 8a). FAOSTAT also reported that of the manure N, about 70% was applied to cropland as organic fertilizer. Because of chemical and microbial transformation of manure N, it substantially contributes to Nr formation, especially in the form of NH_3 [75]. Manure N enters the hydrological system through leaching and runoff, and is partly released to the atmosphere through volatilization and denitrification [76]. Data derived from FAOSTAT [33] revealed that livestock-manure-released NH_3, N_2O, and NO increased significantly in 2017 compared to base year 1961 (Figure 8b). Ammonia emission was 13.89 Gg year^{-1} in 1961, which increased to 39.92 Gg year^{-1} in 2017; during this period, N_2O emissions increased 2.53 to 7.28 Gg year^{-1} and NO emissions increased 0.07 to 0.21 Gg year^{-1}. Trends in NH_3, N_2O, and NO emissions followed a similar trend, as these data were derived from same carcass and slaughter weights, dressing percentage, and emission factors subjected to conversion by several steps, as mentioned in the Methods section.

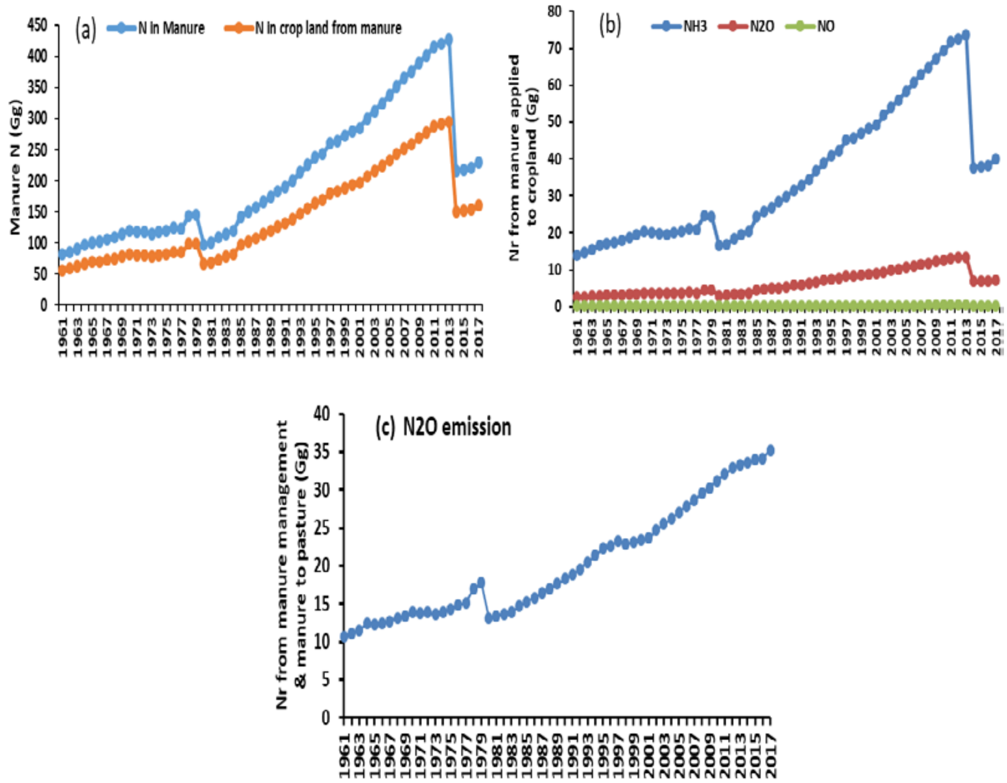

Figure 8. Nitrogen and Nr production from manure in Bangladesh from 1961 to 2017: (**a**) N in manure, and N in crop land from manure, (**b**) Nr from manure, and (**c**) N2O from manure management and manure to pasture (raw data from FAOSTAT [33]).

From aerobic and anaerobic decomposition processes, manure before application to crop fields and manure left on pasture conjointly released N_2O at about 34.18 Gg in 2016, but only 10.67 Gg in 1961 (Figure 8c). The concern is that a huge amount of N is lost from livestock production systems in Bangladesh, which needs to be addressed to reduce the overall emission budget. Livestock manure is traditionally considered as waste material in Bangladesh that can potentially pollute the environment and poses a serious threat to human health. Smallholders traditionally use a large amount of manure (37.3% of total manure) as a fuel source, while 56.2% of total manure is accumulated by medium and large farmers in open pits and is applied as fertilizer to crop fields after a few months of storage and partial composting [21]. Such unscientific manure management might create eutrophication of surface water, enhance leaching of NO_3^-, load excess nutrients, contaminate soil and water resources, and release NH_3, methane (CH_4), and other gases to the atmosphere.

4. Conclusions

N use efficiency in Bangladesh is low; thus, a large amount of Nr remains superfluous in the environment. The annual Nr production from the crop sector is 435 Gg, while the contribution of inorganic N fertilizer alone is 317 Gg. Aquaculture contributes approximately 88 Gg, while livestock sector adds about 83 Gg Nr to the environment. This excess Nr is posing challenges for human health, and agricultural and environmental sustainability not only in Bangladesh but also around the globe as a component of the N cycle. From our analysis on the use and management of N fertilizer, manure, and crop residues in crop, fishery, and livestock sectors of Bangladesh, we concluded that unused Nr will likely pollute the soil, water, and atmosphere. The collated information can help policy makers to better understand N management scenarios and their possible impacts on the environment. This might ensure the adoption of technologies for a viable, productive agroecosystem and a sustainable environment.

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