

Article

Not peer-reviewed version

Scenario Analysis of Japan's Food and Feed Systems: Integrating Nutrient Flows with Sustainable Agricultural Policy

[Kimiko Ushiyama](#)* and Masao Takano

Posted Date: 30 April 2026

doi: 10.20944/preprints202604.2148.v1

Keywords: nitrogen and phosphorus flow; food and feed systems; sustainable agriculture; MIDORI strategy; scenario analysis



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC, OpenAlex.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Scenario Analysis of Japan's Food and Feed Systems: Integrating Nutrient Flows with Sustainable Agricultural Policy

Kimiko Ushiyama * and Masao Takano

Nagoya University Graduate School of Environmental Studies

* Correspondence: ushiyama.kimiko.b2@s.mail.nagoya-u.ac.jp

Abstract

Recently, the Japanese government has introduced ambitious policies for agricultural sustainability, specifically the MIDORI Strategy, aimed at reducing chemical fertilizer use, expanding organic farmland, and increasing calorie-based food self-sufficiency. To evaluate the feasibility of these goals, this study quantified nitrogen and phosphorus flows within the 2021 food and feed system using a normalized "Nutrient Index." A scenario analysis was conducted using policy targets as parameters, where currently non-circulated waste streams were modeled as potential sources for domestic nutrient recovery. The results indicate that Scenario A (a 30% reduction of chemical fertilizers) is the most feasible, achieving significant improvements in circulation ratios through recovery of nutrients from sewage and livestock waste. While Scenario B (increasing organic farmland) shows similar trends, its success depends on technological advancements to mitigate the yield gap between organic and conventional systems. Scenario C (increasing calorie-based food self-sufficiency) presents the greatest challenge: maintaining current dietary patterns requires a 20% expansion of farmland and total nutrient recovery from waste. However, shifting dietary habits toward higher domestic rice consumption (Scenario C-2) significantly mitigates land and fertilizer demand. Achieving these targets requires a holistic approach that integrates technological infrastructure with socio-political shifts in land use planning and consumer behavior.

Keywords: nitrogen and phosphorus flow; food and feed systems; sustainable agriculture; MIDORI strategy; scenario analysis

1. Introduction

Nitrogen and phosphorus play a vital role in human society across the entire food and feed system, from production and consumption to disposal and circulation. In agricultural production, the development of chemical fertilizers containing these nutrients triggered the "Green Revolution," which significantly increased yields and supported global population growth. Consequently, global fertilizer demand has risen steadily since the 1960s [1,2], and is predicted to continue growing [3,4]. However, current practices are unsustainable. Nitrogen fertilizer production is energy intensive and relies heavily on fossil fuels, while phosphorus fertilizer is derived from finite mineral resources. These practices result in negative environmental impacts, including greenhouse gas emissions, eutrophication, and soil degradation. Under the "Planetary Boundaries" framework, researchers warn that the global use of nitrogen and phosphorus is nearing the planet's ecological capacity [5]. Reducing chemical fertilizer use is therefore a critical challenge for agricultural sustainability and beyond. To address this, several strategies have been promoted, including improved nutrient management, the substitution of chemical fertilizers with organic alternatives, the promotion of organic farming, and the circular recovery of nitrogen and phosphorus from waste and wastewater [6].

This study focuses on Japan, a country facing unique challenges in its transition to sustainable

agriculture [7,8]. While total fertilizer usage in Japan has been decreasing, the input trend of nitrogen and phosphorus fertilizer per unit of farmland has remained higher than the world average since the 1960s. Phosphorus input, in particular, is nearly four times the average of the United States, the EU and the global average [9]. This is partly due to Japan's volcanic soil, which contains high levels of aluminum that bind with phosphorus. To ensure crops take up sufficient nutrients, farmers often over-apply phosphorus to maintain "free" phosphorus in the soil [10]. Japan also faces significant resource security issues. The country relies heavily on imports for food, feed, and energy. Nearly all chemical fertilizer materials are imported, and self-sufficiency rates remain low: 27% for feed, 38% for calorie-based food [11–13], and only 13% for energy [14]. This reliance on trade impacts global sustainability through "virtual water and nutrient flow" where the resources used for production are effectively exported from the origin country [15,16]. Furthermore, because Japan imports more than it supplies domestically, it must treat the resulting nitrogen and phosphorus waste using imported fossil fuels. Although Japan has made significant strides in sewage treatment and water quality regulation to prevent eutrophication in rivers and enclosed seas over the last decade[17], these nutrients are not circulated back to the exporting countries. This creates a nutrient imbalance, effectively preventing natural circulation in the countries that export these materials to Japan. Increasing self-sufficiency and reducing imports are essential steps for Japan to contribute to the sustainable, global-scale circulation of nitrogen and phosphorus.

Farmland area is primary limiting factor for food production in Japan; therefore land use changes must be considered in conduction with shifts in nitrogen and phosphorus circulation. Approximately 70% of Japan's land area consists of mountainous and forested terrain, which seriously limits the flat land available for agriculture, residential, commerce and industrial use. Following the population growth and economic development of the post-World War II era, farmland has been further reduced through conversion to residential and industrial zones, as illustrated in Figure 1 [18,19].

Besides the land-use changes, the reduction of farmland is also attributed to Japan's declining population. In contrast to global trends, Japan's population peaked in 2008 and is projected to continue decreasing due to a low birth rate[20]. Consequently, the agricultural population is both shrinking and aging, leading to an increase in abandoned farmland [21].

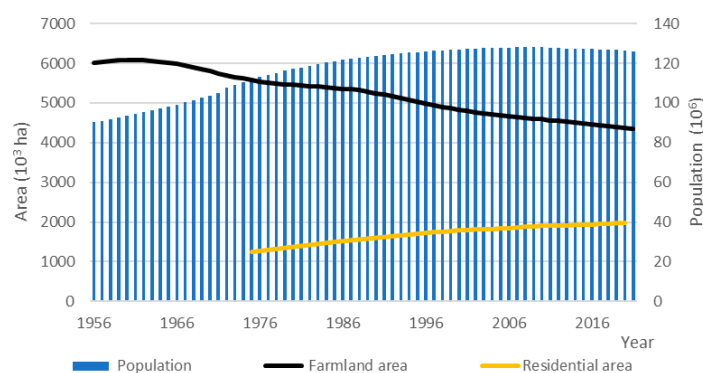


Figure 1. Farmland and residential area trends along with population.

Government policies are essential for improving the sustainability of the nitrogen and phosphorus input-output balance[22]. The FAO's "International Code of Conduct for the Sustainable Use and Management of Fertilizers," promotes the appropriate management of both chemical and organic fertilizers to mitigate global environmental issues such as climate change, biodiversity loss, and desertification[23,24]. While there is no global target for organic agriculture, the market for organic products and area of organic farmland are expanding[25]. For example, the EU's "Farm to Fork Strategy" aims to reduce chemical fertilizer use by 20% and increase organic farmland to 25% by 2030[26]. Similarly, the United States has launched the Agriculture Innovation Agenda, targeting

a 40% increase in production and a 50% reduction in environmental footprint by 2050[27]. There is also a target to reduce nutrient losses from agriculture by 30% by 2050 to improve water quality[28].

Japan's Ministry of Agriculture, Forestry and Fisheries (MAFF) introduced "MIDORI Strategy," which aims to reduce chemical fertilizer use by 30% and expand organic farming to 25% of total farmland by 2050[29]. Furthermore, the "Basic Plan for Food, Agriculture and Rural Areas" (revised in 2020 and 2025) targets a calorie-based food self-sufficiency of 45%[30,31]. However, the feasibility of these quantitative targets has not been fully explored in political or academic spheres[32]. It is essential to clarify the potential of alternative fertilizers to replace chemical input and to evaluate the farmland required to meet those goals. Previous scenario analyses have been conducted for chemical fertilizer reduction for several countries and regions[33,34]. However, they often focus solely on inputs and overlook the total food and feed system, including waste outputs.

Japan possesses highly developed municipal treatment facilities; approximately 93% of the population is connected to wastewater infrastructure, and household and industrial waste are managed through incineration or other treatment processes[35].

It is necessary to quantify the current state of nitrogen and phosphorus flows within this overall circulation before conducting the scenario analyses. Previous studies in Japan have quantified these flows, but data points vary and waste treatment outputs are rarely included. Furthermore, the most recent available data for nitrogen and phosphorus are from 2015 and 2016, respectively, necessitating an update[36,37].

The objective of this article is to grasp the current nitrogen and phosphorus flows throughout the entire Japanese food and feed system as of 2021. Based on these results, this study conducts a scenario analysis to evaluate the feasibility of government targets regarding chemical fertilizer reduction, organic farmland expansion, and food self-sufficiency. It is hoped that these findings will support progress toward a sustainable food and feed system in Japan.

2. Materials and Methods

2.1. Nitrogen and Phosphorus Flow Calculation

To determine the current nitrogen and phosphorus flows in Japan's food and feed system, government statistical data for the 2021 was primarily utilized. Where 2021 data was unavailable, the most recent available datasets were used. The system is illustrated in Figure 2, with numbered items described in Table 1. Calculation methodology and references are provided in Supplementary Materials.

As shown in Figure 2, imported fertilizer materials (4-1) enter the "Industry" sector, where chemical fertilizers are produced alongside domestic materials. Chemical fertilizers (4-2) and circulated fertilizers (4-3), comprising livestock compost manure and sewage sludge, are applied to farmland (4-6). This land produces domestic food (2-2) and feed (3-2). Livestock feeds (3-4) are supported by domestic (3-2), imported (3-1) and circulated feed (3-3). Food resources are derived from "Livestock" (2-3) and "Fisheries" (2-4), domestic crops (2-2) and imports (2-1). Some food resources are processed in "Industry" (2-6) and supplied to "Households" together with net food (2-5), which includes non-edible waste. From "Industry" and "Households," wastewater (6-1) and food waste (6-2) are generated and treated in "Treatment Facilities."

Within the connected population 87% use sewage facilities and 10% use night soil treatment[35]. Treated wastewater (7-1) is discharged to watersheds (12) and generated sludge is landfilled (7-2), recycled as construction material or fuel, or circulated as fertilizer. More than 70% of industrial food waste is circulated as feed or fertilizer, but 92% of household food waste is incinerated in incineration facilities with other wastes[38]. Ash from incineration (7-3) is landfilled or recycled as construction material. Japan exports food and chemical fertilizer. In this article, recycled construction material is considered as "non-circulated" along with land-filled wastes (13) because it cannot be used as circulated fertilizer.

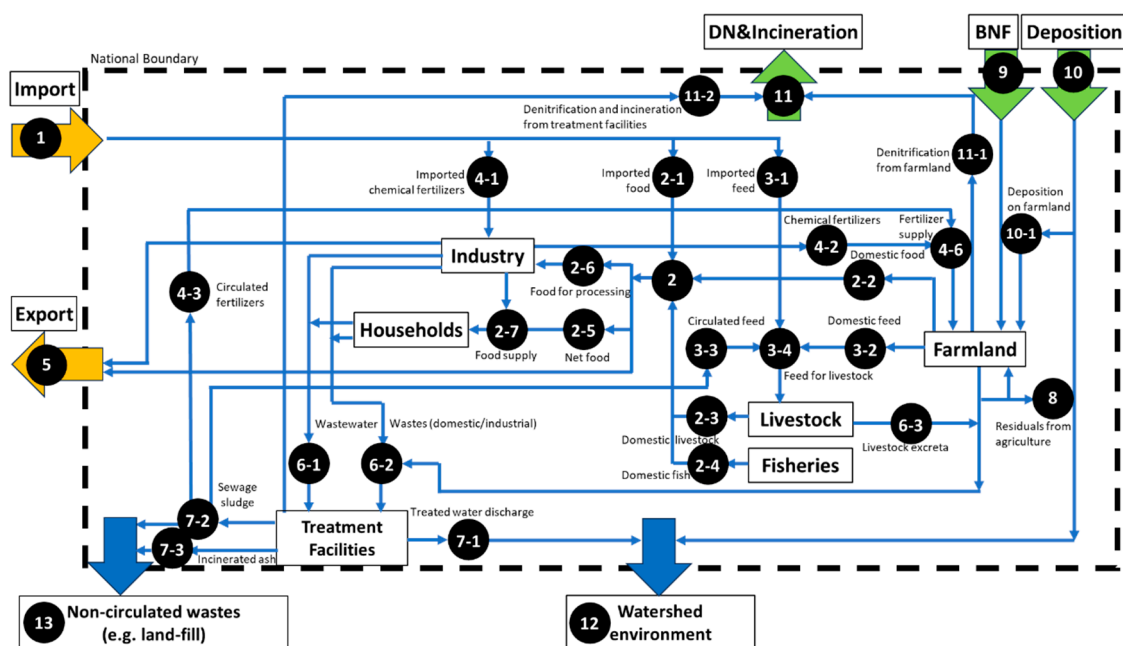


Figure 2. Flow of food and feed system in Japan.

Table 1. Numbered items in Figure 2.

No.	Item
1	Import
2	Food
3	Feed
4	Fertilizers
5	Export
6	Input to treatment facilities
7	Output from treatment facilities
8	Residuals from agriculture
9	Biological nitrogen fixation (BNF)
10	Deposition by rain
11	Denitrification (DN) and incineration
12	Watershed environment
13	Non-circulated wastes
14	Circulated wastes

Studies listed in Table 2 were reviewed and compared to verify the validity of data obtained in this study. It should be noted that this study includes discharges to the environment from treatment facilities, not considered in many previous studies.

Table 2. Referred previous studies.

Reference	Nitrogen	Phosphorus
A	Nakanishi & Ukita 1978 [39]	-
B	Hakamata 1996 [40]	-
C	Miwa et al. 2006 [41]	-
D	Matsumoto et al. 2017 [42]	-
E	Mizutani 1997 [43]	Mizutani 1997 [43]
F	Kawashima 1996 [44]	-
G	Tezuka et al. 2002 [45]	Tezuka et al. 2002 [45]
H	Shindo et al. 2009 [46]	-
I	Takahashi 2011 [47]	Takahashi 2011 [47]

J	Katagiri et al. 2018 [38]	-
K	Hayashi et al. 2021 [36]	-
L	-	Matsubae 2009 [49]
M	-	Nattorp et al. 2019 [37]
N	Current study	Current study

Note: One study by Mishima & Kohyama 2010 [50] was excluded due to results being in different units.

2.2. Scenario Analysis

A scenario analysis was conducted based on targets set by the MIDORI Strategy for Sustainable Food Systems and the Basic Plan for Food, Agriculture and Rural Areas [29,30]. Quantitative targets are summarized in Table 3. Three scenarios were considered: **Scenario A** is a reduction of chemical fertilizer use, **Scenario B** is an increase of organic farmland area, and **Scenario C** is an increase in calorie-based food self-sufficiency, of which two patterns are considered. **Scenario C-1** maintains the same food composition as in 2021, while **Scenario C-2** allow for changes in food composition. Required farmland area for **Scenarios C-1** and **C-2** were calculated based on how much production was increased for each crop. Details of each scenario are described in the Results section. Quantitative targets are compared using 2020 as the base year. Changes in demand due to population decrease are not considered. Thus, it is assumed that there would be no change in calorie-based food demand in 2050 regardless of expected population decrease. For reference, the projected population in 2050 is about 105×10^6 , representing a 17% decrease from 2020[20]. The basis of the policies assumed that socio-economic factors—such as agricultural working population, economic values and costs related to agriculture, and behavior of farmers and consumers—remain the same as in 2021. Consequently, these factors are not taken into consideration within the scenarios of this study.

Table 3. Scenarios and policy objectives.

Scenario	Description	Status in 2021	Policy targets
Control	Calculated nitrogen & phosphate flow in 2021 (The result of 2.1)	-	-
A	Chemical fertilizer reduction by 2050	-	30% reduction
B	Organic farmland increase by 2050	27,000 ha, 0.7%	Increase to 1,000,000 ha, 25% of total area
C-1	Food self-sufficiency increase	38%	Increase food self-sufficiency to 45%
C-2	Food self-sufficiency increase with food composition change	38%	Increase food self-sufficiency to 45%

3. Results

3.1. Nitrogen and Phosphorus Flows in Japan (2021)

3.1.1. Calculated Flows in 2021

The calculated flow values for 2021 are presented in Table 4. For circulated fertilizers, denitrification and non-circulated waste, additional details regarding the sources described in the flow diagram (Figure 2), such as sewage and livestock excreta, are indicated. Each flow value represents the annual weight per item. In this study, we introduce the “Nutrient Index,” which represents the ratio of each item relative to the “Food supply” to households (indicated as 2-7 in Figure 2). Specifically, the nitrogen and phosphorus flow values were divided by those of “Food supply (2-7).” This index was developed for this article to visualize and simplify the characteristics of the nutrient flow. It should be noted that the index depends heavily on the food supply value, it is

not considered highly sensitive index; however, it provides a clear and simple overview of the total flow.

Table 4. Calculated nitrogen and phosphorus flows and correspondent Nutrient Indices (ratios relative to household food supply).

No.	Item	Flow Value (10 ³ t/year)		Nutrient Index (-)	
		N	P	N	P
1	Imports	834.5	192.2	0.87	1.63
2	Food				
2-1	Imported food	380.5	27.1	0.37	0.19
2-2	Domestic food	223.8	43.1	0.23	0.36
2-3	Domestic livestock	181.8	15.0	0.19	0.13
2-4	Domestic fish	103.5	8.3	0.11	0.07
2-5	Net food	742.2	90.5	0.77	0.77
2-6	Food for processing	221.0	27.7	0.23	0.23
2-7	Food supply	963.2	118.2	1.00	1.00
3	Feed				
3-1	Imported feed	180.2	42.9	0.19	0.36
3-2	Domestic feed	314.9	58.1	0.33	0.49
3-3	Circulated feed	61.5	17.3	0.06	0.15
3-4	Feed for livestock	556.7	118.2	0.58	1.00
4	Fertilizers				
4-1	Imported fertilizers	273.8	122.2	0.28	1.03
4-2	Chemical fertilizers	354.9	140.6	0.37	1.19
4-3	Circulated fertilizers	255.3	119.0	0.27	1.01
4-4	Circulated fertilizers from sewage sludge	28.4	16.1	0.03	0.14
4-5	Circulated fertilizers from livestock excreta	212.8	83.4	0.22	0.71
4-6	Fertilizer supply	610.2	259.6	0.63	2.20
5	Export	137.0	5.2	0.14	0.04
6	Input to treatment facilities	758.9	116.6	0.79	0.99
6-1	Wastewater	595.1	70.6	0.62	0.60
6-2	Waste (domestic / industrial)	163.8	45.9	0.17	0.39
6-3	Livestock excreta generation	523.6	102.6	0.54	0.87
7	Output from treatment facilities				
7-1	Treated water discharge to watershed	197.3	15.4	0.20	0.13
7-2	Sewage sludge	98.2	55.3	0.10	0.47
7-3	Incinerated ash	-	17.8	-	0.15
7-4	Livestock excreta	310.2	102.5	0.32	0.87
8	Residuals from agriculture	102.6	13.1	0.11	0.11
9	Biological nitrogen fixation (BNF)	86.7	-	0.09	-
10	Deposition by rain (whole land)	556.0		0.58	
10-1	Deposition on farmlands	64.0	-	0.07	-
11	Denitrification (DN)	615.6	-	0.64	-
11-1	DN from farmlands	81.9	-	0.09	-
11-2	DN from treatment facilities	533.7	-	0.55	-
11-3	DN from sewage	257.3	-	0.27	-
11-4	DN from livestock excreta compost	212.8	-	0.22	-
11-5	Nitrogen from incineration	63.5	-	0.07	-
12	Watershed environment	417.3	28.2	0.43	0.24
13	Non-circulated waste	167.2	76.1	0.17	0.64
13-1	Non-circulated waste from sewage	69.8	39.2	0.07	0.33
13-2	Non-circulated waste from livestock excreta	97.4	19.1	0.10	0.16

14	Circulated Waste	316.9	136.3	0.33	1.15
----	------------------	-------	-------	------	------

3.1.2. Input/Output Comparison

In many previous studies, an *a priori* balance between system inputs and outputs for each system was assumed, with these values often equalized by adding or subtracting arbitrary figures to achieve equilibrium. In contrast, this study separately calculated each item using corresponding statistical data, which were then aggregated for each system. Theoretically, the sum of these calculated inputs and outputs should be equal. To verify the accuracy of our analysis, the resulting inputs and outputs were compared for "Farmland," "Households and Industry," "Treatment facilities," and Japan as a whole, as shown in Table 5.

Table 5. Comparison of nitrogen and phosphorus inputs and outputs got farmland, livestock, households, treatment facilities, and Japan as a whole.

													10 ³ t/year							
													Nitrogen		Phosphorus					
													Input		Output		Input		Output	
Farmland	4-2	Chemical fertilizers	354.9	2-2	Domestic food	223.8	4-2	Chemical fertilizers	140.6	2-2	Domestic food	43.1								
	4-3	Circulated fertilizers	255.3	3-2	Domestic feed	314.9	4-3	Circulated fertilizers	119.0	3-2	Domestic feed	58.1								
	9	BNF	86.7	8	Residuals	102.6				8	Residuals	13.1								
	10-1	Deposition	64.0	11-1	DN	81.9														
		Input	760.9			Output	723.2			Input	259.6			Output	114.4					
		Total				Total				Total				Total						
Livestock	3-1	Imported feed	180.2	2-3	Domestic livestock	181.8	3-1	Imported feed	42.9	2-3	Domestic livestock	15.0								
	3-2	Domestic feed	314.9	4-5	Circulated fertilizers	212.8	3-2	Domestic feed	58.1	4-5	Circulated fertilizers	83.4								
	3-3	Circulated feed	61.5	11-4	Livestock excreta DN	212.8	3-3	Circulated feed	17.3											
				13-2	Non-circulated waste	97.4				13-2	Non-circulated waste	19.1								
		Input	556.7			Output	704.8			Input	118.2			Output	117.5					
		Total				Total				Total				Total						
Households & Industry	2-5	Net food	539.8	6-1	Wastewater	595.1	2-5	Net food	70.3	6-1	Wastewater	70.6								
	2-6	Food supply	221.0	6-2	Wastes	163.8	2-6	Food supply	27.7	6-2	Wastes	45.9								
		Input	760.8			Output	758.9			Input	98.0			Output	116.6					
		Total				Total				Total				Total						

Treatment	6-1	Wastewater	595.1	7-1	Treated water	197.3	6-1	Wastewater	70.6	7-1	Treated water	15.4
Facilities	6-2	Wastes	163.8	4-3	Circulated fertilizer	255.3	6-2	Wastes	45.9	4-3	Circulated fertilizer	119.0
	6-3	Livestock excreta	523.6	3-3	Circulated feed	61.5	6-3	Livestock excreta	102.6	3-3	Circulated feed	17.3
				13	Non-circulated waste	164.4				13	Non-circulated waste	71.0
				11-3	Sewage DN	257.3						
				11-5	Incineration DN	63.5						
				11-4	Livestock excreta DN	212.8						
		Input Total	1282.5		Output Total	1212.3		Input Total	219.2		Output Total	222.6
Japan	2-1	Imported food	380.5	5	Export	137.0	2-1	Imported food	27.1	5	Export	5.2
	3-1	Imported feed	180.2	12	Watershed	417.3	3-1	Imported feed	42.9	12	Watershed	28.2
	4-1	Imported fertilizers	273.8	13	Non-circulated waste	164.4	4-1	Imported fertilizers	122.2	13	Non-circulated waste	71.0
	9	BNF	86.7	11	DN	615.6						
	10	Deposition(Land)	556.0									
		Input Total	1477.1		Output Total	1334.3		Input Total	192.2		Output Total	104.4

In the "Farmland" sector, inputs consisted of fertilizers, biological nitrogen fixation (BNF), and atmospheric deposition, while outputs included denitrification (DN) from soil, crops for food and feed, as well as crop residuals. In this study, crop uptake accounted for 80% of nitrogen and 40% of phosphorus. Nitrogen inputs and outputs largely balanced, demonstrating the accuracy of the analysis; however, phosphorus inputs were significantly greater than outputs. This discrepancy may be attributed to phosphorus accumulation in the soil and leaching into groundwater. Conversely, nitrogen runoff was not observed, although it is generally known to occur in agricultural systems.

In "Livestock" sector, inputs consisted of feed, while outputs included livestock products and excreta. The latter is processed into circulated fertilizer (manure) and non-circulated waste, with DN occurring during manure production. Nitrogen inputs were lower than outputs, which may be attributed to statistical variance, as the nitrogen content in various feed crops had highly variable data. Phosphorus inputs and outputs were nearly equal.

In the "Households and Industry" sector, representing human society, inputs were net food and the food for processing to industry, while outputs consisted of wastewater and food waste. Inputs

and outputs for both nitrogen and phosphorus were nearly equal. Regarding outputs, more than half of the nitrogen and phosphorus was discharged as wastewater which exceeded the volume of solid waste.

For "Treatment Facilities," inputs included wastewater, solid waste and livestock excreta, while outputs consisted of treated water, circulated fertilizer and feed, non-circulated waste, and DN from the treatment process. Inputs and outputs were largely balanced for both nitrogen and phosphorus. Approximately half of the total inputs originated from livestock manure. Furthermore, nearly half of the nitrogen output was discharged into the atmosphere through denitrification and incineration.

For "Japan" as a whole, inputs consisted of imports, BNF and deposition, while outputs included exports, nitrogen and phosphorus present in watersheds, non-circulated waste, and DN. Nitrogen inputs and outputs were mostly equal; however, phosphorus showed discrepancy as seen in "Farmland", indicating accumulation in the soil and leaching into groundwater.

3.1.3. Comparison with Previous Studies

The results presented in Table 4 were compared with previous studies listed in Table 2 to verify the validity of the values determined in this article. Figure 3 illustrates the historical nitrogen supply for food to households and feed to livestock in Japan, incorporating data from previous studies. Figure 4 shows the nitrogen inputs to treatment facilities and the corresponding outputs of treated water; these figures demonstrate the effectiveness of the wastewater treatment process. Because calculation methods and references vary across studies, significant discrepancies exist between the results even when separate studies were conducted in the same year, such as in 1992 or 2007. However, the values obtained in this study are within the same range as those in other research, which demonstrates their validity. Several studies indicated that feed supply exceeds food supply, implying that livestock consume more nitrogen and phosphorus than humans.

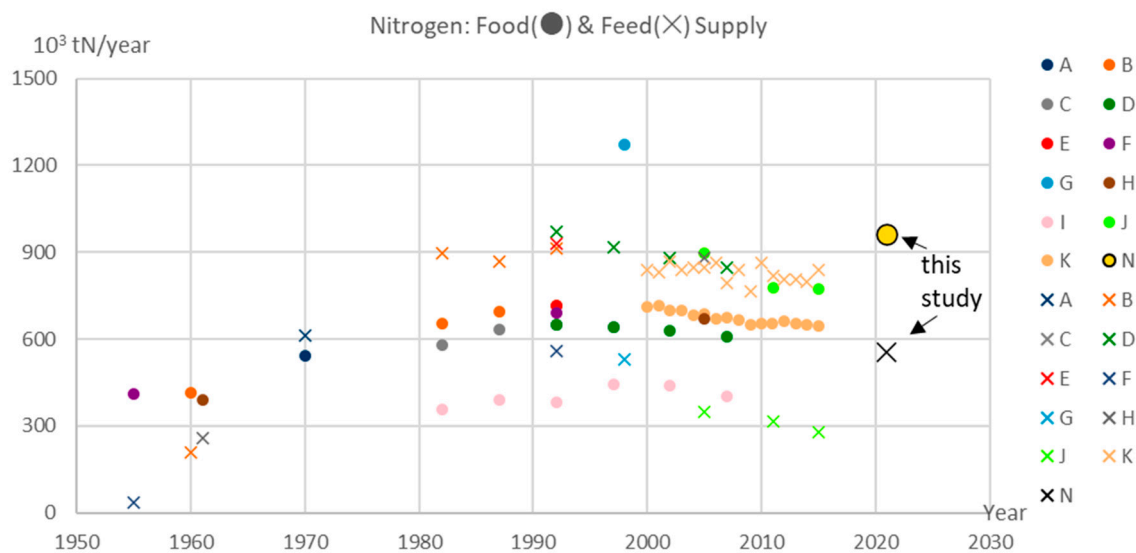


Figure 3. Historical trends in nitrogen supply for household food and livestock feed in Japan, based on previous studies (Table 2) and the current study.

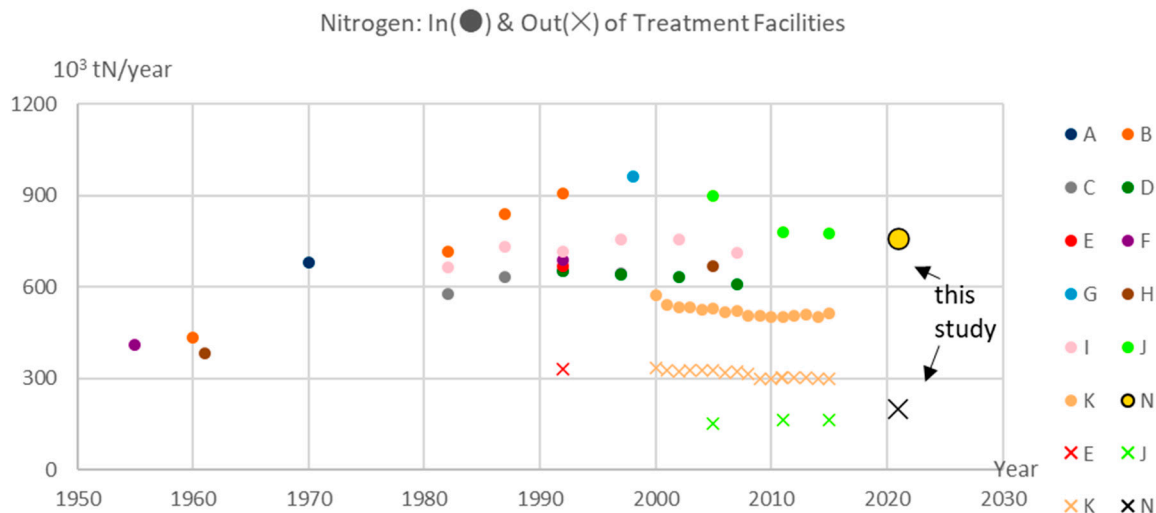


Figure 4. Nitrogen inputs to treatment facilities and corresponding treated water outputs: a comparison of previous research (Table 2) and the current study results over time.

3.1.4. Simplified Flow Diagrams Based on the Nutrient Index

The nitrogen and phosphorus flow diagrams for the entire food and feed system, simplified and visualized using Nutrient Index, are shown in Figures 5 and 6, respectively.

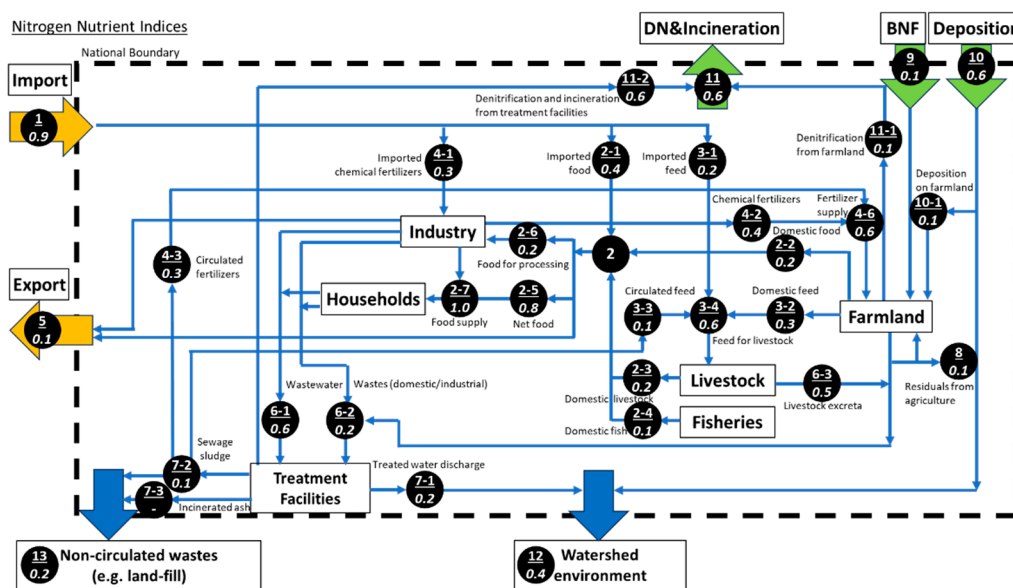


Figure 5. Nitrogen flow diagram highlighting the Nutrient Index in italic for each specific item.

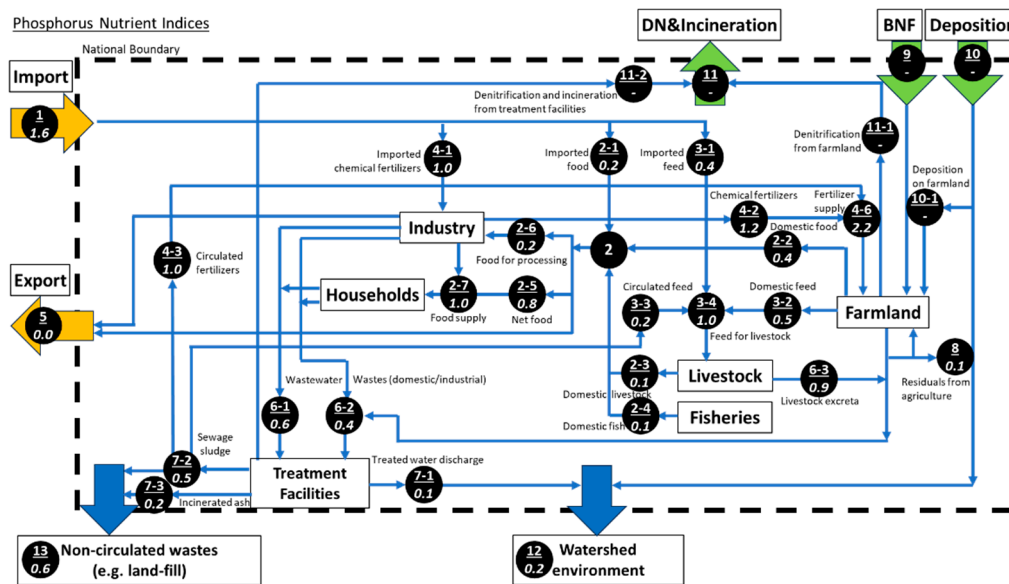


Figure 6. Phosphorus flow diagram highlighting the Nutrient Index in italic for each specific item.

The following findings can be extracted from these diagrams.

- Household food supply (2-7): Imports (2-1) support 40% of the nitrogen and 20% of the phosphorus in the household food supply. Domestic food (2-2) contributes 20% of the nitrogen and 40% of the phosphorus, while domestic livestock (2-3) provide an additional 20% of the nitrogen and 15% of the phosphorus.
- Domestic livestock requirements and production: Domestic livestock (3-4) require a nitrogen supply three times greater—and a phosphorus supply ten times greater—than the household livestock supply (2-3). Livestock (3-4) consume 60% of the nitrogen and 100% of the phosphorus required by households (2-7). Approximately 30% of the feed supply (3-4) is supported by imported feed (3-1), and 80% to 90% of the total feed supply (3-4) is excreted as livestock waste (7-4).
- Household outputs: From the "Households" sector, two-thirds are nutrient outputs are discharged as wastewater (6-1) and one third is discarded as solid food waste (6-2).
- Treatment facilities: The total input to "Treatment Facilities" is 0.8 for nitrogen and 1.0 for phosphorus (relative to the Nutrient Index). Regarding nitrogen output, 75% of the input is discharged to the atmosphere (11-2), a volume three times greater than that of non-circulated waste (13). For phosphorus, three-quarters of the input (6-1 and 6-2) is disposed of as non-circulated waste (13).
- Most denitrification and incineration (11) losses are anthropogenic, originating from the incineration of food waste and aerobic treatment in sewage facilities
- Virtual nutrient dependency: "Virtual nitrogen" (the sum of imported nitrogen), amounts to 90% of household requirements, while "virtual phosphorus" reaches 160% of requirements (2-1, 3-1, and 4-1). These high values demonstrate that Japan's food and feed system is heavily dependent on imported nutrients, posing a significant challenge for reduction efforts.

3.2. Scenario Analysis

3.2.1. Scenario Details

The results obtained for the year of 2021 were used as a control in the scenario analysis, with the calorie-based food supply held constant at 2021 levels for all scenarios. Table 6 provides the details for each scenario; specifying which items were manipulated and which remained unchanged.

“Resulting items” refer to those values that changed accordingly in response to the manipulated parameters.

Table 6. Scenario details.

Scenario	Description	Unchanged Items	Manipulated Items	Resulting Items
Control	-	-	-	-
A	Reduction in chemical fertilizer use	Fertilizer supply (4-6) Food supply (2-7)	Chemical fertilizers (4-2)↓, Circulated fertilizers (4-3)↑	Imported fertilizers (4-1), Non-circulated waste (13), Circulated waste Imported fertilizers (4-1), Non-circulated waste (13), Circulated waste Circulated fertilizers (4-3), Fertilizer supply (4-6), Feed supply (3-4), Livestock excreta (6-3), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area Circulated fertilizers (4-3), Fertilizer supply (4-6), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area
B	Expansion of organic farmland area	Fertilizer supply (4-6) Food supply (2-7)	Chemical fertilizers (4-2)↓, Circulated fertilizers (4-3)↑	Imported fertilizers (4-1), Non-circulated waste (13), Circulated waste Circulated fertilizers (4-3), Fertilizer supply (4-6), Feed supply (3-4), Livestock excreta (6-3), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area Circulated fertilizers (4-3), Fertilizer supply (4-6), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area
C-1	Increased food self-sufficiency (current dietary patterns)	Food supply (2-7) Food composition in 2021	Imported food (2-1)↓, Domestic food (2-2)↑, Domestic feed (3-2)↑	Imported fertilizers (4-1), Non-circulated waste (13), Circulated waste Circulated fertilizers (4-3), Fertilizer supply (4-6), Feed supply (3-4), Livestock excreta (6-3), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area Circulated fertilizers (4-3), Fertilizer supply (4-6), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area
C-2	Increase of food self-sufficiency (shifted dietary patterns)	Food supply (2-7) Calorie consumption per capita	Imported food (2-1)↓, Domestic food (2-2)↑	Imported fertilizers (4-1), Non-circulated waste (13), Circulated waste Circulated fertilizers (4-3), Fertilizer supply (4-6), Feed supply (3-4), Livestock excreta (6-3), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area Circulated fertilizers (4-3), Fertilizer supply (4-6), Non-circulated waste (13), Circulated waste, Residuals (8), BNF (9), DN (10-1), farmland area

In **Scenario A**, the total fertilizer supply remained unchanged, while the chemical fertilizer values were reduced to meet the quantitative target; consequently, the values of circulated fertilizer were increased. Imported fertilizer decreased in proportion to the reduction in chemical fertilizer. The additional circulated fertilizer was supplied from sewage sludge and livestock manure, which were previously categorized as non-circulated waste, thereby increasing nutrient circulation. Incinerated ash was not considered as a circulated fertilizer due to concerns regarding heavy metal contamination. The underlying assumption is that the chemical fertilizer supply was reduced by 30% across all farmland without affecting crop yields.

In **Scenario B**, the total fertilizer supply and fertilizer application rate per hectare were held constant; therefore, circulated fertilizer was redirected to the expanded organic farmland area, and

chemical fertilizer use was reduced accordingly. The supply of circulated fertilizer was managed using the same methodology as in **Scenario A**. Crop yields were assumed to remain unchanged.

In **Scenario C**, an increase in food self-sufficiency was evaluated. Figure 7 illustrates the details of **Scenario C** regarding food composition and self-sufficiency rates [51]. Food composition is defined as the consumption ratio of rice, livestock products, oil, wheat, sugar, fish, vegetables, soy beans, fruits, and miscellaneous items. **Scenario C** was divided in two patterns: **Scenario C-1** maintains current food composition but increases self-sufficiency rates specifically soybeans, wheat, oil, and livestock; **Scenario C-2** modifies food composition by increasing the caloric intake of rice while reducing the consumption of livestock and oil, while maintaining the total caloric intake. The reductions in livestock and oil consumption are assumed to be achieved by reducing imports of these items, thereby increasing their domestic self-sufficiency. For **Scenario C-1**, imported food decreased due to the increased domestic harvest of soybeans, wheat, oilseeds (rapeseed), and livestock feed. The amount of fertilizer required for each crop was calculated based on the "Basis of Main Crops for Fertilization Application" by MAFF [52]. This scenario prioritizes the use of domestic feed and circulated fertilizer for the expanded farmland area. The increased demand for circulated fertilizer was met by utilizing non-circulated waste and the increased volume of livestock excreta. **Scenario C-2**, the reduction in oil and livestock consumption was subtracted from imported food totals, while the domestic harvest of rice was increased.

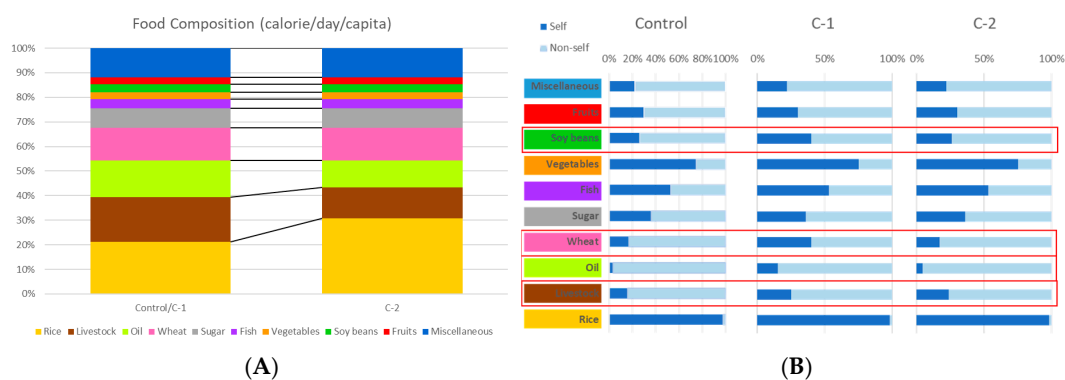


Figure 7. Details of Scenario C regarding food composition(kcal/day/capita) and corresponding food self-sufficiency rates: (A) represents food composition where oil, meat, and rice are manipulated for Scenario C-2; (B) shows the self-sufficiency rate for each category.

3.2.2. Results of the Scenario Analysis

The results of the scenario analysis for the following items – which demonstrate the impacts of the manipulations in each scenario – are shown in Figures 8–14: imports, domestic production, fertilizers, waste, and farmland area.

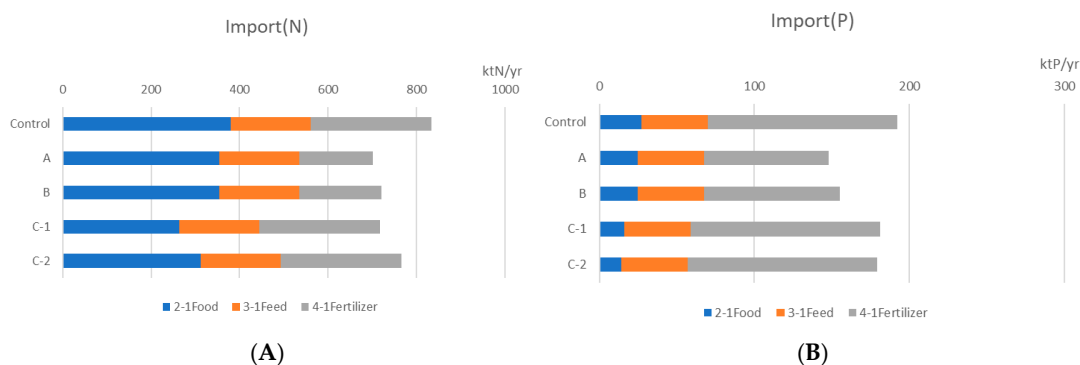


Figure 8. Scenario analysis for nitrogen (A) and phosphorus (B) imports: resulting items include imported food, feed, and fertilizer.

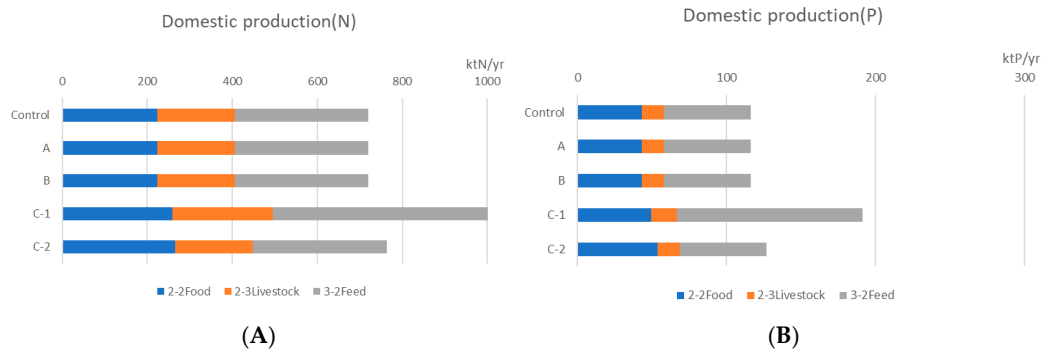


Figure 9. Scenario analysis for nitrogen (A) and phosphorus (B) domestic production: resulting items include domestic food, livestock products, and feed.

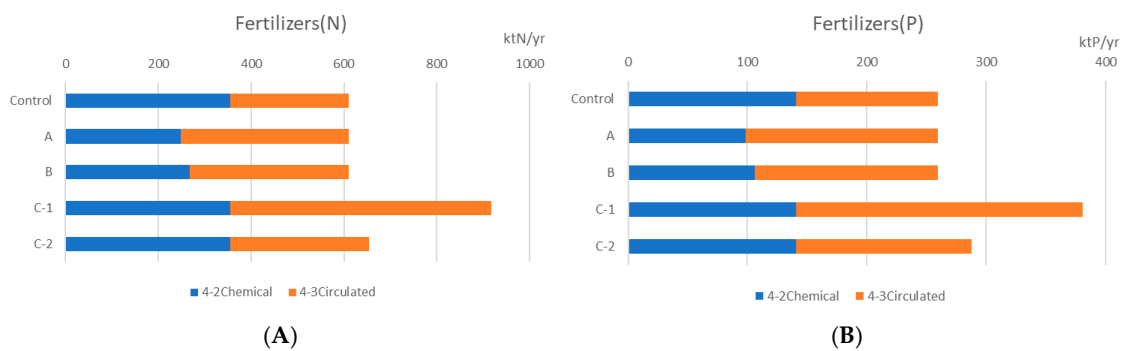


Figure 10. Scenario analysis for nitrogen (A) and phosphorus (B) fertilizers relative to current demand: resulting items include chemical and circulated fertilizers.

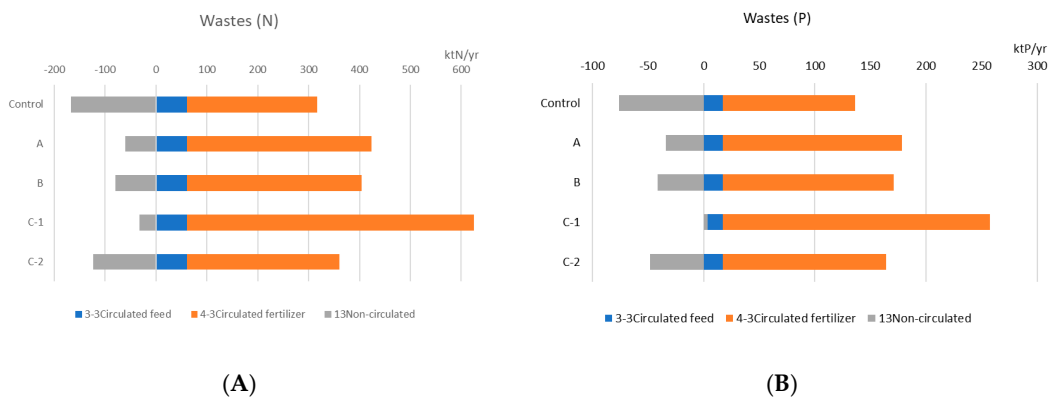


Figure 11. Scenario analysis for nitrogen (A) and phosphorus (B) waste from treatment facilities. The right side represents current circulation (the sum of circulated feed and fertilizer), while the left side shows currently non-circulated wastes, such as landfill.

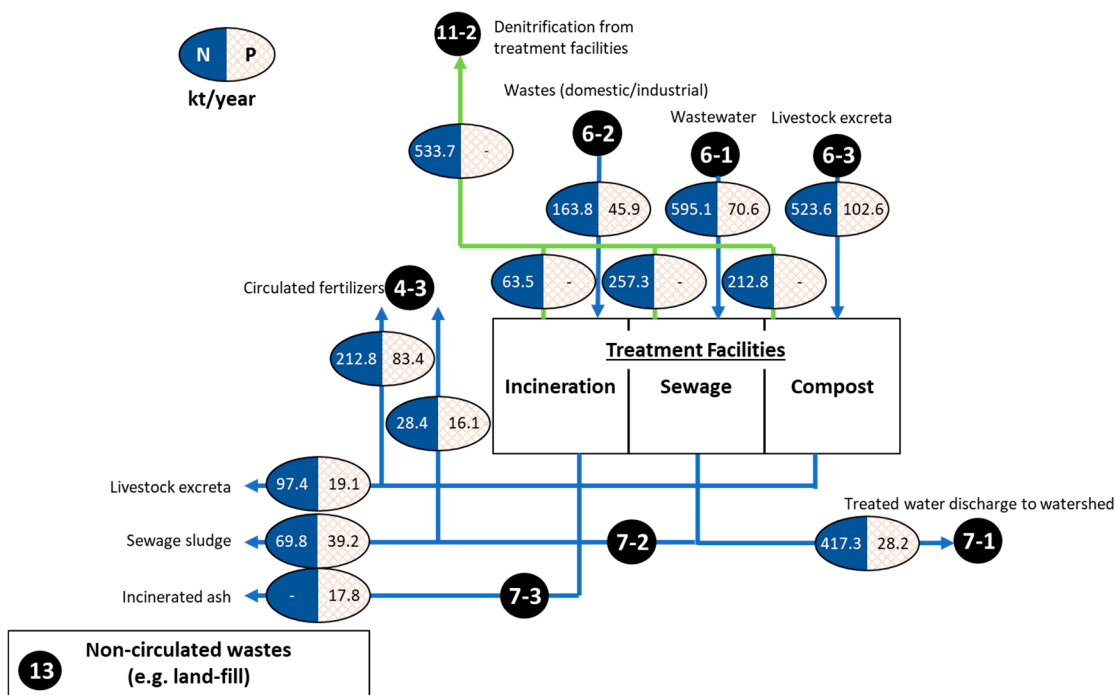


Figure 12. Detailed flow diagram and results for treatment facilities. Input and output values are provided for food waste incineration facilities, sewage treatment facilities, and composting facilities for livestock manure.

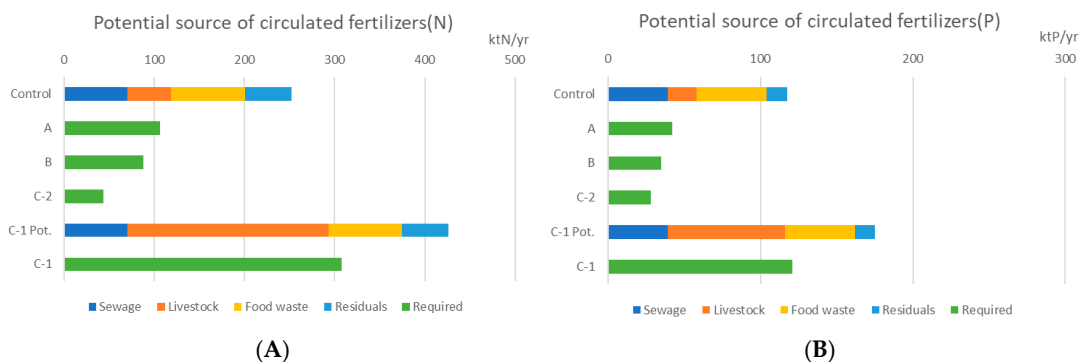


Figure 13. Scenario analysis results for nitrogen (A) and phosphorus (B) potential fertilizers. Current waste in the control – including sewage, livestock waste, food waste, and agricultural residuals – were determined as the potential source for increased circulated fertilizer demand in the scenarios. The potential source in **Scenario C-1** increased due to the growth in domestic livestock production. The nitrogen loss ratio due to compost for circulated fertilizer production is set at 0.5 for livestock excreta and food waste prior to incineration [53].

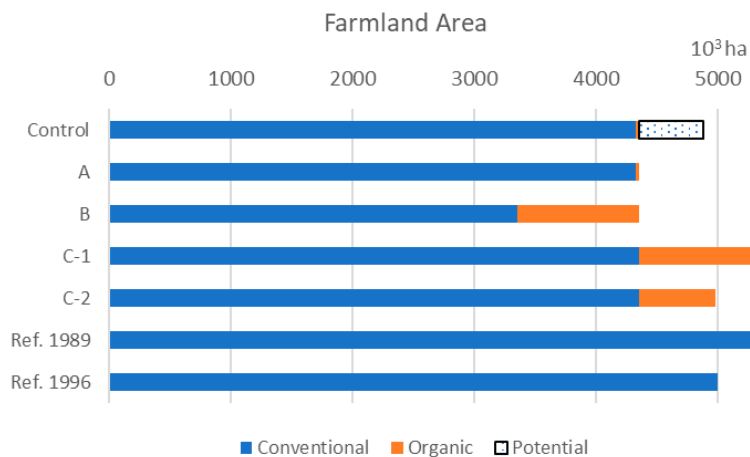


Figure 14. Scenario analysis results for farmland area, illustrating total and the ratio of conventional to organic farmland. Current potential farmland is indicated in the control. The results for Scenario C-1 and C-2 are comparable to the total farmland areas recorded in 1989 and 1996, respectively. .

Scenario A aims to reduce chemical fertilizer use (4-2) while maintaining a constant total fertilizer supply to farmland (4-6); consequently, the volume of circulated fertilizer (4-3) was increased. As shown in Figure 10, chemical fertilizer (4-2) use was reduced from 354.9 kt N/yr (Nutrient Index 0.37) to 248.4 kt N/yr (0.26) for nitrogen and from 140.6 kt P/yr (1.19) to 98.4 kt P/yr (0.83) for phosphorus – a 30% reduction as targeted in the MIDORI Strategy. The ratio of circulated fertilizer to the total fertilizer supply expanded from 42% to 59% for nitrogen and from 46% to 62% for phosphorus. The increase in circulated fertilizer (4-3) by diverting nutrients from non-circulated waste (13), rising from 255.3 kt N/yr (0.27) to 361.8 kt N/yr (0.38) for nitrogen and from 119.0 kt P/yr (1.01) to 161.2 kt P/yr (1.36) for phosphorus (Figure 11). Because most of chemical fertilizer in Japan is imported, the value of imported fertilizer (4-1) decreased, resulting in a reduction in total imports (1) of 16% for nitrogen and 23% for phosphorus (Figure 8). In this scenario, there were no changes to domestic production volumes or total farmland area.

Scenario B, representing an increase in organic farmland area, also maintains the total fertilizer supply (4-6) at a constant level. It increases the use of circulated fertilizer (4-3) for organic farmland while decreasing chemical fertilizer supply (4-2). Circulated fertilizer (4-3) increased from 255.3 kt N/yr (Nutrient Index 0.27) to 342.8 kt N/yr (0.36) for nitrogen and 119.0 kt P/yr (1.01) to 153.7 kt P/yr (1.30) for phosphorus (Figure 10). Accordingly, chemical fertilizer (4-2) decreased from 354.9 kt N/yr (0.37) to 267.5 kt N/yr (0.28) for nitrogen and 140.6 kt P/yr (1.19) to 106.0 kt P/yr (0.90) for phosphorus. These results show a trend similar to **Scenario A**. The basis of **Scenario B** is the assumption that the fertilizing effects of chemical and circulated fertilizers are equivalent; therefore, the same application rate (kg/ha) was applied to maintain the total domestic food and feed supply. However, it is documented that the average yield from organic farmland is approximately 75% of that from conventional farming using chemical fertilizers [54]. While the total farmland area remains unchanged in this scenario, 25% of it is converted to organic farming. A detailed consideration on required farmland, accounting for the yield gap between organic and conventional systems, is provided in the Discussion section.

Scenario C-1 increases calorie-based food self-sufficiency while keeping the total food supply (2-7), per capita caloric consumption (2,265 kcal/day/capita), and food composition unchanged [51]. In this pattern, domestic production of soybeans, wheat, rapeseed oil, and livestock was increased to achieve higher self-sufficiency. Fertilizer for the increased crop production and feed for expanded livestock population were both sourced domestically. Imported food (2-1) decreased from 380.5 kt N/yr (0.37) to 264.3 kt N/yr (0.27) for nitrogen (a 21% reduction) and from 27.1 kt P/yr (0.19) to 16.1 kt P/yr (0.14) for phosphorus (an 18% reduction) (Figure 8). Domestic food (2-2) increased by 17% from 223.8 kt N/yr (0.23) to 259.1 kt N/yr (0.27) for nitrogen and from 43.1ktP/yr (0.36) to 49.1ktP/yr (0.42) by 17% for phosphorus. Domestic feed production – specifically corn and pasture – increased from 314.9 kt N/yr (0.33) to 628.0 kt N/yr (0.65) for nitrogen (a 97% increase) and from 58.1 kt P/yr (0.49) to 124.7 kt P/yr (1.05) for phosphorus (a 114% increase). The total farmland area required for this increased production was $5,283 \times 10^3$ ha, 21% increase compared to 2021, which is comparable Japan's total farmland area in 1989 (Figure 14). Only circulated fertilizer (4-3) was used for the additional farmland, resulting in a 53% increase for nitrogen and a 100% increase for phosphorus (Figure 10). The sources for this circulated fertilizer are existing “non-circulated” wastes, such as sewage sludge and livestock excreta, which are currently disposed of in landfills or recycled as construction material, as well as food waste collected prior to incineration. Non-circulated waste reached nearly zero for both nitrogen and phosphorus, indicating that 100% circulation of waste is required to fulfill the fertilizer demand in this scenario (Figure 11).

Scenario C-2 also increases calorie-based food self-sufficiency and maintains the total food supply (2-7) but modifies the caloric composition to favor higher rice consumption and reduced oil

and livestock consumption. Rice consumption was increased from 21% of the calorie consumption per capita to 31%, oil and livestock were decreased from 15% and 18% to 11% and 13%. Imported food (2-1) decreased from 380.5ktN/yr (Nutrient Index 0.37) to 312.5ktN/yr (0.32), by 18% for nitrogen and 27.1ktP/yr (0.19) to 14.1ktP/yr (0.12) for phosphorus, by 48% (Figure 8). Domestic food (2-2) increased by 22% from 223.8ktN/yr (0.23) to 266.0ktN/yr (0.28) for nitrogen and by 28% from 43.1ktP/yr (0.36) to 53.8ktP/yr (0.46) for phosphorus (Figure 9). As in **Scenario C-1**, only circulated fertilizer (4-3) was applied to the additional farmland, but with significantly lower demand compared to **C-1**. Circulated fertilizer demand increased from by 13% from 255.3 kt N/yr (0.27) to 298.8 kt N/yr (0.31) for nitrogen and by 19% from 119.0 kt P/yr (1.01) to 147.0 kt P/yr (1.24) for phosphorus, representing the smallest increase across all scenarios (Figure 10). The required farmland area was $4,980 \times 10^3$ ha, a 15% increase, which is similar to the total farmland area recorded in 1996 (Figure 14).

Each scenario contributes to an increase in the input and output circulation ratios, defined by the following equations.

$$\text{Input Circulation Ratio (ICR)} = \frac{\text{Circulated Utilization}}{\text{Circulated utilization} + \text{Natural Resource Input}} \quad (1)$$

$$\text{Output Circulation Ratio (OCR)} = \frac{\text{Circulated Utilization}}{\text{Waste Generation}} \quad (2)$$

The calculation methodology for the material circulation ratio was adapted from the “Environmental White Paper, Annual Report on the Environment, the Sound Material-Cycle Society, and Biodiversity in Japan,” utilizing nitrogen and phosphorus mass flows determined in this study [38].

The results for each calculation are presented in Table 7. The circulation ratios improved in every scenario compared to the control. “Waste generation” refers to the total input to treatment facilities; thus, the OCR indicates the efficiency of nutrient recovery versus loss at these facilities. Nitrogen exhibits lower circulation ratios compared to phosphorus because of denitrification losses to the atmosphere within the nitrogen cycle. Enhanced nitrogen recovery of nitrogen would be required to achieve higher circulation ratio. **Scenario C-1** yielded in the highest values for both ICR and OCR. Additionally, **Scenario A** resulted in higher ICR and OCR values compared to **Scenario B**.

Table 7. Input and output circulation ratios for each scenario.

	Input Circulation Ratio		Output Circulation Ratio	
	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Control	28%	41%	25%	62%
A	38%	55%	33%	81%
B	36%	52%	32%	78%
C-1	47%	59%	40%	80%
C-2	32%	48%	28%	75%

4. Discussion

4.1. Current Nitrogen and Phosphorus Flows in Japan

By determining the nitrogen and phosphorus flows for Japan in 2021, this study identified significant imbalances and inefficiencies within the national food and feed system. These insights were made possible by the separate aggregation of inputs and outputs, which revealed the actual current status of nutrient movements rather than assuming a pre-existing equilibrium.

A substantial imbalance was observed in the national input-output profile. As a country with low self-sufficiency in fertilizers, food, and feed, Japan’s total imports – or “virtual nutrients” – account for a Nutrient Index of 0.9 for nitrogen and 1.6 for phosphorus. In contrast, exports account for only 0.1 and 0.0, respectively, while the household food supply index stands at 1.0 for both. This massive disparity indicates that a large volume of imported virtual nutrients must be managed internally, requiring significant energy input to meet national environmental regulations.

Furthermore, about 45% of phosphorus is lost throughout the system; it is assumed this nutrient accumulates within Japan, most likely in agricultural soils.

From a circulatory perspective, nutrient discharge into the atmosphere via denitrification (DN) and incineration, as well as runoff into watersheds, hinders total nutrient circulation. DN and incineration accounts for a Nutrient Index 0.6, with the majority being anthropogenic emissions from treatment facilities. Combined, discharge and non-circulated waste reach a Nutrient Index of 0.3 for nitrogen and 0.8 for phosphorus. The ICR and OCR values demonstrate that Japan could achieve greater sustainability by enhancing circulation processes.

Furthermore, specific "inefficiencies" are identified Farmland, Livestock, and Treatment Facilities that currently obstruct nutrient circulation.

- **Farmland:** Phosphorus fertilizer use is notably inefficient, with approximately 50% of applied fertilizers not reaching plant uptake due to soil accumulation or runoff. This is largely caused by the over-application of phosphorus, which chemically bonds with aluminum in Japanese soils [10]. Implementing customized fertilization plans based on local soil diagnostics can reduce chemical fertilizer use without compromising yields [55]. Additionally, advancements in precision management – such as optimized timing, slow-release fertilizers, and AI/IoT integration – offer pathways to improvement [56]. Enhanced-efficiency fertilizers, in particular, have demonstrated positive effects on yield, nutrient uptake, and the reduction of greenhouse gas emissions and water pollution [57,58].
- **Livestock:** The nitrogen feed supply is three times the volume production while phosphorus is six times higher. Although domestic livestock products represent only 20% of the nitrogen and 10% of the phosphorus in the total food supply, the feed required to produce them equals 60% of the nitrogen and 100% of the phosphorus in the human food supply. As shown in Figure 3, these findings align with previous studies. While composting livestock excreta is common, the ratio of feed input to final production remains inefficient. These inefficiencies are driving global movements toward diets with reduced meat consumption [59]. Technically, circulation could be improved through ammonia recovery from gases volatilized during composting, a process that has already shown effective fertilizing results (Figure 15a) [60].
- **Treatment Facilities:** Approximately 60% of nitrogen relative to the human food supply is lost to the atmosphere during treatment. For phosphorus, a significant portion is not circulated but is instead landfilled or repurposed as non-circulated construction material. While over 80% of livestock manure is returned to farmland after via composting [61], food waste is typically incinerated, and sewage is treated aerobically. Currently, incinerated ash is recycled as construction material, not as fertilizer, and only about 10% of the generated sewage sludge by weight is circulated as fertilizer [62]. Government policies have been promoting to expand the use of sewage sludge utilization, progress has been hindered by negative public perceptions, odor concerns, and distribution challenges [63].

Directly circulating waste from Treatment Facilities to Farmland as fertilizer is the most effective approach to accelerating nutrient circularity in Japan. Reducing heavily reliance on imported chemical fertilizers through domestic recovery would promote environmental sustainability and positively impact global virtual nutrient flows [64]. Potential recovery methods are illustrated in Figure 15. These include installing phosphorus recovery facilities to produce pure phosphorus fertilizer (Figure 15c) [65], composting food waste prior to incineration (Figure 15d), and implementing anaerobic treatment at sewage treatment facilities to produce liquid fertilizer (Figure 15e). Although are currently implemented only in a few municipalities they represent significant potential for widespread adoption [66].

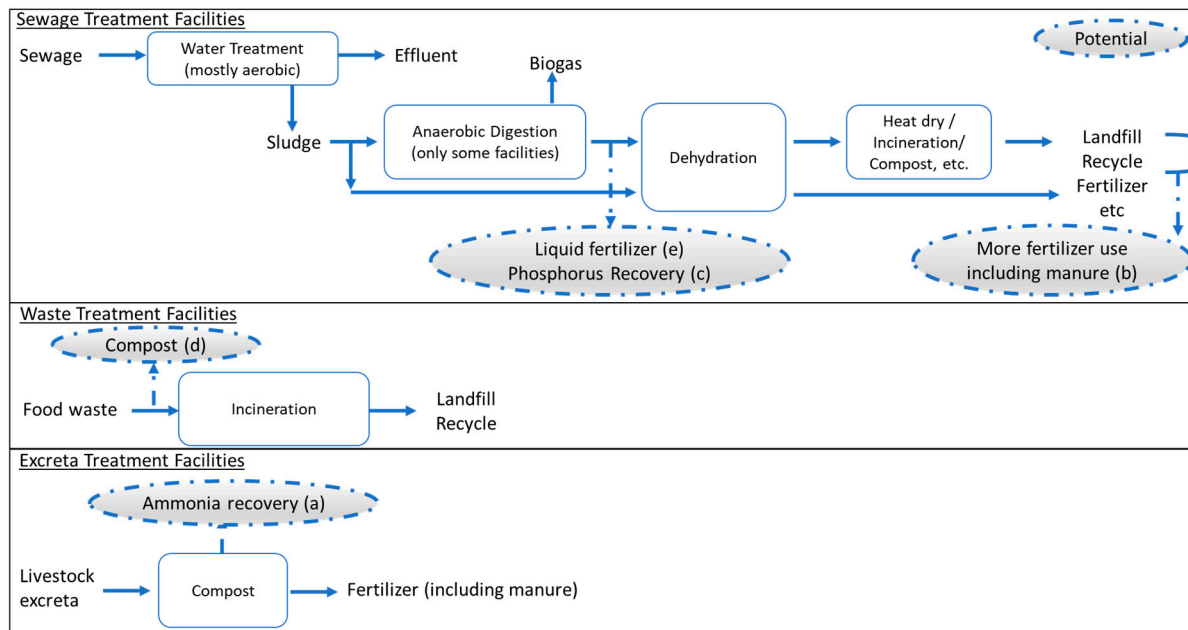


Figure 15. Diagram of potential nutrient recovery locations within treatment facilities where new technologies or facilities could be implemented: (a) ammonia recovery from volatilized gas during composting; (b) increased recycling of sewage sludge as circulated fertilizer; (c) installation of phosphorus recovery facilities; (d) composting of food waste as an alternative to incineration; (e) utilization of anaerobic digestion effluent as liquid fertilizer.

As shown in Table 8, based on the total mass of nitrogen and phosphorus, it is currently impossible to replace 100% of chemical fertilizer demand with recovered circulated fertilizers alone. Furthermore, the fertilizing effect and resulting crop yields of circulated fertilizers remain a subject of debate, as they function differently with the soil matrix compared to synthetic options. Consequently, an equivalent weight of circulated fertilizer may not provide the same yield-stabilizing effects [67]. There are also documented risks associated with circulated fertilizers, including heavy metal accumulation and hygiene concerns [68,69]. To achieve higher levels of circularity, additional domestic sources, such as steel slag for phosphorus recovery or atmospheric ammonia synthesis, will be necessary [70]. Promoting the production and use of circulated fertilizer requires a three-fold approach; first, the modification of current waste treatment methods; second, the construction of new recovery facilities; third, the establishment of efficient distribution and matching systems between producers and farmers.

Table 8. Current chemical fertilizer demand versus potential nutrient recovery from circulated sources (10^3 t/year).

	10^3 t/year	
	Nitrogen (N)	Phosphorus (P)
Current chemical fertilizer demand	354.9	140.6
Total potential circulated fertilizers	251.7	117.4
Non-circulated sewage sludge	69.8	39.2
Food waste *	81.9	45.9
Non-circulated livestock excreta	48.7	19.1
Agricultural residuals *	51.3	13.1

* Nitrogen loss ratio during composting is determined as 0.5 [53].

4.2. Scenario Analysis

The scenario analysis, based on quantitative targets from current government policies, reveals the following:

- **Scenario A (Reducing chemical fertilizers):** Reducing chemical fertilizer use requires a significant shift toward domestic waste resources, increasing the circulation ratio by approximately 30%. Realizing this scenario, requires a shift in nutrient management strategies; chemical fertilizers are valued for their rapid nutrient release, whereas circulated fertilizers typically have a slower release profile. As discussed in Section 4.1, while soil diagnostic analysis is not yet widespread in Japan, transition to precision fertilizer planning based on soil conditions is essential to minimize the environmental runoff. Proper management is critical regardless of the fertilizer type, as the risk of runoff exists for both synthetic and organic sources [71].
- **Scenario B (Increasing Organic Farming):** In this scenario, the circulation ratio increases by 25% to 30% due to the increased application of circulated fertilizers, assuming total fertilizer supply and cropland area remain constant. However, if the lower average yield of organic farming (discussed in Section 3.1) is accounted for (defined here as **Scenario B'**) total farmland area and chemical fertilizer use would actually need to increase to maintain the national food supply (Table 9). It remains unclear whether the MIDORI Strategy accounts for this yield gap. To compensate for the reduced yield from organic plots, an additional 669,354 hectares of conventional farmland using chemical fertilizer would be required. Consequently, the net reduction in chemical fertilizer use would be negligible.

Table 9. Comparison of farmland area and fertilizer accounting for the organic yield gap (**Scenario B'**).

	Organic Farmland ha	Conventional Farmland ha	Chemical Fertilizer (N) 10 ³ t/year	Chemical Fertilizer (P) 10 ³ t/year	Circulated Fertilizer (N) 10 ³ t/year	Circulated Fertilizer (P) 10 ³ t/year
Control	26,600	3,950,400	354.9	140.6	255.3	119.0
Scenario B	1,000,000	2,977,000	267.5	105.9	342.8	153.7
Scenario B' *	1,000,000	3,646,354	327.6	129.8	298.3	139.0

*Scenario B' accounts for the lower yield from organic farmland.

Land use and organic farming: In this context, focusing solely on the expansion of organic farming areas does not directly lead to increased nutrient circulation. Furthermore, the relationship between organic farming and environmental load remains a subject of ongoing academic debate [72,73]. Policies promoting organic farming should be integrated with the development of advanced agricultural technologies, such as utilizing bio-char to increase crop yields [74] or leveraging mycorrhizal fungi inoculation to enhance nutrient uptake [75].

- **Scenario C-1 (Self-Sufficiency via Current Diet):** As demonstrated in **Scenario C-1**, increasing calorie-based self-sufficiency while maintaining the current food composition requires farmland area 1.2 times larger than the current total. This requirement is close to the land used in 1989, a period when both the total population and the agricultural workforce were significantly larger. Due to the inherent inefficiencies of livestock production, increasing caloric self-sufficiency for meat requires doubling the current domestic feed production area. Expanding meat production also necessitates additional land and facilities for livestock management. To meet the resulting phosphorus demand, nearly 100% circulation of sewage sludge and livestock excreta would be required. As discussed in Section 4.1, food waste composting is not yet widespread; however, it must be promoted, as 100% circulation of current waste streams is otherwise unrealistic. Consequently, the feasibility of **Scenario C-1** depends on significant infrastructure modifications and the social challenge of transforming food waste collection methods and incentivizing a return to agriculture labor to manage expanded farmland.
- **Scenario C-2 (Self-Sufficiency via Dietary Shift):** **Scenario C-2**, which achieves higher self-sufficiency by increasing rice consumption while decreasing meat and oil calories, requires

significantly less farmland area because it eliminates the need for a massive increase in domestic feed production. In this scenario, the caloric composition was modified from the current levels (21% rice, 18% livestock, 15% oil) to 31% rice, 13% livestock, and 11% oil. Compared to 1965 when it was rice 44%, livestock and oil 6%, the modification does not look so great[51]. Although the government policy predicts the same meat consumption amount per capita[30], the modification in food composition should also be considered to satisfy food self-sufficiency target with feasible farmland area. Although it is a big challenge to change food diet that has shifted overtime, government could promote in this direction for sustainable food and feed system with higher food self-sufficiency.\

Figure 16 summarizes the feasibility of the proposed scenarios based on the “hard” (technological/infrastructural) and “soft” (socio-political) dimensions of social change. This framework directly reflects the challenges of promoting circulated fertilizer utilization discussed in Section 4-1. While **Scenario C-1** achieved the highest circulation ratio, it presents the most significant barriers across both dimensions. To improve Japan’s food self-sufficiency, **Scenario C-2** appears to be more viable, as it requires less intensive investment in new facilities and technology.

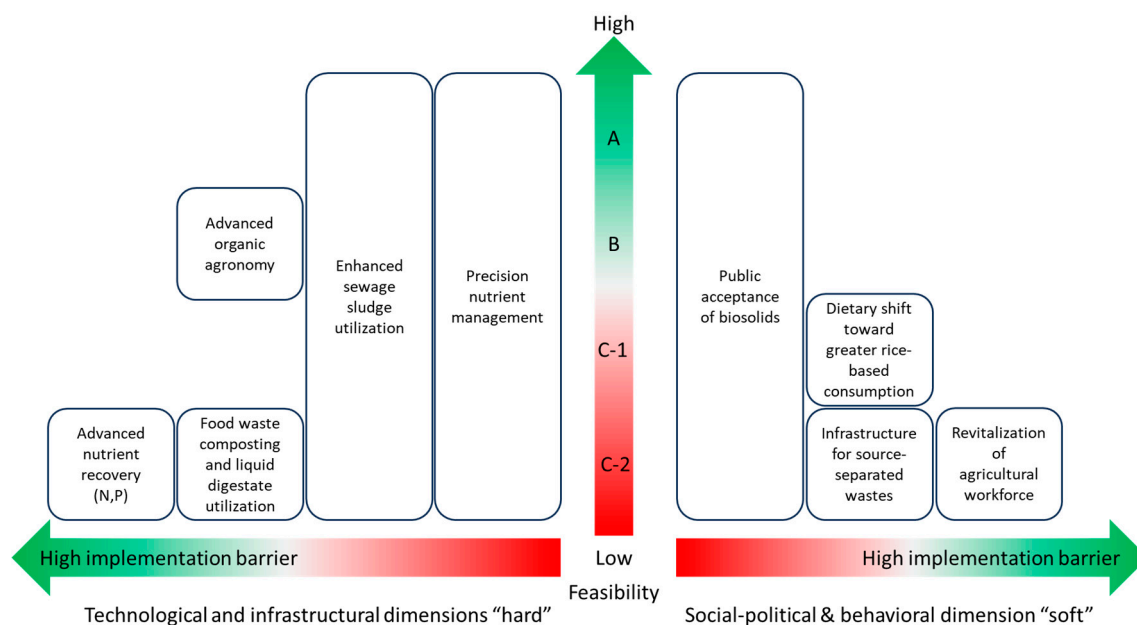


Figure 16. Summary and feasibility assessment of scenarios: The requirements for scenario implementation are categorized into two types of challenges: “hard” (technological advancement and infrastructure modification) and “soft” (social change and policy adoption). The magnitude of implementation difficulty is indicated by arrows left and right, while feasibility of the scenarios is indicated by the vertical arrow. Based on this framework, **Scenario A** is identified as the most feasible, while **Scenario C-1** presents the greatest overall challenge.

Although not explicitly addressed in current national policies, land-use planning that prioritizes the expansion of farmland – potentially by constraining the expansion of residential or industrial areas – residential is a critical factor for sustainable agriculture in Japan, where flat land area is a finite resource. Government policy should extend beyond setting key performance indicators (KPIs), to include integrated land-use planning and dietary recommendation to make these targets achievable. Finally, **Scenario A** offers the second highest circulation ratio with relatively low implementation barriers compared to other scenarios. Consequently, prioritizing the reduction of chemical fertilizers should be the primary focus for immediate policy enforcement.

5. Conclusions

This study quantified the 2021 nitrogen and phosphorus flows for Japan's entire food and feed system using the "Nutrient Index," a normalized indicator that allowed for a clear visualization of systemic imbalances. By integrating the waste treatment sector into the nutrient flow, significant inefficiencies were identified, particularly regarding the loss of virtual nutrients to the atmosphere and landfills.

The scenario analysis evaluated the feasibility of current national sustainability targets, yielding the following conclusions:

Scenario A (Chemical Fertilizer Reduction): This remains the most feasible immediate policy. A 30% reduction in chemical fertilizer is achievable by strategically recovering non-circulated nutrients from sewage sludge and livestock waste.

Scenario B (Organic Farming Expansion): While theoretically sound, the feasibility of this scenario is constrained by the "yield gap." Without significant technological breakthroughs in organic agronomy (e.g., biochar or mycorrhizal fungi), expanding organic farming may inadvertently increase the demand for conventional land and fertilizers to maintain the national food supply.

Scenario C (Food Self-Sufficiency): Achieving higher self-sufficiency with current dietary patterns (**Scenario C-1**) is the most challenging goal due to its massive requirements for additional farmland and a 100% nutrient circulation rate. However, **Scenario C-2** demonstrates that a dietary shift toward rice-based consumption can reconcile self-sufficiency targets with limited land resources.

To achieve a truly sustainable food and feed system, Japan must adopt a holistic approach that synchronizes waste treatment, land-use planning, and consumer dietary behavior. The government must look beyond quantitative KPIs and engage in proactive land-use management to protect and expand farmland.

While this paper reviews national trends, the next essential step is to investigate these flows at the local level. Because a national goal is the sum of local actions, further research into regional spatial characteristics and prefecture-level supply-and-demand balances, building on recent work such as Mishima (2025) [76], is required to provide a comprehensive roadmap for nutrient circularity in Japan.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Figure S1: title; Table S1: title; Video S1: title.

Funding: This research was funded by "Nagoya University Knowledge Co-creation Program."

Institutional Review Board Statement: Not applicable.

Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at <https://www.mdpi.com/ethics>.

Acknowledgments: Authors would like to thank Hiroki TANIKAWA and Yasushi MARUYAMA from Nagoya University for their helpful review and feedback.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ANRE	Agency for Natural Resources and Energy
BNF	Biological nitrogen fixation
DN	Denitrification

FAOSTAT	Food and Agricultural Organization Statistical Databases
ICR	Input Circulation Ratio
MAFF	Ministry of Agriculture, Forestry and Fisheries
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
MOE	Ministry of the Environment
OCR	Output Circulation Ratio

References

1. Lu, C.; Tian, H. Global Nitrogen and Phosphorus Fertilizer Use for Agriculture Production in the Past Half Century: Shifted Hot Spots and Nutrient Imbalance. *Earth System Science Data* **2017**, *9*, 181–192, doi:10.5194/essd-9-181-2017.
2. *World Food and Agriculture – Statistical Yearbook 2022*; FAO, 2022; ISBN 978-92-5-136930-2.
3. Lim, J.Y.; Islam Bhuiyan, M.S.; Lee, S.B.; Lee, J.G.; Kim, P.J. Agricultural Nitrogen and Phosphorus Balances of Korea and Japan: Highest Nutrient Surplus among OECD Member Countries. *Environmental Pollution* **2021**, *286*, 117353, doi:10.1016/j.envpol.2021.117353.
4. Nedelciu, C.E.; Ragnarsdottir, K.V.; Schlyter, P.; Stjernquist, I. Global Phosphorus Supply Chain Dynamics: Assessing Regional Impact to 2050. *Global Food Security* **2020**, *26*, 100426, doi:10.1016/j.gfs.2020.100426.
5. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347*, 1259855, doi:10.1126/science.1259855.
6. Greentumble 10 Sustainable Farming Methods and Practices | Greentumble 2024.
7. Food Sustainability Index Available online: <https://impact.economist.com/projects/foodsustainability/fsi/about-the-food-sustainability-index/> (accessed on 11 December 2025).
8. Fuhrmann-Aoyagi, M.B.; Miura, K.; Watanabe, K. Sustainability in Japan's Agriculture: An Analysis of Current Approaches. *Sustainability* **2024**, *16*, 596, doi:10.3390/su16020596.
9. FAOSTAT Available online: <https://www.fao.org/faostat/en/#data/RFN> (accessed on 30 March 2025).
10. Takahashi, T.; Dahlgren, R.A. Nature, Properties and Function of Aluminum–Humus Complexes in Volcanic Soils. *Geoderma* **2016**, *263*, 110–121, doi:10.1016/j.geoderma.2015.08.032.
11. MAFF Situation of Fertilizers [肥料をめぐる情勢] 2025.
12. MAFF Japan's Food Self Sufficiency Rate [日本の食料自給率] Available online: https://www.maff.go.jp/j/zyukyu/zikyu_ritu/012.html (accessed on 30 March 2025).
13. MAFF Situation of Feed [飼料をめぐる情勢] 2025.
14. ANRE FY2021 Actual Figure on Energy Supply-Demand [2021年度におけるエネルギー需給実績] 2023.
15. Rosa, L.; Chiarelli, D.D.; Tu, C.; Rulli, M.C.; D'Odorico, P. Global Unsustainable Virtual Water Flows in Agricultural Trade. *Environ. Res. Lett.* **2019**, *14*, 114001, doi:10.1088/1748-9326/ab4bfc.
16. Chen, X.; Hou, Y.; Kastner, T.; Liu, L.; Zhang, Y.; Yin, T.; Li, M.; Malik, A.; Li, M.; Thorp, K.R.; et al. Physical and Virtual Nutrient Flows in Global Telecoupled Agricultural Trade Networks. *Nat Commun* **2023**, *14*, 2391, doi:10.1038/s41467-023-38094-4.
17. MOE Monitoring Results of Public Waters Quality in FY2022 [令和4年度公共用水域水質測定結果] 2024.
18. MAFF Crop Survey, Long-term Area Survey [作物統計調査 面積調査 長期累年] Available online: <https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00500215&tstat=000001013427&cycle=0&tclass1=000001032270&tclass2=000001034721&tclass3val=0> (accessed on 11 December 2025).
19. MLIT White Paper on Land (2024) [令和6年土地白書].
20. National Institute of Population and Social Security Research Regional Population Projections for Japan:2020-2050 [日本の地域別将来推計人口（令和5（2023）年推計）報告書] 2024.
21. MAFF Survey of Movements in Agricultural Structure [農業構造動態調査 長期累年] Available online: <https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00500211&tstat=000001015214&cycle=7&year=20190&month=0&tclass1=000001034376&tclass2=000001101255&tclass3=000001101256> (accessed on 11 December 2025).

22. Peñuelas, J.; Sardans, J. The Global Nitrogen-Phosphorus Imbalance. *Science* **2022**, *375*, 266–267, doi:10.1126/science.abl4827.
23. *The International Code of Conduct for the Sustainable Use and Management of Fertilizers*; FAO, 2019; ISBN 978-92-5-131705-1.
24. Programme, U.N.E.; Organization, W.H.; Nations, F. and A.O. of the U. Chapter 1/12: Global Drivers, Actors and Policies Affecting Pesticides and Fertilizer Use. **2022**.
25. Willer, H.; Trávníček, J.; Meier, C.; Schlatter, B. Frick, and IFOAM -Organics International, Bonn. *The World of Organic Agriculture Statistics and Emerging Trends 2021*; **2021**.
26. European Union Farm to Ford Strategy 2020.
27. U.S.Department of Agriculture U.S. AGRICULTURE INNOVATION STRATEGY 2021.
28. U.S.Department of Agriculture Agriculture Innovation Agenda: Year One Status Report 2020.
29. MAFF MIDORI Strategy for Sustainable Food Systems 2021.
30. MAFF The Basic Plan for Food, Agriculture and Rural Areas 2025.
31. MAFF The Basic Plan for Food, Agriculture and Rural Areas 2025.
32. Nishina, K.; Hayashi, K.; Oita, A.; Asada, K.; Hayakawa, A.; Okadera, T.; Onodera, T.; Hanaoka, T.; Tsuchiya, K.; Kobayashi, K.; et al. Feasibility Assessment of Japan's Fertilizer Reduction Target: A Meta-Analysis and Its Implications for Nitrogen Waste. *Journal of Environmental Management* **2025**, *373*, 123362, doi:10.1016/j.jenvman.2024.123362.
33. Daramola, D.A.; Hatzell, M.C. Energy Demand of Nitrogen and Phosphorus Based Fertilizers and Approaches to Circularity. *ACS Energy Lett.* **2023**, *8*, 1493–1501, doi:10.1021/acsenergylett.2c02627.
34. Springmann, M.; Clark, M.; Mason-D'Croz, D.; Wiebe, K.; Bodirsky, B.L.; Lassaletta, L.; de Vries, W.; Vermeulen, S.J.; Herrero, M.; Carlson, K.M.; et al. Options for Keeping the Food System within Environmental Limits. *Nature* **2018**, *562*, 519–525, doi:10.1038/s41586-018-0594-0.
35. MLIT Dissemination Status of Wastewater Treatment Facilities (2021) [令和3年度末の処理施設別汚水処理人口普及状況] 2022.
36. Hayashi, K.; Shibata, H.; Oita, A.; Nishina, K.; Ito, A.; Katagiri, K.; Shindo, J.; Winiwarer, W. Nitrogen Budgets in Japan from 2000 to 2015: Decreasing Trend of Nitrogen Loss to the Environment and the Challenge to Further Reduce Nitrogen Waste. *Environmental Pollution* **2021**, *286*, 117559, doi:10.1016/j.envpol.2021.117559.
37. Nättorp, A.; Kabbe, C.; Matsubae, K.; Ohtake, H. Development of Phosphorus Recycling in Europe and Japan. In *Phosphorus Recovery and Recycling*; Ohtake, H., Tsuneda, S., Eds.; Springer: Singapore, 2019; pp. 3–27 ISBN 978-981-10-8031-9.
38. MOE Formation of the Sound Material-Cycle Society [循環型社会の形成]. In *Annual Report on the Environment, the Sound Material-Cycle Society and Biodiversity in Japan*; 2024.
39. Nakanishi H.; Ukita M. Ecological Aspects of Nitrogen and Phosphorus Sources in Japan. *Japan journal of water pollution research* **1979**, *2*, 133–151, doi:10.2965/jswe1978.2.133.
40. Hakamata, T. Resource Management and Environmental Issues in Agriculture. *Environmental research quarterly* **1996**, *100*, 120–126.
41. Miwa, E.; Oda, K.; Matsumoto, N. Analysis of Nitrogen Load to the Environment Based on Nitrogen Flow in Food Supply System of Japan. *J. Soil Sci. Plant Nutr.* **2006**, *77*, 627–634, doi:10.20710/dojo.77.6_627.
42. Matsumoto, N.; Oda, K.; Miwa, E. Changes in nitrogen flow in food and feed supply during 1992–2007 in Japan. *J. Soil Sci. Plant Nutr.* **2017**, *88*, 1–11, doi:10.20710/dojo.88.1_1.
43. Mizutani, J. Nitrogen and Phosphorus Material Cycle in Japan. *Japanese Journal of JSCE* **1997**, *1997*, 103–108, doi:10.2208/jscej.1997.566_103.
44. Kawashima, H. Food Supply and the Nitrogen Cycle in Japan. *Environmental Science* **1996**, *9*, 27–33, doi:10.11353/sesj1988.9.27.
45. Tezuka, K.; Nouchi, M.; Sudo, R. Mass Balance of Nitrogen and Phosphorus in Japanese Society. *Journal of water and waste* **2002**, *44*, 13–20.
46. Shindo, J.; Okamoto, K.; Kawashima, H.; Konohira, E. Nitrogen Flow Associated with Food Production and Consumption and Its Effect on Water Quality in Japan from 1961 to 2005. *Soil Science and Plant Nutrition* **2009**, *55*, 532–545, doi:10.1111/j.1747-0765.2009.00382.x.

47. Takahashi, T. Research challenges on nutrient management for coexistence of food self-sufficiency improvement and environmental conservation in Japan [わが国の自給率向上と環境保全を両立させるための養分管理に関する研究課題]. *Journal of the NARO Research and Development* **2011**, 73–103.
48. Katagiri, K.; Mizoguchi, M.; Matsubae, K.; Nagasaka, T. Material Flow Analysis of Nitrogen Around Industries in Japan from 2005 to 2015. *Journal of Life Cycle Assessment, Japan* **2018**, *14*, 319–331, doi:10.3370/lca.14.319.
49. Matsubae-Yokoyama, K.; Kubo, H.; Nakajima, K.; Nagasaka, T. A Material Flow Analysis of Phosphorus in Japan. *Journal of Industrial Ecology* **2009**, *13*, 687–705, doi:10.1111/j.1530-9290.2009.00162.x.
50. Mishima, S.; Kohyama, K. The database and the methodologies to estimate recent trend of nitrogen (N) and phosphate (P) flows and residual N and P in Japanese national prefectural scales and examples their application. *Bull. Natl. Inst. Agro-Environ. Sci* **2010**, 117–139.
51. MAFF Annual Report on Food, Agriculture and Rural Areas in Japan. In; 2023.
52. Miyazaki Prefecture Fertilizer Application Standards for Major Crops [主要作物の施肥基準] 1999.
53. Katayama, A.; Mizutani, H.; Suzuki, S.; Tada, Y.; Yoshida, S. Estimation of nitrogen emission in the recycle system of cattledung compost. *Environmental science* **2001**, *14*, 373–390, doi:10.11353/sesj1988.14.373.
54. Seufert, V.; Ramankutty, N.; Foley, J.A. Comparing the Yields of Organic and Conventional Agriculture. *Nature* **2012**, *485*, 229–232, doi:10.1038/nature11069.
55. Aomori Prefecture Healty Soil Preparation Technology Manual Available online: https://www.maff.go.jp/j/seisan/kankyo/hozen_type/h_sehi_kizyun/aomori01.html (accessed on 15 September 2025).
56. Barlóg, P. Improving Fertilizer Use Efficiency—Methods and Strategies for the Future. *Plants* **2023**, *12*, doi:10.3390/plants12203658.
57. Chen, M.; Schievano, A.; Bosco, S.; Montero-Castaño, A.; Tamburini, G.; Pérez-Soba, M.; Makowski, D. Evidence Map of the Benefits of Enhanced-Efficiency Fertilisers for the Environment, Nutrient Use Efficiency, Soil Fertility, and Crop Production. *Environ. Res. Lett.* **2023**, *18*, 043005, doi:10.1088/1748-9326/acb833.
58. Hopkins, B.G.; Fernelius, K.J.; Hansen, N.C.; Eggett, D.L. AVAIL Phosphorus Fertilizer Enhancer: Meta-Analysis of 503 Field Evaluations. *Agronomy Journal* **2018**, *110*, 389–398, doi:10.2134/agronj2017.07.0385.
59. Sanchez-Sabate, R.; Sabaté, J. Consumer Attitudes Towards Environmental Concerns of Meat Consumption: A Systematic Review. *International Journal of Environmental Research and Public Health* **2019**, *16*, 1220, doi:10.3390/ijerph16071220.
60. Abe, Y.; Honda, Y.; Fukujyu, N. Recovery of ammonia and its utilization in the process of composting using vacuum type aeration. *Japan Association on Odor Environment* **2009**, *40*, 221–228.
61. MAFF Current Livestock-Related Environmental Issues and Responses 2024.
62. MLIT Current Status of Utilization of Sewage Sludge Resources as Fertilizer [下水汚泥資源の肥料利用に関する現状について] 2022.
63. Katoh, M. Challenges and Prospects for Utilization of Sewage Sludge Fertilizer and Compost. *Material cycles and waste management research* **2021**, 32.
64. Chojnacka, K.; Skrzypczak, D.; Szopa, D.; Izydorczyk, G.; Moustakas, K.; Witek-Krowiak, A. Management of Biological Sewage Sludge: Fertilizer Nitrogen Recovery as the Solution to Fertilizer Crisis. *Journal of Environmental Management* **2023**, *326*, 116602, doi:10.1016/j.jenvman.2022.116602.
65. Hagino T.; Hirajima T. Development of a Process for Recovering Phosphorus from Sewage Sludge. *Resources Processing* **2005**, *52*, 172–182, doi:10.4144/rpsj.52.172.
66. MAFF Good Practices for utilizing methane fermentation biofertilizer 2024.
67. The Effect of Integrated Organic and Inorganic Fertilizer on Soil Fertility and Productivity. *JENR* **2021**, *5*, doi:10.23880/jenr-16000248.
68. Koumoulidis, D.; Varvaris, I.; Pittaki, Z.; Hadjimitsis, D. Sewage Sludge in Agricultural Lands: The Legislative Framework in EU-28. *Sustainability* **2024**, *16*, 10946, doi:10.3390/su162410946.
69. DeliBacak, S.; VroniNa, L.; Morachevskaya, E. Use of Sewage Sludge in Agricultural Soils: Useful or Harmful. *EURASIAN JOURNAL OF SOIL SCIENCE (EJSS)* **2020**, *9*, 126–139, doi:10.18393/ejss.687052.

70. Matsubae, K. Importance of Ensuring Sustainable Fertilizer Resource Management. *Material cycles and waste management research* **2021**, *32*, 445–452.
71. Wei, Z.; Hoffland, E.; Zhuang, M.; Hellegers, P.; Cui, Z. Organic Inputs to Reduce Nitrogen Export via Leaching and Runoff: A Global Meta-Analysis. *Environmental Pollution* **2021**, *291*, 118176, doi:10.1016/j.envpol.2021.118176.
72. Ahrens, F.; Land, J.; Krumdieck, S. Decarbonization of Nitrogen Fertilizer: A Transition Engineering Desk Study for Agriculture in Germany. *Sustainability* **2022**, *14*, 8564, doi:10.3390/su14148564.
73. Litskas, V.D. Environmental Impact Assessment for Animal Waste, Organic and Synthetic Fertilizers. *Nitrogen* **2023**, *4*, 16–25, doi:10.3390/nitrogen4010002.
74. Alkharabsheh, H.M.; Seleiman, M.F.; Battaglia, M.L.; Shami, A.; Jalal, R.S.; Alhammad, B.A.; Almutairi, K.F.; Al-Saif, A.M. Biochar and Its Broad Impacts in Soil Quality and Fertility, Nutrient Leaching and Crop Productivity: A Review. *Agronomy* **2021**, *11*, 993, doi:10.3390/agronomy11050993.
75. Matsuzaki, K. Arbuscular mycorrhizal fungi and their uses [アーバスキュラー菌根菌とその利用]. *Agriculture and horticulture* **2009**, *84*, 170–175.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.