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RESEARCH ARTICLE

On the feasibility of an agricultural revolution: Sri Lanka's ban of chemical fertilizers in 2021

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Abstract

Sri Lanka Government's ambitious decision to ban synthetic agrochemicals, including chemical fertilizers (and pesticides), in April 2021 made it the first nation in the world to embark on a full-scale transition to – as the Government called it—organic farming, and address concerns about human health and the environment. Previous policies had envisioned a gradual shift, but the sudden ban caught agriculture off guard. Declining foreign exchange reserves to import chemical fertilizers and coinciding peak fertilizer prices appeared to support the timing of the move. However, the ensuing rush for organic fertilizers failed to meet the national demand, resulting in severe losses in rice and export-oriented plantation crops. Facing decreasing yields and food insecurity, the government lifted the ban in November 2021. The events raised critical questions about the necessity and feasibility of such a drastic transition and alternative ways. To explore the general feasibility of transitioning toward organic fertilizers, this study considered the actual and potential availability of biomass to "replace" chemical fertilizers at the national scale as was envisioned by the Government. The analysis focused on the four main national crops and showed that in none of the selected scenarios, Sri Lanka's actual and potentially available organic fertilizer could supply rice- and plantation-based agrosystems with sufficient nitrogen, not to mention other crops or nutrients. The Government will in every scenario, including one that assumes a stepwise transition, remain compelled to spend significantly on importing organic fertilizer to maintain the required crop yields, which would cost the Government more foreign currency than purchasing chemical fertilizer. Even more costly is purchasing rice to close the national production gap, as Sri Lanka eventually did at the end of its nationwide experiment, which resulted in major food security concerns.

Keywords Organic fertilizer · Chemical fertilizer · Paddy rice · Tea · Coconut · Compost

1 Introduction

Moving towards ways of more 'healthy' farming is an uncontested need to reduce the negative environmental impacts of agriculture (Mateo-Sagasta et al., 2018). A key challenge is, however, not to compromise food security, welfare, and economic stability as the often-cited example of Bhutan shows (Feuerbacher et al., 2018). While Bhutan could not achieve its goal of becoming a 100% organic country over nearly 20 years (Tashi, 2022), the island country of Sri Lanka banned in April 2021 all synthetic agrochemicals to made it practically over-night the first nation to embark without transition to "organic farming"[1] as its President announced, to address concerns about human health and the environment.

The Sri Lankan context In 2019, the island of Sri Lanka moved into its most severe economic crisis since its

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[1] *The term "organic farming" is used in this paper* ***only*** *as it was used by the Sri Lankan Government. It refers in this context solely to the ban of synthetic agrochemicals, and does not apply to the systems approach of organic farming as defined, for example, in the norms of the International Federation of Organic Agriculture Movements (*IFOAM, 2014*). As such, it does neither relate to the four Principles of Organic Agriculture (Health, Ecology, Fairness and Care) nor includes the required attention to ecological processes, biodiversity and cycles adapted to local conditions.*

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Table 1 Changes in fertilizer subsidies over time (Sources: Weerahewa et al., 2022; MoA, 2022; MoA, 2023a)

Period	*Type of Fertilizers*	*Type of Crops*
1962—1974	Urea, Muriate of Potash (MOP), Triple Super Phosphate (TSP), Sulphate of Ammonia (SA), subsidies	Paddy
1975—1987	Urea, MOP, TSP, SA, subsidies	All crops
1988 –1989	Urea, MOP, TSP subsidies	All crops
1990—1994	No Subsidies due to economic crisis	
1995—1997	Urea, MOP, TSP, SA, subsidies	All crops
1997—2004	Urea, subsidies	Paddy
2005—2009	Urea, MOP, TSP, subsidies	Paddy (less than 5 acres land) Plantation crops (Tea, Coconut, Rubber)
2010—2015	Urea, MOP, TSP, subsidies	Paddy (less than 5 acres land) Plantation crops (Tea, Coconut), Vegetables
2016 –2020	Urea, MOP, TSP Cash Grant (2016–18), subsidies (2018), free fertilizer (2020)	Paddy (up to 2 ha) Potatoes, Chili, Maize, Onions, Soybean (up to 1 ha)
2021 (ban)	No subsidies for chemical fertilizer	
2022/23 (post-ban)	Urea, MOP, TSP; Alternatively, cash grant/voucher for organic fertilizer purchase (paddy farmers)	Paddy, tea, vegetables

independence in 1948. Facing unprecedented levels of inflation and a significant decline in foreign currency income and reserves, which was accelerated by Covid-19 travel restrictions (devastating the important tourist market), the Sri Lankan Government limited imports since 2020 to essential items. This did not prevent significant shortages even in medical goods or fuel, affecting among others the national electricity supply and public transport. On 22nd of April 2021, Sri Lanka's president at that time, Gotabaya Rajapaksa, announced a ban on importing agrochemicals to free the country from pesticides and chemical fertilizers. The cabinet verified the ban on 27th April and a Gazette (No. 2226/48) was published on 6th May 2021 by the Ministry of Finance to legalize the reform with immediate effect (Farzan, 2021a).

The sudden nature of the ban came as a surprise, given that the National Agricultural Policy of 2007 suggested to gradually reduce the use of chemical fertilizers through Integrated Plant Nutrition Systems (IPNS) (Wijayaratne, 2020; MoA, 2020), and the Agricultural Minister reiterated still in September 2020 the plan to increase the usage of organic fertilizers by up to 30% within a 3-year period. This target was in line with the National Policy Framework "Vistas Prosperity of Splendor (2020–2025)" that aimed at the promotion of organic agriculture over the next ten years. Despite plans for a gradual shift, the 2021 ban on agrochemicals abruptly upended these strategies.

The ban helped the Government to curtail the mounting debt crisis, given that Sri Lanka was at the brink of bankruptcy in early 2020, by saving about US$ 400 million the country was spending every year on fertilizer imports and subsidies (Gupta, 2022; Nordhaus & Shah, 2022; Singh, 2022). Officially, however, the message was that 'the cost of human lives outweighs harvest profits' (Fonseka, 2021; Perera & Amarasinghe, 2022). This timing of the ban proved fortunate as the global fertilizer industry increased in 2021 and 2022 due to severe supply issues due to reduced production in Europe, sanctions on Russia and Belarus, and China prioritizing domestic needs.

The reasoning of the ban The call for reducing the use of agrochemicals was not a novel approach in Sri Lanka. In 2016, the government launched a program under the name of "Toxin-free nation' to uplift the use of organic fertilizers which however failed (Figeczky & Kariyawasam, 2022; Fonseka, 2021). Already in 2004 and 2015, the use and sale of selected pesticides were banned under protests in particular from the tea sector (Economynext, 2021).

The 2021 decision to ban all agrochemicals was officially based on public health concerns and related health care costs due to overuse of chemicals in agriculture. The concerns focused on the "chronic kidney disease of unknown etiology" (CKDu) in and around the North Central region of Sri Lanka, as well as other diseases. Although the government did not reference specific studies supporting the need for a broad ban of pesticides and fertilizers, the media took enthusiastically care of this (e.g. Kulatunga, 2021).

Fertilizer overuse was facilitated by the Governmental long-standing fertilizer subsidy program. While the original aim was of encouraging farmers to switch from traditional rice varieties to high-yielding varieties, that are highly responsive to chemical fertilizers, the provision of the subsidy has become customary for every Government (Table 1) despite its severe budgetary implications. Instead of keeping the fertilizer price low, during 2016 – 2020 a cash grant was given depending upon type of crop cultivated, season and land size. As a result, the imported solid fertilizer quantity dropped in 2016/17 by over 30% and so rice yields, but the result was confounded by prevailing drought conditions (Edirisinghe et al., 2019; Weerahewa et al., 2022).

The reaction With the imposed ban, stores were quickly running out of synthetic pesticides and chemical fertilizers (Farzan, 2021b). While some academics applauded the government's environmental initiative, others cautioned against overly simplifying and rushing such a transition (e.g. De Costa, 2021; Dharmakeerthi, 2021). Even proponents of organic farming expressed concerns about the abruptness of the change, with farmers and soils unprepared (Figeczky & Kariyawasam, 2022). Despite increasing efforts, domestic organic fertilizer producers struggled with the exploding demand. There were about 27 licensed producers at that time, of which the by far largest could allegedly supply fertilizer for up to a fifth of the land under paddy rice, at the cost of other cropping sectors. This shortfall in capacity to meet national fertilizer demand encouraged further private sector investments but also discussions about organic fertilizer imports (Adaderana, 2021; Hamza, 2021).

In fact, the fertilizer ban triggered a surge in local organic fertilizer producers, with over 200 registered entities by the end of 2021, offering products of stark varying quality. However, even with military support (Farzan, 2021c), domestic production remained insufficient fertilizer imports were initiated. The first larger shipment, a 99,000-ton seaweed compost order from China was however rejected due to microbial safety concerns (Dharmawardana, 2021; Ethirajan, 2021; Lilani, 2021; Pandey, 2021) Meanwhile, an Indian liquid Nano-N fertilizer, also faced rejection for lacking national standards, potential health risks, and its low nitrogen content (Wickramasinghe, 2021; Vitarana, 2021). In fact, its organic origin was questioned (Rubatheesan, 2021a; The Island Online, 2021), The confusion increased when the Government announced the arrival of 30,000 mt of "organic" potassium chloride from Lithuania (Farzan, 2021b).

In view of pesticides, prices of conventional pesticides exploded (+67%), application rates and frequencies decreased. As a result, between 73 and 81% of 483 interviewed farmers in various sectors experienced higher insect, disease, and weed infestations (Kynetec, 2022). The pesticide ban was less dominant in the public discussion than the fertilizer ban. While most media welcomed the ban initially, opposing voices increased over time especially in private newspapers compared to governmental (78% vs 22%) (Schölin et al., 2024). There remained however a data gap in how far the pesticide ban affected crop yields compared to the more widely discussed fertilizer ban.

Farmers were deeply concerned about the increasing supply uncertainty and increased their protest (Rubatheesan, 2021b; Sunday Times, 2021a). Without sufficient inputs (at the right time), some farmers reduced the cultivated area or abandoned their farms (Petersen, 2022). Similar confusion and protests arose in the crucial plantation sector, already struggling from COVID-19's effects (Sunday Times, 2021b). Following the first media reports of decreasing harvests, and strong pressure from the plantation sector, the government lifted the chemical fertilizer ban through a gazette notification on 24th November 2021, re-allowing the import and use of chemical fertilizers, pesticides, herbicides and fungicides (PTI, 2021; Samaraweera, 2021). However, Sri Lanka's ongoing foreign currency shortage prevented both government and private sector to show the bank guarantees required to procure fertilizer imports (Economynext., 2022), calling the development aid sector (FAO, USAID, etc.) on the plan to assist. The situation improved slowly in 2023, after the International Monetary Fund (IMF) approved a US$ 3 billion loan to Sri Lanka to help resolve the spiraling economic crisis (Gupta, 2022; Kankanamge, 2023).

The 2021 events in Sri Lanka highlighted the crucial need for strategic planning when undertaking radical agricultural shifts. This includes ensuring the sector's preparedness, having data for planning and alternative fertilizers readily available, and establishing standards for quality assessment. Additionally, it is vital to understand the limitations of transitions, including biomass requirements and potential costs compared to anticipated savings. This paper aims to contribute to such planning by exploring answers to some of the key research questions which focus—except for question 1 – on the **fertilizer component** of the wider agrochemical ban:

- What was the scientific evidence for the agrochemical ban?
- How far is it possible to 'replace' the banned chemical fertilizers with organic fertilizers?
- Would the government have saved foreign reserves through the ban?
- How did farmers perceive the chemical fertilizer alternatives?
- Which agricultural sector has the highest potential to 'go organic' from a spatial perspective?

2 Methodology

The study combined several approaches:

2.1 Literature review

To answer the first, third and fourth questions, a comprehensive literature review was carried out on agrochemicals and human and environmental health in Sri Lanka to understand their significant contribution towards the decision to officially implement a fertilizer ban in 2021. Scopus and Google Scholar were used to obtain peer- and non-peer-reviewed papers and reports (e.g. from USAID, WHO) as well as media reports given that the events were still ongoing during the study period. Furthermore, material and data were provided by key informants from the Government, like the Ministry of Agriculture. The literature review focused on the period 2014 to 2023/4 and covered over 80 national articles and reports, over 100 media reports, and complemented by a previous IWMI review covering the time before 2014 which was dedicated to the reasons of CKDu (Noble et al., 2014).

2.2 Stakeholder interviews

To verify secondary information, especially on questions 1 and 4, about 30 key stakeholders were interviewed through a purposive sampling technique to access institutional data and gain insights into perceptions regarding the fertilizer ban. The interviews targeted agricultural experts from universities, non-governmental organizations (NGOs) and research institutes, governmental officers from agriculture departments and municipal councils, representatives from three national fertilizer production companies, and paddy farmers, including those specialized in "organic farming" in the Western and Southern Province. Data were collected through in-person interviews using semi-structured questionnaires addressing aside available data stakeholders' perspectives on the transition from chemical fertilizers to organic fertilizers, reasons, challenges, impacts, and the perceptive pathways for the fertilizer transition.

2.3 Nutrient demand—supply comparison

To approach the second and fifth questions, crop nutrient demand and supply options were compiled. From a soil science perspective, chemical and organic fertilizers are distinctly different in their composition, nutrient release pattern, and effects on soil. Chemical fertilizers are comprised solely of crop nutrients and provide them rapidly, while organic fertilizers constitute a soil amendment and mainly consist of organic matter that enhances soil health, physical soil properties, and microbial activity over a longer period. Additionally, organic fertilizers contain a variety of plant nutrients, but in much lower quantities than chemical fertilizer and in various forms of which some support an often-beneficial gradual release. Thus, from a soil science and plant nutrient point of view, it is hard to support a call for 'replacing' chemical with organic fertilizers, or more precisely for replacing the nutrients chemical fertilizer offer crops with the nutrients organic fertilizer offer them, in particular in view of seasonal crops, like rice.

In the Sri Lankan context, farmers were however requested to substitute the contribution of chemical fertilizers to crop yields with organic fertilizers. To show the limitations of this request, we assumed that the nutrients of both 'fertilizer types' behave similarly. Both inputs were thus compared quantitatively, based on the provided crop nutrients, ignoring other beneficial functions organic fertilizers offer soils and crops.

2.3.1 Demand

The national nitrogen demand of the rice crop was estimated in two different ways. One approach was using the fertilizer recommendations of the Department of Agriculture (DoA) which vary by climate zones, regions, soil types, and environmental considerations (DOA, 2022; Department of Census and Statistics, 2022) and resulted in an estimated nitrogen demand of 89,000 tons per year (Hashim et al., 2015). This number assumes that most of the rice straw remains in the field. An alternative approach used the average rice yield over 5 years (ca. 3.8 tons of grain per hectare), the cultivated area of around 1.0–1.2 million hectares, and a nitrogen content of about 1.6% (Rice Knowledge Bank, 2022), resulting in a total nitrogen requirement for rice crops of approximately 66,000 tons. The gap between DOA recommendations and the actual crop N content can largely be attributed to fertilizer use efficiency (Cassman et al., 1998; Hashim et al., 2015).

2.3.2 Supply

Among the organic nutrient sources available in the country, various scenarios were considered, with main sources including crop residues, compost from different providers, and livestock manure. Other sources, such as the biomass of invasive plants and fecal sludge from households, were also considered. Data variations for organic waste sources were high and multiple sources were studied to arrive at a sensible approximation.

Municipal waste compost A theoretical priority source for organic fertilizer in Sri Lanka are the municipal compost stations. In 2008, the government of Sri Lanka launched the "Pilisaru Project" under the Central Environment Authority (CEA), which supported the setup of 121 compost stations across the country (CEA, 2016) and extrapolated to the total of 175 stations, as estimated for 2021, based on Karunarathna et al. (2020), and sector expert interviews.

Across the country, about 25% of the collected waste or 10% of the generated waste is composted (Basnayake et al., 2018; Saja et al., 2021). The low percentage is primarily attributed to notable collection inequalities between rural and urban areas, inefficiencies, lack of infrastructure etc. which was considered for the scenarios (see below). The assessment of the produced compost quantity was based on available data from the existing composting facilities. Based on the latest (external) survey an average N content of 1.5% was considered for municipal compost (Roy et al., 2021). The share of paddy farmers using compost before the ban varies between and within sources from 4 to 33% (Bandara et al., 2023; Dominish et al., 2021).

Private-sector compost Compost production boomed after the fertilizer ban. Based on the available data, there were 325 commercial compost producers registered in 2020 with the government for quality certification. Based on their monthly production, they were categorized as small-scale (< 5 tons/month), medium scale (5 to 25 tons/month), and large-scale (> 25 tons/month). The manufacturers were using a variety of materials from cattle dung, poultry manure, goat manure, fish wastes, *Gliricidia sepium,* aquatic plants, dried leaves, paddy husk, as well as mineral enrichments like sand, ash, Eppawala rock phosphate or dolomite, etc. (Dias et al., 2022). The advertised percentages of nutrients (if shown at all) is usually in ranges but seldom exceeds the required minimum (e.g. 1% N; Sri Lanka Standards Institution, 2019a, b).

Animal manure Cattle and buffalo manure can be significant sources for different cropping systems where livestock is common. It can be a key resource in home and vegetable gardens, but also coconut and banana plantations. Data for paddy farming – before the ban—vary between 2 and 16% of farmers using it (Bandara et al., 2023; Dominish et al., 2021). The dung of both manure types holds about 1.55% N on dry basis (Tennakoon & Bandara, 2003). Cattle and buffalo records are available from three different systems: intensive, semi-intensive, and extensive livestock keeping (Department of Animal Production & Health, 2020). Manure application can be seen in dry form or as slurry entering irrigation channels. Poultry manure was not considered as it is mainly used and needed in vegetable production, rarely in paddy fields (Dias et al., 2022). According to Dias et al. (2022), the total cattle dung available from Sri Lanka is 5,517.85 tons/year, and the total buffalo dung is 1,615 tons/year in 2020 in their dry forms. The calculated total N supply of livestock manure (intensive rearing, semi-intensive rearing, and extensive rearing) is 40,354 tons/year. As the regional variations of paddy cultivation and livestock overlap, all manure that can be collected in stalls should be a priority source.

Human manure Composted fecal sludge (FS) or septage from onsite sanitation systems is not yet widely used in Sri Lanka. Onsite sanitation systems, like septic tanks, serve over 90% of Sri Lanka's population while sewer systems and wastewater treatment plants have a very low coverage. FS can be co-composted at a 1:3 ratio with organic municipal waste to sanitize it and elevate the nitrogen content of the final mix to about 3% (Nikiema et al., 2020). Currently, only one compost station in Sri Lanka uses FS to make co-compost (Hettiarachchi et al., 2020). Co-composting is supported by the National Sanitation Policy.

Rice straw The straw constitutes a noteworthy nitrogen source (0.55% N). It is returned to the field where threshing is conducted using tractor-powered threshers, but not where small farmers transport the harvested rice to a thresher at the side of the field where the straw accumulates and is later burned (Ahamed, 2021; Pabasara et al., 2019). The DOA strongly recommends applying paddy straw on the fields right after the harvesting (DoA, 2013, 2022). According to Dias et al. (2022), regional differences in rice straw conservation differ between 71 and 97%. The lowest return is recorded in the Northern province, where the straw is e.g. also used as animal feed. Overall, paddy straw covers across the provinces between 22 and 31% of the paddy rice nitrogen demand, and is reported as input from about 85–90% of the paddy fields (Department of Census and Statistics, 2022).

Rice straw was also a key input for compost produced by paddy farmers during the ban. About 64% of the rice farmers interviewed by Bandara et al. (2023) produced their own compost (up from 33% before the ban) with 79% using rice straw next to *Gliricidia*, other green cuttings and crop residues, and cow dung.

Other organic inputs There are other organic inputs locally available that are or could be used by farmers, such as dried or composted invasive plants (e.g., *Gliricidia*, water hyacinths), banana waste, coconut husk, sawdust, algae harvested from lakes and water courses, or organic waste from different agro-industries (Dias et al., 2022, Abeygunawardana, 2018; (SLSEA, 2021; Padmasiri, 2020). While these materials are not used to any notable extent in paddy farming, they were actively sought during the ban by the more than 300 commercial producers of organic fertilizers, resulting in stiff competition for biomass. A first quantitative assessment of the available nitrogen of the most common water hyacinths showed, however, that the contribution would be very marginal (IWMI, unpublished).

Not considered was **biological nitrogen fixation (BNF)** in the root zone of rice as the fields are only intermediately flooded, N fertilizer rates high, and lack of scalable field data from the country. Under optimal conditions, BNF could contribute more than 20% of the nitrogen in the grains (Kundu & Ladha, 1995; Perera et al., 2021b).

GIS analysis was used to map regions of nutrient supply versus demand using maps in the public domain.

2.4 Scenarios for the replacement of chemical fertilizers

To finally answer questions 2 and 5, supply scenarios were developed. We focused initially on the main stable crop, irrigated paddy rice, covering the two main growing seasons, and the by far largest area of arable land in the country. In the second step, we continued the assessment with the next major crops coconut, tea and rubber. Considered were all described organic sources with a primary emphasis on nitrogen, followed by phosphorus and potassium, under consideration of alternative uses and geographical distances.

2.4.1 Baseline scenario

The baseline scenario describes the situation of organic fertilizer usage in 2020 before the ban was enacted. While two thirds of the rice farmers rely fully on [subsidized] chemical fertilizer, approximately one-third is in addition using some limited amounts of organic materials. There is also a small community of fully organic paddy farmers, mostly cultivating traditional paddy varieties. These farmers were using cattle or buffalo dung and compost (ca. 2 tons/acre each) according to DOA (2022). Total land cultivated with traditional paddy varieties is, however, less than 1% of the total paddy cultivated area in Sri Lanka (DOA, 2022), highlighting the scale of the envisioned revolution. The baseline scenario assumes that the official statistics are correct and that up to 90% of rice straw stays on the field. Use of municipal compost is not common and there is a significant lack of data on the types or amounts of manure usage in rice farming which was for the scenario limited to the existing organic farming community.

Table 2 Compost production in 175 compost stations (Source: DOA data from 2020/2021; Roy et al., 2021; expert interviews)

Size of the compost station	Number of compost stations	Total production (tons/year)
Small (5 t/month)	73	4,380
Medium (93 t/month)	73	81,468
Large (195 t/month)	28	65,520
Special (600 t/month)	1	7,200
Total	175	158,568

2.4.2 Scenario 1

In this scenario, which reflects approximately the 2001 situation, farmers and organic fertilizer suppliers seek and use all available organic resources. This includes the available stock of the 175 compost stations, which were stratified and categorized based on their production capacity (Table 2).

In addition, organic fertilizer is sought from 325 registered commercial compost producers (Dias et al., 2022) who transform a large range of organic materials from agro-industrial waste to algae and manure, into approximately 5650 tons of compost per month (or 67,800 tons/year). This scenario also considers the existing co-composting facilities mixing organic waste with fecal sludge, as well as all cattle and buffalo manure from intensively reared animals, and a 100% application of harvested paddy straw (Table 3). Scenario 1 is, however, not factoring in capital investments for establishing new organic fertilizer plants or expanding organic waste collection.

2.4.3 Scenario 2

The second scenario includes all organic inputs from scenario 1 but assumes a stepwise transition between 2021 and 2025 allowing for additional investments to make more organic inputs available. It is assumed that with a significantly increased fleet of waste collection trucks, 80 to 90% of all the biodegradable waste is eventually collected and composted in the existing plus additional municipal or private compost facilities. The assumption is also that 95% of the generated fecal sludge is collected from septic tanks to enrich the municipal waste compost with nitrogen. It is also assumed that farmers can collect about 50% of the manure generated in semi-intensive rearing systems of both cattle and buffalo in addition to the already collected manure from intensive system.

Table 3 Cattle and buffalo population and their manure availability (Source: Vidanarachchi et al., 2019)

Animal type	*Population*	*Intensively reared %*	*Dry dung produced (kg/animal/day)*	*Total dry dung collected (tons/year)*	*N % in dry basis*	*Total N (tons/year)*
Cattle	1,103,570	15	5	302,102.29	1.55	4,682.59
Buffalo	323,000	25	5	147,368.75	1.55	2,284.22

2.5 Challenges and limitations

The main limitation of the study was the required simplification of the terminology to the Governmental understanding of what organic farming implies, compared to how e.g. IFOAM (2014) defines it. A related challenge was the required comparison of chemical and organic fertilizers (see 2.3.) to accommodate the Governmental view in 2021 that the nutrient supply benefit of chemical fertilizers could be substituted by organic fertilizers. However, even under the wrong assumption that the nutrient release of both inputs could be comparable, the quantitative analysis helped to show the limitations of the envisioned transition.

Another limitation was the bias of the academic as well as media responses towards the fertilizer ban compared to the pesticide ban, limiting any comparative assessment. A reason might be that there were previous restrictions on the use of popular pesticides, and farmers had developed coping strategies while they heavily relied on subsidized fertilizers.

There is very limited data in view of soil, water, and environmental concerns related to agrochemicals reflecting also the poor capacity of most laboratories. Available data are spatially and temporarily very limited, allowing hardly larger conclusions.

It is noteworthy that data availability for the nutrient demand–supply scenarios was not a major constraint. There is a significant amount of (also recent) annual data in the Governmental sector and farm survey data by institutions, like the Hector Kobbekaduwa Agrarian Research and Training Institute (HARTI). However, strong discrepancies between and within even the same sources were detected, as well as a lack of sufficient meta data (e.g., on the sampling frame) to understand possible deviations. Data triangulation with additional sources and expert consultations helped to reduce possible errors. Where discrepancies were too large, ranges or multiple data/sources are cited. For the central assessment of the nutrient gap between supply and demand, sensitivity analysis showed that the results for rice had a standard error of about 17%, and below 10% when covering all four main crops.

3 Results and Discussion

This section is structured according to the research questions posed at the end of the introduction.

3.1 What was the scientific evidence for the agrochemical ban?

The government ban on agrochemicals targeted pesticides and chemical fertilizers, citing their risks to soils, water resources, the environment, and human health due to excessive use, as the main rationale for the ban. The leading public health issue in central parts of the country is **c**hronic **k**idney **d**isease (Beillard & Galappattige, 2021; Noble et al., 2014), academically known as "CKDu" to flag with the additional "u" that its origin (etiology) remains unknown (Figeczky & Kariyawasam, 2022). Within an endemic village, some households manifest the disease, while others have never reported a case; thus, a combination of environmental and genetic factors may contribute to the etiology and progression of the disease (Arambegedara et al., 2021). For most of the media, there was, however, no question that banning those "hazardous chemicals" was years overdue (Kulatunga, 2021).

Several studies pointed at potential causes of the disease, often associated with specific elements and groundwater contamination. However, these studies frequently lacked a control site or control group and related data to fully comprehend the interaction of factors preventing the disease to surface in other regions of the country where the same agrochemicals are used, or similar e.g. arsenic levels are analysed. More comprehensive and peer-reviewed studies incorporating control groups could, at best, confirm that agrochemicals should be regarded as a risk factor. However, establishing causal linkages between agrochemicals and the disease remains challenging (Balasubramanya et al., 2020).

Most of these studies focused on heavy metals, like cadmium (Cd) and Arsenic (As) which can potentially derive from triple super phosphate (TSP), however with contradicting conclusions (Bandara et al., 2008, 2010; Jayatilake et al., 2013; Chandrajith et al., 2010; Edirisinghe & Jinadasa 2019; Jayasumana et al., 2013). Other studies did not find different metal concentrations between CKDu in endemic and non-endemic areas or test groups (Diyabalanage et al., 2017; Herath et al., 2018). In fact, CKDu seems to appear also in areas with very low and acceptable element levels, making it unlikely that arsenic, cadmium, lead, and/or chromium cause CKDu (Herath et al., 2018; Perera et al., 2021a; Wickramarathna et al., 2017).

A stronger fertilizer influence was found for nitrate contamination of groundwater with concentrations exceeding WHO thresholds in agricultural areas along Sri Lanka's coast (Xu et al., 2021). This indicates intensive leaching from excessive use of chemical fertilizers, such as urea (Jayasingha et al., 2011). In certain locations, like Jaffna, poor sanitation was also identified as a contributing factor to groundwater contamination. The Blue Baby (skin) Syndrome can be caused by milk powder mixed with nitrate-rich water (Prabagar et al., 2020), potentially derived from excessive fertilizer use (MoA, 2021). Another cause can be Propanil which is a widely used herbicide for rice cultivation. However, research on water and crop contamination with pesticides remains so far limited (Jayasiri et al., 2022), despite often observed poor pesticide handling practices (Padmajani et al., 2014).

Compared to data related to human health, the literature review showed in general only a patchwork of spatially and temporarily limited data on soil, water, and environmental issues potentially related to agrochemicals, not allowing any conclusions.

In summary, elevated levels of water contaminants as reported from various studies are likely to be attributed to excessive fertilizer use. In view of CKDu, studies incorporating control groups have not been able to confirm any significant differences between CKDu affected and unaffected populations in view of agrochemicals. A typical management response in such cases involves supporting capacities for adopting good agricultural practices (GAP) and restructuring the fertilizer subsidy system to minimize misuse of fertilizers or pesticides while promoting organic soil amendments. None of the studies provided evidence to warrant or justify a nationwide ban on agrochemicals across all regions, soils, and crops to safeguard human and environmental health. However, it can be argued that it is the prerogative of any Government to be proactive to protect public health instead of waiting for any final scientific proof.

3.2 How far is it possible to 'replace' the banned chemical fertilizers with organic fertilizers?

With the removal of chemical fertilizers, crops do not receive the amount of nutrients they need to achieve the same yields as in previous years. There are different options on how to fill the nutrient gap, each with its own opportunities and limitations, cost and benefits. This applies to all the different nutrients the crop needs. To start the analysis, the study focused on the most discussed nutrient, nitrogen, and the main food crop, paddy rice, and how far the actual and potential organic fertilizer market can replace imported chemical fertilizers. Two nutrient supply scenarios were compared with the annual nutrient demand of the rice sector:

- Scenario 1, which builds on the situation in 2021, it is assumed that all the generated compost, ready-available manure, and paddy straw are used for paddy farming, which can be achieved by increasing the efficiency in each sector involved.
- Scenario 2 reflects a slower transition over a few years which allows significant investments in the organic fertilizer supply chain. These investments would include more fecal sludge treatment and co-composting plants, increasing the fleet of trucks collecting organic waste, etc. This will have to be supported by an enabling environment facilitating, for example, private sector investments (green finance) resulting in more public–private partnerships.

Figure 1 shows that neither Scenario 1 nor 2, could generate enough organic fertilizer to supply only the rice sector with sufficient nitrogen, not to mention other nutrients. The Government will, in both scenarios, remain obliged to spend foreign currency on importing fertilizer to maintain crop yields.

If the important plantation sector (tea, coconut, and rubber) is added to the rice sector, the dimension of the nutrient gap becomes even more visible, showing the harsh limitations of the suggested nutrient replacement strategy (Fig. 2).

In summary, even with significant investments, there is not enough raw material (biomass) in the country to produce enough organic fertilizer that could contain the amounts of nutrients needed to satisfy crop demand.

3.3 Would the government have saved foreign reserves through the ban?

Realizing that despite efforts by the private sector, the army, etc. not enough organic fertilizer entered the market, the

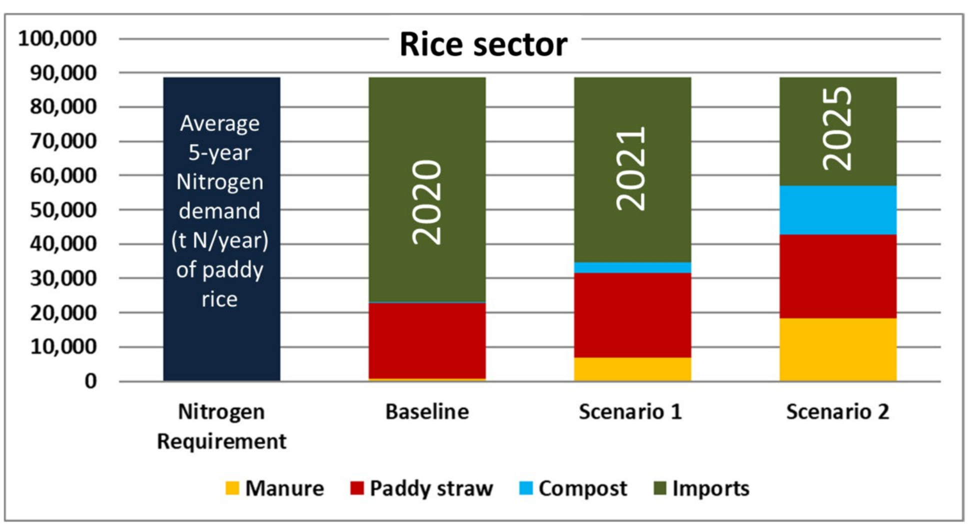

Fig. 1 Nitrogen demand (t N/year) coverage of paddy rice under different scenarios (Source: Authors)

Government initiated large-scale imports of two types of fertilizers, which are Nano-N liquid fertilizer from India and a Seaweed-based fertilizer from China. Urea imports in the past covered the baseline N requirement of rice (65,500 tons/year) at an average cost of about US$114 million per year (± 10%). Table 4 illustrates that under scenarios 1 and 2, importing the prioritized alternative fertilizers would entail a substantially higher cost for the government compared to using urea; not only to fill this nutrient gap, but more than the annual expenditure of US$114 million on urea to cover the rice nitrogen demand. Transitioning to organic fertilizers would thus result in higher costs for the government, even under the most favorable organic fertilizer scenario. The costs would surpass the expenses associated with chemical fertilizer imports before the ban, even if the government managed to secure an exporter offering the organic replacement at half the price discussed in 2021.

Based on data by Ji et al. (2017), a small leverage would be that the same organic fertilizer also provides about 15% of the required import cost for phosphorus and potassium.

It should be noted that the reduced use of chemical fertilizers, and the reduction of food waste ending in landfills will improve the carbon balance of the overall system and could qualify for green finance (MoE, 2022). Based on a first assessment, the related green revenue stream would, however, only cover a small percentage of the fertilizer import expenditures (Thilini Bandara, unpublished).

In summary, the cost analysis showed that the required import of organic fertilizers (matching the urea-N demand of rice) would cost the Government (due to the required volumes) significantly more than buying urea. Going organic would cost even in the best national supply scenario more than the chemical fertilizer import before the ban.

3.4 How did farmers perceive the chemical fertilizer alternatives?

The governmental promotion of a complete transition to organic farming, highlighting aspects such as environmental sustainability, human health and frugality, was hailed by

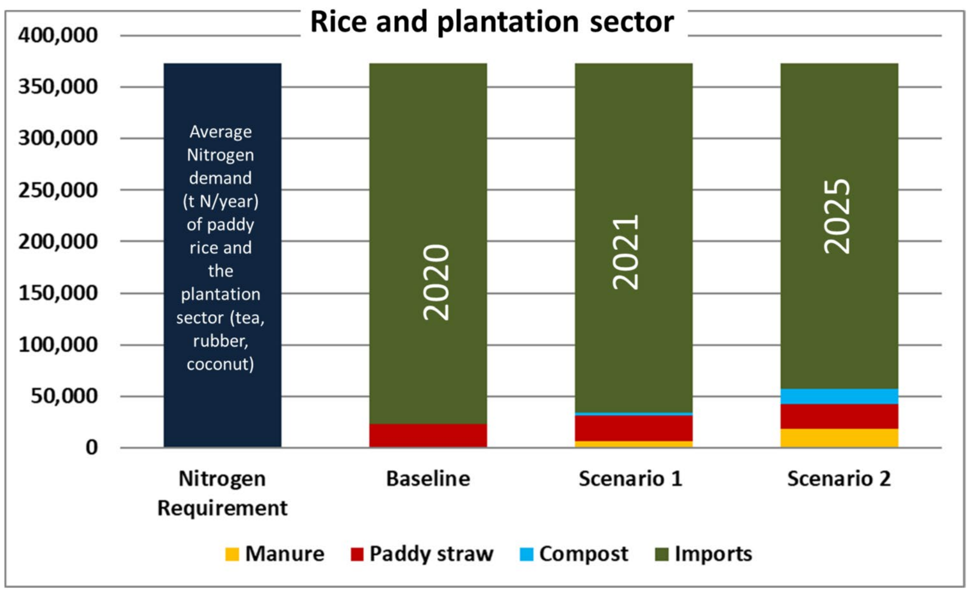

Fig. 2 Nitrogen demand (t N/year) coverage of paddy rice and the plantation sector under different scenarios (Source: Authors)

Table 4 Cost comparison of the imported urea vs import fertilizer types for the rice sector

Fertilizer type	*Cost for 1 ton of fertilizer (US$)*	*Cost for 1 ton of N (US$)*	*Cost to cover the N gap in scenario 1 (US$ Million)*	*Cost to cover the N gap in scenario 2 (US$ Million)*
Urea (Trading economics, 2022b)	803	1,745	95	55
Seaweed fertilizer (Chinese) (Ethirajan, 2021; Trading economics, 2022a)	502	5,020	272	159
Nano-N (Indian) (Chamara, 2021; Dias, 2021; Lilani, 2021)	2,500	63,131	3,402	2,020

only 3% of farmers surveyed by Bandara et al. (2023). On the contrary, the majority favored either a mixed approach of using both organic and chemical methods, while 46% opposed organic farming altogether.

Dominish et al. (2021) studied farmer responses in 2019, i.e. before the ban. The authors reported that farmers who do not use compost lacked related technical know-how, did not trust the product, or complained about its price. The low yield from compost if used alone (not in combination with chemical fertilizers or animal manure) was mentioned by compost users and non-users. Price concerns were based on farmers being used to receiving subsidized low-priced or free chemical fertilizers over decades. Bandara et al. (2023) reported that 66% of farmers mentioned time constraints to source sufficient raw materials for organic fertilizer production, and 95% of all farmers starting compost production did not manage to produce the suggested minimum application rate of 5t/ha. Still, the percentage of rice farmers using organic fertilizers increased significantly from 13% prior to the ban to 89% during the ban, given the lack of chemical alternatives. Compost was only used by 3–4% of farmers before the ban and increased to 34% (76%) during the ban while the percentage of farmers using manure (5–16%) or commercial granular or liquid fertilizers remained low (<5%) (Bandara et al., 2023).

Quality concerns related to commercial compost increased in 2021, based on the limited nutrient (nitrogen) content (Box 1), its slow release, as well as unwanted substances such as plastic, potential chemical contaminants, germs, and other impurities. This concerned municipal compost as well as private sector compost. Following the fertilizer ban and the subsequent rise of private suppliers, inferior quality compost, such as mud from water reservoirs, became more prevalent in the market undermining the compost image (MoA, 2022).

Box 1: Management implications of shifting to organic fertilizers

As Bandara et al. (2023) and Dharmakeerthi (2021) showed, key challenges related to compost are the sourcing of raw materials and related time efforts, as well as the low nutrient content vis-à-vis chemical fertilizers resulting in significant compost volumes to be organized, transported and stored. A 100-kg bag of urea (46 kg of N), for example, would require about 1 ton of poultry manure or ca. 2.4 t of quality compost (2% N) for the same nitrogen supply, ignoring fertilizer use efficiency. While the two organic inputs will be cheaper on the local market and have other advantages for soil fertility, their lower bulk density has significant implications. The 2.4 tons of compost would require about 50 times the space of two 50 kg bags of urea, increasing labor cost for field application. A more common lower-quality compost with only 1% N would even require twice the capacity, implying for the farmer a range of transaction costs.

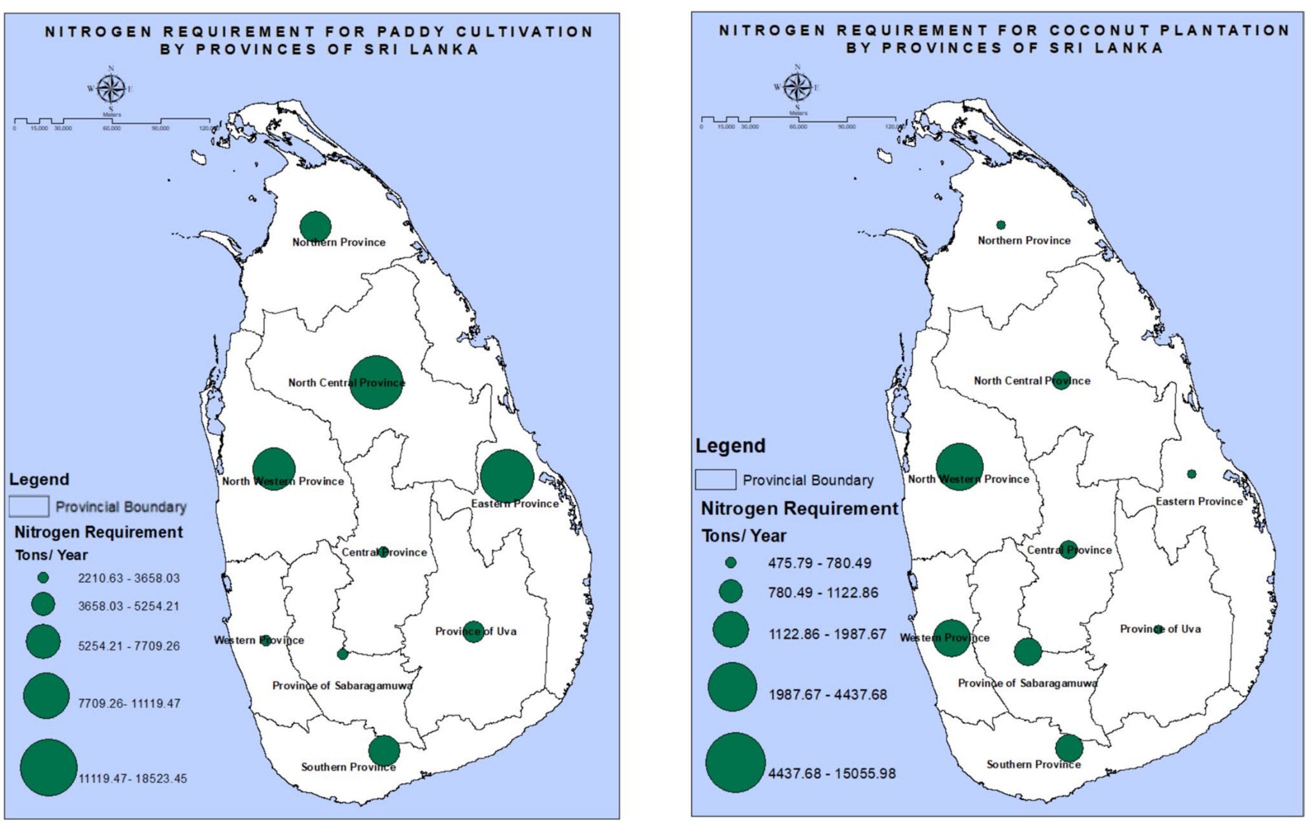

Fig. 3 N demand for paddy (left) and the coconut plantation sector (right) (Graphic: Authors based on DOA data from 2020/2021)

Given the logistical implications for adopting organic fertilizers (Box 1), their nutrient content is of paramount importance. Farmers recognized that a waste compost enriched with human manure (fecal sludge) would have a higher nutrient content, which could cut the required compost volume by half, but asked for certificates once it entered the market that it did not contain harmful components. This hesitation was also reflected in interviews done by Dominish et al. (2021) who found that before the ban only about half of the farmers were willing to use co-compost that contains fecal sludge (septage), with coconut farmers (86%) showing most interest.

In summary, farmers who are used to subsidized industrial fertilizer struggled with the philosophy of the sudden ban. Although the ban stimulated farmers to invest in compost production, they hardly managed the recommended minimum quantity. The private sector boom in compost production resulted in competition for limited raw materials, and low-quality products on the market, which did not help the transition.

3.5 Which agricultural sector has the highest potential to go organic from a spatial perspective?

As organic fertilizers, like compost, require significantly higher transport volumes (see above) than chemical fertilizers, transport becomes more expensive and distances matter for matching nutrient demand and supply. This applies across all scales. In this section, the focus is on the national scale and the four top commodities, area-wise (rice, tea, coconut and rubber).

The largest spatial mismatch between nutrient demand and supply for paddy rice relates to organic (food) waste produced by Sri Lanka's population. The Western province, with the highest population, generates most organic municipal waste in the country but has the lowest paddy area and related nutrient demand (Fig. 3). On the other hand, the main coconut farms (Fig. 3) overlap much better with the key consumption areas, distribution of compost stations and opportunities for municipal waste co-composting with fecal sludge as included in scenario 2 (Fig. 4). As reported by Dominish

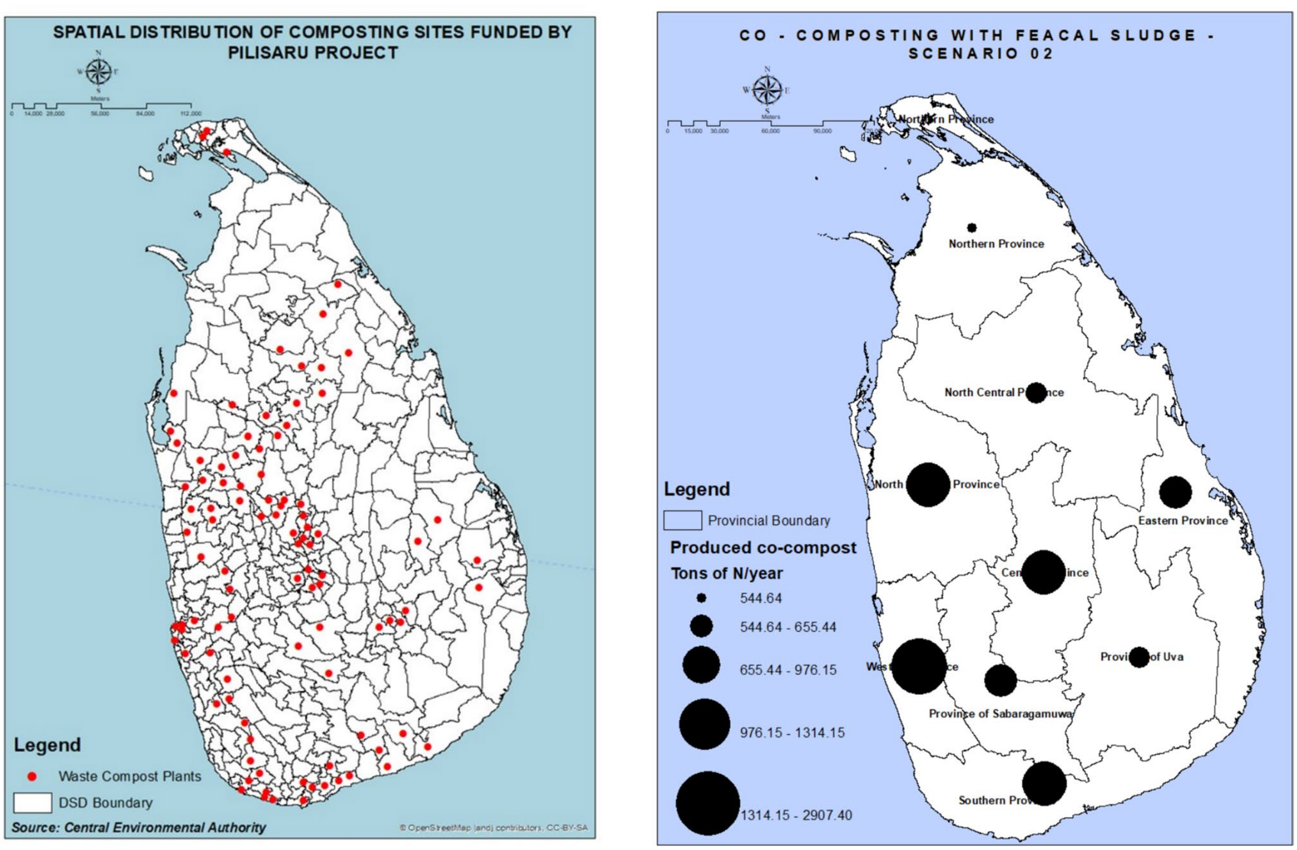

Fig. 4 Geographical distribution of Pilisaru compost stations (left) and opportunities for fecal sludge co-composting (right) (Sources: Authors based on CEA (2016) data (left) and DOA data from 2020/2021 (right))

et al. (2021) a significant share of coconut farmers expressed interest in fecal sludge co-compost. Moreover, the long-term benefits of compost would fit well a plantation crop.

When comparing the theoretically available amounts of nitrogen under scenario 2 with the demands of various plantation crops, the coconut sector showed the highest probability to transition 100% to organic fertilizer from national sources.

In summary, the distance between predominantly agricultural areas and those areas which can supply raw materials for organic fertilizer production can be far apart, like between rural farms and urban consumption centers. Larger distances require more logistical and financial investments, and might turn the nutrient replacement idea financially unviable. GIS can help mapping likely win–win scenarios for waste management and agriculture, as shown for the coconut sector.

4 Conclusions

Many countries, including Sri Lanka, struggle with agrochemical overuse, often fueled by Governmental subsidies, with potential harm to soil, water bodies, and human health (Mateo-Sagasta et al., 2018). In Sri Lanka, the challenge has been associated with the occurrence of chronic kidney disease of unknown etiology (CKDu) in particular areas of the country resulting in a plethora of studies looking for its roots, in particular among environmental factors. The implications of agrochemical use for human health and the rising costs of the health sector, especially related to CKDu were cited as key reasons for the 2021 government ban on agrochemicals. However, there is so far hardly any scientific evidence linking (specific) agrochemicals to CKDu. While elevated levels of nitrates, heavy metals, and pesticides have been found in some areas, studies with control groups have not shown a cause-and-effect relationship with CKDu. While more studies especially on pesticides are needed, the documented environmental challenges (like nitrates in groundwater) require from a policy side more emphasis on Good Agricultural Practices (GAP) and a revised subsidy strategy to minimize the overuse of fertilizers, but do not justify in any way a general ban of all types of agrochemicals across all soils and crops.

The ambitious plan of transitioning to “organic farming” as the Government called it, was supported by the prospect of saving foreign currency reserves on fertilizer imports. While the ban received instantaneous support from most media, the agricultural sector was caught off guard. Not only that the presidential advisors at that time allegedly missed expertise in organic farming (De Costa, 2021; Gupta, 2022), there was also no data or plans on how to support the required infrastructure, capacities, and processes, from organic fertilizer sourcing to its appropriate application.

After the ban was affected, and data released by the Department of Census and Statistics showed a 36% decrease in paddy yield during the 2021/2022 Maha season, fears of a national food crisis emerged, compounded by the general economic emergency with food inflation rates of up to 90%, and food-insecure households reaching ‘millions’ (Gupta, 2022; WFP, 2022). Although the average monthly cost of a nutritious diet soared 156 percent between 2018 and 2022, direct implications of the agrochemical ban on food security were difficult to isolate from the Covid-19 impact, the war in Ukraine, and generally declining economic situation in the country at that time (WFP, 2022; Gupta, 2022).

The impact on the rice harvest was in many areas even stronger. A survey by Bandara et al. (2023) revealed an average paddy yield loss of 53%, with 62% of the farmers experiencing more than 50% yield loss blaming the lack of sufficient chemical fertilizers (54% of the farmers) or its unavailability at the right time (40%). Ghose et al. (2024) calculated across regions a historically unusual 32% post-ban decline in rice yields compared with the previous 9 years, which is particularly noteworthy since the cultivated rice area remained unchanged. The authors state that the decline cannot be explained by variation in environmental variables and is directly correlated with the reduction in fertilizer availability ensuing from the import ban.

The fertilizer ban's consequences extended beyond rice, impacting crops like tea (with an 18% drop) through both the ban itself and the subsequent subsidy removal. The drop in tea production alone is estimated to result in economic losses of US$425 million (Economynext, 2023; Nordhaus & Shah, 2022; TeaBiz, 2022).

Attempts to fill the nutrient gap through imports, like the legally disputed Chinese compost, only contributed to the insecurity farmers faced, and resulted in farmers shifting to other income opportunities (Perera & Amarasinghe, 2022). Due to the yield gap, the Government had to supplement national production by importing 800,000 tons of rice and animal feed, for more than those US$400 million usually spent on fertilizer imports (Nordhaus & Shah, 2022; MoA, 2023b).

With the media praising the ban, only a few scientists dared publicly to question the decision (e.g. De Costa, 2021; Dharmakeerthi, 2021). Crucial questions around organic fertilizer availability, replacement feasibility, logistics, and farmer training remained unanswered. There was also no analysis of any lessons from Bhutan which started a similar transition in 2002 and encountered similar challenges, such as the shortage of organic inputs aside missing human and institutional capacities, albeit more than 80% of the Bhutanese farms are traditionally organic, without using synthetic agrochemicals (Feuerbacher et al., 2018; Tashi, 2022). The findings of the here presented study– that Sri Lanka's current and potential organic fertilizer production cannot meet the needs of the major rice and plantation sectors, requiring significant organic fertilizer imports at high costs – should be crucial for any future consideration of such a transition, even at a slower pace.

The DOA recommends today an integrated approach: 70% chemical fertilizer and 30% organic fertilizer (MoA, 2022), which was confirmed as best option for a high nitrogen use efficiency in long-term trials in China (Zhu et al., 2023) and is supported by the Rice Research and Development Institute (RRDI) of Sri Lanka (Perera & Amarasinghe, 2022). This strategy is expected to become national policy (Adaderana, 2023). In support, the Ministry of Agriculture made subsidies (e.g., vouchers) available also for organic fertilizers, promoting choice and encouraging smart farming without forcing anyone to obtain one or another (Adaderana, 2022; MoA, 2022). To support the adoption of organic fertilizers, the existing compost quality standards must be enforced. That a significant number of sub-standard products entered the market severely undermined farmers' acceptance of compost, with potentially negative consequences for the organic movement in Sri Lanka in the long run. Gupta (2022) stated that the 'organic' brand has gained notoriety, bringing negative thoughts in the minds of ordinary citizens who are not even involved in organic farming. Based on this and in view of the discussions around each of the imported 'organic fertilizers', the Ministry of Agriculture urged related authorities to create quality standards also for any types of organic fertilizers (Adaderana, 2022).

To implement the new strategy, also organic fertilizer application guidelines and related capacity development are required as most farmers are only used to chemical fertilizers. These guidelines could incorporate the experience of Sri Lanka's organic paddy farmers but do likely require additional research targeting modern rice varieties.

More research is also suggested to further explore opportunities for BNF in the root zone of rice (Perera et al., 2021b), while crop rotations with a nitrogen-fixing legume intercrop might have a smaller potential based on their labor and land demands (Crews & Peoples, 2004).

With the approval of the IMF loan, government institutions and international donor agencies are now shifting away from emergency humanitarian assistance to more sustainable long-term solutions, also for paddy rice production. The strategy aims at increasing the productivity and resilience of the rice-based ecosystems in the dry and intermediate zones by using less water and chemical inputs along with cost-effective production methods (Kankanamge, 2023).

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Declarations

Conflict of interest The authors declared that they have no conflict of interest.

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