Cleaner Environmental Systems 14 (2024) 100220

Contents lists available at ScienceDirect

Cleaner Environmental Systems

journal homepage: www.journals.elsevier.com/cleaner-environmental-systems

Phosphorus recovery potential revealed by substance flow analysis of the Indian food, agricultural and sanitation system

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ARTICLE INFO

Keywords:
Fertilizer
Circular economy
Human waste
Nutrient recovery and recycling
Sustainable phosphorus management

ABSTRACT

Phosphorus is a finite resource that is in high demand due to its essential role as a fertiliser. We undertook a substance flow analysis of phosphorus for India's agri-food system to identify where the biggest losses of phosphorus occur and which flows could be targeted to move phosphorus from a linear use and waste approach to a circular approach encompassing recovery and re-use. A novel aspect of the analysis was the inclusion of sanitation systems in India. National phosphorus flows were calculated annually for the five years 2015–2019, and the mean was then used to provide a representative annual flow. The analysis showed that India is dependent on imports for 95% of applied mineral phosphorus fertiliser and has a low phosphorus-use efficiency of 32%. The largest recoverable flow is human excreta (urine and faeces), equivalent to 21% of the current phosphorus applied in mineral fertiliser in India. Phosphorus recovery from septic tanks, the most prevalent sanitation system in India, could alone replace 8% of phosphorus applied in mineral fertiliser in India. Alongside the ongoing development of sanitation systems in India this provides an opportunity to ensure that nutrient recovery is included in sanitation developments.

1. Introduction

Phosphate rock is a non-renewable resource and the primary source of phosphorus (P), a macronutrient essential to plant life, for which demand is growing as global food production and fertiliser use increase, and soils become increasingly nutrient depleted (Sarvajayakesavalu et al., 2018; Scholz et al., 2013). Globally, fertiliser manufacture is the greatest demand on dwindling phosphate rock resources, accounting for 88% of mined P (ESPP, 2022). Although a finite resource, P is often transferred from agricultural soils into aquatic systems resulting in their degradation through nutrient loading (Hashemi et al., 2016). The effects of nutrient loading have been observed globally, with eutrophication of marine and freshwater systems (Seitzinger et al., 2010; van Beusekom, 2018) causing a loss of biodiversity, and increasing the numbers of harmful algal blooms and hypoxic sites or 'dead zones' (Diaz and Rosenberg, 2008; Gilbert and Burford, 2017). Anthropogenic activities, such as fertiliser application, poor animal manure management, generation of industrial wastewater, and untreated sewage, are the primary causes of eutrophication and surface water pollution (Malone and Newton, 2020; Schindler, 2012).

After China, India is the highest consumer of P globally (IFA, 2023). With a growing population and increasing P footprint per capita as a result of dietary shifts towards more meat consumption (Gandhi and Zhou, 2014; Metson et al., 2012), India's demand for P will continue to rise. According to the Indian Government, India is currently reliant on imports for 90% of its raw phosphate and finished fertiliser requirements (Department of Fertilizers, 2021), and has been categorised as 'highly vulnerable' in terms of P scarcity (Nanda et al., 2019), posing a risk to food security (Rao et al., 2015). The critical reliance of India on P imports is reflected in increases in the Indian Government subsidy rate (Rs per kg P) from 14.89 to 45.32 in October 2021 and to 72.74 in April 2022, to ensure affordability for farmers (Ministry of Chemicals and Fertilizers, Government of India, 2022) as global P prices have increased (Brownlie et al., 2023). This has a significant financial impact for the Indian Government, with fertiliser subsidies in 2022–23 accounting for 5% of 'Expenditure on Major Items' at a cost of Rs 225220 crores (27.3 billion USD), double the spend on education and on health combined (Government of India, 2023). The Indian Government announced a new

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https://doi.org/10.1016/j.cesys.2024.100220
Received 30 May 2024; Received in revised form 5 August 2024; Accepted 22 August 2024
Available online 26 August 2024

scheme in their 2023–24 Budget speech, the 'PM Programme for Restoration, Awareness, Nourishment and Amelioration of Mother Earth' (PM-PRANAM), with the aim of incentivising states and union territories to adopt alternatives to mineral fertiliser and therefore decrease the subsidy spend. States and union territories will be granted 50% of the saving to develop alternative fertiliser systems and reward and encourage farmers and groups to reduce fertiliser use (Ministry of Agriculture and Farmers Welfare, 2023). Currently, 98% of the P flowing into the agricultural system in India is in the form of mineral P, the highest reported of any country, and in stark contrast to the Netherlands which has the lowest dependence at 9% (Chowdhury and Zhang, 2021). Although mineral fertiliser application rates have been increasing in India, the P fertility of most soil in India is extremely low (Das et al., 2022). Sanyal et al. (2015) reviewed data on P soil analysis undertaken in India and found that over 90% of districts represented had low to medium P fertility. The continuing high use of mineral fertilisers, alongside P in industrial effluents and detergents (Ramachandra et al., 2017) and livestock and human excreta, is causing nutrient loading of aquatic systems in India (Prasad and Prasad, 2019), and contributing to the exponential growth of the number of coastal algal blooms (D'Silva et al., 2012).

India has previously been identified as a hot-spot globally for potential P recovery from human excreta due to having high population density areas in close proximity to cultivated areas (Powers et al., 2019). However, more studies are required to improve knowledge regarding which strategies should be targeted in an attempt to move P use towards a sustainable system (Nanda et al., 2020), including an understanding of how P flows through the Indian agricultural, food and sanitation systems. Substance flow analysis (SFA) provides a method for evaluating how a specified substance flows within a set system boundary and within a pre-determined time-scale, usually annual. It encompasses inflows, outflows and stocks. SFAs have been shown to be an effective tool for the investigation of such P flows (Brunner, 2010). Thus far, the majority of SFAs for P (P-SFA) have been undertaken in high income countries, partly as a result of a lack of accurate data for low- and middle-income countries (Roy et al., 2019). In the case of India, one P balance study (Pathak et al., 2009) and one P-SFA (Keil et al., 2018) have been conducted. Pathak et al. (2009) estimated that 78% of agricultural P input was in the form of mineral fertiliser, with annual total P inputs exceeding P removal by crops by 1.0 million tonnes. This was supported by Keil et al. (2018), who also reported P accumulation in soils, and in addition estimated that recovered P from wastewater and household waste could replace 21% of applied mineral P fertiliser in India. However, their estimate was based on limited specification of outflows of P-containing wastes (Rahman et al., 2019) since they did not disentangle household waste and wastewater flows and incorporated solid waste, grey water and black water into one flow.

We used a P-SFA at the national scale for India, focussed on the P flows in the agricultural, food and sanitation system to advance knowledge of where P is lost and identify opportunities for it to be recovered and re-used. A novel element of our study was the characterisation of separate sanitation flows allowing for an improved understanding of where to target recovery efforts. This P-SFA therefore has relevance to the broader national and international issues already mentioned such as: dwindling global P supplies; the environmental impact of P in waste streams; the reliance of India on costly imported P and its associated effect on Indian Government expenditure and food security; and ongoing sanitation development in India. The primary aims of the analysis for India were to: 1) determine the scale of P associated with human excreta at a national level, and how that compares to agricultural requirements; 2) identify which flows should be targeted for P recovery or for initial prevention of P loss; 3) understand the potential P recovery from different types of sanitation. This P-SFA will also provide a template for conducting analyses to address similar questions relating to P recovery to support food security for countries in the global south with limited data availability.

2. Materials and methods

2.1. Substance flow analysis design

The P-SFA in this study followed how P flows in the agri-food and sanitation systems of India on an annual basis using an average calculated across five years, 2015–2019 inclusive, with the geographical border of India used as the system boundary. Substance flow analysis takes account of both how a substance flows within a system, as represented by proportional arrows, and where the stocks are within a system, shown as a value inside boxes. The 'stock' values were calculated as the difference between the in- and out-flows and, as such, represent the annual change or accumulation in 'stock' rather than the total value of that stock. When there is no difference between the in- and out-flows the box is shown as having no value, as is the case with 'Crop Residue' and 'Livestock and Fishery'. All values are expressed as P, with any input data in P_2O_5 converted to P using the conversion factor of 0.4364. STAN (subSTance flow ANalysis), a free software developed by the Technical University of Vienna to support material flow analysis (Mnthambala et al., 2021), was used for the visualisation of the P-SFA undertaken. In total we examined 31 flows: 27 internal and 4 import/export flows that cross the system boundary. We included flows that we considered to be part of the P food and agriculture system and for which data existed. Flows that could be assumed to be comparatively small, and for which no reliable data could be found, were omitted, such as tourist food consumption (detail in 2.3), P in abattoir waste and other unused meat industry animal by-products, and P in food and flower temple offerings. In order to avoid potential temporal uncertainty or data skewing resulting from outlying years, we calculated the flows for each year (where data were available) and used the mean of the annual flows for the final analysis. Where flows were calculated using the P values from other flows, the mean of the annual flows was used rather than calculating separate values for each year. Data sources and further information on all SFA calculations can be found in Supplementary Material S1, Table S1 and Sheets 1–10.

2.2. Phosphorus flows in mineral fertiliser, rock phosphate, elemental phosphorus and phosphoric acid

Phosphorus in rock phosphate mined in India (F1 Mined Rock Phosphate) was calculated from production data (Indian Bureau of Mines, 2020) in kg of mined rock classified into various phosphate grades, relating to the P_2O_5 content. The median P_2O_5 content of each phosphate grade range was used for calculating total P content (see Supplementary Material S1, Table S1 - Overview SFA calcs and Sheet 1 for the calculation details). Phosphorus in flows 'F2 Imported P' and 'F3 Exported P' comprised P in mineral fertilisers (FAI, 2022a; FAO, 2022a; FAO, 2022b), rock phosphate (Indian Bureau of Mines, 2020), and elemental P and phosphoric acid (UN Comtrade, 2023). Phosphate rock imports were converted into P amounts using annual mean P concentrations as reported by USGS (2019) for Morocco and Jordan, the primary countries from which India imports phosphate rock (see Supplementary Material S1, Table S1 - Overview SFA calcs and Sheet 2 for the calculation details). Flow 'F4 Fertiliser Applied', refers to the amount of fertiliser used in the agricultural sector annually, comprising P in all forms of mineral fertiliser and directly applied rock phosphate (FAI, 2022b; FAO 2022a).

2.3. Phosphorus flows in commodities

We calculated flows F5 to F12 by multiplying the P concentration of individual commodities by the magnitude of the commodity in each flow. Phosphorus concentrations from Kiel et al. (2018) were used alongside FAOSTAT Food Balances sheets, issued annually, for the amount of commodities in each flow (FAO, 2022c; Keil et al., 2018), (see Supplementary Material S1, Table S1 - Overview SFA calcs and Sheet 3 for the calculation details). The FAOSTAT Food Balances sheet is a replacement for the FAOSTAT Commodity Balances sheets that were discontinued after 2013, however not all commodities required for our P-SFA are included in the replacement Food Balances sheet. The 2019 value for those missing commodities in each flow was estimated using a scaling approach to values of similar products present in both the FAOSTAT Commodity Balances sheet 2013 and the FAOSTAT Food Balances sheet 2019, and assuming that the missing commodity followed the same trajectory from 2013 to 2019. Further information on these commodities and how their values were calculated can be found in Supplementary Material S1, Table S1 - Overview SFA calcs, Sheet 4 and Sheet 5.

2.4. Phosphorus flows in waste, household food waste and crop residues

Flow 'F13 Distribution Wastes' was calculated by combining data for waste occurring between the market and household stage (FAO, 2022c; FAO, 2022d) and waste between the farm and market stage (World Bank, 1999). The World Bank Report also provides data for waste occurring between the market and household stages which correspond to the more recent FAO data, indicating that the values have likely changed little since 1999 (see Supplementary Material S1, Table S1 - Overview SFA calcs and Sheet 6 for the calculation details). Loss of P associated with food waste at the household level in India is reported as 46 mg P capita^{-1} day^{-1} (Chen et al., 2020). As there was only one value for household food waste, we scaled this up for the whole population using 2018 population data (UN DESA, 2019), to give 23 kt P year^{-1} for the flow 'F18 Household Food Waste'.

According to the Indian Government 'National Policy for Management of Crop Residues' (NPMCR) India produces around 500 Mt of crop residue annually (Government of India, 2014). We calculated the total P in crop products as a percentage of total crop product weight and used that value to calculate the P in crop residue. Of the total crop residue, 18.5% is burned, 9.57% is left on the soil, and 71.93% is utilised (Bhuvaneshwari et al., 2019; Government of India, 2014), and of the total P present in the burned residue Mandal et al. (2004) states that 25% is lost. Further details of these calculations can be found in Supplementary Material S1, Table S1 - Overview SFA calcs and Sheet 7. The various uses of crop residues include: livestock bedding material and feed, mulching, bio-gas and biomass energy generation, bio-manure/compost, thatching material, and fuel for domestic and industrial use (Government of India, 2014). Although some crop residue may therefore return to the soil in the form of compost or end up lost to the environment, we allocated the entire flow to its own end point shown by the box 'Various Uses', as there are insufficient data available to allocate values to the possible uses.

2.5. Phosphorus flows in manure and grazing

Since FAOSTAT data do not include P flows in manure, these were calculated from FAOSTAT data on the total amount of nitrogen (N) excreted in manure and the amount of manure applied to soils (FAO, 2022e). A conversion factor of 0.4, based on a ratio of N:P_2O_5 in farmyard manure (Tarafdar, 2016), was used to convert the N value in manure to P_2O_5, allowing estimation of flows 'F19 Applied Manure' and 'F20 Manure Losses'. The P in flow 'F22 Other Fodder' was calculated as the difference between the in- and out-flows of the 'Livestock and Fishery' box. This flow includes grazing on cultivated and uncultivated land and feeding by-products such as grasses, weeds and tree leaves, the predominant feed matter used for livestock in India (Dikshit and Birthal, 2010). (See Supplementary Material S1, Table S1 - Overview SFA calcs for the calculation details).

2.6. Phosphorus flows in soil erosion and runoff

Nutrient losses from soil occur via three main routes: attached to eroded soil, dissolved in surface runoff, and dissolved in leachate percolating through the soil profile. Annual P flow in soil erosion in India was calculated by multiplying the P concentration in topsoil (1143 mg kg^{-1}) (Sanyal et al., 2015), the mean erosion rate (16.35 t ha^{-1} year^{-1}) (Narayana and Babu, 1983) and the total area of agricultural land (179045 $\times$ 10^3 ha) (FAO, 2022f). Of the P lost in eroded soil, 39% was allocated to the flow 'F23 Soil Erosion' with the other 61% assumed to remain in the soil due to intersite transfer (Narayana and Babu, 1983) and as such has been left in the 'Agricultural Soils' stock box. We calculated P in surface runoff (flow 'F24 Runoff') as 2.6% of applied mineral P fertiliser, as this was the mean of reported % loss rates collated by Hart et al. (2004). Further information on the calculations used for soil erosion and runoff can be found in Supplementary Material S1, Table S1 - Overview SFA calcs and Sheet 8. Although experimental studies have indicated that some P may be lost in leachate from fertilised Indian soils (Rashmi et al., 2020) we did not include this flow as P lost in leachate is negligible compared to P lost in surface runoff (Turner and Haygarth, 2000).

2.7. Phosphorus flows in human excreta

Phosphorus in human excreta (urine and faeces) was calculated using the amount of protein intake per capita in India as reported by FAOSTAT (FAO, 2022c), and the method described by Mihelcic et al. (2011), and then scaled up for the entire population using 2018 population data (UN DESA, 2019). Flows relating to P in human urine and faeces through various sanitation systems were calculated using the most recent data available (2018) at that time rather than using a mean from a range of years, as these flows are not affected by yearly fluctuations. Where calculations required the use of human population data, population data from the UN for 2018 was used (UN DESA, 2019) to align with the time period used for other data. Aggregated survey data provided by the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) were used to calculate how much P flows through each type of sanitation system (JMP, 2023). Further information on these calculations can be found in Supplementary Material S1, Table S1 - Overview SFA calcs, Sheet 9 and Sheet 10. We made the assumption that, with the exception of 'F24 Composting Toilets', P flowing through all other sanitation types would end up lost to the environment, shown as flow 'F25 Human Excreta'.

2.8. Phosphorus efficiency calculations

Phosphorus efficiency of the agri-food system in India was calculated by expressing P 'out' (sum of: 'F6 Exported Produce', 'F7 Other Uses', 'F10 Animal Feed', 'F12 Food Products') as a percentage of P 'in' (sum of: 'F4 Fertiliser Applied', 'F19 Applied Manure'). Phosphorus 'out' was restricted to end products and P 'in' to P applied to the soil.

2.9. Uncertainty analysis

To account for data uncertainties and error in the SFA, we used a method, first developed by Hedbrant and Sörme (2001) and adapted by Antikainen et al. (2005), that determines data uncertainty according to the sources used. Data are categorised into levels 1 to 8 according to the reliability of the source. We used the data categories as defined by Antikainen et al. (2005). Level 1 are data from official statistical offices that have the lowest degree of uncertainty, whilst level 8 data encompass factors from literature that have the highest degree of uncertainty. Each of those levels has a corresponding uncertainty interval ranging from $\times \div 1$ to $\times \div 4$ (details can be found in Table S2.1 in Supplementary Material S2), and those uncertainty intervals are used in the uncertainty calculations. For flows calculated by the multiplication or addition of data sets, the uncertainty interval was calculated using the following equations described in Antikainen et al. (2005) and set out by Mnthambala et al. (2021). For flows calculated by multiplying data sets:

$$\textit{Flow uncertainty factor} = 1 + \sqrt{(f_a - 1)^2 + (f_b - 1)^2} \quad \text{(Eq. 1)}$$

where f_a, f_b are the uncertainty intervals for factors a and b, respectively.

For flows calculated by adding data sets and for stocks:

$$\textit{Flow uncertainty factor} = 1 + \sqrt{\frac{[m_a\cdot(f_a - 1)]^2 + [m_b\cdot(f_b - 1)]^2 + [m_c\cdot(f_c - 1)]^2 + [m_d\cdot(f_d - 1)]^2}{m_a + m_b + m_c + m_d}} \quad \text{(Eq. 2)}$$

where m_a, m_b, m_c, m_d are the phosphorus masses for factors/stocks a–d, respectively, and f_a, f_b, f_c, f_d are the uncertainty intervals for factors/stocks a–d, respectively, used in flow/stock calculations.

The multiplication of uncertainty factors results in an increase in the relative uncertainty and the addition of uncertainty factors results in a decrease in relative uncertainty (Antikainen et al., 2005). Final uncertainty factors assigned to flows and stocks are shown in Tables S2.2 and S2.3 in Supplementary Material S2, and example calculations are in Supplementary Material S2 section S2. The uncertainty factors calculated are expressed as being × ÷, as the uncertainty relates to the maximum and minimum value of the flow once uncertainty has been considered. For ease of understanding these are converted into % values using the method outlined by Cooper and Carliell-Marquet (2013), wherein an uncertainty factor of × ÷ 1.33 becomes ± 33%. This simplifies the process of entering uncertainties into the STAN software and allows for an easier comparison of uncertainties (Mnthambala et al., 2021).

3. Results and discussion

3.1. Overview of phosphorus substance flow analysis of Indian agri-food and sanitation systems

To understand how P flows in the agri-food and sanitation systems of India and the opportunities for a circular P economy, a multiyear (mean 2015–2019) P-SFA was developed (Fig. 1). Mean annual data across the 5-year study time period were used to avoid skewed data that might result from years with outlying figures for certain flows, particularly P import flows that are strongly influenced by fluctuating phosphate rock prices affected by global events (Brownlie et al., 2023). The P-SFA quantifies P flows and provides a visual representation of how P flows within the system. The largest flows for India during the study period were 'F2 Imported P' and 'F4 Fertiliser Applied' (both ~3000 kt P year^{-1}); 'F9 Crop Products', 'F10 Food Products', 'F20 Applied Manure', 'F21 Other Fodder' and 'F22 Soil Erosion' (all ~1100–2000 kt P year^{-1}); and 'F25 Human Excreta' and 'F17 Crop Residues' (~600 kt P year^{-1}).

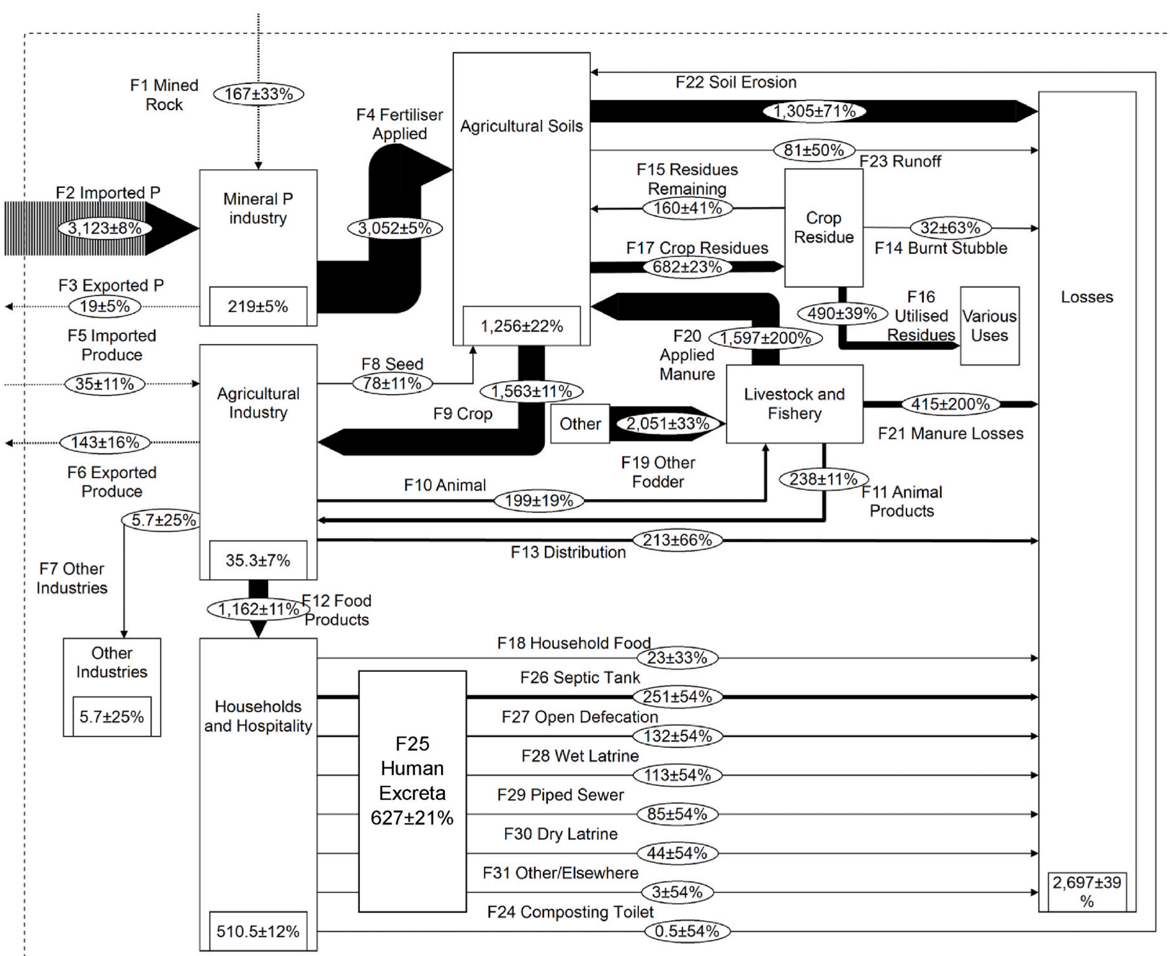

Fig. 1. Mean annual P flows and annual stocks (kt P year^{-1}) for period 2015–2019 for India (geographical boundary represented by dotted line). The thickness of the arrow corresponds to the size of the flow. Each 'stock' is calculated as the difference between the inflows and outflows of each box, and thus represents the annual change in stock. Where there is no difference, as for 'Crop Residue' and 'Livestock and Fishery', no stock is shown. The calculated uncertainty of each flow and stock is shown as ±%. Also shown is total P lost in human faeces (F25 Human Excreta), which includes all sanitation flows except composting toilets since composting will not result in a P loss.

3.2. Dependency of India on phosphorus imports

Fig. 1 shows that applied fertiliser in India is dependent on P imports, in the form of mineral fertilisers, rock phosphate, elemental P and phosphoric acid. As the single largest flow and primary source of P flowing in, accounting for at least 95% of applied fertiliser, imported P is currently a cornerstone of P in India, without which the rest of the system would collapse. This reliance on P imports for fertiliser exposes Indian food security to the impacts of global events affecting phosphate rock prices. The 800% price spike in phosphate rock in 2008 resulted in farmers in India being unable to access sufficient fertilisers, leading to protests, rioting, and unrest (Cordell and White, 2014). In response the Government of India changed its market policies, including increasing its fertiliser subsidy (Nanda et al., 2019) and doubling P-fertiliser imports, potentially exacerbating the price spike further (Khabarov and Obersteiner, 2017).

Increasing rock phosphate mining in India could alleviate the reliance on imported P to some extent. However, it has been estimated that, even at current rates of mining, India will have depleted its P reserves within 30 years (Blackwell et al., 2019). There are also reported negative impacts of phosphate rock mining in India on the environment and health of those living in proximity to mined areas (Chraiti et al., 2016; Yang et al., 2014). A more sustainable option would involve targeting P flows that end up as a 'loss', and moving those flows towards a circular economy approach to recovery and re-use.

3.3. Potential of human excreta to replace P in fertiliser

3.3.1. Magnitude of P recovery from human excreta

Whilst soil erosion was the largest loss flow of P and reducing soil erosion is an important component of more sustainable P management in agricultural systems (Alewell et al., 2020, and see section 3.4), human excreta constitute the largest loss flow of recoverable P. From the SFA estimates, P lost in human excreta could in principle replace 21% of P in mineral fertiliser applied in India (Fig. 2), assuming current levels of fertiliser use. The over application of mineral fertilisers in certain regions (Bora, 2022) and the build-up of P in some agricultural soils in India (MacDonald et al., 2011) indicate that the amount of fertiliser applied could be reduced, although it is unclear how much of the legacy soil P is plant available. A reduction in fertiliser applied would result in the recovered P from human excreta having the potential to replace a larger percentage.

This calculation also assumes 100% P recovery from human excreta. However, actual recovery rates will be dependent upon the recovery methods adopted and the fraction of the waste stream treated by each method. Present recovery rates for P in wastewater treatment plants have an average efficiency of 20% to a maximum efficiency of 50%, while recovery rates for various types of wastewater sludge vary from 25% to over 96%, with thermal methods having the highest efficiency (Witek-Krowiak et al., 2022). Full recovery of P from excreta entering piped sewers could only replace 2.9% of P in applied mineral fertiliser (Fig. 3). Wastewater treatment plants in India are concentrated in a few major cities. They have the capacity to treat 44% of urban generated wastewater, but only operate at ~60% capacity (Bassi et al., 2022), indicating that the actual figure for P recovery will be much lower. Recovering P from septic tanks alone could potentially replace 8% of the P content in applied mineral fertilisers (Fig. 3), indicating that efforts should be concentrated on recovery from this stream.

The bioavailability of the P form present in any fertiliser or soil amendment will also need to be taken into account in assessing the potential for substituting for P supplied in mineral fertiliser. The bioavailability of P in organic wastes varies according to the recovery method and the soil environment (Fuentes et al., 2008). For example, a comparison of farmyard manure, compost and sewage sludge found that long term application led to an increase of soil bioavailable P content in all cases, however the percentage of bioavailable P to total P was lowest for sewage sludge application (Scherer and Sharma, 2002).

3.3.2. Potential environmental implications of P recovery

As well as taking into account the efficiency of each recovery method, consideration should also be given to the wider environmental impacts of P recovery methods and associated sanitation systems, as well as other methods of P production. A life cycle assessment (LCA) for India comparing the impact of the production of diammonium phosphate (DAP) against recovery of P from centralised (wastewater treatment plants) and decentralised (septic tank liquor) sanitation systems revealed that DAP production had a lower total impact score, followed by recovery from a decentralised system, whereas recovery from a centralised system had the highest total impact (Goel et al., 2021). DAP production had a lower energy demand and less impact on global warming, but scored higher in terms of resource consumption, eutrophication and particulate matter formation compared to decentralised recovery. However, the LCA gave a very low weighting to the impact of rock phosphate consumption and transport, a resource-intensive process, and omitted consideration of toxic phosphogypsum, a by-product of DAP production. Furthermore, the analysis only considered one method of recovery from each waste stream. Notably, as highlighted by Lam et al. (2020) in their review of LCA studies of nutrient recovery from wastewater, most studies have been restricted to a comparison between alternative methods applied to the specific scenario covered in

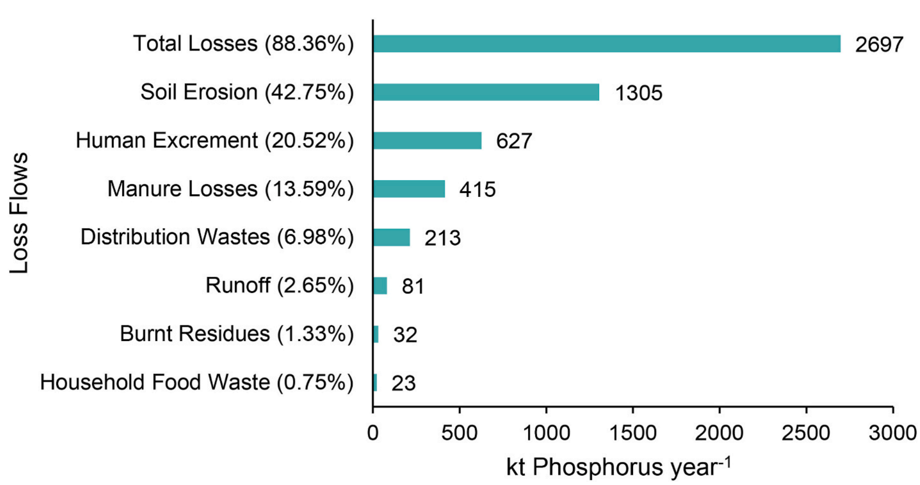

Fig. 2. Comparison of the mean P loss flows (kt P year^{-1}) for India for 2015–2019 from Fig. 1. Percentage shown by each loss flow is % of P in applied mineral fertiliser that could be replaced with P from that flow.

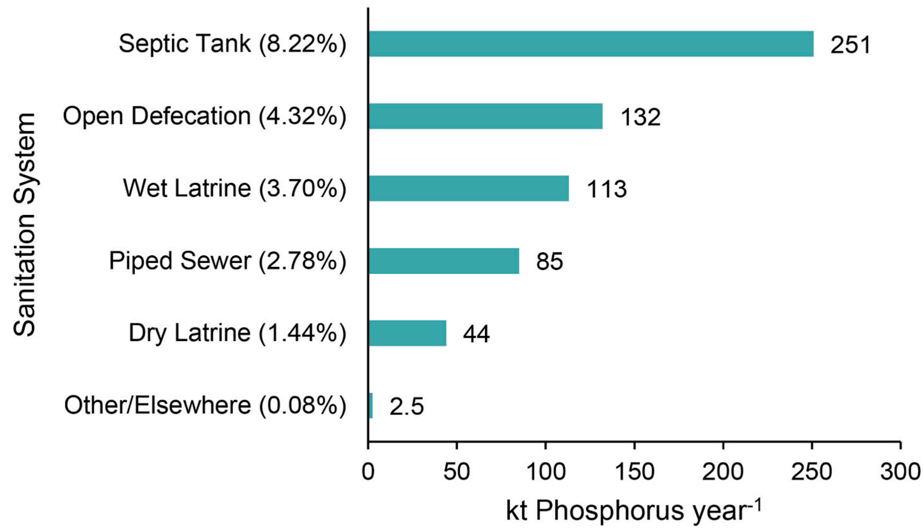

Fig. 3. Mean P loss flows (kt P year^{-1}) in India for 2015–2019 in different sanitation system types from Fig. 1. Percentage shown by each loss flow is % of P in applied mineral fertiliser that could be replaced with P from that sanitation system, assuming 100% recovery of all P in each sanitation system.

the study, rather than considering absolute impacts. Other LCAs have demonstrated that recovery of P in comparison to mined P has a net positive impact both in terms of environmental and societal costs, although further efforts are required to maximise the net positive impact of recovered P and enhance the economic viability of recovery methods (Cheng et al., 2023; Diaz-Elsayed et al., 2020; Lam et al., 2022; Tonini et al., 2019).

The India-wide SFA conducted by Goel et al. (2021) showed that P recovery from decentralised sanitation (septic tank liquor) generated approximately 40% fewer negative externalities (e.g., greenhouse gas emissions, freshwater eutrophication, consumption of non-renewable resources) than recovery from centralised sanitation (wastewater treatment plants). Reuse and recovery of wastewater from treatment plants can also introduce wider environmental and potential health problems relating to antibiotic resistance and the presence of toxic elements, partially as a result of mixing human waste and industrial waste streams. Globally, wastewater from treatment plants has been reported to be a primary source of antibiotics, antibiotic resistant bacteria, and antibiotic resistant genes spreading in the environment (Pazda et al., 2019). The presence of these contaminants, other pathogens, and toxic elements, has led to ongoing debate over the direct use of sewage sludge as a soil amendment (Harder et al., 2019). Higher concentrations of antibiotic substances have been found in India in industrial effluents than in human excreta (Mutiyar and Mittal, 2014) and use of treated wastewater in India for irrigation has also been demonstrated to cause heavy metal accumulation in crops (Ghosh et al., 2012; Singh and Agrawal, 2010). However, heavy metals originating from human excreta make up less than 10% of the total heavy metal load in sewage (Tervahauta et al., 2014). To minimise these wider environmental impacts, nutrient recovery efforts should be targeted at human sanitation streams that are not mixed with other waste streams, such as industrial effluents in urban areas.

3.3.3. Cultural context of P recovery from human excreta

Since open defecation is still widely practised in India, the potential for resource recovery would be greatly enhanced by diverting this flow into septic tanks. However, there are barriers to making such a shift that are specific to India and which would first need to be addressed. In comparison to other low and middle income countries, including poorer countries with lower literacy rates, the transition away from open defecation in India has been slower (Nagla, 2020). This has been reflected in the outcomes of the Swacch Bharat Mission (Clean India), which included a goal for the cessation of open defecation in India by 2019. For example, although Rajasthan state was recorded as defecation free by March 2018, surveys in June 2018 revealed that, whilst there had been improvements, 46% of rural households and 9% of urban households still practised open defecation, despite having access to toilets in many cases (Exum et al., 2020). Affordable latrines are often rejected because they are seen as polluting (Gupta et al., 2016) and areas that practised untouchability, as related to the caste system and the notion of purity and pollution, showed a preference for maintaining practices of open defecation (Spears and Thorat, 2019).

The concept of purity and pollution, principles originating from Hindu texts, relates to what can be considered clean or unclean both in a physical and religious sense, and guides normative behaviours across India. Individuals from Dalit castes are considered to be both ‘polluted’ and ‘polluting’ to others (Nagla, 2020), and traditionally are expected to undertake tasks that are considered to be dirty, with manual cleaning of human excreta regarded as the most ‘dirty’ and degrading of these (Shah et al., 2013). When Dalits do perform this type of ‘dirty’ work it then reinforces the idea that they are ‘polluted’ (Valmiki, 2003). Any development actions that involve sanitation and the handling of human excreta, in any form, need to give careful consideration to this cultural environment in order to avoid perpetuating prevailing structures of oppression.

3.4. Potential for phosphorus recovery from flows other than human excreta

When considering how to move P flows within the Indian agri-food system away from a linear use and waste approach to a circular approach based on P recovery, attention should be focussed on not only the largest loss flows but also those that are most easily recovered. Total P losses are 2697 kt P year^{-1}, equivalent to 88% of applied mineral fertiliser. This is an increase of 25% from the total P losses reported by Keil et al. (2018) for the time period 2006–2011, and follows the trend they reported of losses increasing over time. The SFA (Fig. 1) highlights the ‘leakiness’ or poor efficiency of P use, where P is lost from, and which flows account for the largest losses in the Indian agri-food system as a whole. Our calculated P efficiency of the Indian agri-food system is 32%, lower than the average P efficiency of 46% reported by Chowdhury and Zhang (2021) in a review of national scale P–SFAs for multiple countries.

The largest proportion of total lost P is in eroded agricultural soil (48%), followed by P in human excreta (23%) and P in manure that is not utilised as fertiliser (15%). The prevention of soil erosion will be critical in securing future phosphorus sustainability, with global P losses in eroded soil contributing to over 50% of total losses (Alewell et al., 2020). The adoption of certain agricultural practices that lead to soil conservation has been identified as the best management option for avoiding the loss of P via this route (Sharpley et al., 2015; Wuepper et al., 2019). Soil protection methods are divided into agronomical and engineering methods, with the most suitable method being dependent on a number of variable factors such as climate, soil type and predominant crop grown. The application of organic matter as fertiliser in place of mineral fertiliser has been demonstrated to reduce soil erosion and runoff through the improvement of the soil structure (Ahmad et al., 2020; Singh et al., 2017). The P in the retained soil could potentially decrease the overall P fertiliser application requirements of the soil for crop growth.

The third largest P loss flow relates to manure that has not been used as fertiliser. This loss estimate was based on the assumption that any manure not designated by the FAOSTAT data as being applied to soils is lost. However, some of this 'lost' manure P may end up in soils if animals are grazing on cultivated land. Our estimate aligns with a review by Chowdhury and Zhang (2021) of P–SFAs at the national scale which found that all Asian countries have a markedly higher mineral fertiliser input compared to animal manure input. The increasing consumption of meat and dairy in the Indian diet is resulting in an increasing P footprint per capita, as well as increases in livestock numbers. From the SFA we calculated the P footprint (P provided in in food) as 850 g P capita^{-1} year^{-1}, an increase of over 40% from the 2011 value of 597 g P capita^{-1} year^{-1} for India (Keil et al., 2018). Given the lower P use efficiency associated with livestock systems, it is likely that this loss flow will increase in future and it will be crucial that policies to increase manure use as fertiliser are introduced.

Another potential source of relatively large-scale P recovery is from crop residues. As discussed in section 2.4, crop residues are utilised in various ways including as fuel, animal feed and bedding, and for mulching and composting. However, apart from 'F14 Burnt Stubble', there is not sufficient data to divide the P in crop residue according to use, and to therefore determine: how much P could be recovered, how much is already recovered as compost or mulching material, and how much is used as animal feed and hence cannot be recovered. Historically crop residues that had not been utilised would be ploughed into the soil contributing to soil fertility, however, these practices have declined and been replaced with burning as farming has become increasingly industrialised (Bhuvaneshwari et al., 2019). Stubble burning contributes to air pollution and greenhouse gas emissions and has a negative impact on soil fertility, through diversion of nutrients in the stubble away from the soil, and damaging the soil leading to a loss of bacteria and nutrients (Abdurrahman et al., 2020; Kumar et al., 2015; Lan et al., 2022; Porichha et al., 2021). Practices focussed on the incorporation of stubble, such as mulching and composting, have been shown to have a positive impact on soil fertility (Porichha et al., 2021; Withee and McCalla, 1954).

Distribution wastes and household food waste flows, although comparatively small, will still need to addressed in order to achieve a circular economy of P. This could include improvements in distribution that prevent waste, as well as policies focussed on improved solid waste management incorporating composting of food. Although some distribution and household food wastes are being composted or used as animal feed, we assumed that these wastes all end up as P lost to the environment since there were insufficient data available to assign values to those flows.

If 100% of P were recovered from all of the loss flows identified, 88% of P in applied mineral fertiliser could be replaced. All these flows will need to be targeted if a circular economy of P is to be achieved in India. However, the work that is currently ongoing in the Indian water and sanitation sectors to meet the United Nations Sustainable Development Goal (SDG) Targets 6.1 and 6.2 (which focus on safe drinking water and sanitation) presents a timely opportunity to include circular economic thinking and nutrient recovery policies from the outset (Sarkar and Bharat, 2021). An additional benefit of recovering P from human excreta would be the reduction of P entering water systems and leading to eutrophication, particularly in India where the primary source of P loading is from wastewaters (Brownlie et al., 2022).

3.5. Phosphorus stocks and options for recovery

Large annual accumulation of P stocks in India are present in 'Agricultural Soils', 'Households and Hospitality', and 'Various Uses' (utilised crop residue) (Fig. 1). As discussed in section 3.4 there are not enough data to determine how much of the total utilised crop residues are used for each possible outcome. It should be noted that some of the uses would result in a loss of P (such as use as fuel), whilst others would result in P returning to the agri-food system (such as mulching and composting or use as animal feed). 'Agricultural Soils' is the largest annual accumulation P stock (1256.5 kt P year^{-1}), which may be partially due to the analysis not taking into account farmers holding back products for their own consumption or for use as seed. However, this large stock addition is likely also representative of ongoing P accumulation in soil in India (Brownlie et al., 2022; Keil et al., 2018; Pathak et al., 2009). The accumulation of soil P or 'legacy P' has a direct environmental impact through increasing the amount of P present in eroded soil and runoff, which ends up in the aquatic system. Investment into methods enabling use of legacy soil P alongside more precise application of nutrients could drastically reduce the amounts of P required for crops and entering the environment via soil erosion and runoff. A large annual accumulation P stock (510.5 kt P year^{-1}) is present in the 'Households and Hospitality' box. However, we did not account for the P present in humans, or P lost from the system as the result of mortality, which may explain the apparent size of this annual stock addition. Due to a lack of data we also did not account for P remaining in livestock or the flow of P losses from death and slaughter of animals, although this flow could provide a valuable source of recovered P. Meat and bone meal constitutes 30% of the weight of an animal and has a high P content (Leng et al., 2021). Whilst bone meal is commonly used directly as a fertiliser in high income countries, the adoption of recycling technologies in other countries is more challenging due to the lack of infrastructure and available finance for development (Chojnacka et al., 2019). There are many informal slaughterhouses operating in India, primarily in rural areas (Kennedy et al., 2018), from which the waste is discharged directly into sewers and water bodies without any treatment, posing a risk to human health and causing ecological damage (Roy et al., 2016). As this is also a potentially rich source of nutrients, alternative low-cost methods of recycling abattoir and slaughterhouse waste materials are being investigated in India (Bhunia et al., 2021; Roy et al., 2013, 2016).

4. Study limitations and future work

4.1. Limitations

This SFA provides a broad country-wide overview of how phosphorus flows within the Indian agri-food system and which are the primary contributors to P losses. Flows included in the P-SFA were those that were considered key to the food, agricultural and sanitation system of India, and were broadly in line with those included by other national scale P-SFAs (Cooper and Carliell-Marquet, 2013; Keil et al., 2018; Roy et al., 2019; Smit et al., 2015). The study was limited by the need to omit certain flows for one or more of the following reasons: lack of available high-quality data; flows were expected to be relatively small; or flows expected to have minimal significance for our study aims. The key flows omitted included: the various possible utilisations of crop residues, P in detergents and greywater, P in abattoir waste and other unused meat industry animal by-products, P in food and flower temple offerings, and P in tourist food consumption and waste. Given that the number of international tourists arriving in India in 2019 (pre-COVID-19) was only equivalent to 1.3% of India's population (World Bank, 2023) and considering the transient and short-term nature of these visits, it was decided not to separately quantify tourist food consumption and waste beyond what was included in 'F7 Other Industries', defined as 'quantities of the commodity in question consumed mainly by tourists' (FAO, 2022c). Although domestic tourism is likely a much larger figure, given this SFA is concerned with P flows at the India-wide scale and that the movement of people is internal within India, and therefore within the bounds of the SFA, it was deemed an acceptable omission.

Uncertainties in SFAs can often be introduced as a result of calculation methods, issues around data quality, availability of data, and study assumptions (Wang and Ma, 2018). Data uncertainties were quantified as they are unavoidable, owing to a lack of available high-quality data, in particular for the use of crop residues, P in manure, and build-up of P in agricultural soils. Our uncertainty analysis identified the two largest flows with relatively high levels of uncertainty as 'F22 Soil Erosion' (±71%) and 'F19 Applied Manure' (±200%). In the case of soil erosion, uncertainties arose due to a lack of available data on P content in Indian soils and the impact of generalising from data for specific areas to the whole of India. Applied manure uncertainties arose due to FAO reporting manure application rates only in terms of nitrogen (N) values and a lack of data relating to P:N ratios in manures.

4.2. Future work

To reduce uncertainty in the estimate of P loss in soil erosion, a process-based model such as the EPIC model (Raj et al., 2023; USDA, 2006) could be used, coupled with spatially resolved data on the P content of eroded soil across the whole of India. The SFA could be also made more granular through further work incorporating aspects such as P dynamics and bioavailability of P from various recovery methods. More in-depth work taking into consideration the potential benefits (P recovery magnitude of different recovery technologies, environmental benefits) and potential costs (environmental and fiscal costs) of P recovery systems would need to be undertaken before any policy recommendations could be made. Any such recommendations would have to be developed alongside work assessing the cultural and behaviour attitudes and barriers to using recovered P.

5. Conclusion

As the Indian population continues to grow so will its demands for food and therefore P, a finite resource that is primarily imported. A shift to a circular economy approach based on recovery and reuse of P from waste-streams could mitigate the dual problems of insecurity of access to P and its position as a finite resource, whilst simultaneously reducing environmental pollution from P. This P-SFA has shown that P flowing through the agri-food system in India is lost at numerous points and that the system as a whole is less efficient than the global average. Increasing the overall efficiency in combination with P recovery and reduced application of P fertiliser could move India towards a closed loop system. Transitioning to such a system requires not only investment, technological advancements, and infrastructural changes but also significant behavioural modifications. The recovery of P from human excreta, the reduction of P lost in eroded soil through preventative measures, and the improved management of crop residue and manure, should be the primary targets of development work, as these represent the largest losses from the system. Prioritising initiatives aimed at recovering P will mitigate dependence on phosphorus imports, which render Indian food security susceptible to international price volatilities, and help reduce the substantial expenditure by the Indian Government on fertiliser subsidies, amounting to 27.3 billion USD in the fiscal year 2022–23 (Government of India, 2023).

Analysing P flows within the agri-food and sanitation systems on a smaller scale than the national level would be valuable for gaining insights into which strategies would prove most effective for P recovery. Tailoring policies based on various factors specific to each location, such as the predominant farming type, and the availability and system of sanitation, could further enhance the efficacy of P recovery. The effectiveness of such policies will also depend upon an improved understanding of the obstacles associated with adopting organic fertilisers, particularly those derived from human excreta, in a cultural setting where concerns regarding purity and pollution prevail.

Funding

This work was supported by the Natural Environment Research Council (NERC) part of UK Research and Innovation (UKRI), via the University of Edinburgh E4 Doctoral Training Partnership (Grant number NE/S007407/1).

CRediT authorship contribution statement

Diorbhail Wentworth: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alfred Gathorne-Hardy:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Priyanka Jamwal:** Supervision, Conceptualization. **Kate Heal:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available in published databases and literature

Acknowledgements

We thank Prof. Hugo Gorringe and Divya Veluguri (The University of Edinburgh) for useful discussions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2024.100220.

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