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Phosphorus recovery potential from sewage sludge by struvite precipitation: remodelling policy framework in Rajasthan, India

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ABSTRACT

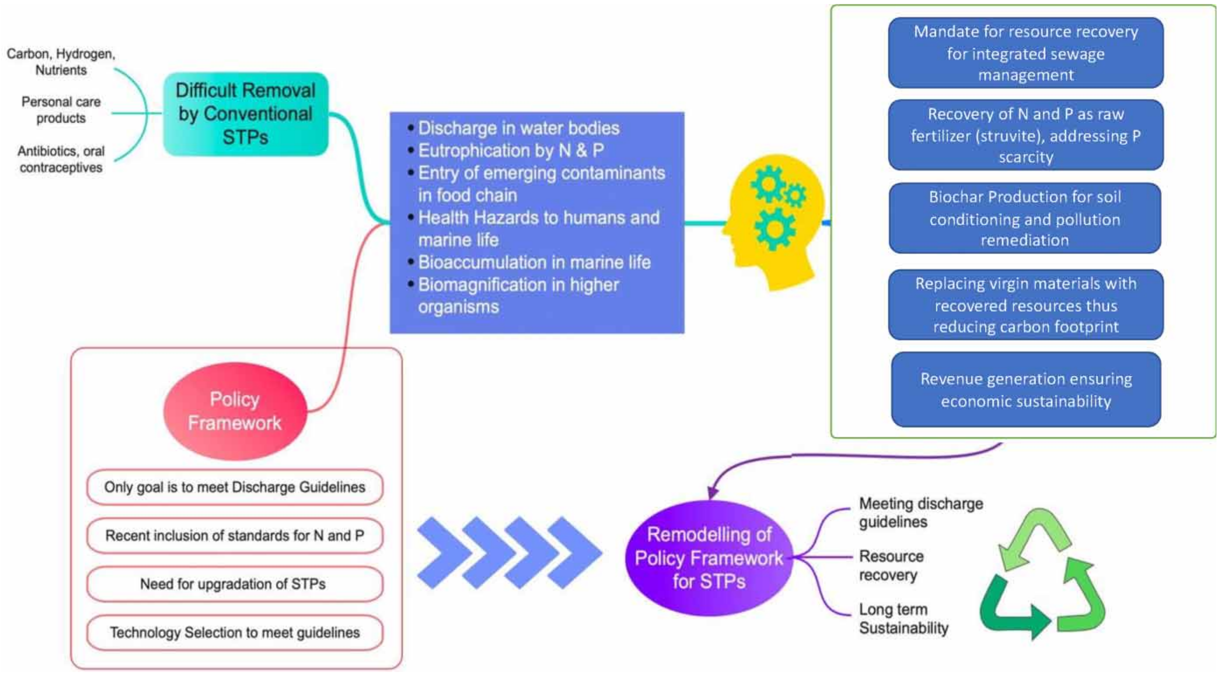
The manufacturing of fossil-based fertilizers by extraction of rock phosphate has contributed to carbon emissions and depleted the non-renewable phosphorus reserves. Sewage sludge, which is a waste product from Sewage Treatment Plants (STPs), is rich in phosphorus. The existing techniques for sludge management contribute to carbon emissions and ecological footprint. Struvite (raw fertilizer) and biochar recovery from sludge has emerged as viable methods to reduce carbon emission and ensure economic sustainability of STPs. In this work, the potential for phosphorus recovery and revenue generation is discussed for Rajasthan state in India. The fate of phosphorus and heavy metals in STPs is evaluated which indicates that about 70% of the phosphorus and trace amounts of metals end up in sewage sludge. Further, the power consumption is high in STPs due to industrial wastewater ingress. There is a need to bridge the gap between sewage treatment and generation in Rajasthan, improve STP performance before resource recovery inclusion at policy-level and scale-up. Mixing struvite with biochar can lead to safe application of struvite as raw fertilizer as heavy metals are sequestered by biochar. A business framework is developed to serve as a blueprint and potential model for linking technical and market viability.

Key words: biochar, phosphorus recovery, sewage management, struvite precipitation

HIGHLIGHTS

- This article highlights the concept of integrated sewage management for conforming to discharge guidelines and resource recovery from sewage sludge.
- The present policies for wastewater management in India are discussed.
- The carbon footprint and revenue generation from struvite and biochar are discussed.
- A business framework has been developed.
- The fate of phosphorus and heavy metals in STPs is evaluated.

GRAPHICAL ABSTRACT



1. INTRODUCTION

About 50% of the global carbon emissions are dissipated by the five key sectors, i.e., transportation, agriculture, power, hydrogen and steel. Agriculture accounts for 18% of gross emissions in India because of fossil-driven fertilizer production (Bhushan *et al.* 2019). In the UN Climate Talks 2022 (Conference of Parties – 27 (COP-27)), the member countries including India have jointly launched a package for the decarbonization of these five key sectors. Hence, for decarbonization and sustainable development, a paradigm shift is inevitable which calls for resource recovery as a key facet of the bustling Indian economy. Environmental and economic sustainability go hand in hand and so is true for water and wastewater treatment technologies where economic sustainability is necessary to ensure long-term environmental sustainability. The potential of domestic wastewater to be used as a resource to reduce carbon emissions and generate revenue is now being given much impetus by policymakers and industries. Therefore, the reuse of treated wastewater has been explored in many industrial processes where high-purity water is not required. Hence, the installation of sewage treatment plants (STPs) and common effluent treatment plants (CETPs) across the country has gained prominence under various government schemes. As per the data of the Central Pollution Control Board (India), in 2020–2021, the sewage generation in India in urban centres was 72,368 million litres per day (MLD). The installed and operational capacity was 31,841 and 26,869 MLD, respectively (CPCB India 2021). Hence, 72% of the wastewater is finding its way into the nearby water bodies and aquifers. The discharge of sewage directly into the water bodies and its direct application on agricultural land has its associated challenges. The heavy metals, antibiotics, oral contraceptive pills and various other refractory compounds which cannot be removed by conventional STPs are taken up by the plants and smaller marine lifeforms and enter the food chain thus resulting in bioaccumulation and biomagnification. The nutrients in wastewater also lead to the eutrophication of water bodies. The risk assessment has shifted the attention of researchers towards extracting resources from sewage in such a form that it can be reused without any health hazard.

To tackle wastewater management, the policy framework plays a pivotal role as it puts binding responsibilities on various entities of government and industries. Prevention of water pollution by recycling and reuse of wastewater has been time and again stressed by the Indian government in its policies. However, the concept of resource recovery is relatively new, and now the policy framework must be modified to make resource recovery an intrinsic part of waste management. The present policy framework in India requires STPs to comply with the discharge guidelines. In India, the National Green Tribunal (NGT) revised the effluent discharge guidelines and added discharge standards for nitrogen and phosphorus. Much importance has already been given to the reuse of treated STP effluent, but the sewage sludge is presently being discarded as waste that is incinerated or ultimately reaches landfill sites or sludge drying beds.

Municipal wastewater or sewage includes the wastewater generated from bathing and kitchen and other household activities. In an STP, the solids are separated from the wastewater by various physicochemical and biological processes. The concentrated solids in the liquid form are anaerobically digested to form a tarry black product in a semi-dry state, which is known as sludge which is rich in nutrients such as nitrogen and phosphorus. On a dry basis, sludge consists of 30–60% of organic matter, 1.5–4.5% of nitrogen and 1.0–2.2% of phosphorus. Various minerals such as quartz and calcite and heavy metals such as Cr, Cu, Fe, Ni, Pb, Zn, Hg and Cd are also present in sludge (Tyagi & Lo 2013). Resource recovery from sludge is not yet seen as an integral part of sewage management. Remodelling the regulatory framework is urgently required to see STPs as resource recovery centres rather than treatment centres, which have an enormous potential to recover rare elements such as phosphorus from sludge.

90% of the extracted mineral phosphorus is used for food production, i.e., for fertilizer manufacturing and livestock farming (Figure 1). Out of the total phosphorus used for food production, 17% ends in water bodies. The water entering an STP contains about 4–15 mg/L phosphorus, out of which 90% ends up in the sludge (Gowd *et al.* 2022). Sewage sludge, the tarry product left after anaerobic digestion, offers the potential to extract good quality fertilizer rich in phosphorus. Naturally available phosphorus is derived from rock phosphate, a non-renewable resource which is under threat as with the current rate of extraction, the phosphorus reserves may exhaust in some 100–250 years which is a threat to food security. It was only in 2014 that the European Commission added phosphorus to the list of 20 critical raw materials. In 2016, Switzerland and in 2017 Germany announced legal requirements for phosphorus recovery (Zorpas *et al.* 2011; Shaddel *et al.* 2019; Gowd *et al.* 2022). The phosphorus recovery potential of sewage sludge has not yet been exploited in India. Given the mammoth quantum of sewage and consequent sludge generated every day in India, sewage sludge is still an untapped resource as there lies a huge potential for the recovery of phosphorus. Out of the total fertilizers consumed in India, ~38% is imported. The fertilizer imports of India roughly account for about 0.25% of the GDP (Gowd *et al.* 2022). Hence, there is a need to close the phosphorus loop for economic and environmental benefits and consequently reduce carbon emissions which was a 'Breakthrough Agenda' at the COP26, which was launched by 45 world leaders including the Indian Prime Minister.

Various technologies are available for recovering energy and resources from sewage sludge (Cao & Pawłowski 2012; Chow *et al.* 2020). The sewage sludge can be used in cement kilns for making building materials and as a source of minerals and metals for high-value products. It can also be used for energy recovery by gasification, incineration, pyrolysis, hydrothermal

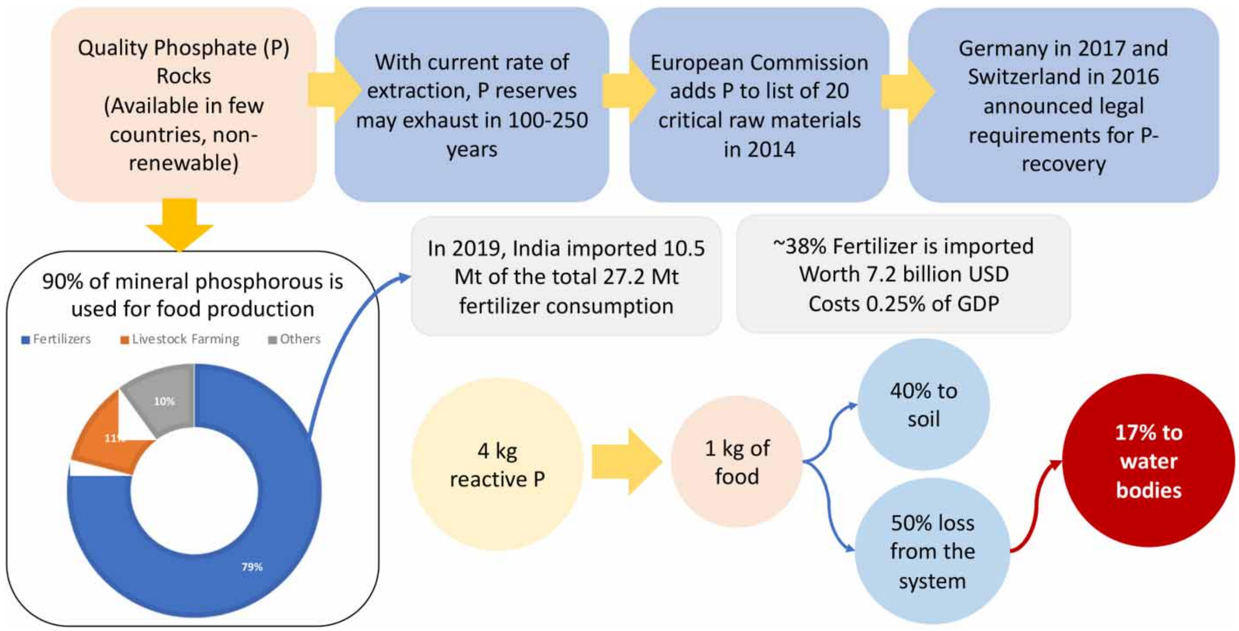


Figure 1 | Current scenario of phosphorus utilization for fertilizer production and its impact on GDP and environment (Zorpas *et al.* 2011; Shaddel *et al.* 2019; Gowd *et al.* 2022).

liquefaction (HTL) and heat recovery (Hu *et al.* 2021). Among these technologies, phosphorus, which is a scarce resource can be recovered from incineration ash or by precipitating it as struvite, which can be used as a fertilizer. Incineration can be a highly intensive process. Hence, struvite precipitation can be exploited to address the phosphorus scarcity. The agricultural application of sewage sludge has been thought of as the most economical process for sludge reuse. The sewage sludge can be used as a resource by extracting struvite from it. Struvite or magnesium ammonium phosphate can be used as a fertilizer as it is highly rich in phosphorus. Various studies have been conducted to address the economic and process feasibility of struvite precipitation.

Wu *et al.* integrated ammonia stripping, adsorption and struvite precipitation for optimized yield (Wu & Vaneeckhaute 2022). Yetilmezsoy *et al.* performed a financial and economic analysis of the struvite process and indicated that breakeven can be achieved when the market price of struvite exceeds €482/tonnes (Yetilmezsoy *et al.* 2017). Krishnamoorthy *et al.* studied the engineering principles of struvite precipitation and highlighted that research is needed for market development strategy with a more holistic approach, which considers cost, product purity, storage, transportation, distribution and toxicity assessment (Krishnamoorthy *et al.* 2021). The application of struvite has its associated risks because of the presence of heavy metals in sewage sludge. The quantity of heavy metals typically varies from 0.5 to 4% of dry weight in sewage sludge. Metal toxicity has been considered one of the major reasons limiting the application of sewage sludge as fertilizer as the crops can bioaccumulate heavy metals (Wong 2005; Pathak *et al.* 2009; Camargo *et al.* 2016; Hazra *et al.* 2017). Another resource that can be derived from sewage sludge is biochar, which can be used as a conditioner for heavy metal adsorption to reduce the toxic effects of heavy metals for application of struvite as fertilizer. However, this aspect has not been discussed in detail in previous works. Hence, the properties, carbon emission, revenue generation and risk assessment of struvite and biochar recovery from sewage sludge need to be discussed.

This work addresses multiple aspects such as the economics and technical feasibility of resource recovery methods, establishing the fate of phosphorus and heavy metals in STPs and associated risk assessment due to heavy metal toxicity. This article aims to identify the scope for resource recovery from sewage sludge by struvite precipitation and analyse the scope of reducing the risk and toxicity due to heavy metals with biochar. Further, it is aimed to highlight the concept of integrated sewage management which is important not only for conforming to discharge guidelines but also includes the idea of resource recovery from sewage sludge. For this, the status of wastewater generation and treatment in Rajasthan, India is discussed. The present policies for wastewater management in India are discussed and the need for policy remodelling is highlighted. The potential of resource recovery from sewage sludge is discussed by highlighting the fate of phosphorus and heavy metals in a typical STP. The carbon footprint and revenue generation from various resource recovery strategies are discussed. The carbon footprint of traditional practices for sludge management is discussed. Considering policy and practices for sewage management, a business framework has been developed to further the concept of integrated sewage management.

2. METHODS

2.1. Analysis of influent and effluent samples from STPs

The samples of influent and effluent wastewater were collected from an STP to understand the fate of heavy metals, N and P in STPs. In this study, composite sampling was done to evaluate the influent and effluent characteristics. Heavy metal concentration has been evaluated to predict their potential to end up in sewage sludge. The samples were determined for pH, TSS, VSS, TKN, NO_3-N, NH_4-N, COD (total and soluble), BOD (total and soluble), TOC, TP, $PO_4^{3-}-P$. The samples were tested for the parameters using the methodology as given in Table 1. The samples were collected in glass or polytetrafluoroethylene (PTFE) containers by composite sampling and stored at 4 °C (if required) for not more than 24 h. For composite sampling, the volume of the wastewater was collected in proportion to the flow to neutralize the effect of peak flow and lean flow. These samples were then homogenized using a magnetic stirrer for further analysis. For soluble BOD_5 and soluble COD, the samples were filtered by using a 2.5 micron pore size filter paper. All the analyses were conducted in triplicates. More data on STP efficiency has been included in the Supplementary data.

2.2. Secondary data collection for sewage generation and collection

The data for sewage generation, collection and treatment by STPs in Rajasthan was collected from the NITI Aayog Government of India Report on Urban Wastewater Scenario in India (Niti Aayog 2022). Rajasthan has been chosen as a model state due to its proximity, data availability and close association with the government.

Table 1 | Parameters and methods used for sewage analysis (American Public Health Association 2017)

S. No.	Parameters	Method	Equipment/Instrument
1.	pH	APHA 4500-H + B. Electrometric Method	Hanna HI98130
2.	TSS	APHA 2540 SOLIDS D. Total Suspended Solids Dried at 103–105 °C	Filter paper Whatman no. 42
3.	VSS	APHA 2540 SOLIDS G. Total, Fixed and Volatile Solids in Solid	Suspended solids filtered (Whatman no. 42) and ignited at 550 °C in muffle furnace
4.	NO_3-N	APHA 4500-N NITROGEN D. Conductimetric Determination of Inorganic Nitrogen	Portable Multiparameter Meter (HQ40d Hach) with Intellical™ ISENO3181 Nitrate (NO_3^-) Ion Selective electrode
5.	NH_4-N	APHA 4500-NH_3 NITROGEN (AMMONIA) D. Ammonia-Selective Electrode Method	Portable Multiparameter Meter (HQ40d Hach) with Intellical™ ISENH3181 Ammonia (NH_3) Ion Selective electrode
6.	BOD_5	APHA 5210 BIOCHEMICAL OXYGEN DEMAND (BOD) B. 5-Day BOD Test	Incubated at 20 °C for 5 days
7.	Soluble BOD_5	APHA 5210 BIOCHEMICAL OXYGEN DEMAND (BOD) B. 5-Day BOD Test after filtration by 0.45 μm filter	Incubated at 20 °C for 5 days
8.	COD	APHA 5220 CHEMICAL OXYGEN DEMAND (COD) D. Closed Reflux, Colorimetric Method	Hach DRB200 block digestor, Shimadzu UV1800 Spectrophotometer
9.	Soluble COD	APHA 5220 CHEMICAL OXYGEN DEMAND (COD) D. Closed Reflux, Colorimetric Method after filtration by 0.45 μm filter	Hach DRB200 block digestor, Shimadzu UV1800 Spectrophotometer
10.	TKN	APHA 4500-Norg NITROGEN (ORGANIC) B. Macro-Kjeldahl Method	Kelplus TKN digestor, Sohxlet distillation apparatus
11.	Soluble TKN	APHA 4500-Norg NITROGEN (ORGANIC) B. Macro-Kjeldahl Method after filtration by 0.45 μm filter	Kelplus TKN digestor, Sohxlet distillation apparatus
12.	TOC	APHA 5310 TOTAL ORGANIC CARBON (TOC) B. High-Temperature Combustion Method	Shimadzu TOC-L
13.	Total phosphorus	APHA 4500-P PHOSPHORUS D. Stannous Chloride Method	Sohxlet digestion apparatus, Colorimetric determination by Shimadzu UV1800 Spectrophotometer Shimadzu UV1800 Spectrophotometer
14.	PO_4-P (soluble phosphorus or orthophosphate)	APHA 4500-P PHOSPHORUS D. Stannous Chloride Method after filtration by 0.45 μm filter	Sohxlet digestion apparatus, Colorimetric determination by Shimadzu UV1800 Spectrophotometer Shimadzu UV1800 Spectrophotometer
15.	Heavy metals	APHA 3125 B	Atomic absorption spectrophotometer

2.3. Comparison of technologies for sludge management and resource recovery

Secondary data for carbon emission and cost have been used for validation of technical and economic feasibility of struvite and biochar derived from sewage sludge as they are relatively economical strategies as compared with incineration, pyrolysis, gasification, HTL, etc., which requires high energy input to recover useful resources from sewage sludge and generate revenue for STPs and reduce the space requirement for sludge drying beds (Cao & Pawłowski 2012; Chow *et al.* 2020). The applications, advantages and disadvantages of these technologies are discussed.

2.4. Estimation of resource recovery potential in Rajasthan

From a vast array of technologies available and the generation of wastewater in India, the potential of revenue generation in Rajasthan was analysed for struvite precipitation.

2.5. Development of business model

Based on the technology, economics and revenue generation, a comprehensive business model has been developed.

3. RESULTS AND DISCUSSION

3.1. Sewage and sludge generation statistics

In 2020–2021, the sewage generation in India in urban centres was 72,368 MLD. The installed and operational capacity was 31,841 and 26,869 MLD, respectively. In Rajasthan, wastewater generation was 2,736 MLD, however, the installed capacity is 865 MLD. The capacity to generation ratio stood at 0.32 in Rajasthan which is low compared with the national average of 0.37 (CPCB India 2021). There are presently 107 STPs in Rajasthan (Central Pollution Control Board & Ministry of Environment Forest and Climate Change 2021). The numbers of STPs in Rajasthan state with their capacity and numbers are shown in Figure 2. Most of the STPs are between 6 and 10 MLD and only a few larger STPs with a capacity >50 MLD are there which are situated in tier II cities like Jaipur and Jodhpur in Rajasthan. There are several small decentralized STPs in the state where the treated water is being used on-site for horticulture. The sludge production in India is estimated to be 144 kg/MLD of sewage. The specific production is estimated to be 7.34 kg/capita/year. Also, it is estimated that the complete treatment of sewage would generate 3.96 million tonnes of dry sludge yearly (Singh *et al.* 2020). Presently, the sludge is being disposed of by using landfills (14%), incineration (27%), agriculture (42%) and other miscellaneous applications (17%) like recovery of energy recoveries, adsorbent manufacturing, etc.

3.2. Policy framework

In India, the NGT is the apex statutory body that is responsible for hearing and disposal of cases concerning environmental issues in India. The effluent disposal standards have been revised by NGT in 2019. NGT has stated that more than 90% of rivers are polluted in India due to a relaxation in effluent discharge standards. NGT has revised the standards for various parameters: COD $<$ 50 mg/L, BOD $<$ 30 mg/L, TN $<$ 10 mg/L, TP $<$ 2 mg/L and TSS $<$ 2 mg/L (National Green Tribunal 2019). The concept of zero liquid discharge (ZLD) is well understood in the case of industrial wastewater treatment to ensure circularity. However, resource recovery is still not made an integral part of sewage management to ensure circularity in STPs, as such it remains an untapped resource. In India, the solid waste disposal protocol has been elaborated by the Central Public Health and Environmental Engineering Organization (CPHEEO) Rules 2013 and Solid Waste Management Rules 2016 (Sude *et al.* 2023).

Many earlier ordinances were introduced to reduce water pollution such as the National Urban Sanitation Policy, India's National Water Policy, the National Water Mission, the National Water Quality Monitoring Programme of India, the National Guidelines on ZLD developed by CPCB and the National Framework on the Safe Reuse of Treated Water (Niti Aayog 2022). All these ordinances focus directly or indirectly on controlling and preventing water pollution, and resource conservation by the safe reuse of treated water by routes such as incentivization and planned tariff systems. However, to

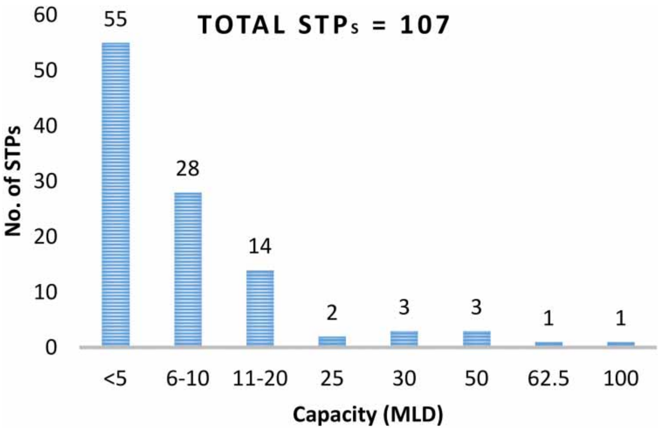


Figure 2 | Sewage treatment plants in Rajasthan (Niti Aayog 2022).

move a step further for a circular economy, a policy framework for resource recovery is much warranted. All regulations emphasize treated water recycling and reuse, but resource recovery is still not included in any mandate.

In India, presently the policy framework of the government for STPs is more focused on meeting the discharge standards. The concept of resource recovery is not given a mandatory status in sewage management. There is not a centralized framework which can be adopted by the local governments. Much has to be done at the policy level to make resource recovery from STPs mandatory. If resource recovery is made an integral part of the STP operation, two goals are simultaneously met, i.e., the revised guidelines for N and P removal are met if N and P are recovered from the STPs. The STPs constructed before the mandate of honourable NGT have not been designed for the removal of N and P. Now those STPs need upgradation for N and P removal. Instead of suggesting nitrification and denitrification where the nitrogen is ultimately released as N_2 in the atmosphere and is not recovered, resource recovery options are a better opportunity to meet two goals simultaneously.

3.3. Present practices for sewage sludge management and greenhouse gas (GHG) emissions

The STPs contribute to about 2% of the world's greenhouse gas (GHG) emissions and are responsible for about 1% of the national power consumption. The STPs consume power, which is typically about 0.33 kWh/m^3 of treated WW (wastewater). The main energy demand in the STPs is because of the aeration system. The aeration unit consumes the major portion of input power (~75%) (Luo *et al.* 2019). Depending upon the biological system used in any STP, the GHG emissions of STPs can range from 0.268 to 0.738 kg CO_2-eq./m^3. Electricity consumption is responsible for 68% of GHG emissions in STPs (Xi *et al.* 2021). In the coming years, this power consumption is only going to increase because of the rapid urbanization and consequent WW generation (Liao *et al.* 2020). In highly populated countries such as India and China, the most common method for sludge disposal is landfill (40–50%), followed by energy/product recovery or disposal (Fang *et al.* 2019; Chen *et al.* 2022).

Conventionally, many processes have been used to manage or convert sludge to inert forms such as aerobic composting, anaerobic digestion and landfill disposal. Various disadvantages have emerged due to the use of such conventional methods such as the requirement of space, time taken to decompose and emission of CO_2. Further, in these processes, the anaerobic decomposition converts the carbonaceous matter into methane and CO_2, which is dissipated as a gas in the environment causing GHG emission. Hence, the carbon which has the potential to be utilized as a resource is dissipated into the environment. In anaerobic processes, the sewage sludge is recycled to methane (20–30% by weight) and the rest of the CO_2 (70–75% by weight) is emitted to the environment (Biller *et al.* 2018). Further, complex hydrocarbons such as pharmaceuticals, heavy metals and pathogens cannot be destroyed. The removal of impurities is incomplete through such routes and hence poses a problem for health and the environment.

The conversion of sewage sludge into bio-oil, biochar and fuel gas by thermochemical conversion is certainly more advantageous than disposal techniques as such methods result in more volume reduction, greater product conversion, pathogen removal, fuel production and reduced GHG emission (Samolada & Zabaniotou 2014; Jiang *et al.* 2016). In the case of thermal technologies, the energy input is the prime contributor of GHG. HTL, pyrolysis and incineration processes of sewage sludge result in carbon footprints of 172.50, 322.23 and 242.02 kg CO_2-eq./tonnes, respectively, and energy consumption of 906.742, 1,416.834 and 11,190.150 MJ/tonnes of sewage sludge, respectively. In the anaerobic digestion process of sludge, the carbon recovery rate is typically limited to 25% by weight (Cao & Pawłowski 2012; Chow *et al.* 2020). About 60% by weight carbon efficiency in the HTL process and 100% by weight carbon conversion to valuable products in the pyrolysis (i.e., biochar formation by pyrolysis) can be achieved (Li *et al.* 2023). Although biochar formation by pyrolysis is an energy-intensive process, biochar can be used as a soil conditioner and can be used to replace activated carbon as it is six times cheaper than activated carbon hence reducing net GHG emission. Biochar can adsorb dyes, heavy metals, pharmaceuticals, etc., and offers slow leaching of nutrients and thus conditions the soil for a longer duration.

The recovery of carbon and other nutrients such as phosphorus depends upon the method used for sludge conversion. Further, recovery of phosphorus is dependent on whether the phosphorus is recovered from sludge supernatant, dried sludge, etc. About 85–90% phosphorus can be recovered from sludge and sludge supernatant after anaerobic digestion. The recovery from the liquid phase of raw sewage is limited to 20–40%. Various options have emerged from recent research. Phosphorus can be precipitated by using magnesium salts as struvite (magnesium ammonium phosphate) which is a raw material for fertilizers (Singh *et al.* 2020; Gowd *et al.* 2022). Microalgae cultivation is another way to produce dry biomass rich in nitrogen and phosphorus. For microalgae cultivation, the biological treatment step such as the activated sludge process

(ASP) or the sequential batch reactor (SBR) has to be replaced by a microalgae cultivation reactor, hence this may be included in the design of new STPs to simultaneously meet the N and P discharge limits (Abeysiriwardana-Arachchige *et al.* 2020).

3.4. Technology selection

The technologies for resource recovery, i.e., struvite precipitation and biochar recovery, are compared in this work (Figure 3). Phosphorus ends up in different phases in an STP, i.e., liquid (influent and effluent), sludge (after anaerobic digestion) and sludge ashes (after incineration). About 90–95% of phosphorus ends up in the sludge. The recovery from the liquid phase is nearly 20–40% while recovery from sewage sludge and sludge ash is higher (Gowd *et al.* 2022). The recovered compound known as struvite (magnesium ammonium phosphate) can be used as a raw fertilizer. This process has emerged as a scalable and cost-effective method for nutrient recovery. Struvite precipitation can be done by using salts of magnesium. The selection of technologies is highly dependent on economic feasibility, technical viability, scale-up and risk potential. The application of untreated as well as treated sewage for agriculture can lead to bioaccumulation of heavy metals and other carcinogens into the food chain by plant uptake as the conventional processes in an STP are unable to remove xenobiotics and carcinogens such as dye compounds, personal care products and heavy metals. The application of treated sewage or sludge for agriculture can be made safer by conditioning the soil by using biochar.

Biochar can be prepared by pyrolysis of sewage sludge in an oxygen-free environment. Pyrolysis includes drying of the sewage sludge, followed by carbonization of dehydrated sludge and further physical or chemical activation to increase the surface area (Van Wesenbeeck *et al.* 2014). Pyrolysis of sewage sludge offers 100% conversion of carbon to biochar and offers long-term storage of carbon (Silva *et al.* 2017). Biochar can be used for improving soil quality (Paz-Ferreiro *et al.* 2012). Because of its surface area, it can be used for the adsorption of heavy metals and pesticides (Callegari & Capodaglio 2018) for crop quality improvement (Khanmohammadi *et al.* 2017) and soil conditioning, soil quality improvement (Liu *et al.* 2014), remediation (Kahiluoto *et al.* 2015; Zhou *et al.* 2017; Bogusz *et al.* 2019), remove dyes and as an alternate for activated carbon for slow leaching of nitrogen (Callegari & Capodaglio 2018). Technology selection should be dependent on the environmental and economic sustainability of the process for long-term continuation. Further, the scalability of the process is another important factor for successful implementation.

3.5. Resource recovery potential

Few studies have been conducted which have experimentally validated the economic sustainability of precipitation of struvite which can be used as a raw fertilizer (Gowd *et al.* 2022). Among the various technologies discussed, struvite precipitation has emerged as the most economical one. The calculation of revenue generation (in USD) from struvite precipitation for India and Rajasthan state in India is given below:

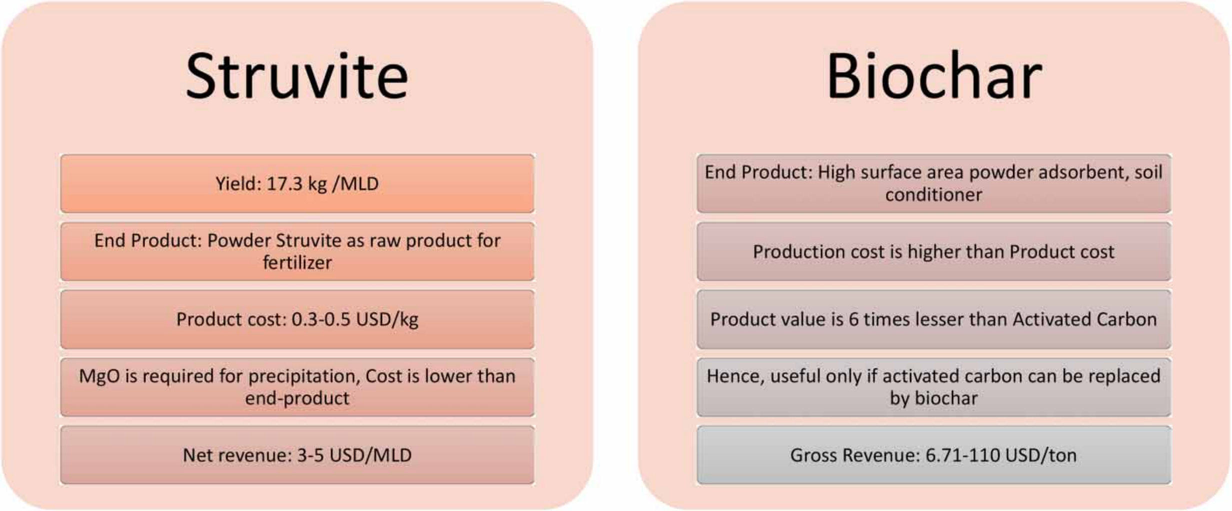


Figure 3 | Technologies for resource recovery (Singh *et al.* 2020; Gowd *et al.* 2022).

With the present installed capacity of 865 MLD, there is a potential to recover 14,964 kg of struvite per day which can generate net revenue of 2,595–4,325 USD/day. Further, if the entire wastewater is collected, the net revenue would stand at 6,64,848–11,08,080 INR/day in Rajasthan. The calculations are shown in Table 2.

3.6. Reduction potential of CO_2 emissions by struvite and biochar recovery

For fertilizer production, naturally available phosphorus is derived from rock phosphate, a non-renewable resource, which is under threat as with the current rate of extraction, the phosphorus reserves may exhaust in some 100–250 years which is a threat to food security (Zorpas *et al.* 2011). 90% of the extracted mineral phosphorus is used for food production, i.e., for fertilizer manufacturing and livestock farming. The annual consumption of fertilizer in India in 2019 was 27.2 Mt which accounts for 0.25% of GDP. Out of this, 38% is imported costing 7.2 billion USD (The Fertilizer Association of India 2019). It is reported that nutrient recovery from sewage can avoid 0.38 Mt/a in imports and 663.2 kg CO_2-eq./ha in emissions (53%) (Gowd *et al.* 2022). There is net-positive energy generation from biochar production from sewage sludge. The net carbon emission from sewage sludge biochar production is reported to be positive (1.16 kg CO_2-eq.), but it is ~20% less than that of activated charcoal (1.44 kg CO_2-eq.). The biogenic carbon sequestration offered by biochar derived from organic sources has a great potential for emission abatement (Ramachandran *et al.* 2017).

Hence, struvite precipitation and biochar production come out as net-positive energy-generating processes. Hence, more research is sought to be conducted in this direction for scaling-up these processes for resource recovery. Further studies are warranted to reduce carbon emissions by using fly ash instead of virgin magnesium salts. Hence, there is scope for even more reduction in carbon emissions in these processes.

3.7. Fate of phosphorus and heavy metals

Raw and treated wastewater were collected from STP. The influent and effluent characteristics are shown in Figure 4. The total phosphorus is evaluated. The influent TP was 7.35 mg/L. The average removal of TP is 70 ± 12%. Hence, this ~70% TP eventually goes into the sludge digestion unit and ultimately finds its way into the sewage sludge. This is slightly less than what is reported in the literature (i.e., ~90% P removal). Hence, there is still a need to improve the efficiency of the STPs.

The influent and effluent samples from the STP were analysed for the presence of heavy metals (Table 3). Toxicity analysis by heavy metal analysis could be helpful for evaluating the reuse potential of treated wastewater and sludge. If the heavy metal removal is better, it is likely that the heavy metals are being carried away in the settled sludge, hence increasing the toxicity of sludge and recovered products from sludge. Saha *et al.* reported the concentration of various heavy metals in sewage sludge. The concentration of metals such as Zn, Cu, Pb, Cd and Ni in sludge samples were 1,268.98, 293.40, 413.54, 4.93 and 174.96 mg/kg dry weight of sludge (Saha *et al.* 2015). Hence, to prevent the toxicity potential of sewage, it is necessary that industrial wastes are treated separately and should not be mixed with domestic WW. However, some trace amounts of heavy metals are likely to find their way into the wastewater. Therefore, during the resource recovery, measures will have to be taken which will ensure that heavy metal toxicity is reduced. Hence, biochar recovery and mixing of biochar with struvite becomes important to reduce the toxicity potential of struvite.

Table 2 | Calculation of revenue generation from struvite precipitation

	Rajasthan state	India	Reference
Installed capacity	865 MLD	26,869 MLD	
P concentration in influent wastewater		4 mg/L	Gowd *et al.* (2022).
Total P entering in STP each day		3,460 kg/day	
Struvite recovery potential for 1 MLD		17.3 kg	
Struvite recovery potential	14,964 kg/day	4,64,834 kg/day	
Cost of MgO for 1 MLD		2 USD	Gowd *et al.* (2022).
Cost of struvite for given capacity	0.33–0.42 USD/kg (27–34 Rs/kg)	0.33–0.42 USD/kg (27–34 Rs/kg)	
Cost of struvite for 1 MLD		5–7 USD	Gowd *et al.* (2022).
Net revenue generation for 1 MLD		3–5 USD	
Net revenue generation for given capacity	2,595–4,325 USD/day	80,607–1,34,345 USD/day	

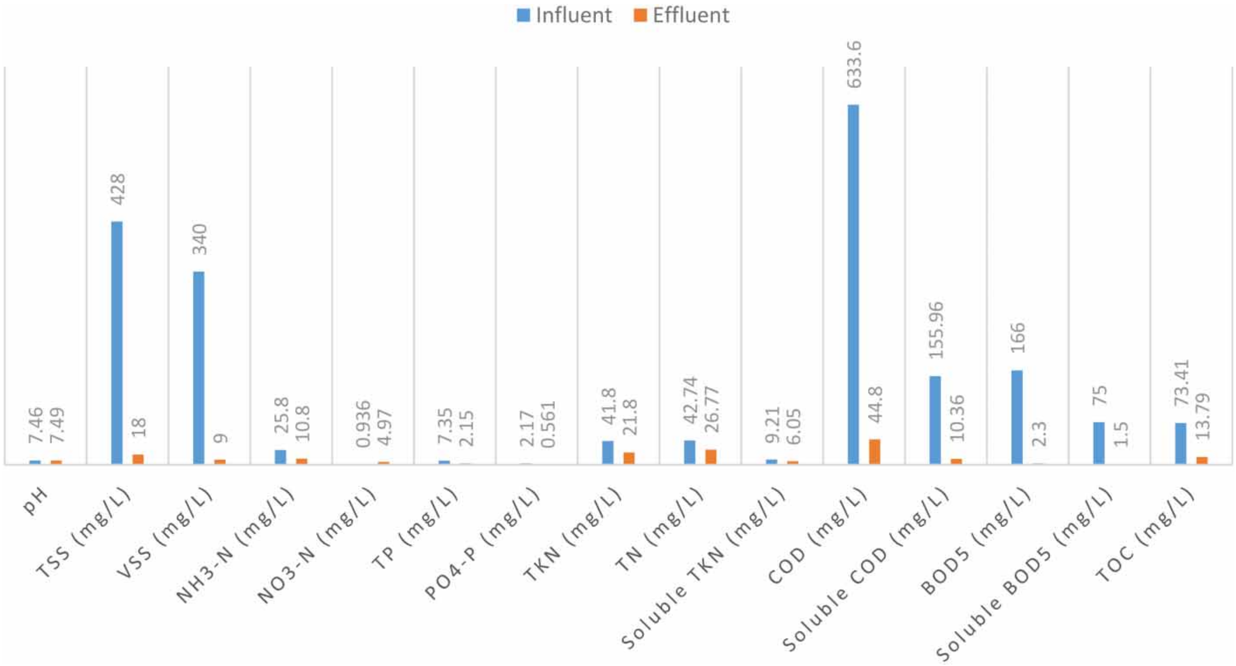


Figure 4 | Influent and effluent wastewater characteristics.

Table 3 | Heavy metal concentration in influent and effluent wastewater

S. No.	Heavy metal	Influent (mg/L)	Effluent (mg/L)
1.	Al	0.86	BLQ
2.	As	BLQ	BLQ
3.	Cd	0.09	BLQ
4.	Cr	BLQ	BLQ
5.	Fe	4.77	0.31
6.	Mn	0.13	BLQ
7.	Pb	BLQ	BLQ
8.	Ni	BLQ	BLQ
9.	Zn	0.65	0.10

BLQ, below limit of quantification.

3.8. Comprehensive framework and business model

Largely, environmental concerns are often given the least priority by the industrialists. In this direction, the efforts of the government to implement the disposal guidelines have been proven helpful. As the industries have advanced, more and more problems have emerged. The STPs and CETPs have been installed in the entire country to treat domestic and industrial waste. However, the concept of circularity still needs to be implemented. The implications of standards or guidelines for the industries should be such that the industries have a way to earn or generate revenue from them which incentivizes the entire idea of circularity as the industries are driven by economic forces and governments are driven by environmental concerns and larger benefits of the people.

A business model and technical and legislative outlook are given in Figures 5 and 6, respectively. First of all, including a mandate for resource recovery is crucial. Since sewage management is a multi-stakeholder program, it is crucial to involve expertise from institutions, administrators and consumers. After this, the development of necessary infrastructure is needed such as resource recovery stations. For larger STPs, on-site recovery stations could be economically beneficial.

However, for small STPs, transportation to a centralized resource recovery station may be worked out. The selection of a viable technology is important to ensure economic and environmental benefits. Further, phase-wise pilot-validation for improved scalability of the technology and business model is necessary. The involvement of institutions is crucial to achieving market validation. Phase-wise decentralized application of technologies to ensure successful scalability is crucial for the full-scale application of this business model. The option for setting up an on-site or centralized resource recovery facility is subject to local conditions. In the Indian context, much research has to be done for the scale-up of these technologies. There is a lot of potential for on-site recovery of phosphorus at larger STPs. For smaller STPs, centralized resource recovery stations may be developed. Firstly, there is a need to improve the connectivity of sewer lines to bring maximum sewage to the treatment plants

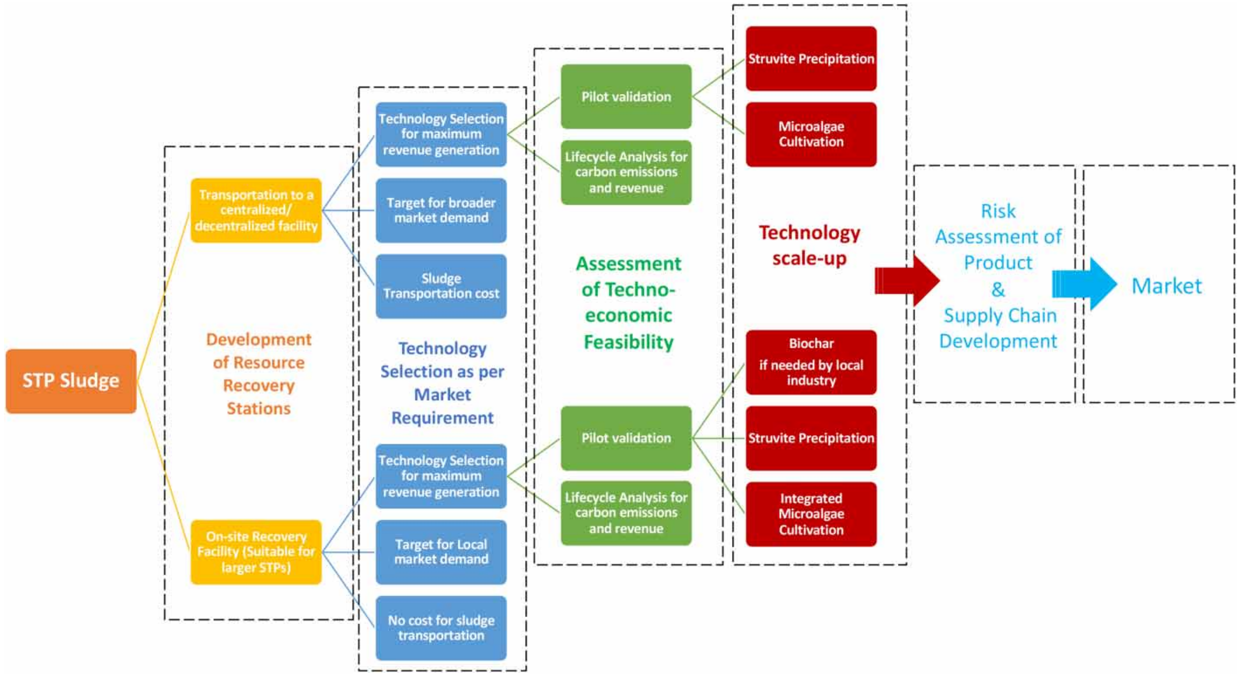


Figure 5 | Business model for resource recovery.

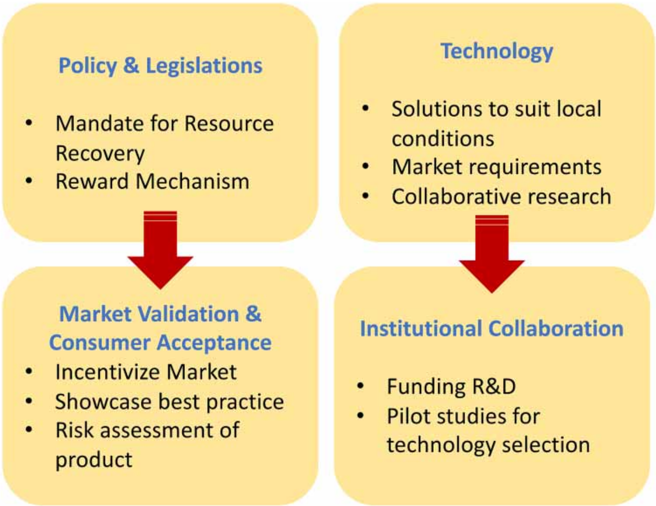


Figure 6 | Broad strategy for technical and legislative outlook.

to sequester valuable and scarce resources. A strategic roadmap for resource recovery needs to be conceived as per the local economy and geography. A multi-stakeholder business model calls for:

i. A mandate for resource recovery;
ii. Collaborative R&D and pilot studies for technology selection and validation;
iii. Incentivization of market and reward mechanism;
iv. Risk assessment of the product; and
v. Market acceptance.

4. CONCLUSIONS

This work highlights the need for nutrient recovery and sludge management. Remodelling the regulatory framework is urgently required to see STPs as resource recovery centres rather than treatment centres which have an enormous potential to recover rare elements such as phosphorus from sludge. The biggest challenge is bridging the gap between sewage generation and collection in India. The maximum advantage of resource recovery facilities can be availed when the infrastructure for sewage collection is further expanded to tap the remaining wastewater. Presently, around 70% of the total phosphorus in the influent WW in STP is finding its way into the sewage sludge which is less than that reported in the literature (~90%). Hence, there is a need to optimize the working of STPs to reduce excess power consumption since many STPs are working as partial CETPs because of the intrusion of toxic industrial wastewater in the STPs. Power consumption and equipment wear and tear are the two parameters which add substantially to the operating costs of an STP. Hence, the performance evaluation of STPs is crucial to understanding the direct and indirect impacts on power consumption and equipment health. Hence, before the inclusion of sludge recovery systems, it is important to upgrade the STPs in terms of performance so that they can offer the added advantage of nutrient/product recovery, revenue generation and environmental sustainability. A number of resource recovery technologies have emerged. The best selection of resource recovery facility depends essentially on consumer demand, local economy and geography.

The process of struvite precipitation can be scaled up in a phase-wise manner in Rajasthan, India. The potential of revenue generation from struvite precipitation in Rajasthan is 2,595–4,325 USD/day (for 865 MLD) and for India, it is 80,607–1,34,345 USD/day (72,368 MLD). Biochar mixing has the potential to reduce heavy metal toxicity and offer slow leaching of nutrients in soil. Presently, in India, a mandate for resource recovery is needed urgently to address the management of this mammoth quantum of wastewater and to address resource scarcity. The successful implementation of a resource recovery program lies not only in the application of efficient technology for the recovery of nutrients/products but also reuse of the recovered nutrients in the market such that there is economic viability of the process and emerges as a profitable business for the government and other stakeholders.

In Rajasthan, firstly the application of struvite precipitation can be developed as a pilot at one STP for demonstration which can be helpful for establishing maximum process efficiency, risk assessment, addressing field challenges (in the form of additional costs for equipment, logistics, etc.) and producing data availability for scale-up of struvite precipitation technology. Secondly, partnering with market experts can be done to bring the users of this product closer to the producers to ensure commercial success and subsequent revenue generation. Once all the dimensions are addressed in a field study, then more expansion at full-scale can be ensured.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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