

## Research Paper

# Technology choices in scaling up sanitation can significantly affect greenhouse gas emissions and the fertiliser gap in India

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### ABSTRACT

Nearly 800 million people in India lack access to adequate sanitation. The choice of technology for addressing this need may have important sustainability implications. In this study, we used life cycle assessment to compare environmental impacts and nutrient recovery potentials of four different options for providing everyone in India with access to improved sanitation: (i) centralised wastewater treatment with sequential batch reactors (SBR), (ii) twin-pit latrines, (iii) latrines with source separation only and (iv) latrines with source-separation of urine and faeces connected to biogas plants. Results revealed large variability. Closing the sanitation gap through pit latrines would be expected to cause large increases of India's annual greenhouse gas (GHG) emissions, equivalent to 7% of current levels. Source separation only and centralised plants with SBR will be associated with lower GHG emissions, while the biogas scenario shows a potential to provide net emission reduction. The study revealed that source separating systems can provide significant quantities of plant available nitrogen and phosphorus at the country level. Future research should include more technological options and regions. Methodology piloted in this study can be integrated into the planning and design processes for scaling up sanitation in India and other countries.

**Key words** | greenhouse gases, India, LCA, life cycle assessment, nutrients, sanitation

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### INTRODUCTION

India belongs to the world's fastest growing economies but 60% of people are still lacking access to improved sanitation (World Bank 2016). In 2014, prime minister Narendra Modi announced the 'Swachh Bharat' (Clean India) mission with the aims to fully eradicate open defecation by 2019 and significantly increase the number of individual household latrines. If each Indian household is to be ultimately provided with improved sanitation, this would require construction of nearly 170 million new, fully functioning toilets (authors' calculations based on World Bank (2016)).

Providing sanitation is necessary from a public health perspective, but creates some sustainability issues. Large-scale infrastructure investments require vast amounts of construction

materials, like bricks and concrete, production of which uses energy (Kellenberger *et al.* 2007). Sewage treatment using centralised wastewater treatment plants (WWTP) is also energy intensive (Kalbar *et al.* 2014). On the other hand, sanitation provides the opportunity to recover valuable resources from human waste, potentially avoiding the need for some industrial production and reducing environmental impacts.

Impacts of infrastructure projects can be considered using various environmental impact assessment approaches such as data envelopment analysis (e.g., Zhao *et al.* 2006) or computational modelling approaches (Muttli & Chau 2007; Wang *et al.* 2014). However, comparing technologies at the scale of the entire large country requires simultaneous consideration

of a broad spectrum of impacts. Assessing only one source of pollution and trying to eliminate it by switching technology creates the risk of shifting the impacts elsewhere. Life cycle assessment (LCA) is a methodology that allows a holistic consideration of environmental impacts across the full life cycle of products, processes and systems (Hellweg & Milà i Canals 2014) and is codified by the International Organization for Standardization (ISO 2006) and promoted by organisations such as United Nations Environment Programme (e.g., Milà i Canals *et al.* 2007). The method has been widely used for process design and optimisation as well as comparative assessments of different technologies fulfilling similar functions. Several previous studies looked at sanitation systems using LCA, both in developed (Benetto *et al.* 2009; Ishii & Boyer 2015) and in Developing & Emerging (D&E) countries (Cornejo *et al.* 2013; Lam *et al.* 2015). However, none of the results of previous research can be applied to assess the environmental impacts of a large-scale toilet building programme in India. This is due to relatively high population densities in India compared to other regions studied, differences in supporting infrastructure (e.g. WWTPs), as well as cultural differences (e.g., anal cleansing with water and pour-flushing are typical toilet practices).

This paper describes the use of LCA to identify emission hotspots and compare the environmental impacts as well as nutrient recovery potentials (NRPs) of four different technologies for large-scale provision of sanitation in India: centralised wastewater treatment, twin-pit latrine, twin-pit latrine with source-separation and biogas toilet. The study goal was to understand the scale of potential impacts depending on technological choices.

## METHODS

We followed the LCA methodology, according to the principles of the International Organization for Standardization's standard ISO14040 (ISO 2006).

Figure 1 presents the scope of analysis. The study covered the whole life cycle of a toilet and the associated waste treatment infrastructure. The following impacts were assessed:

1. Annual impact to construct and use a toilet and wastewater treatment infrastructure for an average household of 5.3 people (Government of India 2001).

2. The aggregated impact to construct 169 million toilets together with associated wastewater treatment infrastructure (i.e. to meet the estimated need in 2019 for improved sanitation in India).
3. The annual impact to operate 169 million toilets and treat generated waste.

The environmental benefits of materials recovered from human waste were considered through the system expansion approach, a method recommended by the International Organization for Standardization (ISO 2006). The underlying assumption is that the additional recovery of fertilisers for agriculture and biogas for cooking will reduce the future need for fertiliser and cooking fuel, avoiding the environmental impacts that would be related to their future production. The alternative allocation methods require partitioning of co-products and were identified as unsuitable for the goal of this study which assesses the forward looking situation. We have also considered results without any allocation.

## System boundary: sanitation technologies

Figure 2 presents a schematic representation of the technologies under study. Previous research has shown that sanitation interventions focusing on the provision of toilets do not guarantee positive health outcomes (Clasen *et al.* 2014). To ensure that toilets are used, it is necessary to adapt them to local practices. Following common habits in India, all the analysed scenarios considered provision of pour-flushing toilets. These toilets will use the same amount of water. As a result, the issue of water consumption was omitted from the scope of this analysis.

All technologies were assumed to be effective in reducing the exposure of humans to pathogens and constructed following best design principles, e.g., avoiding the contamination of surface, subsurface and ground water sources (World Bank 1992; Graham & Polizzotto 2013). WWTPs, pipes and pumping systems were assumed to be built at a sufficient rate to accommodate all the wastewater discharged from the newly built toilets to the sewage network.

Detailed description of all assumptions and data sources used for life cycle inventory (LCI) can be found in the Supplementary material (available with the online version of

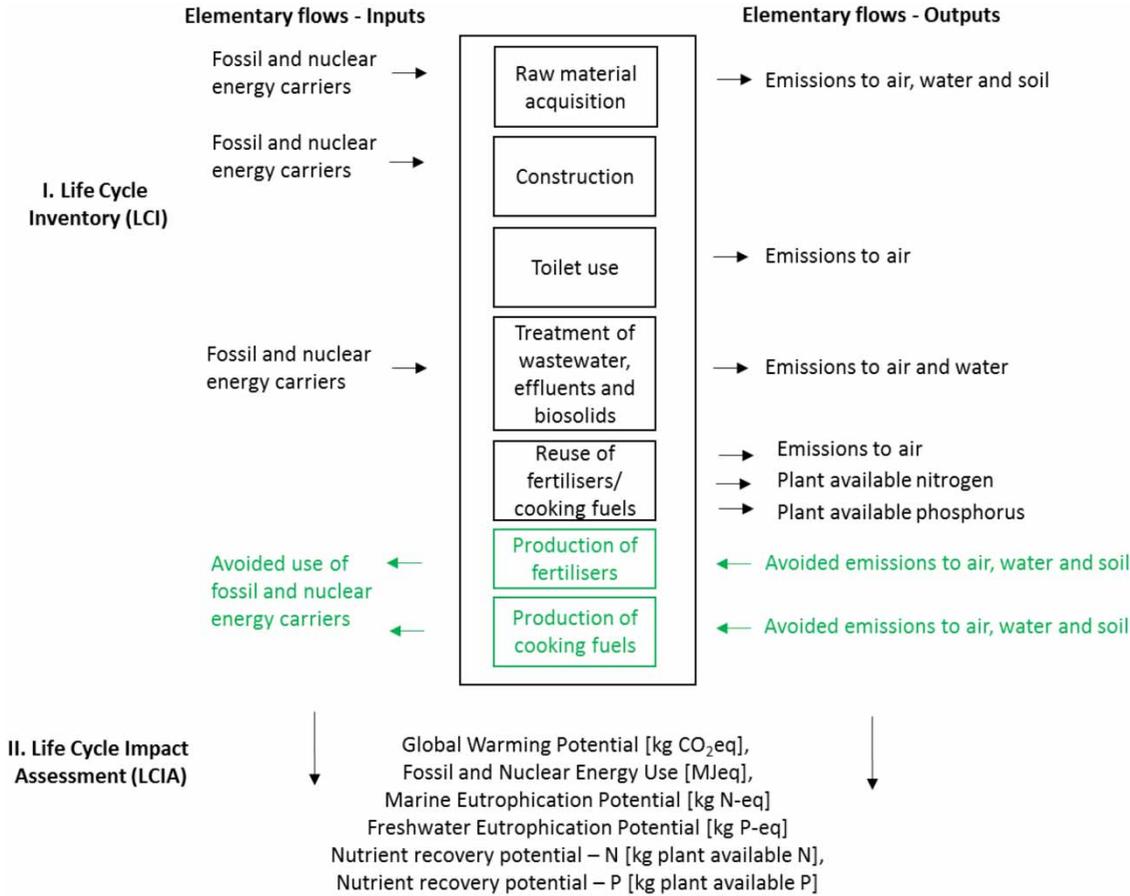


Figure 1 | Scope of the LCA study to assess environmental impacts and NRPs of scaling up sanitation in India.

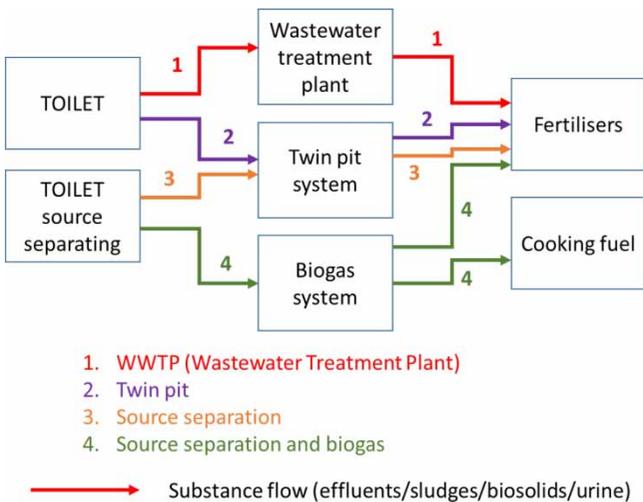


Figure 2 | Technological routes for closing the sanitation gap in India analysed in the LCA study.

this paper). The study was based on a combination of publicly available statistics and publicly available LCI data, mostly using the most comprehensive database of life cycle inventories – ecoinvent v3.3 (Moreno Ruiz *et al.* 2013). Data that have been developed specifically for India were used whenever available. Data on quantities of human waste and its molecular composition were obtained from the recent meta-analysis of Rose *et al.* (2015). The impacts of infrastructure were amortised. Fifty years is a typical amortisation period for buildings and thus was assumed for toilet superstructure (Kellenberger *et al.* 2007). WWTP was amortised over 50 years as well following Kalbar *et al.* (2014). Thirty years was assumed for a sewage network following Central Public Health and Environmental Engineering Organization (1999) and ten years for biogas

systems following [Singh \*et al.\* \(2014\)](#). Direct greenhouse gas (GHG) emissions to air were estimated using factors from the International Panel on Climate Change ([IPCC 2006](#)) and faeces composition data ([Rose \*et al.\* 2015](#)). In a sensitivity analysis, we have also tested the IPCC method based on average biological oxygen demand (details in the Supplementary material).

NRP for nitrogen and phosphorus was estimated as the mass of plant available nutrient that can be recovered from the sanitation system, based on the factors from the literature (details in the Supplementary material).

It is recognised that the four scenarios considered in this study do not represent all the options available for scaling up sanitation in India and that there might be other options available that may have higher or lower environmental impacts.

### WWTP with SBR

This scenario assumes that all the newly built toilets will be connected to the sewerage network and centralised wastewater treatment facilities with sequential batch reactors (SBR). SBRs were chosen as this was the only Indian system for which a complete LCI exists together with the construction and disposal of infrastructure ([Kalbar \*et al.\* 2014](#)). It is also a conventional wastewater system; it does not include recovery of energy although it does include some recovery of nitrogen and phosphorus through the application of sludge to agriculture. To estimate material needs for sewerage infrastructure in India, an average value of 1.3 m of sewers per capita was assumed. The value of 1.3 corresponds to the value for peri-urban areas of medium population density, as reported by [Sundaravadivel \*et al.\* \(1998\)](#). The impact of this assumption (the contribution from the construction of sewers to the total result) was investigated in a sensitivity analysis.

### Twin pit

Twin-pit latrine is connected to two leach pits – underground structures built of bricks and covered with a concrete slab with ventilating pipes. The excess liquid slowly infiltrates into the ground while the rest of the material degrades and turns into compost that is later reused in agriculture. The double-pit system allows alteration when one of the tanks is

filled. Details on construction materials can be found in the Supplementary material. The sludge was considered to be free of pathogens after three years of stabilisation and reused in agriculture as a fertiliser.

### Source separation

The source separation scenario considered the same twin-pit latrine design as in the previous scenario, but with squatting pan allowing separation of urine from the faeces. The faeces are flushed into the leaching pits while urine is collected into the storage container. After stabilisation, both urine and sludge are reused as fertiliser.

### Source separation and biogas

The biogas scenario assumes that the source separation toilet will be connected to a household-scale anaerobic digestion plant utilising faeces and kitchen waste as an input. Similarly to the previous scenario, urine is considered to be diverted and utilised as a fertiliser. The biogas produced is assumed to be used for cooking. Details on the construction and operation of the biogas plant can be found in the Supplementary material. The digestate from the biogas plant is also considered to be reused as fertiliser.

### Valorisation of recovered value streams

The value of recovered nitrogen, phosphorus and biogas was considered using the system expansion allocation approach. All scenarios consider that nutrients recovered from human waste will be used in agriculture, potentially replacing synthetic, water soluble fertilisers at a ratio of their current use in India. A similar approach was used to valorise biogas recovered from human waste. It was assumed that the biogas from the toilet will be utilised for cooking, replacing the currently used mixture of cooking fuels.

### Impacts

The following impact categories were considered in the analysis: global warming potential (GWP) over 100 years ([IPCC 2014](#)); fossil and nuclear energy use (FNEU) according to the lower heating value ([Frischknecht \*et al.\* 2007](#)); marine

and freshwater eutrophication potentials according to the ReCiPe methodology (Goedkoop *et al.* 2013); and NRPs for nitrogen (N) and phosphorus (P), defined as the amount of plant available nutrients that can be reused in agriculture. The potential for the recovery of nutrients is not typically considered in LCA, but we have added this additional impact category based on our own methodology (described in detail in the Supplementary material). India is facing a fertiliser deficit. The authors believe that life cycle thinking could be utilised to understand not only environmental, but to a certain extent, broader implications of technology adoption, like agricultural nutrient recovery.

### Limitations

LCA was initially developed to assess product systems and to guide process selection. These decisions are usually occurring at a small scale. The methodology has some limitations in assessing complex, inter-related systems at a large scale due to uncertainty. There are two sources of uncertainty: data and model. These uncertainties were analysed throughout the study and their potential influence on conclusions was assessed.

### Data uncertainty analysis

The influence of uncertainty in the inventory data on study conclusions was considered using Monte Carlo methods as implemented in Simapro software. It is a quantitative procedure common in LCA and it involves repeated random sampling of data points from assumed probability distributions to derive ranges of results. The ranges of uncertainty for data points were derived from the literature whenever available. In case of the lack of dataset uncertainty information, pedigree approach was applied as implemented in ecoinvent v3.3. Ten thousand runs were performed to derive uncertainty distributions for analysis at the household level. For the macro-scale analysis at the country level, 1,000 runs were conducted for each scenario.

### Model uncertainty analysis

The influence of assumptions on study conclusions was constantly analysed throughout the study using sensitivity

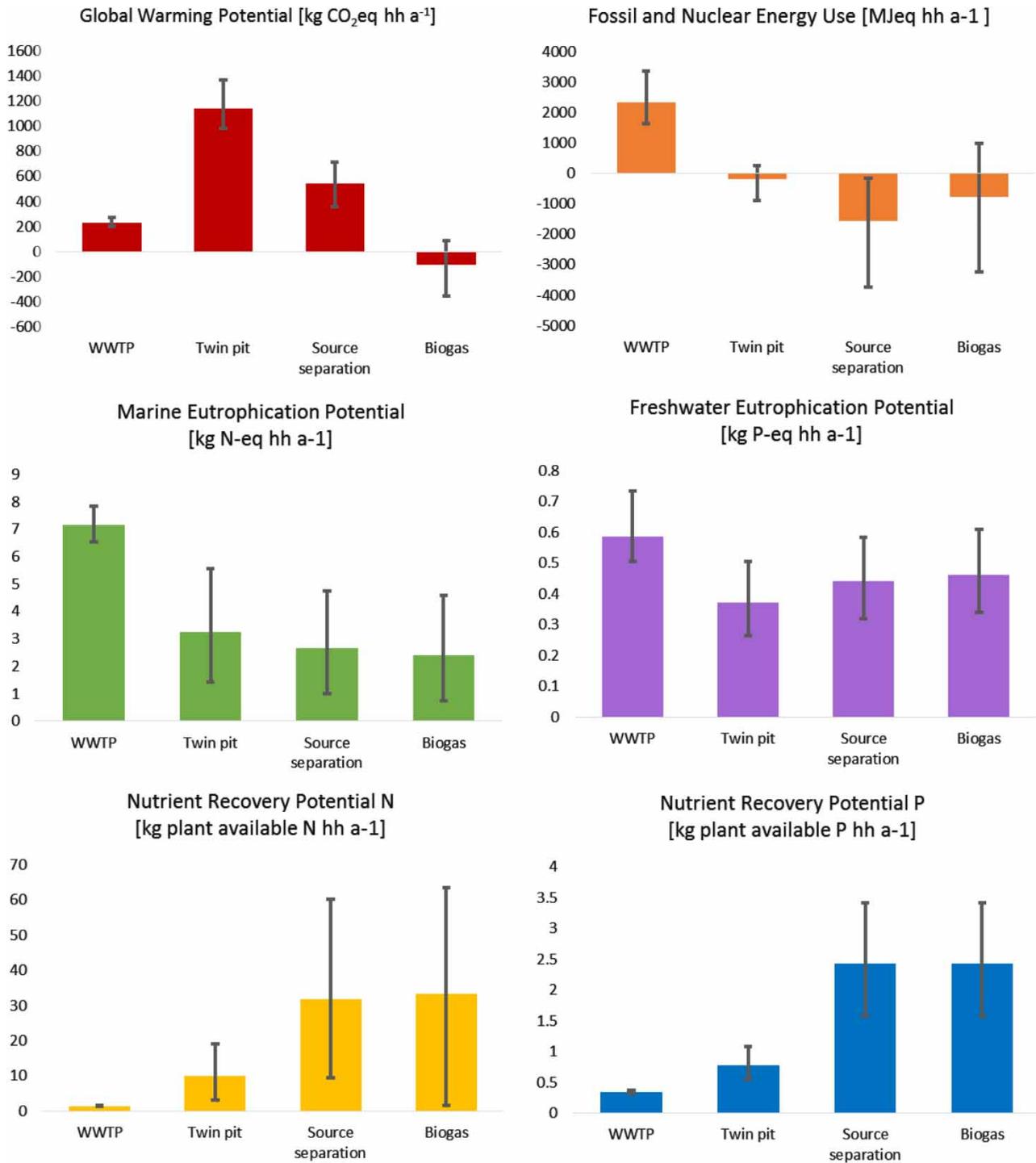
analysis. In case of uncertainty in the modelling or data choice, conservative choices were made that act at the disadvantage of conclusions. One of the key sources of uncertainty is emission factor for direct methane emissions from pit latrines (see Supplementary material for details on sensitivity analysis). For system expansion and amortisation, we analysed and present the results with and without those methodological choices.

## RESULTS

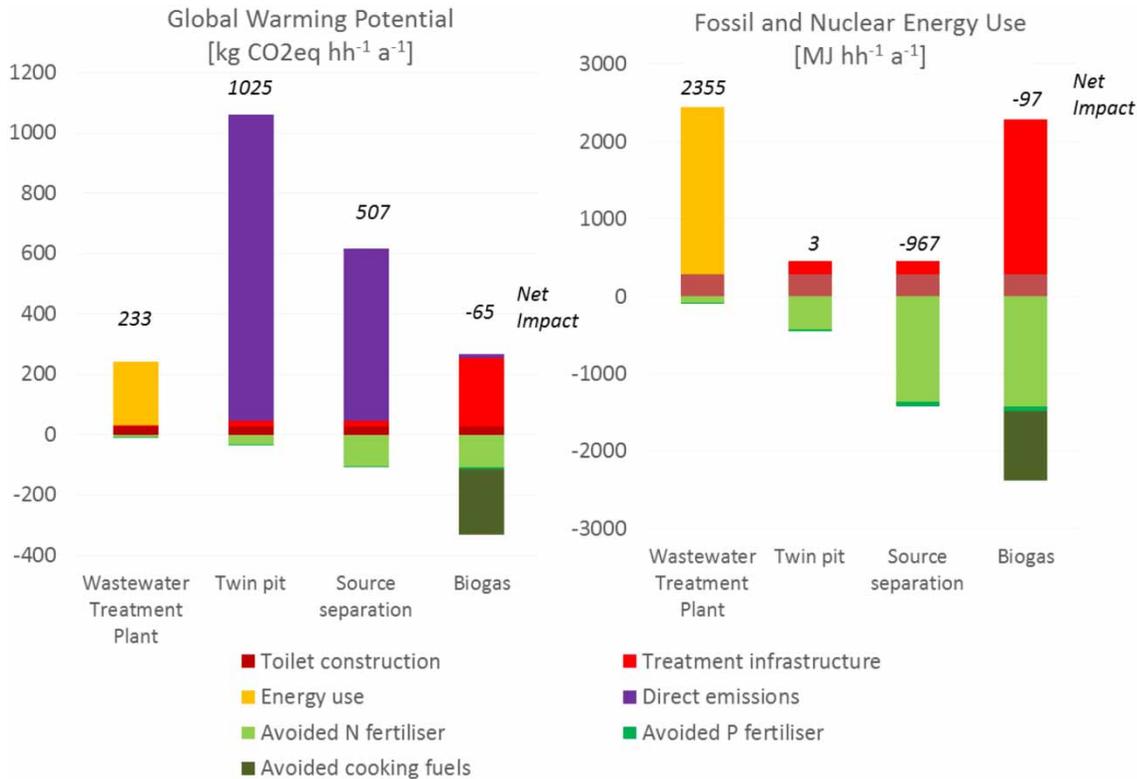
### Comparison across technologies

Figure 3 presents net results including uncertainty analysis while Figure 4 presents emission hotspots, allowing for the distinction between the impacts and credits from the recovery of valuable resources.

Results were characterised by large variability. For the GWP, the net results ranged from the mean annual emission of over 1 tonne of CO<sub>2</sub>eq for twin-pit latrine to a net reduction of 180 kg CO<sub>2</sub>eq for the biogas toilet. The relatively high impacts of twin-pit latrine were due to the direct emission of methane from anaerobic degradation of organic matter in the pit. Source separation showed as reducing these impacts by nearly half. Urine contains around 44% of the daily content of carbon. In a source separating system, this carbon will be removed from the pit and utilised in agriculture where the degradation is more likely to be aerobic. Fossil energy use was the highest for WWTP system due to energy use for operating the plants. Ignoring the offsets from nutrient and biogas recovery, the impacts of WWTP system and biogas system were similar for GWP and fossil energy use. This is due to relatively high use of material for the construction of biogas plants and relatively short lifespan (ten years) that was assumed. It is worth mentioning that ten years presents a conservative assumption and there are sources that indicate this type of biogas installation can last up to 15–20 years (Bagepalli Clean Development Mechanism Project 2007). Considering the value of recovered nutrients and biogas, the impacts of construction were shown to be entirely offset even under the ten-year lifespan.



**Figure 3** | Environmental impacts of sanitation systems at the household (hh) level per annum, including variability and uncertainty analysis (error bars represent 2.5th and 97.5th percentile from 10,000 Monte Carlo runs). Full life cycle including the construction of toilets and wastewater treatment infrastructure. WWTP, wastewater treatment plant with SBR.



**Figure 4** | Relative contribution to the GWP, and FNEU of sanitation systems at the household (hh) level per annum. Full life cycle including the construction of toilets and wastewater treatment infrastructure. Bars allow for the distinction between the estimated impacts (positive numbers) and estimated potential offsets (negative numbers). The net aggregated impacts are provided numerically in italics above the bars.

WWTP with SBR had the highest impacts on marine and freshwater eutrophication potential. The performance of other technologies was comparable for these impact categories.

Source separating systems showed significantly higher NRPs, especially for nitrogen. No difference was found for the three decentralised sanitation scenarios: twin-pit latrine, source separation and biogas in terms of phosphorus recovery. Results for nitrogen and phosphorus at the household level are associated with a high degree of variability due to large differences in elemental composition of urine and faeces between individual people. This variability does not affect the comparability of technologies at the scale of the whole country: the sum of a large number of individuals is expected to be close to the multiplication of the mean.

#### WWTP with SBR

The GWP of the WWTP scenario with SBR was found to be relatively low compared to twin-pit and source

separation, despite high impacts from energy use in wastewater treatment process. The fossil energy use of the WWTP system was the highest among the analysed scenarios due to the amount of electricity consumed for the operation of the WWTP. The wastewater treatment scenario was characterised by the lowest NRPs among the analysed technologies.

#### Twin-pit latrine

Although the construction and the use of a twin-pit latrine is not particularly energy intensive, the GWP was clearly the highest for this system. Regarding this impact, direct methane emissions from anaerobic degradation of wastes were identified as a clear environmental hotspot, accounting for more than 97% of the total annual impact from the construction and operation of a pit latrine. The impact of direct emissions alone was found to be nearly five times higher than the aggregated impact of a toilet connected to a centralised WWTP.

### Source separation

In this scenario, methane emissions were found to be lower compared to the standard twin-pit latrine with potential for higher nutrient recovery. Source separation of urine and faeces prevents 43% of carbon from entering the pit thereby reducing total methane emissions. The daily urine yield of a person contains six times more nitrogen than the faeces and the nitrogen in the urine is in soluble form that is readily available for plants. This means that the separation allows recovery of 95% of the total plant available nitrogen from the daily dose of human excrement.

### Source separation and biogas

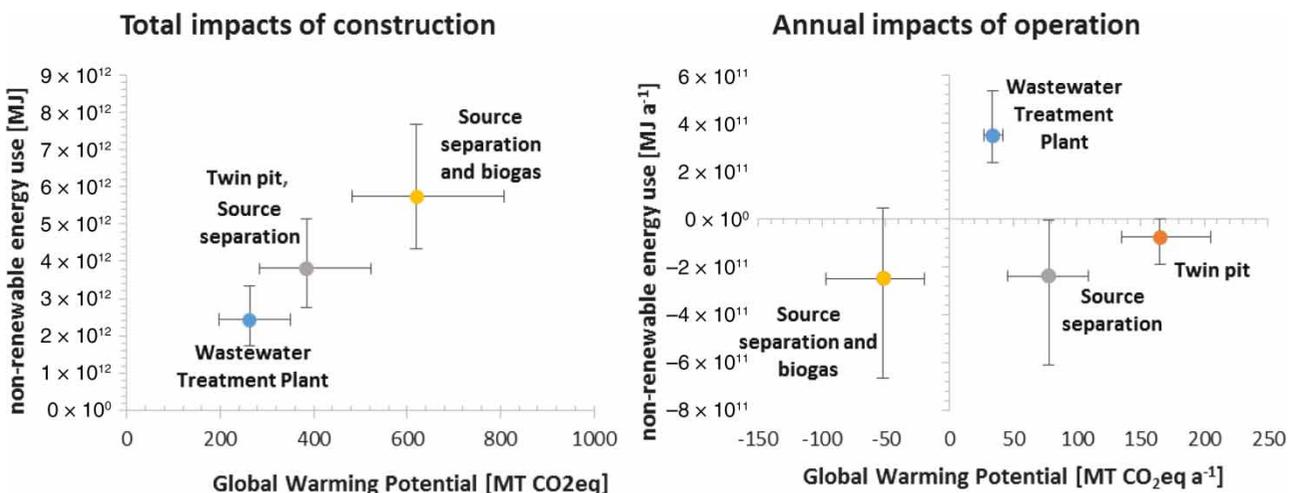
The biogas scenario had higher impacts from infrastructure compared to the alternative scenarios. This is due to the relatively large amount of raw bricks and mortar required for the construction of a household-scale biogas plant and the relatively short lifetime of a biogas plant. The basic conservative study assumption was that the biogas installation will have to be replaced every ten years. If life expectancy of the plant can be extended or if the biogas plant could be constructed from alternative materials with a lower environmental footprint, this would lead to a reduction of impacts. The potential GHG savings from recovered nitrogen, phosphorus and biogas were found to offset all the

fossil energy use and emissions associated with the construction of the plant.

### Cumulative impacts of closing the sanitation gap in India

Connecting all households in India to centralised wastewater treatment facilities would require construction of around 8,943 new WWTPs. Closing the sanitation gap with source separating toilets at this scale was estimated to be able to provide 3,885 ktonnes of plant available nitrogen and 378 ktonnes of phosphorus every year (Figure 5). This is a significant amount, corresponding to around 18% of the total annual projected nitrogen demand in India in 2019 and 4.9% of the demand for phosphorus (Government of India 2011). The net GHG emissions across systems including both operation and amortised construction ranged from -21 M tonnes CO<sub>2</sub>eq to +263 M tonnes per year. The latter number would correspond to about 7% of the annual GHG emissions of India in 2012 as provided by the World Resources Institute (WRI 2015) (baseline emissions including land use change). The annual direct methane emissions from pit latrines alone would have the potential to increase the GHG emissions of India by 6% compared to this baseline.

We have also estimated the needs for cooking fuels (details in the Supplementary material, available with the online version of this paper). Assuming that the family will



**Figure 5** | Environmental impacts of providing 169 million additional toilets in India. Split between impacts of construction on the left (no amortisation considered) and annual impacts of operation on the right. Error bars represent the results of uncertainty analysis (2.5th and 97.5th percentile from 1,000 Monte Carlo runs).

consume three cooked meals per day (conservative assumption for India), this would require 0.21 m<sup>3</sup> of biogas per person per day. The daily biogas yield of 50.8 L per person per day assumed in this study would be able to satisfy 24% of family cooking needs.

## DISCUSSION

Our study indicates that the choice of pit latrines for providing improved sanitation can significantly affect environmental impacts and nutrient availability at the country level. It is widely recognised that improper installation of pit latrines can result in contamination of groundwater with nitrate and phosphate (Graham & Polizzotto 2013). Our study assumed best-case installation practices and shows that, even under these conditions, pit latrines can lead to significant increases in GHG emissions. The global issue of current methane emissions from latrines was previously recognised by Reid *et al.* (2014). If countries invest further in building pit latrines without further management interventions such as methane capture, the scale of GHG emissions will increase. The issue of methane emissions may be particularly relevant to India, as pour flushing toilets are likely to be adopted and this leads to anaerobic conditions in the pit. Such negative impacts could be mitigated by investing in more innovative types of toilets that could reduce methane emissions to the air as well as provide nutrient recycling.

Although household-scale biogas systems have been shown to be an environmentally preferable option, there are some practical challenges related to their wide adoption. Constant supply of organic matter is necessary for an efficient production of biogas. The small quantity of daily household human waste (lack of sufficient supply of organic matter) may be a limit to their extensive adoption. Collecting and burning biogas at very small scale may also be inefficient. This challenge could be overcome by developing multi-feed household level digestors which are, additionally, able to take other organic household wastes (cattle dung, kitchen waste, etc.), or by investments in community-based biogas solutions. However, their installation introduces the need for additional organisational complexity, for example, solving the issue of ownership.

India is facing a fertiliser deficit. The projected demand for nitrogen and phosphorus pentoxide in 2019 is 1.6 times

greater than the current domestic production, and the government has put an action plan in place to increase the internal production capacity (Government of India 2011). Source separation toilets could provide a significant amount of nutrients for farming. Provided that appropriate infrastructure and safety procedures are in place, this could contribute to the reduction of cost for the government for fertiliser imports and contribute to food security.

This study investigated only four potential scenarios. It is acknowledged that there are other, potentially more efficient technologies for centralised wastewater treatment than the one analysed in this study. There is already a number of more efficient centralised upflow anaerobic sludge blanket digestion reactors that can have significantly lower energy consumption and GWP than SBR systems (Kalbar *et al.* 2013). For highly urbanised urban areas, either centralised or container based systems may be the most appropriate solutions. An effort should be put in place for redesigning them further to reduce energy use and emissions and increase nutrient recycling. On the decentralised side, initiatives such as the 'Reinvent the toilet challenge' sponsored by the Bill and Melinda Gates Foundations, led to the development of new, innovative toilet systems for low-income consumers that can efficiently recycle nutrients or even water (e.g., Cranfield University 2012). As demonstrated in the present study, LCA can successfully be used to investigate environmental and nutrient recovery benefits of such technologies. LCA studies can be used to inform engineers developing them by highlighting opportunities for further system improvements. It can also provide useful information to donors and investors about the environmental benefits of a particular technology. This is particularly important for impact investors interested in supporting more sustainable technologies or for those who want to reduce exposure of their portfolio to the environmental risks created by polluting technologies.

## CONCLUSIONS

Everyone should have access to safe sanitation, but decisions over how to provide it will have important sustainability implications.

Depending on the choice of sanitation technologies, providing everyone in India with access to improved sanitation

can have significantly different environmental impacts. We estimate that providing source-separating toilets with biogas could lead to net reductions of GHG impacts while closing the sanitation gap with twin-pit latrines would lead to a significant increase in net GHG impacts.

Direct methane emissions from pit latrines present a clear hotspot for GHG impacts. If all newly built toilets are pit latrines, these emissions alone can increase India's annual GHG emissions by over 6% compared to 2012 levels.

Closing the sanitation gap with nutrient recycling systems can potentially offset GHG emissions while satisfying up to 18% of all nitrogen and 5% of phosphorus fertiliser requirements of India. Although the practical approaches to recover the full amount of nutrients may not yet be available, innovations that can recover portions of the nutrients must be supported.

Household-scale biogas plants utilising toilet waste and kitchen waste have the potential to offset nearly all GHG emissions from construction over ten years and satisfy a large proportion of daily household fuel requirements for cooking.

For future research we recommend extending the scope of the study to more centralised and decentralised wastewater treatment technologies. Other areas worth further investigation are verifying estimates of direct methane emissions by direct field measurements and investigating nitrate leaching potential of twin-pit latrines – currently assumed to cause no water contamination.

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