Science of the Total Environment 799 (2021) 149339

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Phosphorus circular economy of disposable baby nappy waste: Quantification, assessment of recycling technologies and plan for sustainability

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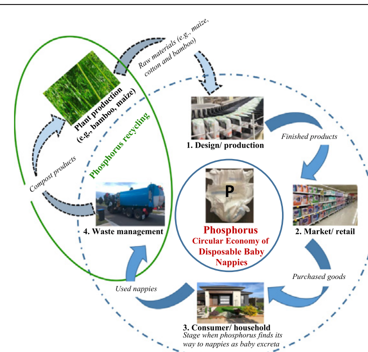
HIGHLIGHTS

- Australia lost 5452 tonne phosphorus (P) in baby nappy waste in 2001–2019.
- P recovery is overlooked in most of the recycling technologies for nappy waste.
- Composting, pyrolysis, and polymer separation are common nappy recycling methods.
- Use of nappy waste compost for bamboo and cotton production can close the loop.
- New product and system design can help achieve P circular economy of nappy waste.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 1 June 2021
Received in revised form 25 July 2021
Accepted 25 July 2021
Available online 30 July 2021

Editor: Frederic Coulon

Keywords:
Circular economy
Phosphorus recycling
Baby diapers
Substance flow analysis
Human waste management
Sustainable design
Environmental management

ABSTRACT

This study assessed the potential for minimizing human excreta bound phosphorus (P) loss through used disposable baby nappies, an area that remained unexplored for nations. Accordingly, it performed a substance flow analysis to assess the national P loss through used disposable baby nappies in the case of Australia. The analysis revealed that approximately 308 tonne P is lost through used baby nappies to landfills in Australia in 2019, which is nearly 2.5% of the overall P excreta as human waste. Although the quantity seems small in percentage term, it could result in the loss of a significant amount of P over several years, as assessed 5452 tonne P over the 2001–2019 period, which is concerning in the context of anticipated future global P scarcity. The review of peer-reviewed literature on available technologies/methods for recycling disposable baby nappy waste indicates that there are some technologies for recycling P particularly through co-composting with food and other organic wastes, while the majority of these are still at the lab/pilot scale. There are also various recycling techniques with purpose ranging from energy recovery to volume reduction, generation of pulp, hydrogel, cellulose, and polymer as well as to increase yield stress and viscosity of concrete, however, these are not effective in P recovery. The study implies that compost made of nappy waste can be used as fertilizer to produce bamboo, cotton, and maize plants to supply raw materials for producing biodegradable nappies, hence, to close the loop. The various product and system design options e.g., designing for flushing, designing for disassembling the excreta containing part, and designing for community composting suggested in this study could be further researched for identifying best suitable option to achieve P circular economy of disposable baby nappies. This study also recommends necessary interventions at various stages of the nappy life cycle to ensure sustainable management of phosphorus.

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https://doi.org/10.1016/j.scitotenv.2021.149339
0048-9697/

1. Introduction

Phosphorus (P) is a non-substitutable essential element for the growth and survival of all living organisms including plant, animal and microorganisms. The modern global food production system is heavily reliant on the application of commercial P fertilizers, which mainly sourced through the mining of phosphate rock, a non-renewable and geographically restricted resource. The dwindling global reserves of phosphate rock with a lifetime of few hundred years is restricted to only a few countries (mainly Morocco with approximately 75% of the global reserves) and the majority of the countries rely on P import for food production. The increasing demand of P for producing food for growing global population, the dwindling reserves, and geopolitical constraints likely to create P scarcity in future and farmers of many countries (mainly economically poor and developing countries) may lose their access to commercial P fertilizers, which may ultimately result in food insecurity (Chowdhury et al., 2017). The excessive loss of P from the agricultural and waste management systems to water bodies around the world not only resulting in the depletion of the limited global P resource but also destroying valuable aquatic ecosystems and water resources by causing algal bloom and eutrophication, which is clearly evident from many recent studies (Chowdhury et al., 2017). The importance of minimizing P loss from various systems particularly the waste management system for the sustainable management of this limited global resource is well-known (Rahman et al., 2019).

The available substance flow analyses of P indicates that worldwide, nearly 17% of the mined P is consumed in human food, which ultimately ends up in human excreta (Cordell et al., 2009; Rahman et al., 2019). Although the importance of P recovery from human excreta that is collected and managed through the wastewater collection and treatment systems in many countries was addressed in numerous literature (Harder et al., 2019; Metson et al., 2018), the fraction of P in human excreta that is lost through disposable baby nappies in a country was not assessed in any of the available substance flow analyses of P that published in peer reviewed journals (Chowdhury et al., 2014; Rahman et al., 2019). Hence, there is a clear knowledge gap of understanding the magnitude of P loss through used disposable baby nappies to landfill for nations. Disposable baby nappies (shortened term for baby napkins, and referred to as diapers in some countries) are the absorbent hygiene product that is mainly used by infant and toddlers to retain urine and feces until they are prepared to use a sanitary facility to dispose of human excreta (mostly up to 2 to 3 years). A snapshot of the components/structure of commonly used baby nappies as presented by Khoo et al. (2019) is provided in the Supplementary Fig. S1 (see Appendix A. Supplementary material 1). The tendency to use disposable baby nappies has increased over time. The global production of disposable nappies is expected to increase to US$ 71 billion per annum by 2022 from US$ 54 billion in 2016 (Markets Insider, 2018). Disposable baby nappy waste that mostly ends up in landfill is currently a big burden for municipal solid waste management in many countries. Our preliminary literature search confirmed that there is a lacking of literature to provide a clear understanding of the potential for P recovery from baby nappies. We are also unaware of a thorough review of available recycling technologies/methods for disposable baby nappy waste to understand the beneficial aspects and limitations, and to assess the methods that are effective in recovery and recycling of P and other nutrients.

Therefore, the objectives of this study are to

i) Quantity of P that is lost through used disposable baby nappies in the case of Australia using basic substance flow analysis approach.
ii) Conduct a systematic review of available recycling methods/technologies of disposable baby nappies worldwide to identify the suitable techniques for P recovery, the limitations/challenges of existing methods in terms of nutrient recovery, and potential areas for improvement. and
iii) Based on that review, present necessary interventions at the various stages of the nappy life cycle to ensure P circular economy.

2. Methods of analysis

2.1. Quantification of P flow through disposable baby nappies in Australia

2.1.1. Method considered for the quantification of P flow

For the quantitative analysis of P flow through disposable baby nappies at the national scale for Australia, this study utilized the methods of substance flow analysis (SFA) that applies the principle of mass balance to assess the flows and stocks of substance in a system defined in space and time (Van der Voet, 2002; Brunner and Rechberger, 2016). The basic steps of this method are: i) Define systems and subsystems, and a selection of system boundaries, ii) define material and process flows associated with each system and subsystem, iii) collect quantitative data on material/process flow and concentration of substance in each materials/process, iv) analyse the data for calculating substance flow and storage using appropriate software modelling, v) assess the reliability and uncertainty of the results, and vi) interpret the results and provide decisions.

2.1.2. Defining system and system boundaries and pathways of flows

The system considered for the current analysis of P loss through used disposable baby nappies in Australia is the food consumption and waste management system. The pathways of P flow across the system and subsystems considered and associated system and subsystem boundaries are presented in Fig. 1. A multi-year (2001–2019) time scale is considered as the temporal scale for analysis.

2.1.3. Data utilized and assumptions considered for the quantification of P flow

Data utilized for the quantification of P flow is baby population data according to the Australian Bureau of Statistics data on estimated resident population by single year of age (ABS, 2019) and the rate of daily P intake data according to 2011–12 Australian Health Survey: Nutrition First Results – Foods and Nutrients (ABS, 2014). This is to clarify that for baby population data, three age ranges are considered i.e., 0 (0 to <1 year), 1 (1 to <2 year), and 2 (2 to <3 year). The reason for considering that age group is, in Australia, potty trainings to babies are given approximately at the age between 2 and 3 years as confirmed based on the review of available reports published online; therefore, nappies are usually used for babies until they turn 3 years. However, in Australia, approximately 95% of the parents use disposable nappies (ABC News, 2015), while the rest use cloth nappies or reusable nappies. Therefore, for this calculation, this study considers 95% population of the (0 to 2 years) age group. Most of the P intake as food in human bodies eventually ends up in human excreta (Cordell et al., 2009; Cordell et al., 2013), therefore, this study consider 95% of the P intake ended up in human excreta. The rate of daily P intake for each age range is determined based on the calculated 'average rate of increment in P intake with age' according to 2011–12 Australian Health Survey data as mentioned above (see Appendix A. Supplementary material 2 for data and calculations). The majority of the human excreta mainly for population of age 3 year or above ends up in wastewater treatment plants, while the baby nappy bound human excreta mostly collected through solid waste stream and eventually ends up in landfill if not systematically recycled. The assumptions considered in this study may vary from nation to nation depending upon the situation of baby nappy use.

2.1.4. Calculation of P flows

The calculation was done by multiplying the total number of baby population of each age range in Australia with the rate of daily P excreta by each baby of that age range and then multiplying the product by 365

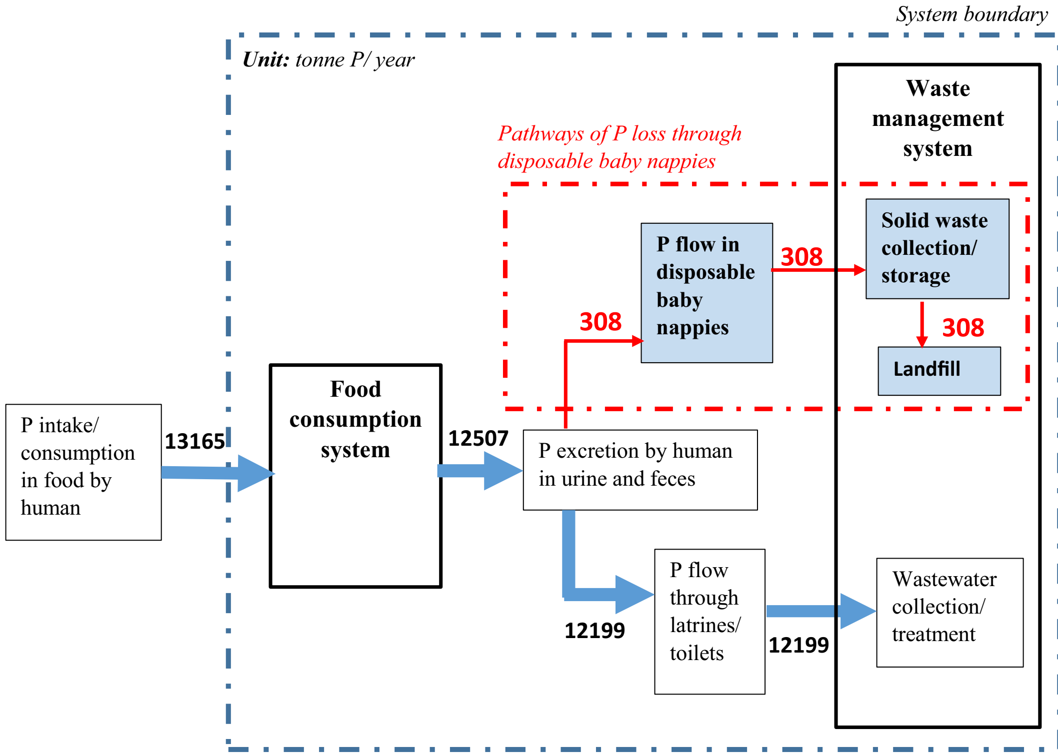

Fig. 1. Schematic representation of the pathways and magnitudes annual national P loss (in tonnes) through used disposable baby nappies in 2019 in Australia.

days to obtain the total annual P loss for a particular year for the babies of that age range. Similarly, we calculated total P loss for babies of other age ranges for that particular year and finally summed up the P loss for all age ranges to obtain the total loss for Australia. The methods of calculation for P flow through disposable baby nappy waste for Australia is briefly presented below:

i) Calculation of baby population that use disposable baby nappies
Total baby population of age 0 to <1 year = A_1
Total baby population of age 1 to <2 year = A_2
Total baby population of age 2 to <3 year = A_3

Considering disposable baby nappies are used for 95% of the total baby population;
Total baby population of age 0 to <1 year that uses disposable baby nappy = $B_1 = 0.95 \times A_1 = 0.95A_1$
Total baby population of age 1 to <2 year that uses disposable baby nappy = $B_2 = 0.95 \times A_2 = 0.95A_2$
Total baby population of age 2 to <3 year that uses disposable baby nappy = $B_3 = 0.95 \times A_3 = 0.95A_3$

ii) Calculation of P excretion rate
Daily rate of P intake in food by a baby of age 0 to <1 year = C_1
Daily rate of P intake in food by a baby of age 1 to <2 year = C_2
Daily rate of P intake in food by a baby of age 2 to <3 year = C_3

Considering nearly the entire P intake (95%) as food by human ends up in excreta;
Daily rate of P excretion (in urine and feces) by a baby of age 0 to <1 year = $D_1 = 0.95 \times C_1 = 0.95C_1$
Daily rate of P excretion (in urine and feces) by a baby of age 1 to <2 year = $D_2 = 0.95 \times C_2 = 0.95C_2$
Daily rate of P excretion (in urine and feces) by a baby of age 2 to <3 year = $D_3 = 0.95 \times C_3 = 0.95C_3$

iii) Calculation of annual P flow in used disposable baby nappies
The total annual P flow through baby nappy waste for Australia = $(B_1 \times D_1 \times 365) + (B_2 \times D_2 \times 365) + (B_3 \times D_3 \times 365) = (0.95A_1 \times 0.95C_1 \times 365) + (0.95A_2 \times 0.95C_2 \times 365) + (0.95A_3 \times 0.95C_3 \times 365)$.

Depending upon the complexity of the analysis, specific software for modelling or quantification of P flow could be used. In some of the previous analyses, for performing SFA of P, various types of software e.g., STAN (Roy et al., 2019), MATLAB/Simulink (Chowdhury et al., 2016), and MS Excel and STAN (Baroi et al., 2020) were utilized. Considering that the current analysis is comparatively less complex, MS Excel software was utilized for the calculation of P loss (for all of the years considered) following the methods explained above (see Appendix A. Supplementary material 2 for data and calculations).

2.1.5. Approach for reliability assessment

To check the consistency of the results, we utilized an alternative data on the rate of P excreta that is the rate of P production per capita per year according to Mihelcic et al. (2011) who estimated the global potential for P recovery from human urine and feces. The results of both calculations were then systematically compared to check the consistency (see Appendix A. Supplementary material 2 for calculations details).

2.2. Review of different technologies for recycling baby nappies

2.2.1. Approach for search and selection of literature for review

For the current review, in order to identify peer-reviewed journal articles that assessed different technologies/methods for recycling disposable baby nappies, we performed a thorough search using Google Scholar and Scopus database. The key words used for search are 'recycling of baby nappies or diapers', 'recovery of nutrients from baby nappies', 'phosphorus recovery from baby nappies', 'composting of baby nappies', 'sustainable management baby nappies' and 'circular economy of baby nappies'. Through a quick reading of the title and abstract (if needed) for each article, we have initially screened 45 journal articles from around the world that somewhat addressed the recycling of baby nappies, and finally, we have selected 22 studies following the below criteria to perform a thorough review:

i) The article adequately assessed/explained a particular technology or method for recycling baby nappies or resource recovery from baby nappies.
ii) The article published in peer-reviewed journals in English between 2010 and 2020 that captured the recent advancement in recycling of baby nappies.
iii) Information necessary to perform the current review is possible to extract and organize in a systematic order.

2.2.2. Approach for extraction of key information from selected literature

To perform an in-depth and systematic review, we have developed a methodical approach that allows extracting all key information from the selected articles for this review. In this approach, we have initially dissected each journal articles into three major parts i. Purpose and methodology, ii. findings/results and discussion, and iii. recommendations and future research needs, and did careful reading of each part to extract the key information. We eventually came up with a tabular structure with a number of columns with headings i.e., 'recovery/recycling technology or method used', 'location of the study', 'considerations for recycling (nutrient recovery/minimizing waste volume)', 'extent of application (lab/pilot project/industry scale)', 'positive/beneficial aspect' and 'limitations' that allowed to systematically capture the key information from each of the selected article.

3. Results and discussion

3.1. Quantitative picture of national P loss through baby nappies in Australia

Each year, around 2 billion disposable baby nappies are used in Australia that eventually ends up in landfills (ABC News, 2015), with traditional disposable baby nappies estimated to take up to 150 years to break down (Sustainability Victoria, 2021). The human excreta (urine and feces) that ends up through baby nappies in Australian landfill also cause the emission of methane, a greenhouse gas that is 21 times more potent than Carbon dioxide. By weight, nearly 75% of the used baby nappies is urine (Colón et al., 2011), containing a considerable amount of P (Mihelcic et al., 2011). Thus, a substantial amount of human excreta bound P and other nutrients (e.g., nitrogen) also ends up in landfills through disposal of used baby nappies. Although a number of city councils (local government administrative bodies) in Australia currently offer rebates to households that switch to cloth nappies from disposable baby nappies mainly with the aim to reduce the amount of wastes reaching to landfills (Cook, 2021), initiatives for the recovery and recycling of P and other nutrients from disposable baby nappies are still lacking.

The first substance flow analysis of P relating to disposable baby nappies in Australia as performed in this study indicates that nearly 308 t of P ended up in landfill areas in 2019, which accounts for approximately 2.5% of the overall P (12,507 t) excreted as human waste in that year (Fig. 1). Although the amount looks small in percentage term for a single year, if not recovered and recycled through a circular economy approach, this could result in the loss of a significant amount of P over a longer term. The multi-year analysis of P loss through baby nappies as presented in Fig. 2 indicates that over the period of 2001–2019, nearly 5452 t of P was lost in landfill areas of Australia. Considering P is a non-substitutable, non-renewable/finite, and geographically restricted resources and the urgency of closing the loops in the global P cycle (Cordell et al., 2009; Chowdhury et al., 2017), recovering and recycling that amount of P is essential. Moreover, considering the associated life cycle environmental impacts (Ng et al., 2013; Cordella et al., 2015), systematic recycling of disposable baby nappies is much required. Although the application of circular economy approaches for recycling baby nappies is underway (Khoo et al., 2019; Mendoza et al., 2019), it is essential to consider the perspective of P loss associated with baby nappies and finding recycling techniques or methods effective in recovery of nutrients along with other elements. Compared to other pathways of P floss mainly from the agricultural system such as soil erosion and runoff loss, it is comparatively easier to track down and manage P flow associated with baby nappies as systematic collection of household wastes and recovery of P through formal municipal waste management system is possible (Rahman et al., 2019).

This study only presents the quantitative picture of P loss through baby nappies in the case of Australia. However, other developed nations with similar socio-economic conditions likely to have more or less similar types and magnitudes of P loss through baby nappies. Utilizing the conceptual model that present systems and system boundaries and pathways of P flow through baby nappies (Fig. 1) as well as the methods for calculation of P flow as presented in this study, similar quantitative assessments should be performed for other economically developed countries where disposable baby nappies are commonly used. Accordingly, it is required to perform a SFA for quantifying the total global P loss through baby nappies, which could be done in our future study. Currently, there is a clear knowledge gap in this regard.

3.2. Review of available technologies/methods for recycling disposable baby nappies

The review of available published peer-reviewed journal articles on various baby nappy recycling technologies/methods as presented in Table 1 helped to understand the potential and limitations in terms of P and other nutrient recovery.

3.2.1. Technologies/methods suitable for nutrient recycling

A number of studies attempted to understand the potential for recycling baby nappies through composting with food and other organic wastes. For instance, Tsigkou et al. (2020a) examined the potential for composting of anaerobic sludge from the co-digestion of used disposable nappies and expired food products, while Colón et al. (2011) assessed the potential for composting of nappies with source-separated organic fraction of municipal solid waste (OFMSW). Although both composting methods were found quite suitable for nutrient recovery, they have some beneficial aspects and limitations as presented in Table 1. For instance, the composting method of Tsigkou et al. (2020a) identified inability to eliminate harmful bacteria like Salmonella and Enterococcus spp. due to low composting temperature as one of the limitations, while the study of Colón et al. (2011) found slightly higher concentration of zinc as the shortcoming.

In an experiment of composting of door-to-door collected organic fraction of municipal solid waste with a 3% w/w (weight per weight) of compostable nappies in Barcelona, Spain, Colón et al. (2013) identified that both the composting process and the final compost product are not altered by the use of compostable nappies in some important aspects like the content of pathogen, stability and elemental (e.g., nutrient and heavy metal) composition. Although they suggested the use of compostable nappies as a real alternative to disposable nappies with no technical issues, they emphasized on the need for a complete life cycle assessment (LCA) of all the processes to assess the sustainability and environmental impact. Another study of the Municipality of Coroico in Bolivia, where the organic fraction (fecal residues and cellulosic polymers) is separated from the plastic part and composted that with locally available components like cow dung, activated bacteria, and Californian red earthworms. Although this was the first approach for utilizing

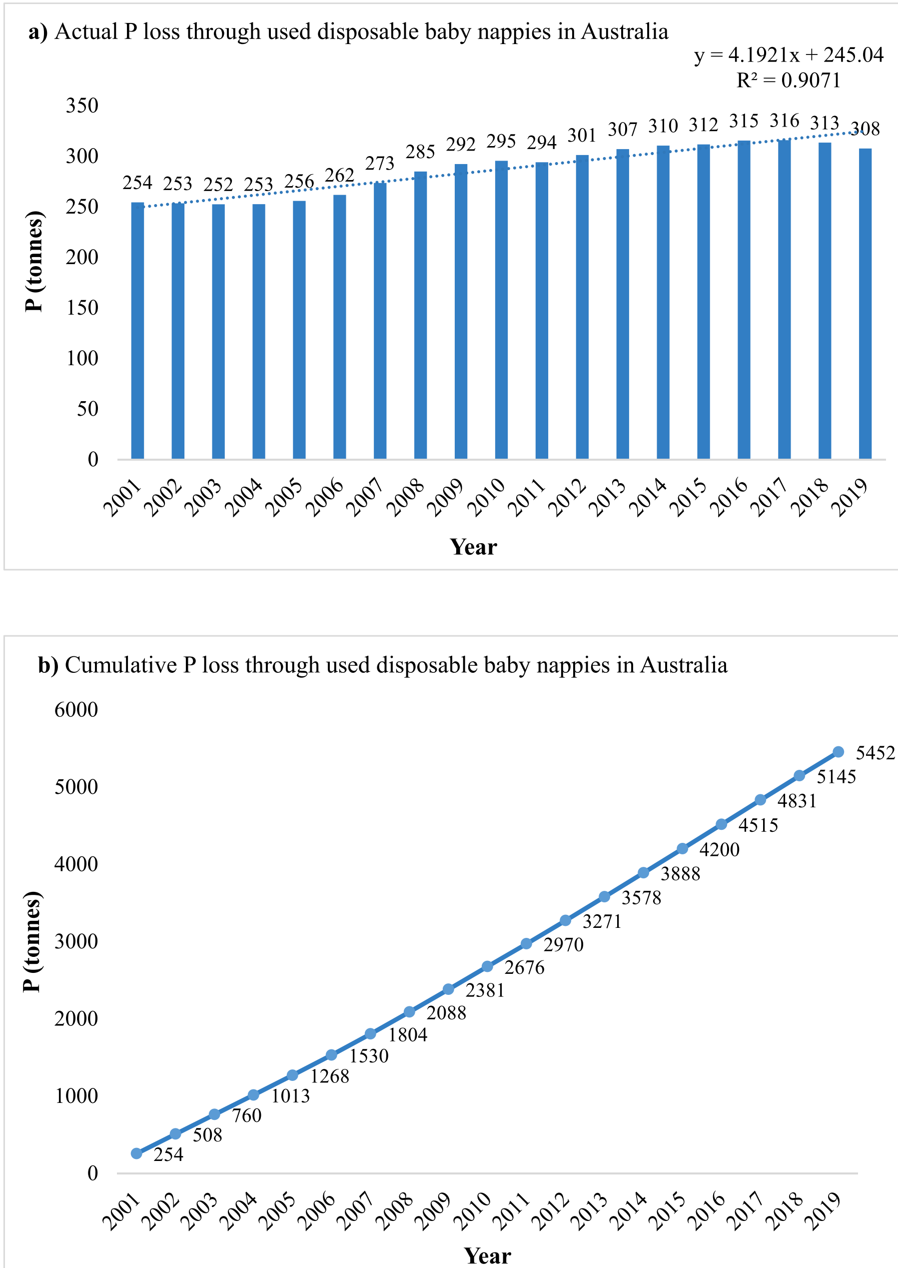

Fig. 2. Magnitudes of annual (a) actual P loss and (b) cumulative P loss through used disposable baby nappies in Australia.

vermicomposting for treating disposable nappies, they found it a suitable approach for circular economy. Another interesting approach which is also suitable for nutrient recovery from used disposable nappies was examined by Nobel and Han (2020) where cellulose and superabsorbent polymers in baby nappies are broken down through soaking shredded nappies in various concentration of sodium hydroxide solutions to release nutrients from urine and feces to the solution. The risk of pathogen borne disease from vegetables produced using fecal sludge is often a key concern (Butte et al., 2021). Espinosa-Valdemar et al. (2011) experimented the biodegradation of used baby nappies by the fungus Pleurotus ostreatus (Oyster mushroom) in Mexico and found that harvested mushrooms had good appearance and protein content, and were free of human disease pathogens. Similar outcome was observed by another study by Ma et al. (2020) in Terengganu, Malaysia that used nappy and food waste as growth substitute for Oyster mushroom. Both studies also indicated significant reduction of weight of biodegradable materials.

3.2.2. Technologies/methods suitable for recycling of other resources

Apart from the technologies and methods suitable for recycling of P and other nutrients, a number of other recycling technologies/methods for baby nappies also reported as presented in Table 1. For instance, Ichiura et al. (2020) examined the possibility of recycling disposable nappy waste pulp after dehydrating the superabsorbent polymer through oxidation using ozone. They observed that the water-absorptivity of the recovered pulp was almost the same as virgin pulp and was higher than the standard value of 10 g/g (grams per gram). Almeida et al. (2019) attempted to identify the composition of each layer of disposable baby nappies and employed thermal analytical techniques TG (Thermogravimetry)/DTG (Derivative thermogravimetry)/

Table 1
Types of used disposable baby nappy recycling technologies/methods reported worldwide, their potential for nutrient (phosphorus) recovery, beneficial aspects, and limitations.

Recovery/recycling technology or method	Country/city/region	Consideration for phosphorus and other nutrient recovery and recycling	Beneficial aspect	Limitation	Reference
Composting of anaerobic sludge from the co-digestion of used disposable nappies and expired food products	Greece	Phosphorus and nitrogen recovery addressed	Stable compost products Heavy metals within acceptable limit	Unable to eliminate harmful microorganisms like Salmonella and Enterococcus spp. Significant losses of nitrogen from digestrate	Tsigkou et al., 2020a
Composting of nappies with source-separated organic fraction of municipal solid waste (OFMSW)	Barcelona, Spain	Phosphorus recovery not addressed but nitrogen recovery addressed	Compost without and with nappies were identical in terms of stability, maturity and phytotoxicity Showed no presence of pathogenic microorganisms	Slightly higher concentration of zinc in compost Uncertainty derives from the unknown behavior of superabsorbent polymers in soil	Colón et al., 2011
Composting of door-to-door collected OFMSW with a 3% (w/w) biodegradable nappies	Barcelona, Spain	Phosphorus recovery not addressed but nitrogen recovery addressed	The composting process and the final products were not altered in main aspects such as stability, pathogenic content, and elemental composition	Only applicable to compostable nappies	Colón et al., 2013
Composting of the organic nappy hydrogel through vermicomposting process	City of Coroico, Bolivia	Phosphorus, nitrogen and other nutrient recovery addressed	Shorter treatment time Increase the number of earthworms. Compatible with poor technical and financial resources	Did not address heavy metal contents	Ferronato et al., 2020
Takakura composting method	Indonesia	Phosphorus, nitrogen and potassium recovery addressed	Require small space, less odor, and easy to conduct because waste produced can be directly processed at any time without special treatment The quality of the compost produced met the composting standard	Quality of compost did not indicate a direct proportionality with the number of disposable nappies added	Zulfikar, 2019
Biodegradation by the fungus Oyster mushroom (Pleurotus ostreatus)	Mexico	Phosphorus and nitrogen recovery not clearly addressed, however it is likely to be possible as mushroom grew well	Weight and volume of degradable materials were reduced up to 90% Harvested mushrooms had good appearance and protein content, and were free of pathogens	Not addressed	Espinosa-Valdemar et al., 2011
Used nappy and food waste as growth substitute for Oyster mushroom	Terengganu, Malaysia	Phosphorus, nitrogen and potassium recovery addressed	Reduced the weight of growth substrate up to 40% Mushroom had similar metabolite profile to that cultured by commercial media No accumulation of toxic and biological substrates	Not addressed	Ma et al., 2020
Valorization of biomass and nappy waste into high nutrient growth substrate for medicinal mushroom Lingzhi (Ganoderma lucidum)	Terengganu, Malaysia	Phosphorus, nitrogen and other nutrient recovery addressed	Nappy core acted as good moisture control agent and nutrient booster for the Lingzhi mushroom Higher mycelium spreading rate and high quality Lingzhi mushroom produced Significant reduction of waste going to landfill	Variable elements e.g., pH, temperature need to be optimized	Khoo et al., 2021
Small-scale biological composting with yard waste	Mexico	Phosphorus recovery not addressed but nitrogen recovery addressed	Up to 87% mass reduction for nappies was possible, and only the plastic films were recovered The compost had good quality and met the limits set in the local regulation and could be effectively used as a soil amendment as examined by the phyto-toxicity tests using tomato	Slightly higher pH level	Espinosa-Valdemar et al., 2014
Nutrient solution extraction from used disposable nappies	Not clear	Phosphorus, nitrogen and potassium recovery addressed	Effective in nitrogen and phosphorus recovery, removal of pathogen, and making plant available nitrogen	Not addressed	Nobel and Han, 2020
Dark fermentation of used disposable nappies and expired food products under different pH values	Spain	Phosphorus and nitrogen recovery addressed	Can produce hydrogen and volatile fatty acids Optimum hydrogen production occurred at pH 6 and maximum volatile fatty acid production occurred at pH 7 Allows valorization of volatile fatty acids	Cost of Sodium hydroxide (NaOH) addition had significant impact on the net economic potential	Zagklis et al., 2021
Pyrolysis	South Africa	Nutrient recovery not addressed	Help to recover pyro-oil, pyro-gas and pyro-char	Not addressed	Khanyile et al., 2020
Microwave pyrolysis	Malaysia	Phosphorus recovery not addressed but nitrogen recovery addressed	Generate pyrolysis products e.g., liquid oil (43 wt%), gases (29 wt%) and char product (28 wt%) Liquid oil can be used as chemical additives, cosmetic products and fuel The solid char has potential for use as	Low nitrogen recovery	Lam et al., 2019

Table 1 (*continued*)

Recovery/recycling technology or method	Country/city/region	Consideration for phosphorus and other nutrient recovery and recycling	Beneficial aspect	Limitation	Reference
			adsorbents and soil additives		
Hydrogel recovery for soil irrigation management	Palestine	Nutrient recovery not addressed	Superabsorbent polymer recovery for increasing water retention in soil and improving irrigation management and plant growth The quantity of total water required for the irrigation can be reduced by 15–50% with soil modified by SAP hydrogel	Did not consider separating various components of the waste nappies, including the plastic parts, the SAPs, and the cellulosic fibers	Al-Jabari et al., 2019
Screening and enzymatic treatment, cleaning, and thickening	Korea	Nutrient recovery not addressed	Effectively separate plastic and fiber fraction for reuse	Not addressed	Kim and Cho, 2017
Combustion, employing the TG/DTG/DTA techniques	Hungary	Nutrient recovery not addressed	Energy recovery and volume reduction	Not addressed	Almeida et al., 2019
Using shredded waste nappies as viscosity modifying admixture (VMA) for cement grouts and concrete	EU	Nutrient recovery not addressed	Modify the rheological behavior of cement grouts and concrete by enhancing the yield stress and viscosity Can be a sustainable source for producing highly effective VMAs in the concrete industry	Not addressed	Karimi et al., 2020
Hydrothermal carbonization	Spain	Nutrient recovery not addressed	Production of hydrochar with better combustion characteristics, and a high carbon content, suitable for energy purposes Volume reduction possible	Produce wastewater with increased chemical oxygen demand and conductivity, requiring further treatment Low nitrogen content in hydrochar	Budyk and Fullana, 2019
Separation of superabsorbent polymer (SAP)	Egypt	Nutrient recovery not addressed	Potential to conserve soil moisture in light soils using water of good quality	Sodium ($Na+$) based, may have impact on soil chemical properties	Zekry et al., 2020
Pre-treatment of nappies	Greece	Nutrient recovery not addressed	Help to separate the biodegradable components from SAP and plastics Allow SAP volume reduction of 92.7% with low residual cation concentrations and minimum cost	Require further anaerobic treatment for the valorization of the biodegradable materials	Tsigkou et al., 2020b
Recycling disposable nappy waste pulp after dehydrating the SAP through oxidation using ozone	Osaka, Japan	Nutrient recovery not addressed	The water-absorptivity of the recovered pulp was almost the same as virgin pulp	Not addressed	Ichiura et al., 2020
Recovery of cellulose and nanocellulose from urinated waste nappy using green method	Tamil Nadu, India	Nutrient recovery not addressed	Uses less harmful acids like acetic and nitric acids Up to 25% of cellulose extraction was possible High purity of extracted cellulose was observed	Despite using 60% sulfuric acid, a minor fraction of unhydrolysed cellulose was present in the spherical cellulose nanocrystals	Trilokesh et al., 2020

DTA (Differential Thermal Analysis) to estimate potential energy through combustion. The technique has potential for energy generation and reducing space occupied by such waste in landfill. Another recent study identified that shredded baby nappies as suitable for manufacturing highly-effective viscosity-modifying admixtures for concrete (Karimi et al., 2020). In their experiment, they observed that shredded waste nappies modify the rheological behavior of cement grouts and concrete by enhancing the yield stress and viscosity. Pyrolysis of baby nappies that uses thermal processes of decomposition could help to recover oil, gas and char products (Khanyile et al., 2020). In another study, Lam et al. (2019) found that microwave pyrolysis of used baby nappies that utilize thermochemical process could produce liquid oil that can be used as chemical additives, cosmetic products and fuel, and solid char that has potential for use as adsorbents and soil additives. A number of studies (Zekry et al., 2020; Al-Jabari et al., 2019) suggested that separating superabsorbent polymer from used baby nappies and utilizing that as soil additives could substantially increase the moisture retention capacity of soil. Some other recycling technologies/methods of used baby nappies are also presented along with their advantages and limitations in Table 1.

This is apparent that all of the various types of recycling approaches explained above have some positive aspects in terms of resource recovery and recycling as well as minimizing life cycle environmental impact. However, most of these methods are either at lab experiment or pilot stage, and without the practical and large-scale implementation, it would not be possible to understand how appropriate or effective these techniques are. Considering the findings of the current review, we suggest that focus should be given on reducing the life cycle environmental impact, diverting these wastes going to landfill through recycling, and a balanced and cost-effective recovery of key resources e.g., P and other nutrients and energy. No single technology alone can meet all these requirement and there is need for further research for innovating technologies that are capable to ensure optimal resource recovery with minimal cost and environmental footprint. Considering P as a critical resource due to anticipated future scarcity, focus should be given on technologies that are capable of recovering and recycling P and other nutrients. Although some nutrient recovery and recycling techniques are already available, further research should be done to assess their environmental and economic feasibilities before large scale implementation. Research should also aim at overcoming the limitations of existing technologies as presented in Table 1.

3.3. Policy/management interventions for disposable baby nappies to achieve phosphorus circular economy

In many nations like Australia, the current management and disposal systems for used baby nappies are not sustainable and P and other nutrient recovery are mostly absent. Therefore, based on the current review, this study recommends necessary interventions to ensure sustainable management of baby nappies to achieve P circular economy. Although the primary focus of this study is to assess the potential for P recovery and recycling from used baby nappies, the recommendations given focus on overall management of baby nappies to ensure recovery of other nutrients and to minimize its life cycle environmental footprints. Such a holistic approach considering its sustainable management is missing from the available literature, and this study likely to make a significant contribution in this regard. A brief description of the policy/management strategies to ensure P circular economy of disposable baby nappies is provided as follows.

3.3.1. Solutions from the product and system re-design perspective to enable regeneration

Most traditional design solutions have identified human excreta as a perishable waste stream, where handling needs to be minimized due to odor rather than a nutrient stream that carries a non-renewable nutrient (P). Hence, the solutions currently used consider the fastest and the most convenient removal of both the excreta and used by nappies from the human interface. If the nutrient recovery is given precedence over stigma created around getting human excreta away at the earliest possible time, there are different solutions that can be explored. Our review indicates that given the already available various types of biodegradable nappies in the market (some even 100% biodegradable) and the availability of published literature on technologies for composting used biodegradable nappies for nutrient recovery, there is a great potential for such nappies in the future. However, necessary research should be conducted for assessing the life cycle environmental impact of biodegradable nappies before large scale production and implementation. Product and system designs around biodegradable nappies could pave the way for achieving P circular economy of disposable baby nappies. In this regard, based on the current review and our understanding of the available information online, a number of possible new design concepts are discussed along with their pros and cons as follows:

3.3.1.1. Designing for disposal through traditional human excreta collection and treatment in wastewater management system. Considering the availability of other flushable hygiene products like flushable sanitary pads (Butkovic, 2020; Thomson, 2020) and flushable wipes (Atasağun and Bhat, 2020), designing biodegradable flushable baby nappy products could be a reality in the near future. Such used flushable nappies containing baby excreta could be readily disposed through the toilet with other human wastes to be collected through the traditional method of wastewater collection, treatment and nutrient recovery systems. The main advantage is that it could be easily disposed into the toilet and there is no transportation cost and nuisance of odor. However, the main drawback is such design approach would not be compatible with existing infrastructure of urban wastewater management and such disposal might create huge burden on the existing wastewater management system. The immediate recovery of P and other nutrients are also not possible through this method. Disposal of flushable wipes has already been reported to cause severe problem of choking/blocking of sewer lines (Patchell, 2012). Therefore, such design could be considered in future urban and wastewater infrastructure planning to make this compatible with increased loads. However, adequate research and risk analysis should be done to check the feasibility of implementing such system.

3.3.1.2. Designing for managing through the systematic collection and disposal through natural processing. This design concept require producing and using biodegradable nappies and systematic collection of the nappies after usage and disposing these to nature/land for soil amendment or improvement for future agriculture production. Shredding of the wipes before placing these on the soil might help to degrade these quickly. The main advantage of this method is that the nappies could be naturally decomposed for land improvement and nutrient recycling. This also requires lower processing and treatment cost compared to the industrial processing/composting. The main drawbacks would be finding suitable lands, transportation cost depending on the distance of the location of lands, nuisance of bad odor while transporting and applying on land, and the time taken for degradation and decomposing on land. The main advantage compared to the first option above is that excreta as well as the nappy materials are recycled, providing the ability of regeneration of P in excreta in used baby nappies.

3.3.1.3. Designing for systematic collection and disposal through industrial processing. As explained in the previous option, the production and use of 100% biodegradable nappies are required for this design concept. The used nappies containing baby excreta could be collected separately from the household and child-care centres, and transported to industrial facilities for processing and treatment to produce nutrient rich products like compost for agricultural use. An initiative called DYCLE in Germany provides parents with a bio-based nappy that is naturally degraded into soil and collects the used nappies for transforming into nutrient rich black soil for plant growth (DYCLE, 2021). The industrial composting has some advantages like handling of large volume of used nappy waste, production of high quality/stable products, removal of odor and quicker processing/treatment time (Matter of Trust, 2021). It is also possible to recover energy during industrial or commercial scale composting (Smith and Aber, 2018). The high quality commercial compost product could also be sold to the market as fertilizer for agricultural use. Therefore, this option provides the opportunity to recover P as a nutrient in the excreta, contained in baby nappies. Some of the disadvantages of industrial processing are high establishment and operational cost, waste transportation cost, and energy use.

3.3.1.4. Designing for managing through traditional human excreta collection and treatment system or through natural/industrial processing. In this approach, nappies could be designed in a way that have two layers, one for holding the absorbing layer with body made of plastic or durable material and the other for absorbing the urine and feces which is made of completely biodegradable materials and could be refilled every time of use. Some cloth nappies with a similar design concept are already available in the market e.g., All-in-Two style nappy (Darlings Downunder, 2021). The excreta containing layer can be flushed through the toilet or could be collected for natural or industrial processing, and the other layer could be recyclable or washable and reused. This approach could help to substantially reduce the volume of used baby nappy wastes, while it is compatible with disposal through traditional wastewater management system, or through natural or industrial processing as explained above.

3.3.1.5. Designing for managing through household or community composting with food and garden waste and other organics. In this design concept, used biodegradable nappies could be composted at home and at community composting facilities mixing with food waste and garden waste. Co-composting of biodegradable baby nappies with other organic wastes has been found to produce good quality nutrient rich end products in a number of studies (Tsigkou et al., 2020a; Colón et al., 2011; Colón et al., 2013). Home composting has been identified to have a number of advantages like no collection and transportation cost, minimum infrastructure and operational cost, production of suitable nutrient rich compost for gardening, and increasing community awareness and involvement in composting and waste management (Barrena et al., 2014, Vázquez and Soto, 2017). However, this method also has some limitations like, nuisance of bad odor around household area, and risk of pathogen borne disease if not properly handled. Lleó et al. (2013) suggested that vermicomposting method could substantially reduce the problem of bad odor. It is essential to perform necessary experiments and feasibility studies before promoting and implementing household composting of used baby nappies.

All these possible design options explained above have the potential for helping towards achieving the P circular economy of disposable baby nappies. However, considering the pros and cons of each options as we discussed, necessary life cycle and economic analysis should be performed to understand the environmental and economic feasibility of each option. Informed with the findings of such analysis and necessary field investigations, the suitable option could be implemented depending upon the socio-economic and environmental condition of the country.

3.3.2. Solutions from the overall life cycle management perspective

Apart from considering solutions from the product and system design perspectives as stated above, necessary planning should be done to ensure the sustainable management of baby nappies in its overall life cycle to ensure effective recovery of P and other nutrients. As presented in Table 2, this study proposes a conceptual plan, that might be considered in this regard. A snapshot of the key interventions required at different stages of the disposable baby nappy life cycle is presented in Fig. 3.

3.3.2.1. Interventions at the production and marketing stage. Cordella et al. (2015) suggests that careful selection and use of materials at the production stage could reduce life cycle impacts of nappy products and associated human health and environmental risks. For instance, nappies produced using biodegradable materials could be suitable for nutrient recovery through composting. Based on appropriate experiments, Colón et al. (2013) demonstrated the potential for used compostable/biodegradable baby nappies for producing good quality compost fertilizers. Tsigkou et al. (2020a) developed new separation methods where the biodegradable part of the disposable used nappies could be separated from non-biodegradable parts, and co-digested that with expired food waste to produce anaerobic sludge for composting to make suitable end product for land application. Another study by Ferronato et al. (2020) also separated organic fraction of the used disposable nappies, and used that for vermicomposting with cow manure to produce suitable compost fertilizers. A completely biodegradable nappy could ultimately reduce the burden of separation organic materials and thus could be readily used for composting.

There are already various types of biodegradable and eco-friendly nappies (made of plant-based materials like maize, bamboo) available at a reasonable price in the market, some of which are 100% biodegradable (Khoo et al., 2019). Use of such nappies need to be promoted among consumers through various awareness and marketing initiatives by producers, retailers as well as the government. Research suggests that the global biodegradable nappy (made of cotton, wool, bamboo, starch) market likely to grow from worth US$ 3.07 billion in 2019 to worth US$ 5.46 billion by 2026, indicating strong growth mainly driven by increased awareness about personal hygiene and increased environmental concerns (Imarc Group, 2019). It should however, be noted that biodegradable materials sometimes are reported to have higher environmental impact compared to the alternatives such as plastic.

3.3.2.2. Interventions at the household/community stage. At the household/community level, it is necessary to enhance the awareness about the importance of recycling P and other nutrients in baby nappies to drive them towards using biodegradable/compostable nappies. Based on an examination of the community participation in household solid waste (HSW) reduction in eastern Surabaya, Indonesia, Dhokhikah et al. (2015) suggested a number of strategies e.g., intensifying the HSW reduction training programs, intensifying the information dissemination through mass media and campaign, increasing the number of environmental cadres, and optimizing the existence of waste bank and its function. Community initiatives for using biodegradable nappies and collecting those nappies after use, and composting utilizing appropriate methods would help to recover and recycle nappy bound nutrients. Local government councils could run tailored waste education/awareness programs targeting households with babies to educate them on this matter. Pickering et al. (2020) suggests that educating residents about the benefits of organic waste diversion increases their behavioral intents for participation in the waste diversion program. Initiatives for involving communities in sustainable management of disposable nappy waste is already underway in some parts of the world, e.g., the DYCLE initiative of Germany, as mentioned before, motivates and supports parents to use compostable nappies through facilitating the collection of used nappies and converting into black soil for growing plants (DYCLE, 2021).

Table 2
A life cycle management plan for achieving phosphorus circular economy of disposable baby nappies.

Stages of baby nappy life cycle	What needs to be achieved?	How to achieve?	Stakeholder responsible
1. Design/production	Reduce life cycle environmental impact Design/production of fully compostable nappies Proper labelling of product about environmental benefit Produce compostable nappies with price cheaper or comparable to high quality nappies	Enhance LCA research and innovation for mitigating impact Incentive to producers for improving design and producing compostable nappies Investment for improving existing design and production technologies and methods Stricter government policy/regulations for producing biodegradable nappies	Designers, producers and distributors of nappies Producers and suppliers of raw materials Government bodies Universities or research organizations
2. Market/retail	Enhance distribution/supply and selling of compostable nappies Reduce the supply of non-biodegradable nappies	Proper marketing strategies to create sustainable market for compostble nappies Creating awareness among shoppers/households to buy compostable nappies Government regulation/policy to ban or regulate selling of non-biodegradable nappies	Owners/managers of retail chain shops Suppliers/distributors Government bodies
3. Consumer/household	Enhance use of compostable nappies at household level Separate storage of used nappies to help recycling	Creating awareness among shoppers about the importance of using biodegradable nappies Government policy/regulations and incentives to motivate households towards recycling of baby nappies Provide separate storage bins	Households Childcare centres Community leaders Local government authorities
4. Waste management	Separate collection/storage of baby nappies for composting Diverting nappy wastes from landfill to composting facilities Decentralized and centralized composting facilities for nappy waste Household/community composting with food and other organic wastes	Incentives to recycling industries for composting baby nappies Government investment for composting infrastructure/facilities for used baby nappies Develop and promote improved technologies for recycling phosphorus from baby nappies Community initiatives to collect and compost used nappies with household food wastes Creating market for compost products from used baby nappies	Waste management authorities Federal/state governments Local government authorities Households/consumers Fertilizer sellers

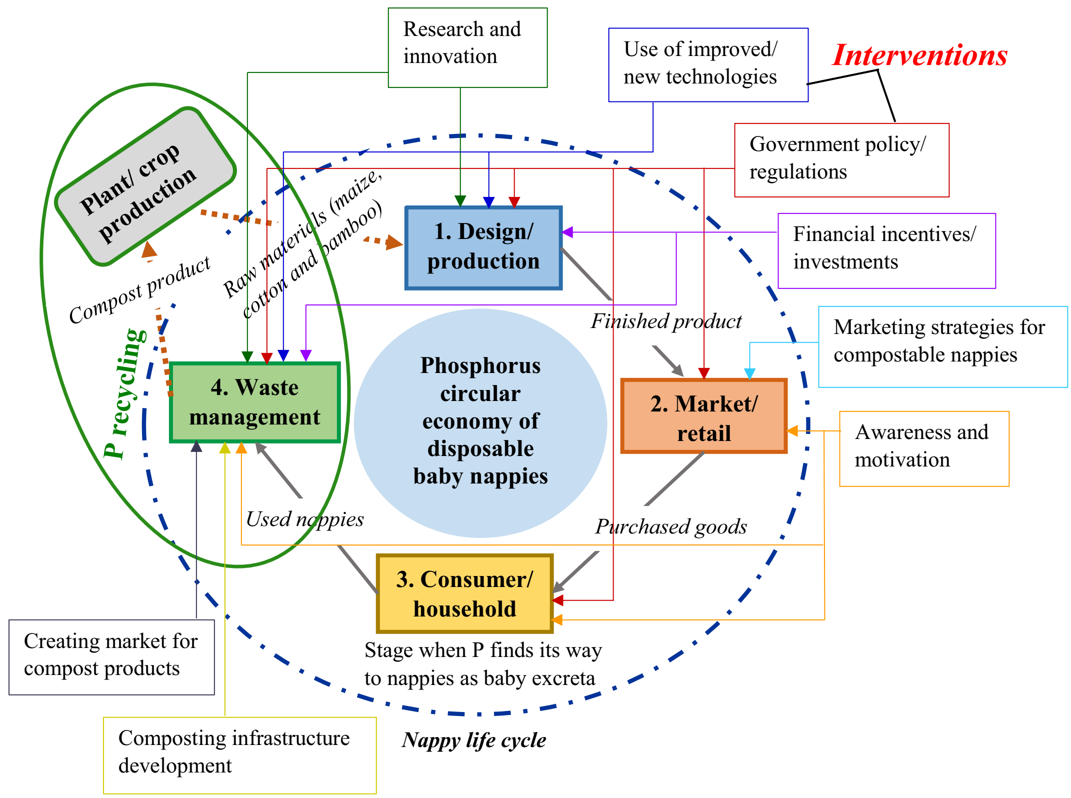

Fig. 3. A snapshot of the key interventions required at different stages of the disposable baby nappy life cycle to achieve P circular economy. Table 2 elaborates these interventions.

3.3.2.3. Interventions at the waste management stage. Waste management is the crucial stage that determines the ultimate fate of the used baby nappies. How the used nappy wastes would be collected, processed/ treated and disposed in turn determines the fate of baby excreta bound P and other nutrients trapped in those nappies. In the traditional management system in many countries, used nappies are usually ends up in landfill with other garbage, resulting in the loss of a considerable amount of P and other valuable nutrients as we assessed for Australia in this study. Although there are various types of resource recovery and recycling technologies or methods for used baby nappies are reported in available literature (as we reviewed in this study), these are mostly at lab experiment or pilot project stage. The capacity for the practical implementation of these techniques to a large scale is still limited mainly due to the lack of policies and regulations for the sustainable management of P and other valuable nutrients in used baby nappy wastes.

The recovery and recycling of a critical and non-renewable nutrient resource like P from human excreta is usually ignored, while the aim for managing human excreta is always to quickly keep away from human. There is a need for shift in the way of people's perception about it by recognising it as a valuable nutrient stream (as it contains a substantial amount of finite element like P), setting a clear goal for P and other nutrient recovery, setting design goals particularly in relation to future urban planning to design a system compatible for P recovery, and finding ways to manage trade-offs.

Developing separate collection systems for used baby nappies as well as establishing both centralized and decentralized composting facilities could allow composting of used baby nappies. Decentralized community composting of organic wastes is appearing as a promising solution for municipal solid waste management in Italy (Bruni et al., 2020). Pai et al. (2019) assessed that decentralized community composting has potential social and economic benefits along with environmental advantages. Local government authorities could take some initiatives/programs on a trial basis to check the effectiveness of household and community composting of used baby nappies with food waste and garden organics, and utilizing the compost products locally for home or community gardening. Such initiatives have the potential for not only to divert wastes from landfill but also to reduce the waste transportation cost and associated environmental impacts. There is also need for developing local markets for the compost products. As currently given for other recycling industries, the government could also consider providing financial incentives and support to recycling industries and community groups trying to produce compost products utilizing used baby nappies. The waste management authorities also need to enhance their capability for the large-scale implementation of P recycling technologies of used disposable baby nappies to achieve a P circular economy.

4. Conclusions

This study estimated that nearly 5452 tonne P was lost through the disposal of used disposable baby nappies to landfills in Australia over the period of 2001–2019. The situation is more or less similar for other developed nations, however, such quantitative analysis is currently absent for nations, emphasizing the need for a global assessment of P loss through disposable baby nappies. This study revealed that although there are various types of technologies/methods that offer nutrient recovery from used baby nappies primarily through co-composting with food and other organic wastes, the majority of these are still being applied at the lab and pilot scales, hence, it is yet difficult to understand the effectiveness before practically implementing to large/industry scale. There are also a wide range other technologies/methods for recycling baby nappies, with purpose ranging from energy recovery to volume reduction, generation of pulp, hydrogel, cellulose, and polymer as well as to increase yield stress and viscosity of concrete. This study recommends that future research and innovation should focus on developing nappy recycling technologies and methods that are capable to ensure optimum recovery of P and other resources with minimum adverse environmental impact and at a reasonable price.

The new product and system design options as well as interventions at the various stages of the nappy life cycle as proposed in this study could be utilized to achieve a P circular economy of baby nappies. Options such as designing for flushing, designing for disassembling the excreta containing part, and designing for systematic collection, storage and treatment through natural or industrial processing as well as through household/community composting were evaluated along with pros and cons, hence providing guidelines for future research needs. In order to close the loop, the study specifically recommends for the design and production of biodegradable nappies using raw materials from bamboo and cotton plants that are fertilized through compost produced from disposable baby nappy wastes. Overall, considering the key interventions as suggested in this study, a coordinated and harmonized effort is required from all the stakeholders involved at various stages of the nappy life cycle to ensure sustainable production, marketing, usage and recycling of disposable baby nappies to achieve sustainable management of P for food and water security.

CRediT authorship contribution statement

Rubel Biswas Chowdhury: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Validation, Writing – original draft, Writing – review & editing, Visualization. **Mayuri Wijayasundara:** Writing – review & editing, Validation, Project administration.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.149339.

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