Journal of Environmental Chemical Engineering 11 (2023) 110015

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

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

Life cycle assessment comparison of point-of-use water treatment technologies: Solar water disinfection (SODIS), boiling water, and chlorination

Sarita S. Nair [a], Ramesh Marasini [b,*], Lyndon Buck [c], Rita Dhodapkar [d], Javier Marugan [e], K.Vijaya Lakshmi [f], Kevin G. McGuigan [g]

[a] Department for Lifelong Learning, The University of Sheffield, Edgar Allen House, 241 Glossop Road, S10 2GW, UK
[b] School of Art, Design and Performance, Buckinghamshire New University, High Wycombe, HP11 2JZ, UK
[c] Mechanical, Biomedical & Design Engineering, College of Engineering and Physical Sciences, Aston University, Birmingham B4 7ET, UK
[d] CSIR, National Environmental Engineering Research Institute (NEERI), Nagpur 440020, India
[e] Department of Chemical and Environmental Technology (ESCET), Universidad Rey Juan Carlos, C/ Tulipán s/n, 28933 Móstoles, Madrid, Spain
[f] Development Alternatives B-32, Tara Crescent, Qutub Institutional Area, New Delhi 110016, India
[g] Department of Physiology & Medical Physics, RCSI University of Medicine and Health Sciences, Dublin D02YN77, Ireland

A R T I C L E I N F O

Editor: Luigi Rizzo

Keywords:
Life cycle assessment
SODIS, Drinking water
Chlorination
Global warming potential

A B S T R A C T

Numerous different point-of-use (POU) water treatment technologies exist that can remove, reduce or inactivate microbial pathogens present in untreated drinking water. However, there have been uncertainties as to which technology is best suited to rural populations. Environmental impacts of these technologies can bring further threats to rural communities, so the life cycle assessment (LCA) approach is frequently used to compare different POU water treatment technologies. The present study uses LCA to compare three treatment options: solar water disinfection (SODIS) using a Transparent Jerrycan (TJC), boiling, and chlorination. A life cycle inventory database is created for each stage, calculating the embodied energy and transportation energy considering daily reliance for all the technologies. Direct carbon dioxide emission at the point of use of energy/fuel, particulate matter formation and smog formation analysis can help to implement the most appropriate technology. The life-cycle assessment in this study indicates that when considering the environmental impact associated with providing sufficient safe drinking water for a family of six over a period of 6 months, SODIS has been found to have better sustainability credentials as a water treatment technology (6.0 kg CO_2e per functional unit) with low contribution in all the three impact categories, followed by chlorination (9.8 kg CO_2 e per functional unit) and boiling water (6808 kg CO_2e per functional unit).

1. Introduction

Access to a clean and safe water supply is a critical factor for a healthy life, good hygiene and is of critical importance for a healthy economy. Millions of people in Indian rural households do not have reliable access to clean water, and consequently, are vulnerable to waterborne diseases [1]. Different household water treatment technologies for point-of-use (POU) are implemented to treat microbially contaminated water. These technologies differ in treatment effectiveness, associated cost, materials required, usage knowledge, and socio-cultural acceptance. The most common treatment is boiling. However, boiling has its own environmental impacts; for example, energy requirement from liquified petroleum gas (LPG), wood fuel or kerosene, risk of burns or injuries, smog formation, and deforestation, which cannot be neglected [2]. One water treatment technology that provides immediate access to clean drinking water is chlorination with bleach or sodium hypochlorite. However, this treatment is dependent on a constant supply of chlorine [3]. Another technology that is now attracting increased attention is solar water disinfection (SODIS) [4]. This technology employs transparent containers within which contaminated water is stored and exposed to direct sunlight to inactivate the pathogens. Typically, SODIS users employ plastic containers since they are more readily available. In this study, 10 Litre Transparent Jerrycans (TJCs) are used for the SODIS treatment which were produced from polypropylene (PP) polymer using a blow moulding process. The TJCs

* Corresponding author.
E-mail address: Ramesh.Marasini@bnu.ac.uk (R. Marasini).

https://doi.org/10.1016/j.jece.2023.110015
Received 12 January 2023; Received in revised form 22 April 2023; Accepted 25 April 2023
Available online 28 April 2023
2213-3437/

Nomenclature

EC	Embodied Carbon.
GHG	Green House Gases.
LMIC	Low-to-Medium-Income Country.
LCA	Life Cycle Assessment.
LPG	Liquified Petroleum Gas.
PM	Particulate Matter.
POU	Point of Use.
PP	Polypropylene.
RO	Reverse Osmosis.
TJC	Transparent Jerrycan.
THM	Trihalomethanes.
UV	Ultra-violet.

are filled with water taken from water sources such as community wells, which are then exposed to sunshine for at least six to eight hours during sunny days. Solar ultra-violet (UV) radiation penetrates the container wall and inactivates the microbial pathogens through a combination of photochemical and photo-thermal processes.

Table 1 shows a comparison of different characteristics of three water treatment options, mainly boiling, chlorination and SODIS highlighting pros and cons of each method. The boiling method is used commonly in the rural communities, which effects taste due to fire smoke, risk of burns and impacts on indoor air quality. Chlorination is quicker for disinfection but impacts on taste and there are health risks associated with large doses of chlorine [5]. SODIS on the other hand does not alter taste and is easy to use. To achieve a 3-log reduction of *E. coli* at water temperatures between 20 and 40°C requires exposure for about 8 h in sunlight with an irradiation intensity of 500–650 W/m^2 [6]. The variability of weather condition necessitates the requirement of minimum of 6 h exposure on sunny days to up to 48 h in cloudy conditions. Thus clear instructions should be provided to the users of SODIS TJCs.

It is important to assess overall environmental impacts in addition to the usual economic factors for the design of any new technology or product to be launched in the market. Life cycle assessment (LCA) is a tool which portrays the environmental impact of everyday activities and helps in making informed decisions on the integrated contribution or environmental footprint through its entire useful lifetime (cradle to grave) and beyond (cradle to cradle) [7].

Again, most of the existing LCA comparative studies for POU drinking water treatments have been based on western countries (UK/Europe/US) [8,9]. The use of chlorine as a disinfectant has diminished in recent years due to the risks posed by the formation of halogenated disinfection-by-product including trihalomethanes (THM) which have been associated with increased risk of bladder and colorectal cancers in humans [10]. Walsh and Mellor [11] have conducted a comparative life cycle assessment of four POU water treatment options, specifically bio-sand filters, boiling water, ceramic filters, and chlorination in Limpopo Province, South Africa. It is reported that boiling had the most impact on global warming potential, energy utilisation, smog formation and land use [11]. There is a comparative LCA study of boiled water, bottled water, and household reverse osmosis (RO) available to urban consumers in India. Bottled water was found to be linked with the highest environmental impact while, purification using a domestic RO device had the lowest impact [12]. However, the problem of unreliable drinking water is more prevalent in rural areas of India, where there have been no detailed studies on LCA or comparisons of available water purification options. The key variables affecting the comparison must comply with the systems available in rural sectors such as (a) Traditional mud stove and fuel wood heating sources for boiled water system (b) plastic jerrycan for the SODIS process. So, a detailed LCA comparison of various POU water treatment technologies in rural communities in India is needed. This study aims to develop a stand-alone LCA of SODIS technology covering environmental impacts of production and usage stage of polypropylene (PP) based transparent jerrycan (TJC) for SODIS treatment. Also, LCA comparisons have been made with two other POU water treatment technologies - boiling and chlorination - to highlight the advantages and disadvantages of the SODIS process.

Table 1
Comparison of various functional parameters amongst three POU water treatment technologies.

	SODIS	Boiling with fuel wood	Chlorination
Water quality	Good	Good	Good
Taste	Good	Smokey/flat	Tastes of chlorine
Time required	Minimum 6–8 h of sunshine, but does not require any special attention	20 min but time is required in collecting wood and requires special attention	Few minutes
Advantages	Saves time and money, and good taste	Communally accepted, warm water, no problem with turbidity	No possible recontamination
Disadvantages	Complex efficacy relationship with turbidity, weather dependant	Adverse effect on indoor air quality, burns or accidental risk	Bad taste and odour, risks with large dosages, availability of chemical

2. Methodology

Life cycle assessment is a methodical investigation of the possible environmental impacts over the entire life and service of the product concerned, ranging upstream and downstream from production, use, and end-of-life stages. LCA spans through four main phases specifically, goal and scope definition, inventory analysis, life cycle impact assessment (LCIA) and interpretation of the results.

2.1. Goal and scope

The goal of this study is to determine the environmental impact of the SODIS process as a POU water treatment technique through its life cycle assessment and to compare it with two other drinking water purification technology options available to rural population in India. Comparison of impacts of these water treatment technologies is made with regard to their energy use and global warming potential. Energy use is identified as reliance on electricity which is primarily based on coal and fossil fuels in India. This can significantly affect human health and the environment around. Global warming potential is an indicator of carbon management and climate change in developing countries and is considered based on the emission of greenhouse gases such as carbon dioxide and carbon monoxide. The main objectives of the current study are:

- Identify the environmental strength of SODIS process using TJCs for its implementation in the rural communities of India
- Contribution of its different life cycle stages and recognising the phase with the highest environmental load for the purpose of improvement
- Comparison with (1) boiling water in a lidded aluminium pan (2.5 L) using a traditional mud stove and (2) the chlorination process using sodium hypochlorite.

This study is divided into two parts: First is the LCA study of SODIS process on a stand-alone basis to recognise the life cycle phases with maximum and minimum environmental impacts. Second is a comparison of SODIS process with water boiling using wood fuel on a traditional mud stove and with the chlorination process of water purification.

2.1.1. System boundaries

The life cycle stages and boundaries for the three water purification options are shown in Fig. 1. The study covers the stage of material production, transportation of consumables to the location of usage, use, and disposal stages. Material production stages comprise raw material extraction, pre-processing of raw material to intermediate material, transport of intermediate material to the site of production, and final material manufacturing. The work covered most of the input and output flows for all systems. The methodologies stated in ISO14040:2006 [13] and ISO14044:2006 [14] were followed in carrying out the life cycle assessment.

The system boundaries for the SODIS process include the energy and material use for the moulding and shaping of the material, consumables and its packaging, distribution of the product to rural village in India from Delhi, water and energy use of the device at home under typical conditions, disposal of the consumables. One of the cut-offs performed in the study is the omission of disparity in the transport phase of three treatment technologies/consumables to the location of usage. Since the weight, transportation means and distances are assumed almost equal, transportation energy calculated in SODIS treatment will be used for the other two processes for comparison. The amount of energy exercised by the user in the POU was not considered.

2.1.2. Geographical boundaries

The study applies to most rural locations in India but for the purposes of veracity, villages in Bundelkhand near Jhansi in India were selected as main location of the study. Bundelkhand is a hot and semi-humid area. Most of the year, the maximum temperature ranges between 38 and 40 °C. Minimum temperature varies from 6 °C to 12 °C in December and January [15]. The Climate Data for Cities Worldwide [16] based on data from 1989 to 2021 shows that the average sunshine hours at Jhansi district as 12 h in May and 7.5 h in January, with an average temperature of 34.7 °C (May) and the average minimum temperature is 15.7 °C (January) lowest average temperature of the whole year. The weather conditions required for SODIS are suitable in this area with longer sunshine exposure required during winter months.

2.1.3. Functional unit

For conducting a comparative LCA, the functional unit (FU) is a critical element so that comparisons made are uniform across all the technologies employed. As per Indian code of basic requirements for water supply, drainage and sanitation IS:1172–1993 [17], under normal conditions, domestic consumption of water for houses for lower income group and economically weaker section of society in India is 135 L/day/capita. Out of this total water consumption, the range of drinking water is 3 L per person per day to survive life in a hot tropical climate[18]. The average Indian household size is 5.3 approximated to 6 [19]. Based on this average, the drinking water requirement per family in rural India is 18 L per day. A putative 6-month life span of a transparent plastic jerrycan was used as the duration of the study. So, the functional unit is defined as 3240 L of water. Therefore, quantities of each technology needed to "facilitate 3240 L of safe drinking water at home" in the assessment period will be taken into account.

2.1.4. Effectiveness of POU water treatment technologies

Each of these three POU water treatments technologies has been shown to be effective in treating drinking water and has been employed in low-to-medium-income countries (LMICs) [20]. The present study focuses on finding and comparing the environmental impacts of these technologies and not dealing with the effectiveness of these technologies. So, for the purpose of this study, each of these treatment technologies was assumed to have the same effectiveness in treating the drinking water.

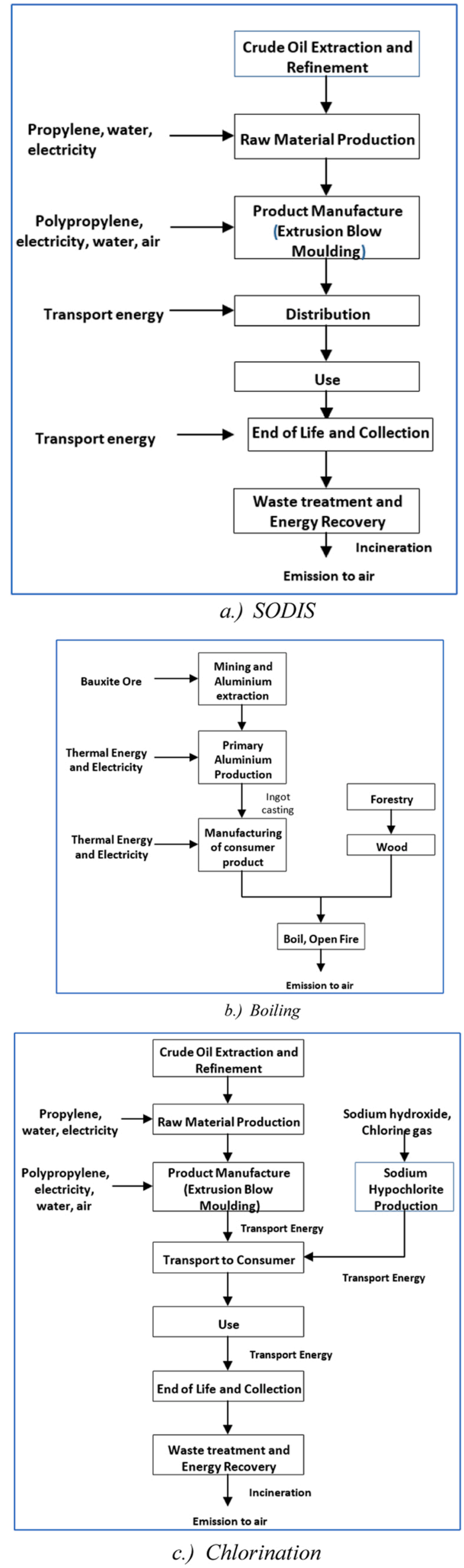


Fig. 1. Process flows and life cycle boundaries of three water purification technologies a) SODIS b) Boiling c) Chlorination.

2.2. Life cycle inventory

In this section we consider the various inputs and complete approach for building up life cycle inventory of investigated scenarios together with the assumptions made and data sources.

2.2.1. SODIS process

The SODIS processes presented in this paper uses TJCs made of polypropylene which are produced using a blow moulding process. Each TJC weighs 450 g (empty) and the capacity is 10 litres. To meet the daily need of the family i.e., 18 L of water, 2 PP jerrycans were required which has been considered in the calculations. The ecoinvent database [21] offers carbon value for PP granules which is cradle to gate embodied which is used herewith for the raw material. Embodied Carbon (EC) value for PP granules from ecoinvent v2.2 [21] is 1.98 $kgCO_2$ e/kg. The carbon produced in the manufacture of the TJC is combined to give total embodied carbon.

Extrusion blow moulding has a process energy load between extrusion and injection moulding i.e., 1.7 kWh/kg. The overall energy consumption per kilogram of product produced can hence be calculated (Table 2). These results are presented as EC, the energy consumed can be converted to EC values by multiplying with suitable CO_2 emission factors [22]. The energy consumed was combined with the conversion factors for electricity of 0.708 $kgCO_2$ e/kWh in Eq. 1. These calculations are based on conversion factors from Indian energy values and constitute the direct emissions at the point of use of the fuel or generation of electricity [23]. Water used in the production stage is recycled in-house, so not considered in the assessment.

$$E \times \alpha = C \tag{1}$$

where E is the energy consumed (kWh/kg), α is the conversion factor ($kgCO_2$/kWh) and C is the embodied carbon ($kgCO_2$/kg).

2.2.1.1. Transport CO_2 emission energy. The EC value calculated above considers the carbon dioxide emissions to the extent when the material is ready to be dispatched from the factory site that is assigned as cradle to gate values in LCA. To advance to the next stage of LCA i.e., gate to site, transport-related emissions are to be considered. In the case of the PP granules, the manufacturer was contacted for details of transportation distance and methods.

The transport CO_2 emissions of the materials were calculated based on a methodology employed in earlier carbon foot printing studies by multiplying the carbon dioxide emission factor of the fuel (kg CO_2/km) with the distance of transportation (km).

A road transport mechanism based on medium duty vehicle MDV < 12 tonne was assumed with a fuel consumption of 4.46 km/l. The CO_2 emissions value for diesel of 2.644 $kgCO_2$ e per L of fuel and actual material transport distances were employed. So, CO_2 emission factor in terms of $kgCO_2$/km is 0.5928 [24]. These results are for CO_2 emission from average goods laden vehicle (50% of its maximum weight carrying capacity or approximately 1 tonne of goods). Studies have shown that MDV emits 8% more CO_2 when fully laden with goods and 8% less CO_2 when empty compared to average laden (50% laden) [25]. The results presented in Table 3 demonstrate the transport distances and CO_2 emission. These values are based on emission factors from the Indian GHG inventory.

The use stage of SODIS process comprises filling the PP TJCs with contaminated water and exposing to sunlight for a minimum of 6 h. No specific maintenance is considered in the use stage of PP TJCs. Reusing PP jerrycans require washing with water. After its useful lifetime of 6 months, TJC will be collected from the site and sent to waste management plant. A transport distance of 200 km is assumed for transport of post-consumer product to waste management plant and CO_2 emission is calculated. Additives were not included in the assessment because of the lack of consistent data and information on the use of additives in the plastics. Further, End of Life (EOL) is projected from the base case scenario in India with a 60% plastic waste collection rate of which 70% is recycled, 25% end up as land fill and rest is incinerated or co-processed in cement kilns. The EOL emissions are adapted from a recent report by Neo et al. [26]. The carbon dioxide emission from base case scenario of EOL mix is 0.34 kg of CO_2 eq. per kg of plastic waste. This inventory includes the avoided burdens such that increased plastic waste recycling help in reducing the virgin plastic production. The worst-case scenario of EOL mix is projected with complete shifting towards incineration (100%). For the incineration process, a material specific life cycle inventory database was available in the ecoinvent v2.2 [21] under the heading municipal waste (incineration with electricity). The process load of incineration is 1000 kWh/tonne, which on multiplication with relevant emission factor of electricity contributes 0.708 tonnes of $kgCO_2$/kg of material. LCA results reported here are indicative of the national average and is not specific to different areas in India. For comparison with other available water treatment technique, a worst case EOL mix scenario is considered.

Table 2
Carbon emission for conversion of PP granules to PP TJC.

Energy Source	Consumption (kWh/kg)	Carbon emission ($kgCO_2$/kg)
Electricity	1.7	1.2036

Table 3
Summary of cumulative transport distances and emissions.

Material	Transport Phases	Cumulative transportation distances (km)	Fuel Consumed (L)	Total CO_2 emissions $kgCO_2$ e/kg
Polypropylene (PP) Granules	Manufacturers to production site	1408	315.7	0.8299
PP TJCs	Manufacturers to Bundelkhand Village	470	105.4	0.2507
PP TJCs after use	Site to waste management plant	200	44.8	0.1067

2.2.2. Boiling

Boiling is thought to be one of the most traditional water treatment options employed to provide safe drinking water. WHO has recommended that the water should be brought to ‘rolling boil’ for at least 3 min [27]. Daily reliance on boiling consumes a lot of energy. In 2011, the census of India reported firewood as the major or primary cooking fuel across 63% of rural Indian households, while crop residues and cow dung accounted for another 23% as cooking fuels. Despite understanding the convenience of using cleaner LPG fuel and induction stoves, solid fuels and conventional mud stoves remain the preferred cooking choices of rural households mainly due to affordability and accessibility. The impact of cooking with wood fuel is thought to be carbon neutral. However, inefficient burning of solid fuels in traditional open mud stoves results in air pollution adversely affecting the health of the person concerned in enclosed spaces.

Likewise, renewable harvesting of wood or agricultural waste-based fuel cycles are greenhouse-gas (GHG) neutral as it is assumed that the CO_2 from the combusted carbon is soon taken up by re-growing vegetation. Unfortunately, this representation is faulty with the reality that traditional stoves are thermally inefficient and convert substantial fuel carbon into incomplete combustion products, and so, their global warming potential is high with a carbon emissions value of 3.5644 kg e CO_2.

A study by Sobsey confirmed that 1 kg of wood is needed to boil 1 L of water [28]. So, treatment of the functional unit of 3240 L of water would require 3240 kg of wood. In rural India, the most used and readily available fuel wood is Acacia (kikkar) wood [29]. So, combustion of 3240 kg of wood produces 6808.5 kg e CO_2.

In this calculation boiling was carried out in a 2.5 L lidded aluminium pot weighing around 180 g. Assuming a loss during punching of the aluminium sheet, the total weight of 200 g is considered in production of the aluminium pot. As the pot can be used for other purposes too than just boiling of water so, life length of aluminium pot is set to 6 months to mirror the lifetime of the SODIS TJCs [30]. One aluminium pot in its lifetime of 6 months is used for boiling 3240 L of water in our analysis. So, primary and secondary processes of aluminium production and product manufacturing are included in the analysis. All the primary steps require approximately 15.5 kWh of electricity per kg of sawn aluminium ingot produced. The secondary process of production of one tonne of the ingot from clean process scrap in a remelter requires about 0.3055 kWh/kg of thermal energy and 0.016 kWh/kg of electricity [31].

2.2.3. Chlorination

Sodium hypochlorite (also known as bleach) is the most employed chemical in the treatment of drinking water. Chlorine tablets, being more expensive, are given a score of 2 compared to score of 3 for liquid chlorine in the report by Sobsey et al., [32] and are avoided in this study. A 250 mL bottle of sodium hypochlorite can treat 1000 L of water and can be used for several days. Therefore, each Indian household will need approximately 4 bottles of sodium hypochlorite for the duration of study. The consumer needs to measure out the liquid and add to the water, mix briefly and allow it to sit for 30 min 5–10 mL of sodium hypochlorite liquid is used to treat per 20 L of water as stated by Sobsey et al. [32]. Production of 1 kg of sodium hypochlorite (15%) requires 3.6082 kWh/kg of electricity, producing 3.5644 kg of CO_2 emission. Typically, people use the same container for treating the water with bleach and water consumption. If the disinfected water is kept in a hygienic and fastened container, then it can stay as such for many hours and days, even though the residence time of the disinfecting agent is typically only 6 h. We assume a 10 L polypropylene jerrycan is the container used for chlorination and 2 jerrycans would be required to meet the daily need of the family (18 L). All calculations are made on the assumption of 2 jerrycans. The jerrycans for chlorination purpose can be made of commonly used high density polyethylene (HDPE) or other plastic materials. For modelling water disinfection by chlorination, jerrycan production data from SODIS process discussed in the previous section is employed. Taking all these input data into account, overall process inputs and outputs of boiling water and chlorination system are detailed in Table 4.

2.3. Impact assessment

Three environmental impact categories namely global warming potential in terms of kg of CO_2 eq, smog formation in terms of g of NOx eq and particulate matter (PM) formation were assessed in this study. The sum of particulate matters with diameter less than 10 μm is considered in the particulate matter formation category. These impact assessments were chosen as they cover the key concerns or aspects of the studied systems. These categories help in understanding the effect of different technologies on living conditions.

3. Result interpretation

3.1. SODIS TJCs

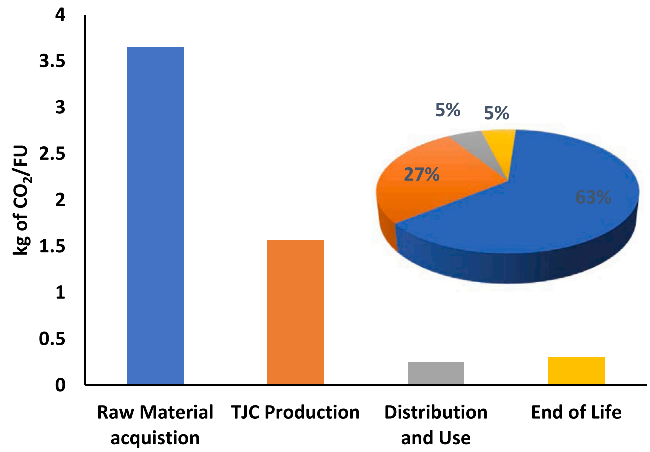
In this study, we have analysed the stages in the life cycle of the PP TJC from the extraction of raw material for their extrusion blow moulding, transportation, till the used TJC or the product becomes PP waste and is managed by the incineration processing at EOL stage. The total life cycle is divided into four steps: Raw material acquisition, TJC production, distribution and use, and finally EOL stage. Several inputs and loads are considered throughout the life cycle analysis, and environmental impact for the SODIS process as a whole and emission to air is quantified, and carbon emission results are summarised in the form of bar graph. A summary of total CO_2 emission in various stages of the SODIS process is shown in Fig. 2.

If the relative contribution of different stages to the total life cycle of SODIS process is considered 100% then the contribution from individual stages in percentages is expressed in the pie chart (inset of Fig. 2). The results of LCA study indicates that the highest contribution to the overall carbon emission from the SODIS process is from the energy intensive raw material (propylene) acquisition (63%) followed by the production process (27%) in the base case EOL mix scenario. Again, a shift of EOL fate from base scenario to 100% incineration results in net increase of CO_2 emission by 7% attributed to active recycling efforts in India [33].

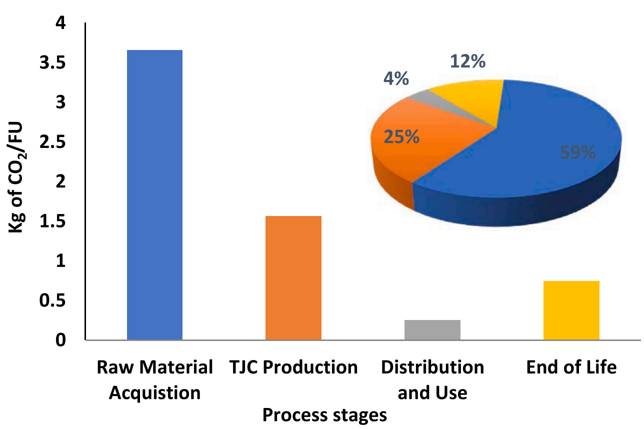
The production stages of PP TJC are based on extrusion blow moulding process. This involved extrusion of PP granules and blow moulding of the preform to the desired shape, which has led to enhanced environmental burden from this stage. A beneficial strategy such as PP scrap looping in the production phase can prove to be an effective solution to promote sustainability [34]. This solution aims to reduce raw material usage, energy input and wastage in the production stages. Although most of the PP scrap/flash as waste during the production process is recycled in the factory, PP scrap was not recirculated in the existing production process. So, a closed looping method can be considered where the flash can be re-melted and recirculated in the production line instead of 100% virgin material for the next run of TJC production. This helps to reduce the environmental burden rested in raw material acquisition and production stages. This strategy is being considered for future production and the results of which will be examined in the forthcoming reports.

Table 4
Comparative input and output data for boiling and chlorination water treatment technology, functional unit: provision of 3240 L of drinking water per household in India.

	Process	Material / Energy flows	Unit	Boiled water	Chlorination	References
Inputs	Energy	Fuel wood	kg	3240		[28]
		Fossils	MJ		5.1342	ecoinvent v2.2, 2010[21]
		Electricity	kWh	3.1032	3.6082	[31]
	Inbound Transport	Truck	km	100	100	Assumption
	Pot material /consumable	Aluminium	kg	0.200		[30]
		Polypropylene			1.300	This study
Outputs	Combustion	CO_2	kg	5702.4		[29]
		CO, CH_4, NO	kg	1106.1		[29]
	Container production	CO_2	kg	2.197	5.2176	ecoinvent v2.2, 2010[21], This study
	Chemical process	CO_2	kg		3.5644	ecoinvent v2.2, 2010[21]



a. With base case end-of-life (EOL) mix scenario



b. Worst case EOL scenario

Fig. 2. Life cycle impact assessment results for various stages of SODIS process (a) with base case end-of-life (EOL) mix scenario (b) worst case EOL scenario.

3.2. Boiling

The overall carbon dioxide emission calculated for individual stages of boiling process are shown in Fig. 3. Boiling water is found to be the worst performer in our study with maximum carbon dioxide emission compared with the other two technologies. Most of the CO_2 emission in boiling water technology is attributed to the burning of wood fuel (99%) (as seen in Table 4).

Boiling water is most widely adapted method of water disinfection owing to its low economic cost as required fuel wood can be collected from nearby trees. But daily reliance on burning fuelwood for boiling of water will produce a lot of CO_2 emissions. Water is boiled on open fires directly at home without any safety precautions or health concerns regarding inhalation of smoke and increased carbon dioxide emissions. It is regarded as having the highest environmental impacts in our study compared to the other two treatments, considering the health impact from smoke inhalation.

3.3. Chlorination

Production of sodium hypochlorite is dominated by particulate formation, CO_2 emission and electricity linked with sodium hydroxide and chlorine gas production required for the process.

Fig. 4 shows the carbon dioxide emission for individual stages of the chlorination process. As with the SODIS process, raw material acquisition and production stages have a maximum contribution to the overall emission of the chlorination process.

Chlorination has been found to have higher CO_2 emissions compared to the SODIS process. Again, dependency on the supply of sodium hypochlorite and the taste of drinking water is a negative contributor to the practice of chlorine disinfection technology [28].

3.4. Comparative analysis of environmental impacts

A visualisation of the effect of the three water treatment techniques on the environmental impact categories like global warming potential, smog formation and particulate matter formation is presented in Fig. 5 and a summary of data and processes used is provided in the supplementary materials.

SODIS process has very low impact in all the three studied impact categories namely global warming potential, smog formation and particulate matter formation. It potentially has low impact on the environment arising majorly from the acquisition of raw material for production of transparent jerrycan. As SODIS is dependent on the climatic conditions and requires exposure of the jerrycans to sunshine for a minimum number of 6 h, training and education to the communities on their use is essential to minimise the potential health risks if disinfection is not fully achieved due to improper use. However, even in situations where intermittent or insufficient sunlight has led to incomplete solar disinfection inactivation of viable waterborne pathogens, surviving bacteria and protozoa have been shown to have significantly reduced pathogenicity [35,36]. Consequently, the SODIS TJCs will contribute

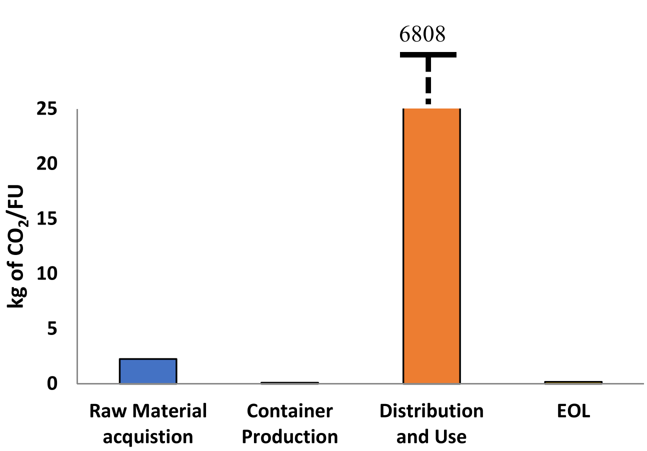


Fig. 3. Life cycle impact assessment results for various stages of boiling water treatment.

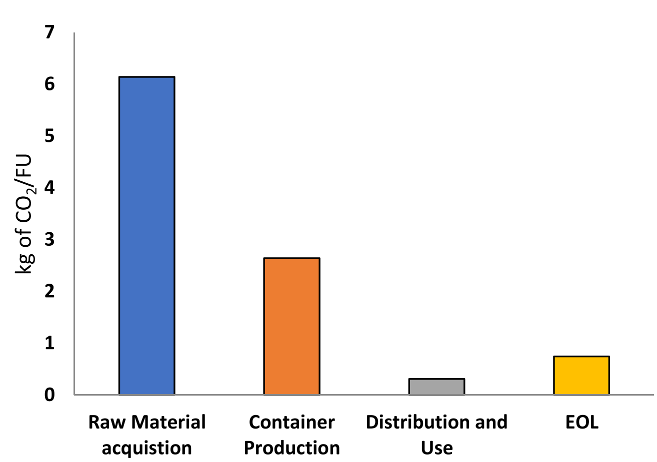
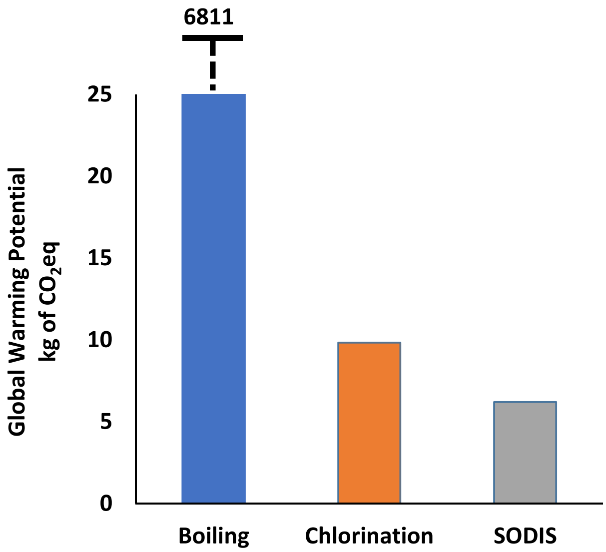
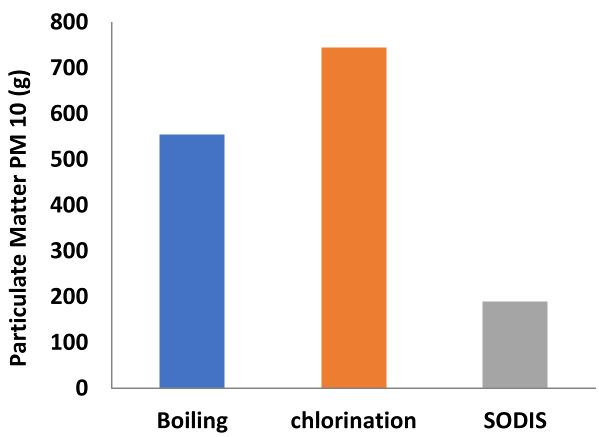


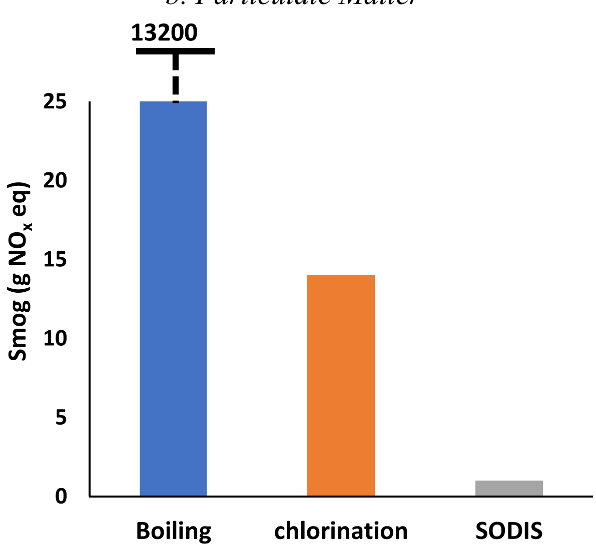
Fig. 4. Life cycle impact assessment results for various stages of chlorination water treatment.



a. Global Warming Potential



b. Particulate Matter



c. Smog

Fig. 5. Life cycle impact assessment for three water treatment technologies a. Global Warming Potential b. Particulate Matter c. Smog.

towards improving the quality of life of people in water collection, storage and treatment for the drinking purpose in rural communities India and other countries with water deprived areas.

Chlorination releases highest level of particulate matter controlled by production of sodium hypochlorite. The major contributing impact category in chlorination is the particulate matter formation and had less contribution from smog formation potential and global warming potential. Chlorination has been found to have higher global warming potential compared to the SODIS process.

Boiling water had the most impact on two of the three impact categories i.e., global warming potential, and smog formation. It also had the second most impact in particulate matter formation. NO_x emissions from burning of wood at $T < 1100°C$ is in the form of NO originating from the organically bound nitrogen in the wood. NO can be readily oxidised to NO_2 which on reaction with oxygen and ionising radiation from sunlight can produce unhealthy ozone (O_3) in the air which is the primary constituent of smog. NO_x emission when captured by moisture can also lead to acid rains [37].

Fig. 6 compares the CO_2 emission from various process stages of SODIS, boiling and chlorination technology. The SODIS TJCs have the lowest CO_2 emissions and the manufacturing of TJC had little impact in comparison to raw material production and EOL. Similar to SODIS, the acquisition of raw material (chlorine) has highest emissions in chlorination followed by container production. Main emissions in boiling water could be attributed to burning of wood fuel. Chlorination has lower impacts in two of the three impact categories which indicates that chlorination has overall emissions lower than boiling. Due to maximum smog formation and CO_2 emissions, the boiling method of treatment has been found to be the least favourable.

Though there have been previous comparative reports on various water treatment technologies in practice in LMICs, their rankings of effectiveness differ depending on the intention of the study and the factors taken into account. The objective of our study was to determine the environmental impact of three different POU water treatment technologies based on the energy related LCA calculations for the implementation of the most appropriate technology for rural communities in India. SODIS (6.0 kg CO_2 per functional unit) is the most appropriate and sustainable water treatment technology, followed by chlorination (9.8 kg CO_2 per functional unit) and boiling water technology being the worst (6808 kg CO_2 per functional unit). Open access and free data sources (including ecoinvent database) were employed in calculating the environmental impacts in this study and some of the

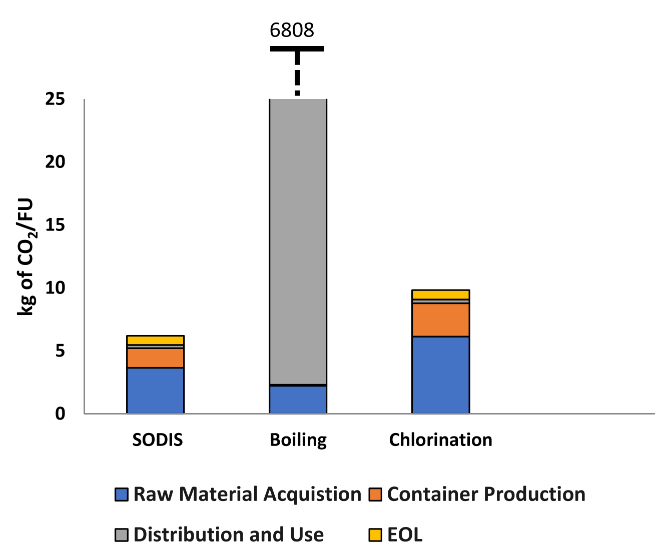


Fig. 6. Comparison of CO_2 emission from various process stages of three POU water treatment technologies.

values are based on global average. So, further studies employing more area specific data sources could result in more accurate LCA prediction by extending the basic flow model set up in this study.

4. Conclusion

This study presents a valuable insight in to the comparison of three point of use water treatment technologies boiling, chlorination and SODIS TJCs using LCA. The LCA findings show that boiling water on an open fire at home using wood fuel was found to be the worst performer, by far. The major contributor of CO_2 emission in boiling water is found to be the burning of wood fuel and daily reliance on wood contributes a significant amount towards the total emission. Chlorination is better than boiling in terms of greenhouse gas emissions but this creates more risks to human health due to the possible formation of halogenated disinfection-by-products. The SODIS technology has a potential to reduce environmental impact in terms of greenhouse gas emissions and is more sustainable than both chlorination and boiling. SODIS had the least contribution to the environmental impact of the three options considered, which is very encouraging for further development. It is crucial to note that SODIS- TJCs are in the early stage of development and parameters of their use such as number of hours to exposure to sunshine under different weather conditions such as cloudy, raining or cold days will need to be established and further studies will be required before the technology will be used in the communities. SODIS TJCs have strong potential to support rural communities in India to collect water from traditional sources and treat for disinfection without having to use fossil fuels/electricity or chemicals such as chlorine.

In the use of SODIS TJCs as water treatment technology, most of the CO_2 emissions is contributed by the raw material acquisition and blow moulding process used in the manufacturing. The EOL base case scenario is found to be beneficial with 7% reduction in carbon dioxide emission than the EOL worst case scenario. Closed looping of PP scrap in the production stage is suggested for future production to further reduce the carbon footprint. This study, through the comparison of three water treatment approaches to provide safe drinking water in the rural sector of India, suggests that SODIS, once fully developed and tested, has potential to lower the environment impact and will provide a viable solution.

CRediT authorship contribution statement

Sarita S Nair: Investigation, Methodology, Data curation, Writing – original draft. **Ramesh Marasini**: Supervision, Conceptualisation, Methodology, Writing – review & editing, Project administration. **Lyndon Buck** – Writing – review & editing**. Rita Dhodapkar**- Writing – review & editing. **Javier Marugan**- Writing – review & editing. **K Vijaya Lakshmi-** Writing – review & editing. **Kevin G McGuigan**- Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Acknowledgement

The authors acknowledge the financial support from the European Union's Horizon 2020 research and innovation programme for the PANIWATER project (GA 820718), funded jointly by European Commission and Department of Science and Technology, India.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2023.110015.

References

[1] World Health Organisation/UNICEF, Global Water Supply and Sanitation Assessment 2000 Report available from: https://www.who.int/water_sanitation_health/monitoring/jmp2000.pdf.
[2] World Health Organization (WHO) 2011. Boil water. Available online: https://www.who.int/water_sanitation_health/dwq/Boiling_water_01_15.pdf.
[3] B.F. Arnold, J.R., J.M. Colford, Treating water with chlorine at point-of-use to improve water quality and reduce child diarrhea in developing countries: a systematic review and meta-analysis, Am. J. Trop. Med. Hyg. 76 (2) (2007) 354–364.
[4] K.G. McGuigan, R.M. Conroy, H.-J. Mosler, M. duPreez, E. Ubomba-Jaswa, P. Fernandez-Ibañez, Solar water disinfection (SODIS): A review from bench-top to roof-top, J. Hazard. Mater. 235–236 (2012) 29–46.
[5] R.D. Morris, A.M. Audet, I.F. Angelillo, T.C. Chalmers, F. Mosteller, Chlorination, chlorination by-products, and cancer: a meta-analysis, Am. J. Public Health 82 (7) (1992) 955–963.
[6] L.F. Caslake, D.J. Connolly, V. Menon, C.M. Duncanson, R. Rojas, J. Tavakoli, Disinfection of contaminated water by using solar irradiation, Appl. Environ. Microbiol. 70 (2) (2004) 1145–1150.
[7] G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.-P. Schmidt, S. Suh, B.P. Weidema, D.W. Pennington, Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications, Environ. Int. 30 (2004) 701–720.
[8] M. Garfí, E. Cadena, D. Sanchez-Ramos, I. Ferrer, Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles, J. Clean. Prod. 137 (2016) 997–1003.
[9] V. Fantin, S. Scalbi, G. Ottaviano, P. Masoni, A method for improving reliability and relevance of LCA reviews: the case of life-cycle greenhouse gas emissions of tap and bottled *water*, Sci. Total Environ. 476–477 (2014) 228–241.
[10] J.A. Cotruvo, H. Amato, Trihalomethanes: concentrations, cancer risks, and regulations, J. - Am. Water Works Assoc. 111 (2019) 12–20.
[11] T. Walsh, J. Mellor, Comparative life cycle assessment of four commonly used point-of-use water treatment technologies, J. Water Sanit. Hyg. Dev. (2020) 862–873.
[12] T. Garcia-Suarez, M. Kulak, H. King, J. Chatterton, A. Gupta, S. Saksena, Life cycle assessment of three safe drinking-water options in india: boiled water, bottled water, and water purified with a domestic reverse-osmosis device, Sustainability 11 (2019) 6233, https://doi.org/10.3390/su11226233.
[13] ISO 14040: 2006–2020 Amendment (2020), Environmental management-Life cycle assessment-Principles and Framework: Geneva.
[14] ISO 14044:2006.- 2020 Amendment (2020), Environmental management-Life cycle assessment-Principles and framework: Geneva.
[15] Bundelkhand (2022). Climate of Bundelkhand Region, Bundelkhand Research Portal, https://bundelkhand.in/info/climate-bundelkhand-region.
[16] Climate Data (2023). Jhansi Climate Data, India, https://en.climate-data.org/asia/india/uttar-pradesh/jhansi-5825/.
[17] IS 1172: 1993 (Revision 2012). Code of basic requirements for water supply, drainage and sanitation, Bureau of Indian Standards.
[18] A. Shaban, R.N. Sharma, Water consumption patterns in domestic households in major cities, economic and political, Weekly (2007) 2190–2197.
[19] International Institute for Population Sciences - IIPS/India and Macro International, 2007. National Family Health Survey NFHS-3, 2005–06: India: Volume I. Mumbai, India: IIPS and Macro International.
[20] World Health Organization. 2019b Sanitation Fact Sheet. Available from: https://www.who.int/en/news-room/fact-sheets/detail/sanitation.
[21] EIC (ecoinvent centre), 2010. Ecoinvent Data v2.2, Ecoinvent reports No. 1–25. Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland.
[22] J. Raja, N. Dixon, G. Fowmes, M. Frost, P. Assinder, Obtaining reliable embodied carbon values for geosynthetics, Geosynth. Int 22 (2015) 1–9.
[23] N.K. Dubash, R. Khosla, N.D. Rao, A. Bhardwaj, India's energy and emissions future: an interpretive analysis of model scenarios, Environ. Res. Lett. 13 (2018), 074018.
[24] C. Gajjar, A. Sheikh, India specific road transport emission factors, India GHG Program (2015), https://doi.org/10.13140/RG.2.2.28564.32646.
[25] DfT (Department for Transport) 2012. Domestic Road Freight Activity (RFS01) – Table RFS0141: Fuel Consumption by HGV Vehicle Type in Great Britain, 1993 to 2010, Department for Transport, London, UK. Available: https://www.gov.uk/government/statistical-datasets/ rfs01-goods-lifted-and-distance-hauled.
[26] E.R.K. Neo, G.C.Y. Soo, D.Z.L. Tan, K. Cady, K.T. Tong, J.S.C. Low, Life cycle assessment of plastic waste end-of-life for India and Indonesia, Resour. Conserv. Recycl. 174 (2021), 105774.
[27] World Health Organization (WHO) 2005. Emergency treatment of drinking water at point-of-use. WHO-Technical Notes for Emergencies no 5.
[28] Sobsey, M.D., World Health Organization & Water, Sanitation and Health Team. 2002. Managing water in the home: accelerated health gains from improved water supply/prepared by Mark D. Sobsey. World Health Organization. Available from: http://apps.who.int//iris/handle/10665/67319.

[29] M. Kaur-Sidhu, K. Ravindra, S. Mor, S. John, Emission factors and global warming potential of various solid biomass fuel cook stove combinations, Atmos. Pollut. Res. 11 (2020) 252–260.

[30] Isberg, U., Nilsson, K., 2011. Life cycle assessment and sustainability aspects of solvatten, a water cleaning device. Available from: https://www.diva-portal.org/smash/get/diva2:645248/FULLTEXT01.pdf.

[31] J.A. Moya, A. Boulamati, S. Slingerland, R. van der Veen, M. Gancheva, K. M. Rademaekers, J.J.P. Kuenen, A.J.H. Visschedijk, Energy efficiency and GHG emissions: prospective scenarios for the aluminium industry, Tech. Rep. (2015), https://doi.org/10.2790/263787.

[32] M.D. Sobsey, C.E. Stauber, L.M. Casanova, J.M. Brown, M.A. Elliott, Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world, Environ. Sci. Technol. 42 (12) (2008) 4261–4267, https://doi.org/10.1021/es702746n.

[33] E.R.K. Neo, G.C.Y. Soo, D.Z.L. Tan, K. Cady, K.T. Tong, J.S.C. Low, Life cycle assessment of plastic waste end-of-life for India and Indonesia, Resour. Conserv. Recycl. 174 (2021), 105774.

[34] V. Mannheim, Z. Simenfalvi, Total life cycle of polypropylene products: reducing environmental impacts in the manufacturing phase, 1901, Polymers 12 (1–18) (2020), https://doi.org/10.3390/polym12091901.

[35] R.J. Smith, S.C. Kehoe, K.G. McGuigan, M.R. Barer, Effects of simulated solar disinfection on infectivity of *Salmonella typhimurium*, Lett. Appl. Microbiol. 31 (4) (2000) 284–288. PubMed I.D. 11068908.

[36] F. Mendez-Hermida, E. Ares-Mazas, K.G. McGuigan, M. Boyle, C. Sichel, P. Fernández-Ibanez, Disinfection of *Cryptosporidium parvum* oocysts in drinking water using natural sunlight and the photocatalyst TiO_2, 2007, J. Photochem. Photobiol. B 88 (2007) 105–111, https://doi.org/10.1016/j.jphotobiol.2007.05.004.

[37] The United States Environmental Protection Agency, (1999) Nitrogen oxides (NOx), why and how they are controlled, Technical Bulletin, EPA 456/F-99–006R.