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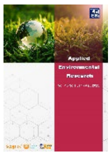

Research Article

Life Cycle Comparative Assessment of Polyethylene Terephthalate (PET) Plastic Bottles: A Case Study of Drinking Bottled Water in Ramathibodi Hospital, Thailand

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Abstract

In the current context where all sectors aim to promote sustainable development, hospitals, as large organizations with significant human interactions, face challenges in managing not only medical waste but also general waste such as water bottles. Improper management of these wastes can lead to environmental problems and high disposal costs. This study performed a life cycle assessment (LCA) of regular (petroleum-based) and alternative (bio-based) polyethylene terephthalate (PET) bottles used in Ramathibodi Hospital, Thailand, to identify effective strategies for mitigating environmental impacts. The assessment was divided into three scenarios: label-free bottles, bio-based bottles, and 100% recycling. The results indicate that using label-free bottles instead of conventional ones merely reduces environmental impacts by 2%. Transitioning to 30% and 100% bio-based PET can decrease greenhouse gas (GHG) emissions by 7 and 13 tons of CO_2 eq per year, respectively. Currently, the hospital's PET bottles contribute 56.2 tons of CO_2 eq annually. Health impacts associated with conventional PET bottles amount to 11.70 disability-adjusted life years (DALYs), a comprehensive measure that includes both mortality and morbidity. Meanwhile, 30% and 100% bio-based bottles reduce this to 7.35 and 4.87 DALYs, respectively. Achieving 100% recyclability in bottle management can cut GHG emissions from disposal processes by up to 90%. Moreover, combining the use of 100% bio-based PET bottles with 100% recycling can lower GHG emissions by up to 40% compared to current practices. These findings highlight the potential for significant environmental and health benefits through improved bottled water management strategies in hospitals.

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Introduction

Climate change is a global issue that is continuously escalating in severity at present [1]. The environmental impact of legal regulations has become increasingly prominent in many countries. It is well known that the main causes of environmental impacts result from various human activities [2–4]. Although many large organizations associated with manufacturing or various industries have started responding to pressure from the government by adjusting their behaviors to be more

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environmentally friendly, these efforts are still insufficient to reduce the occurrence of environmental crises significantly [5–6]. The pressure from the government is being increasingly transferred to medium-sized and small organizations to attempt to address environmental issues systematically before reaching a point of no return, which is anticipated to occur within the next few years [7–8]. As a result, medium-sized and small organizations are required to report their environmental footprint resulting from organizational activities and propose methods to reduce the environmental footprint, aiming to gain a competitive advantage over other organizations. For instance, strategy changes in organizational activities to reduce the carbon footprint for generating carbon credits can add value to the organization through environmental initiatives [9]. Environmental profiles are necessary for organizations involved in manufacturing or industries and for all organizations engaged in various activities, including agriculture, transportation, and even hospitals [10]. Therefore, all organizations must be prepared to report the environmental impacts of their activities.

Previous studies on the life cycle assessment (LCA) of water bottles have generally focused on comparing the production of bottles made from different materials or exploring recycling processes. For example, some studies compare glass and PET bottles based on actual production data and assess the environmental impacts throughout the entire life cycle of the bottles [11]. Other research has examined the recycling of PET bottles, highlighting the environmental benefits of reducing plastic pollution through recycling and reuse [12]. However, there has been limited research on the specific usage phase in particular areas or organizations, such as hospitals. This study focused on evaluating the environmental impacts of water bottle usage within Ramathibodi Hospital, a large organization with significant water bottle consumption. This represents a research gap, offering insights into tailored waste management strategies for water bottles employed in healthcare settings. By assessing the specific context of hospitals, we can develop more effective and practical environmental management measures. This targeted approach provides more benefits than a broad assessment alone, helping to develop customized solutions for waste management in different organizations.

Hospitals are organizations responsible for treating and caring for people's health. However, activities within hospitals also contribute to generating an environmental footprint. The environmental impacts arising from various activities of small-sized hospitals may not significantly affect the overall system. However, when considering a large healthcare organization like Ramathibodi Hospital, Thailand, with over 13,600 personnel and more than 2.25 million annual patients, it might be necessary to report the environmental footprint that occurs each year, along with an environmental management plan. The provision of medical services globally results in approximately 4.4% of the total worldwide CO_2 emissions [13]. The environmental impacts in hospitals mainly result from using electricity in various departments [14]. However, these activities are essential for patient care, making it very challenging to plan for significant reductions in the environmental footprint due to the difficulty of changing these necessary behaviors. Therefore, planning for environmental impact management in hospitals necessitates adjusting environmentally-related behaviors, such as managing the use of water bottles in the hospital. Other examples of environmentally-related behaviors include optimizing energy use through efficient lighting and HVAC systems, implementing waste segregation and recycling programs, reducing water consumption with low-flow fixtures, and promoting the use of digital records to minimize paper waste.

Currently, Ramathibodi Hospital faces challenges in managing the high volume of water bottle waste generated daily by both medical staff and patients. The conventional management approach involves collecting used bottles and sending them to a general waste disposal system, often leading to increased environmental impact due to the lack of systematic recycling or waste reduction strategies. This inefficiency underscores the need for a more structured and sustainable waste management plan. Improving the management of water bottles can significantly reduce the hospital's environmental footprint.

The assessment of the environmental impact of water bottles in Ramathibodi Hospital, Thailand, is an interesting case study since the staff and patients utilize them throughout the year. Planning to reduce the environmental impact caused by water bottles involves various approaches, and it is essential to assess different methods before implementing them to manage the environmental impacts effectively. Assessing the impact of water bottles is essential and requires continuous evaluation throughout the process to study the causes and quantify the resulting impacts on human health and the environment. The tool used for the assessment is the LCA, which can evaluate the impacts that occur throughout the product's life cycle. The aforementioned tool is based on the methodologies outlined in ISO 14040 and 14044, which are environmental management standards used to assess the entire life cycle of a product, starting from raw material acquisition and extending to product disposal [15–16]. This study has developed three scenarios to plan for reducing the impact caused by water bottles used in hospitals: a group with label-free bottles, a group with a switch to biodegradable materials, and a group focusing on achieving 100% recycling of bottles. These scenarios were selected based on their potential to reduce environmental impacts, feasibility within the hospital context, and their ability to provide comparative data on different waste management strategies. The impact assessment of all three water bottle scenarios will be compared with the data from the current water bottles used in Ramathibodi Hospital to serve as decision-making information in the LCA evaluation process.

Materials and methods

This study was conducted in accordance with ISO 14000 standards, using the LCA assessment method. The data used for the analysis can be obtained from the water bottles used in Ramathibodi Hospital, Thailand, or extracted from the Ecoinvent 3 database. The assessment is divided into three groups: a group with label-free bottles, a group with a switch to bio-based materials, and a group focusing on achieving 100% recycling of bottles. The data obtained from the analysis were categorized into two formats: midpoint impact assessment, which indicates the number of impacts that occur, and endpoint impact assessment, which indicates how the impacts affect human health and the ecosystem.

Goal and scope

This study's analysis aims to present guidelines for reducing the environmental impact of water bottles used in hospitals by comparing scenarios with the current conventional water bottle cycle used in Ramathibodi Hospital, Thailand. The scenarios were chosen based on their potential to reduce environmental impact, feasibility within the hospital context, and ability to provide comparative insights into different waste management strategies.

Scenario 1: Comparing the impact between conventional labeled bottles and label-free bottles. The assessment scope follows the gate-to-gate approach, focusing on the production and disposal phases. This scenario aims to evaluate the reduction in environmental impact by eliminating the need for labels, which simplifies the recycling process and reduces material usage.

Scenario 2: Comparing the impact between conventional bottles made from polyethylene terephthalate (PET) with bottles made from 30% bio-based PET and 100% bio-based PET. The assessment scope follows the cradle-to-grave approach. The comparison includes 30% and 100% bio-based PET because these are the common proportions of bioplastics currently produced. Evaluating these ratios helps to assess the practical and economic feasibility of partial versus complete replacement of traditional materials with bio-based ones, providing insights into material properties and performance. This scenario reflects market trends and regulatory pressures pushing for more sustainable packaging options.

Scenario 3: Comparing the proportions of recycling at 30%, 70%, and 100% of the current water bottles used in Ramathibodi Hospital. The assessment scope follows the gate-to-gate approach, focusing on evaluating the impact resulting from the disposal of the remaining bottles after recycling. This scenario explores the potential benefits of increasing recycling rates, which can significantly reduce greenhouse gas emissions and resource usage associated with water bottle waste. The chosen recycling rates of 30%, 70%, and 100% are based on typical recycling rates in Thailand, where approximately 30% of recyclable waste is currently recycled. The 70% and 100% rates are hypothetical scenarios to evaluate the environmental impact if waste management practices were improved to achieve these higher recycling rates.

The assessment in the cradle-to-grave format involves evaluating the environmental impacts throughout the product's entire life cycle, which differs from the gate-to-gate format, which focuses only on specific processes or those relevant to the chosen scenario. The flow diagram of the life cycle of water bottles used in Ramathibodi Hospital compared to the scenario of production using bio-based PET is shown in Figure 1.

Life cycle inventory (LCI)

Scenario 1: Comparing the impact between conventional labeled bottles and label-free bottles.

The data used for the assessment in this scenario are the materials input used in producing water bottles, which includes the processes involved in producing each component, namely the bottle, cap, and label. The quantity of materials input used as data for the 1,000 mL water bottle used in Ramathibodi Hospital will be compared with the label-free bottle of the same size. The raw material model is derived from the Ecoinvent 3 database, and the functional unit for the assessment is set as 1000 water bottles. The analysis would focus on the production and disposal phases. Table 1 presents the data input for each bottle format.

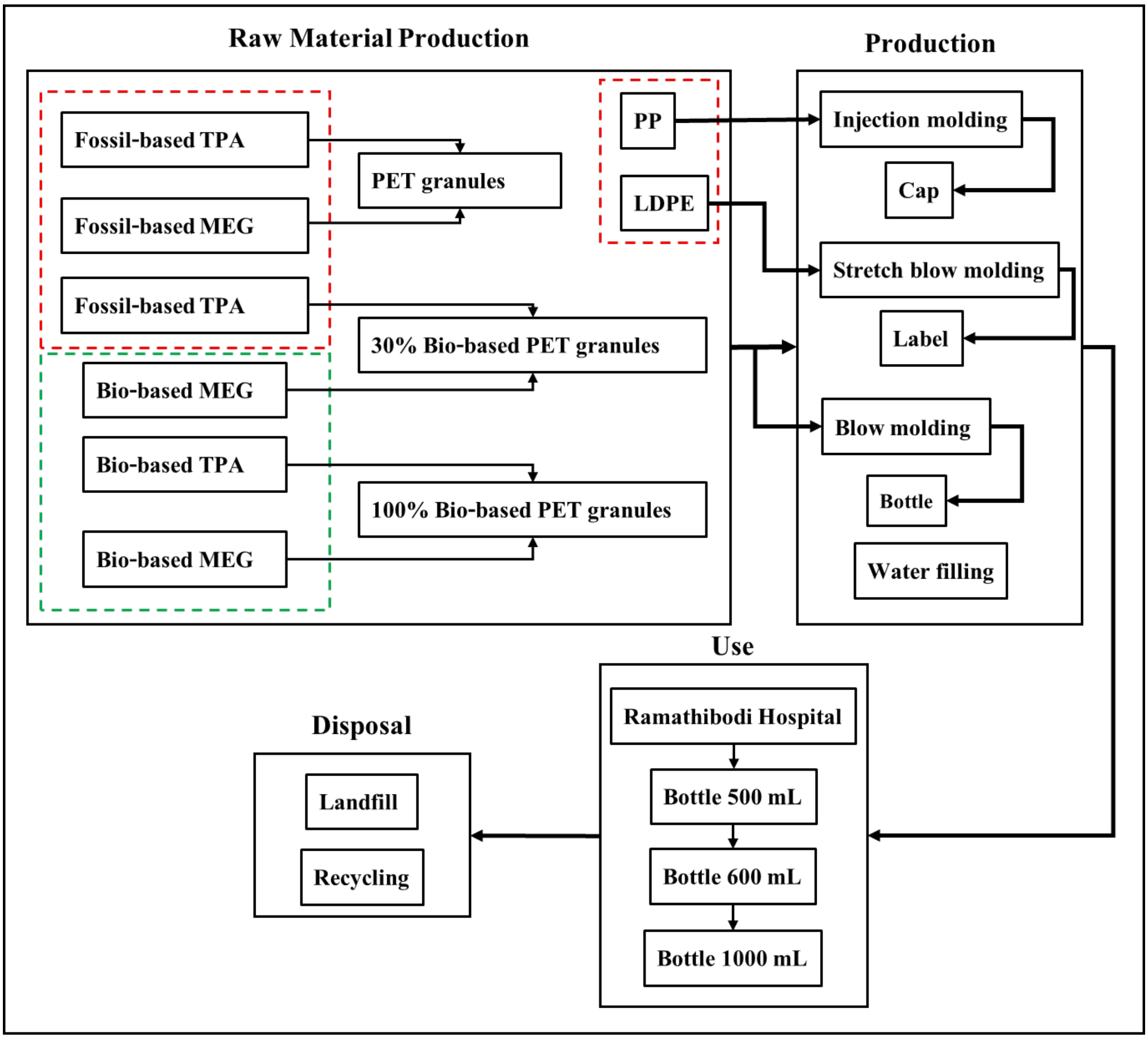

Figure 1 Flow diagram of the system boundary.

Table 1 Data input for conventional labeled bottles and label-free bottles

Material	Normal (kg per 1,000 Unit)	Label-Free (kg per 1,000 Unit)
PET (Blow molding)	34	34
PP (Injection molding)	2	2
LDPE (Stretch blow molding)	0.5	-

Scenario 2: Comparing the impact between conventional bottles made from PET and bottles made from 30% bio-based PET and 100% bio-based PET.

The comparison in this scenario uses the cradle-to-grave assessment format, and the data used cover the entire life cycle, starting from raw materials and extending to disposal. The raw materials will consist of data input for plastic pellet production, divided into PET resin, 30% bio-based PET resin, and 100% bio-based PET resin. The three types of plastic resin are produced from mono-ethylene glycol (MEG) polymerization with terephthalic acid (TPA). Conventional PET resin is manufactured using fossil-based MEG and TPA. In contrast, 30% bio-based PET is produced using 30% bio-based MEG and 70% fossil-based TPA. As for 100% bio-based PET, both components are sourced entirely from bio-based materials. The data input for the raw materials of each group will be modified to align with the sources of the materials. Based on the materials used, the production process data will be divided based on the same production data assessed in scenario 1. The nature of the data will be an assessment over a one-year period of water bottle usage in the hospital. It will include data on the quantity of materials used in the production of bottles of different sizes used in the hospital, namely 500 mL, 600 mL, and 1,000 mL. The data on water bottle transportation to the hospital is calculated based on the average transportation round, the distance from the production facility to the hospital, the type of vehicles used for transportation, and the fuel used. Additionally, the weight of the bottles loaded in each transportation round is considered, and the total quantity for one year of water bottle usage in the hospital is calculated. The data inputs used to assess water bottles produced from PET, 30% bio-based PET, and 100% bio-based PET are shown in Table 2.

Scenario 3: Comparing the recycling proportions of 30%, 70%, and 100% for water bottles used in Ramathibodi Hospital.

The assessment in this scenario involves comparing the environmental impacts of waste generated from different recycling proportions. The recycling rate of plastic in Thailand is at 30%. The remaining waste of the drinking water bottles will be disposed of in landfills according to different proportions of waste management practices. Table 3 presents the data inputs for the remaining waste from the recycling process.

Life cycle impact analysis (LCIA)

The LCIA stage focuses on evaluating the significant impacts of various processes that occur throughout the life cycle of bottled drinking water. This analysis was conducted using the LCA program called SimaPro 9.5. The method used for the assessment is IMPACT World+, which is divided into two evaluation formats: IMPACT World+ midpoint and IMPACT World+ endpoint. The assessment in the mid-point format will present impact data in the following categories: climate change, short-term and long-term, fossil and nuclear energy use, mineral resources use, photochemical oxidant formation, ozone layer depletion, freshwater ecotoxicity, human toxicity cancer, human toxicity non-cancer, freshwater acidification, terrestrial acidification, freshwater eutrophication, marine eutrophication, particulate matter formation, ionizing radiation, land transformation, biodiversity, land occupation, biodiversity, and water scarcity. The assessment in the endpoint format presents the data on the damages in terms of human health and ecosystem quality.

Interpretation

The data from the assessment were interpreted according to the assessment categories. The assessment in the midpoint format indicates the number of impacts that occur according to the specified categories, which can be compared to the predefined scenarios to analyze strategies for reducing the impacts. The assessment in the Endpoint format indicates how the impacts caused by various processes result in harm to humans or ecosystems. Human health impacts will be presented in terms of DALY (disability-adjusted life years; this means different disabilities caused by diseases are weighted), while ecosystem quality impacts will be presented in terms of PDF.m^2.yr (PDF = potentially disappeared fraction of plant species) The unit PDF.m^2.yr represents the PDF in a certain area (m^2) over a certain period (years). This unit helps in understanding the loss of species or the potential risk to biodiversity within a specified area and time frame, highlighting the long-term impacts on ecosystem quality [17–18].

Table 2 Data inputs used for assessing water bottles produced from PET, 30% bio-based PET, and 100% bio-based PET

	Unit (unit per year)	PET	30% bio-based PET	100% bio-based PET
Amount of water bottle (1 year)				
500mL bottle	bottles	14,400	14,400	14,000
600 mL bottle	bottles	36,000	36,000	36,000
1,000 mL bottle	bottles	108,348	108,348	108,348
Raw materials				
Fossil-based MEG	ton	1.56	-	-
Fossil-based TPA	ton	4.02	4.02	-
Bio-based MEG	ton	-	1.56	1.56
Bio-based TPA	ton	-	-	4.02
Bottle production (500,600, and 1,000 mL)				
PET	ton	4.65	-	-
30% bio-based PET	ton	-	4.65	-
100% bio-based PET	ton	-	-	4.65
Polypropylene (PP)	kg	280	280	280
Low-density polyethylene (LDPE)	kg	77.9	77.9	77.9
Water	m^3	137	137	137
Transportation (truck and diesel)				
For 500 bottle	km	228	228	228
For 600 bottle	km	570	570	570
For 1000 bottle	km	3,040	3,040	3,040
Disposal				
Waste from PET recycling	kg	139.8	139.8	139.8
Waste from PET bottle	ton	3.262	3.262	3.262
Waste from cap	kg	280	280	280
Waste from label	kg	77.9	77.9	77.9

Table 3 Data inputs for the remaining waste from the recycling process at different recycling rates

	Unit (unit/year)	Recycling		
		30%	70%	100%
Disposal (Land fill)				
Waste from PET recycling	kg	139.8	326.2	466
Waste from PET bottle	ton	3.262	1.4	-
Waste from cap	kg	280	280	280
Waste from label	kg	77.9	77.9	77.9

Results

Scenario 1: A comparison of the environmental impacts between conventional labeled bottles and label-free bottles

The assessment result using the IMPACT World+ midpoint method is presented in Table 4. The impacts at the midpoint level show differences between the conventional bottles and label-free bottles, which were assessed through the production and disposal processes.

Figure 2 shows a graph comparing the impacts between conventional and label-free bottles, considering the essential impact categories of climate change, fossil and nuclear energy use, ozone layer depletion, freshwater ecotoxicity, human toxicity cancer, and particulate matter formation. These categories were selected due to their significant relevance to environmental and health concerns, providing a focused comparison in the figure. The graph demonstrates that there is only a slight difference in impacts between conventional and label-free bottles, with the production and disposal of label-free bottles resulting in approximately a 2% reduction in the mentioned impacts, except for ozone layer depletion, which shows no significant change. Scenario 1 did not assess the IMPACT World+ endpoint method because the evaluation in this scenario is a simulation of data only for the production and disposal of 1,000 mL bottles. It was conducted as a set unit assessment for only 1,000 bottles.

Scenario 2: Comparing conventional bottles made from PET and bottles made from 30% bio-based PET and 100% bio-based PET

The input data of bottled water used in Ramathibodi Hospital over the past year was employed as factors in the LCA assessment. Table 5 presents the life cycle impacts of bottled water, which involves different bottle materials, namely PET (conventional bottles), 30% bio-based PET, and 100% bio-based PET, throughout their life cycle.

Table 4 Impacts resulting from conventional bottles and label-free bottles

Impact category	Unit	Conventional bottle process	Label-free bottle process
Climate change, short term	kg CO_2 eq	165.5198	161.4515
Climate change, long term	kg CO_2 eq	148.2416	144.5986
Fossil and nuclear energy use	MJ deprived	3767.31	3661.448
Mineral resources use	kg deprived	2.481757	2.44582
Photochemical oxidant formation	kg NMVOC eq	0.555873	0.539802
Ozone layer depletion	kg CFC-11 eq	0.000585	0.000585
Freshwater ecotoxicity	CTUe	1823855	1789873
Human toxicity cancer	CTUh	1.13E-05	1.11E-05
Human toxicity non-cancer	CTUh	2.42E-05	2.38E-05
Freshwater acidification	kg SO_2 eq	1.35E-06	1.32E-06
Terrestrial acidification	kg SO_2 eq	0.001098	0.001071
Freshwater eutrophication	kg PO_4 eq	0.002018	0.001994
Marine eutrophication	kg N eq	0.013194	0.012938
Particulate matter formation	kg PM2.5 eq	0.064411	0.062799
Ionizing radiation	Bq C-14 eq	1351.383	1312.117
Land transformation, biodiversity	m^2 yr arable	0.014948	0.014614
Land occupation, biodiversity	m^2 yr arable	7.046695	6.933867
Water scarcity	m^3 world eq	56.12614	53.91792

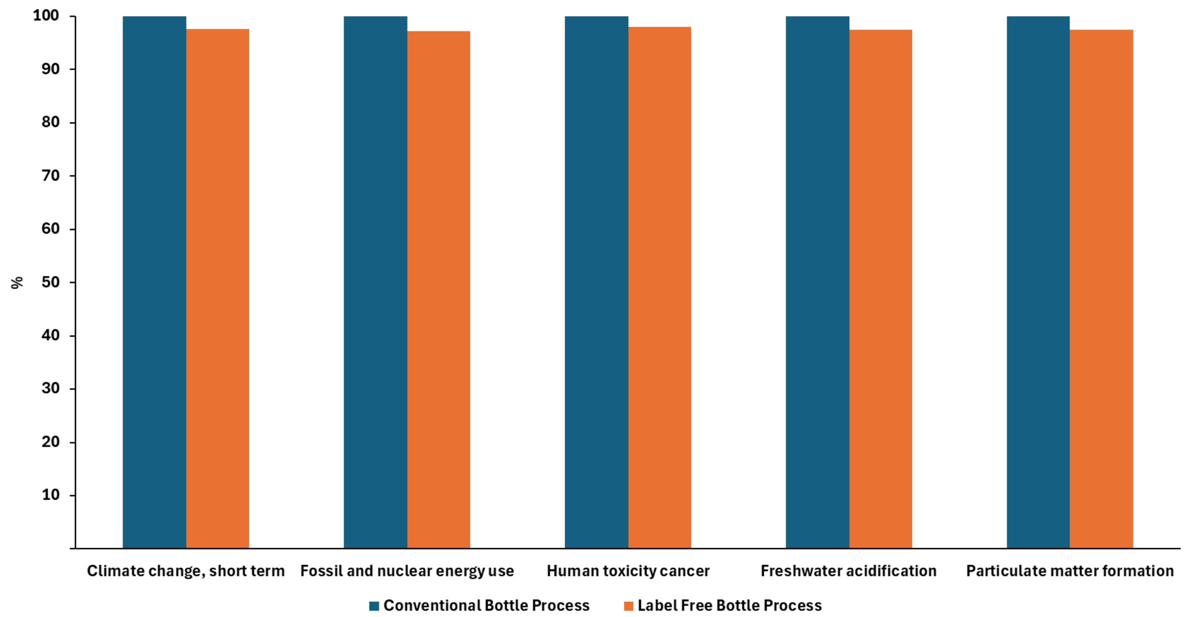

Figure 2 A comparison impact between conventional bottles and label-free bottles.

Table 5 The life cycle impacts of bottled water throughout the one-year period

Impact category	Unit	PET bottle	30% bio-based PET bottle	100% bio-based PET bottle
Climate change, short term	kg CO_2 eq	5.62 x 10^4	4.91 x 10^4	4.29 x 10^4
Climate change, long term	kg CO_2 eq	5.04 x 10^4	4.42 x 10^4	4 x 10^4
Fossil and nuclear energy use	MJ deprived	1.28 x10^6	1.13 x10^6	0.075 x 10^6
Mineral resources use	kg deprived	905.5122	805.5549	627.2688
Photochemical oxidant formation	kg NMVOC eq	191.6955	152.7785	113.2348
Ozone layer depletion	kg CFC-11 eq	0.216374	0.20612	0.003891
Freshwater ecotoxicity	CTUe	6.35 x10^8	5.63 x10^8	4.85 x10^8
Human toxicity cancer	CTUh	0.003979	0.003593	0.00294
Human toxicity non-cancer	CTUh	0.0408397	0.010325	0.011799
Freshwater acidification	kg SO_2 eq	0.000454	0.000605	0.00069
Terrestrial acidification	kg SO_2 eq	0.369518	0.737366	0.985103
Freshwater eutrophication	kg PO_4 eq	0.702419	0.24799	1.777923
Marine eutrophication	kg N eq	4.630902	9.89068	39.33691
Particulate matter formation	kg PM2.5 eq	21.48775	29.99551	34.9006
Ionizing radiation	Bq C-14 eq	4.15 x10^5	5.14 x10^5	6.16 x10^5
Land transformation, biodiversity	m^2 yr arable	4.985404	-5.73239	-10.5642
Land occupation, biodiversity	m^2 yr arable	2061.226	-5681.05	-8549.67
Water scarcity	m^3 world eq	2.48 x10^4	-6785.65	-1.18x10^5

The impact assessment at the midpoint level of Scenario 2 reveals that the conventional PET bottle exhibits higher impacts than 30% and 100% bio-based PET bottles. The main categories indicating significant differences are climate change, short term, showing emissions of 5.6 tons CO_2 eq per year for the conventional PET bottle, whereas the 30% and 100% bio-based PET bottles emit 4.9 and 4.3 tons CO_2 eq per year, respectively. Fossil, nuclear energy, and mineral resources use show clear trends of the reduction in the bio-based bottles. Other impact categories that do not differ significantly among all three bottle types include factors related to human health, such as human toxicity and particulate matter formation. Moreover, beyond these, the impact categories of land transformation, occupation, biodiversity, and water scarcity for bio-based PET show negative impacts, indicating that different processes in the life cycle may contribute to reducing these specific impacts. This can be attributed to the use of efficient and sustainable agricultural practices for producing bio-based raw materials. Such practices include the utilization of existing agricultural land, crop rotation, organic farming methods, and modern irrigation technologies, which collectively minimize the environmental footprint compared to conventional fossil-based PET production. Additionally, bio-based PET production often incorporates biomass that is considered waste, reducing the need for additional land use and contributing to lower overall environmental impacts. These factors result in the observed negative impacts in these categories, demonstrating the potential benefits of bio-based PET in terms of land and water resource management. Figure 3 illustrates the significant impacts of all three bottle types in the form of impact proportions by life cycle processes.

The classification of impact quantities according to the life cycle processes of the bottles shows the proportional differences in impact quantities for each bottle type. A significant proportion of the impact of PET bottles is in the production and transportation stages. The proportion of impact for 30% bio-based PET is slightly reduced in the production stage. The impact proportions for 100% bio-based PET differ significantly in several categories, especially in the ozone layer depletion category, which only has 1% impact in the production phase. Meanwhile, the freshwater acidification and particulate matter formation categories have increased impact proportions in the production phase.

The results of the assessment of all three bottle types using the IMPACT World+ endpoint method are shown in Table 6, which indicates the damages resulting from the midpoint impacts.

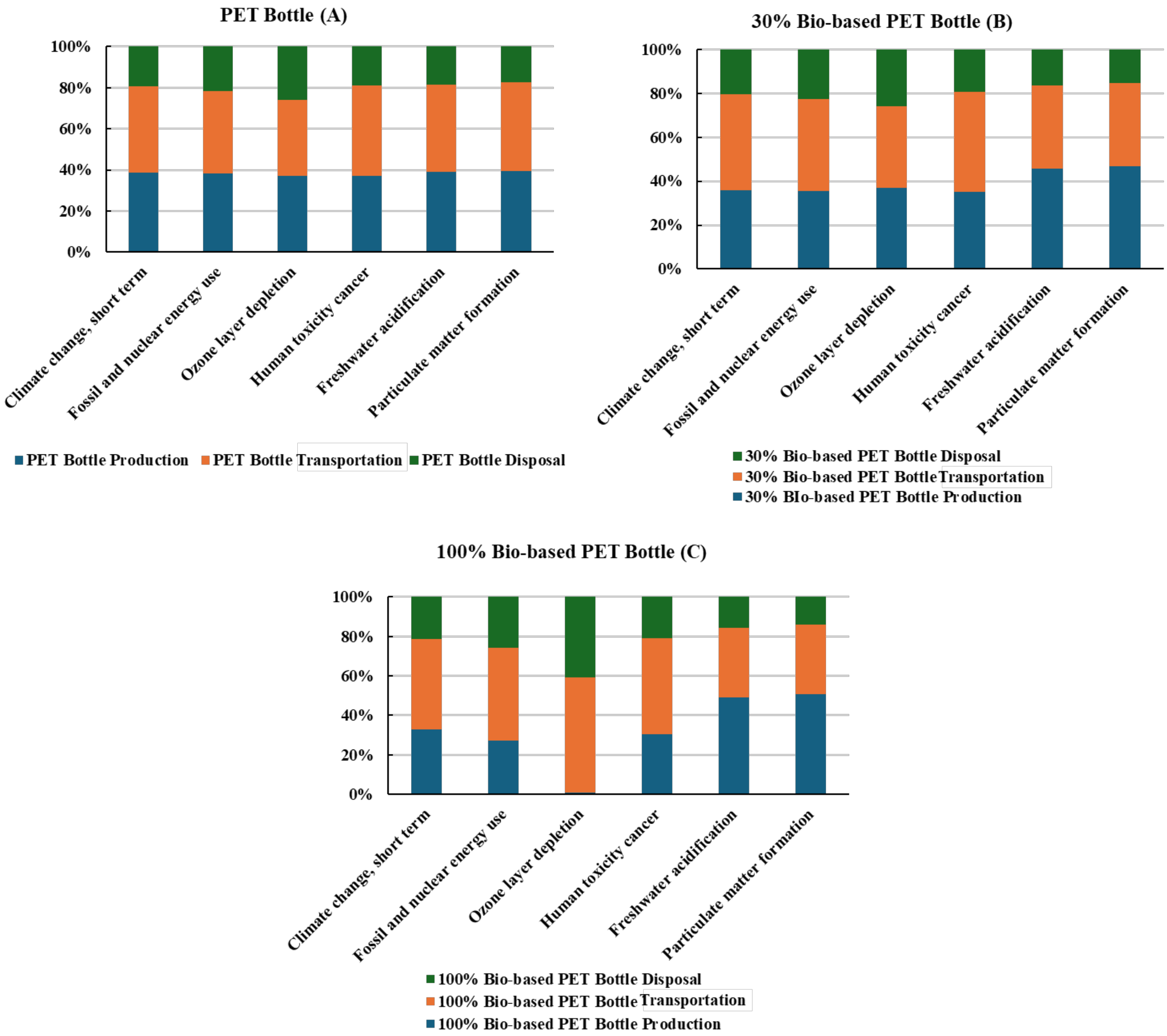

Figure 3 The impacts occurring in each life cycle process of the water bottles, (A) PET bottle, (B) 30% bio-based PET, and (C) 100% bio-based PET.

Table 6 The endpoint impacts of the bottles produced from all three material types

Damage category	Unit	PET bottle	30% bio-based PET bottle	100% bio-based PET bottle
Human health	DALY	11.70	7.35	4.87
Ecosystem quality	$PDF.m^2.yr$	4.18 x10^5	3.69 x10^5	3.16 x10^5

In this study, the endpoint impacts on human health and ecosystem quality for PET, 30% bio-based PET, and 100% bio-based PET bottles were assessed. The results show that bio-based PET bottles have lower impacts compared to conventional PET bottles. Specifically, the 100% bio-based PET bottles demonstrate the lowest impacts on both human health and ecosystem quality.

Human health (DALY): The reduction in DALY observed in our study for 30% and 100% bio-based PET bottles aligns with findings from Chen et al. (2016) [19], which reported a significant decrease in human health impacts when switching from fossil-based to bio-based plastics due to lower emissions of toxic substances during production and disposal processes.

Ecosystem quality (PDF.m^2.yr): The decrease in ecosystem quality impacts for bio-based PET bottles is consistent with the results of Kuczenski et al. (2019) [20], who found that bio-based materials generally have lower impacts on biodiversity and ecosystems. This is attributed to sustainable agricultural practices and reduced usage of fossil resources in bio-based PET production.

Overall, our findings are consistent with these previous studies, reinforcing the conclusion that bio-based PET bottles can offer substantial environmental benefits over conventional PET bottles. These benefits are primarily due to the lower emissions of greenhouse gases and toxic pollutants during the life cycle of bio-based materials. However, differences in specific methodologies and regional factors can lead to variations in the magnitude of these impacts.

Scenario 3: Comparing the proportions of recycling rates at 30%, 70%, and 100% of the water bottles used in Ramathibodi Hospital

The midpoint impacts of Scenario 3 are shown in Table 7 and Figure 4, indicating the number of impacts that occur throughout the year for the disposal of water bottles used in Ramathibodi Hospital, with varying proportions of recycling rates.

The quantity of impacts arising from the process of water bottle disposal, as shown in the recycling rate proportions, demonstrates an apparent reduction. Recycling at a rate of 70% can reduce the impacts from disposal by 50%, while 100% recycling can achieve a reduction of impacts by 90%.

Table 7 The midpoint impact of recycling rates on environmental categories

Impact category	Unit	30% recycling	70% recycling	100% recycling
Climate change, short term	kg CO_2 eq	1.09×10^4	5.31×10^3	1.08×10^3
Climate change, long term	kg CO_2 eq	9.69×10^3	4.68×10^3	928
Fossil and nuclear energy use	MJ deprived	2.79×10^5	1.38×10^5	3.22×10^4
Mineral resources use	kg deprived	196	92.7	15.5
Photochemical oxidant formation	kg NMVOC eq	38	18.6	4.03
Ozone layer depletion	kg CFC-11 eq	0.056	0.024	6.38×10^{-6}
Freshwater ecotoxicity	CTUe	1.3×10^8	6.22×10^7	1.13×10^7
Human toxicity cancer	CTUh	0.000747	0.000367	8.07×10^{-5}
Human toxicity non-cancer	CTUh	0.00167	0.000777	0.000106
Freshwater acidification	kg SO_2 eq	8.48×10^{-5}	4.1×10^{-5}	8.09×10^{-6}
Terrestrial acidification	kg SO_2 eq	0.069	0.0333	0.00658
Freshwater eutrophication	kg PO_4 eq	0.145	0.0653	0.00562
Marine eutrophication	kg N eq	0.958	0.447	0.0638
Particulate matter formation	kg PM2.5 eq	3.74	1.84	0.418
Ionizing radiation	Bq C-14 eq	4.59×10^4	2.18×10^4	3.65×10^3
Land transformation, biodiversity	m^2 yr arable	0.843	0.414	0.0913
Land occupation, biodiversity	m^2 yr arable	124	62.4	16.1
Water scarcity	m^3 world eq	4.22×10^3	193×10^3	207

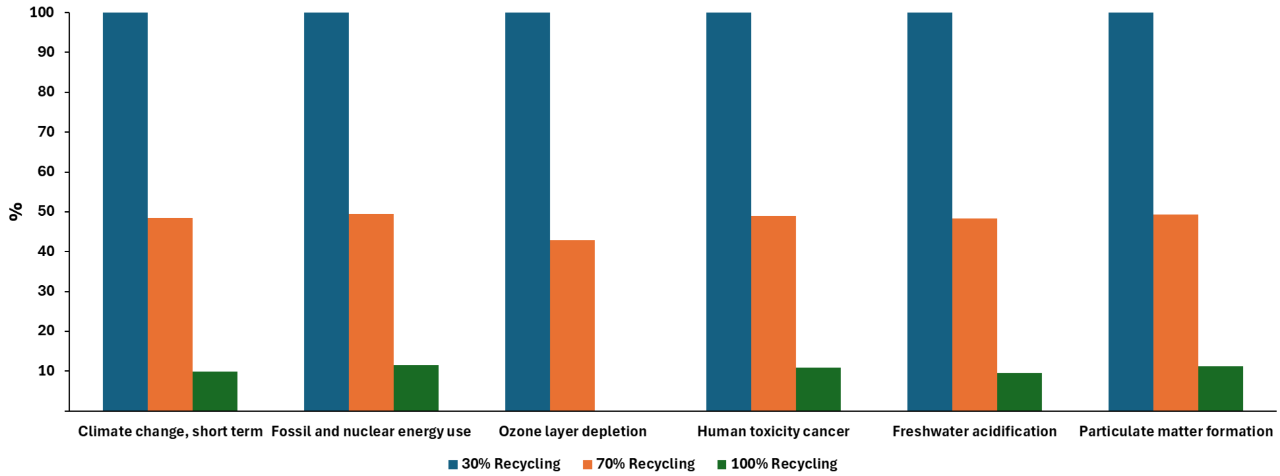

Figure 4 The quantity of impacts that arise from the process of water bottle disposal according to different recycling rates.

Discussion

The impacts in Scenario 1 indicate only a tiny difference in several impact categories. The label-free bottles show a maximum reduction of 2% in important impact categories such as climate change, fossil and nuclear energy use, freshwater ecotoxicity, human toxicity cancer, and particulate matter formation. These quantities suggest that the production and disposal of bottle labels have only a minor impact on the overall life cycle of the water bottles. Therefore, it can be concluded that changing traditional water bottles to label-free bottles may not reduce the overall environmental footprint caused by water bottles. This is because the materials for producing labels constitute only about 2-3% of the total materials used in the manufacturing process. Producing label-free water bottles in hospitals may not be cost-effective as it might require additional mold creation expenses.

The change of material in bottle production in Scenario 2 reveals varying impacts, particularly concerning the climate change factor. It is indicated that conventional PET bottles release more greenhouse gases (GHG) compared to bottles made with bio-based materials. Substituting conventional PET bottles with 30% bio-based PET reduces GHG emissions by 7 tons of CO_2 eq per year, which accounts for a 12.5% reduction in overall GHG emissions. Meanwhile, using 100% bio-based PET reduces GHG emissions by 13 tons CO_2 eq per year, amounting to a 23% reduction in total GHG emissions over the life cycle. The change of material from conventional bottles to bio-based materials, which includes raw materials obtained from plants, significantly reduces the impact of fossil and nuclear energy use. The production of bio-based PET, derived from plants instead of petrochemicals, reduces harmful substances contributing to ozone layer depletion. The presentation of impact quantities for each category of the three bottle groups shows that the changes in impact arise primarily from the production phase.

The material transition in the production phase from fossil-based to bio-based demonstrates noticeable differences. However, GHG emissions are still released from bio-based production processes, possibly from processes involving electricity use, natural gas, or agricultural activities [21–22]. The bio-based production process is advantageous over the fossil-based process because the carbon released is considered "New Carbon" that circulates within the carbon cycle. "New Carbon" comes from plants that absorb CO_2 during photosynthesis. When bio-based products decompose, this carbon is released back into the atmosphere and reabsorbed by plants, maintaining a balance. In contrast, fossil-based processes release "Old Carbon" stored in fossil fuels for millions of years. When burned, this carbon enters the atmosphere, increasing GHG levels because it is not part of the current natural carbon cycle. For example, bio-based production like growing corn for ethanol uses "New Carbon," while extracting oil for plastic production releases "Old Carbon". By using "New Carbon," bio-based processes help maintain the natural carbon cycle and do not contribute to the increase in GHG, unlike "Old Carbon," which adds to the atmospheric CO_2 levels and exacerbates climate change [23–25]. The impact category that shows a significant difference in the 100% bio-based PET production process is ozone layer depletion, with an impact quantity of only 1%. Although the impact of producing 100% bio-based PET tends to be lower than conventional production, there are some impact categories where the quantity is higher compared to PET and 30% bio-PET production, namely particulate matter formation and freshwater acidification. The factors contributing to the aforementioned impacts may arise from the production of raw materials sourced from crops, such as sugarcane cultivation for ethanol production, which is a primary feedstock for bio-based MEG production [26].

Additionally, burning of plant residues for cultivation purposes may lead to an increase in PM 2.5 levels [27]. Furthermore, specific production processes, like ethanol fermentation, might contaminate water bodies with acids. The endpoint impacts indicate the extent of damage caused in each impact category to human health and the environment. Factors related to human health show damage equivalent to 11.70 DALY for conventional PET bottles, representing the number of years of healthy life lost due to the life cycle of the bottles. Bio-based bottles exhibit lower DALY values, indicating a potential reduction in health-related impacts. This finding aligns with Chen et al. (2016) [19], who reported similar health impact reductions for bio-based materials. On the other hand, factors related to Ecosystem quality show damage equivalent to 4.18×10^5 PDF.m^2.yr for conventional PET bottles, signifying the trend of annual disappearance of plant species area. The switch to bio-based bottles could lead to the maximum reduction of up to 100,000 m^2 per year of such losses.

Comparing the impacts resulting from the disposal of residual water bottles from recycling at different proportions, Thailand currently has a recycling rate of 30% of all plastic waste. The remaining plastic waste is disposed of through landfilling rather than incineration, as burning plastic waste produces higher toxicity levels than biodegradable waste [28]. The highest impact is observed from the disposal of 30% recycled water bottles, while recycling at 70% and 100% shows decreasing impacts, respectively. Recycling at 100% can reduce environmental impacts by up to 90% in several impact categories. This may be attributed to the significant reduction in the remaining water content of the bottles in the life cycle, resulting in reduced landfill impacts. The proportion of GHG emissions from conventional PET bottles in Ramathibodi Hospital is 10 tons CO_2 eq annually. By incorporating a 100% recycling model into the life cycle, the GHG emissions could be reduced to just 1 ton CO_2 eq per year.

Apart from the three scenarios, the transportation of water bottles has impacts comparable to those from production. However, reducing the impact of the transportation of water bottles in hospitals can be achieved by managing the turnover of drinking water stock used in the hospital. If transportation turnover is reduced, it may help mitigate the overall impact.

The study of all three scenarios reveals environmental impact outcomes that lead to different management approaches. However, implementing these approaches may necessitate considering factors beyond environmental aspects, such as investment feasibility in the respective processes. Changing traditional bottles to label-free ones shows a minor reduction in environmental impact, and the decision to change bottle formats may not be cost-effective, considering the investment required for creating molds for label-free bottles. Additionally, transitioning to biobased materials for producing water bottles demonstrates potential reductions in various environmental impact categories. Nevertheless, the decision to change materials may require consideration of the cost-effectiveness of biobased materials, which may involve acceptable costs in the production of environmentally friendly bottles. Promoting full recycling or increased recycling quantity may require planning and measures to facilitate such circumstances, which might necessitate sociological factors within hospital practices and policies to be considered.

Conclusions

The life cycle assessment of water bottles in all three scenarios provides insights into reducing the environmental impact caused by water bottles in Ramathibodi Hospital. Although the concept of label-free bottles may not significantly impact the overall life cycle, changing the material to bio-based PET and promoting 100% recycling behavior in the hospital can significantly reduce the environmental footprint. Implementing both approaches together can reduce 22 tons of CO_2 equivalent emissions per year, which accounts for 40% of the total GHG emissions from all water bottles. This assessment highlights the pathways to manage the environmental impacts caused by water bottles in hospitals, aiding decision-making in environmental management to minimize the footprint. Finding strategies to mitigate environmental impacts is crucial, especially in hospitals where various activities are carried out for patient care. Strategies for mitigation include implementing energy-efficient practices, promoting recycling programs, and utilizing renewable energy sources for public hospitals, while private hospitals can invest in advanced medical equipment, develop green building practices, and partner with suppliers for sustainable medical supplies. This study presents new solutions for addressing climate change issues and forthcoming regulations. Evaluating the life cycle of every activity can reveal its impacts, leading to improvements for better health outcomes for both humans and the environment, thus promoting sustainable practices.

Competing Interests

The authors declare no conflict of interest regarding the publication of this article.

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