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Life cycle assessment and cost analysis of locally made solar powered cooler for vaccine storage

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ABSTRACT

Storing vaccines and perishable food in regions without access to the national grid presents significant challenges. Solar power generation technologies have emerged as a viable alternative solution to address these issues. This study conducted a life cycle assessment (LCA) and cost analysis (CA) of the locally developed solar-powered cooler to assess its economic viability and potential environmental impacts. The cooler was designed to preserve vaccines and perishable foods for use, especially in areas with no electricity connectivity, as a cheaper alternative to electricity-powered coolers. The results of LCA show that battery manufacturing was a slightly higher contributor to environmental impacts across various indicators, with terrestrial ecotoxicity identified as the highest impact among other environmental impacts. Cost analysis results further revealed that a solar-powered cooler project demonstrated a positive economic outlook, with the unit manufacturing cost estimated at USD 2682. This quantitative analysis of life cycle and cost will help decision-makers comprehend both the economic aspects and environmental impacts throughout the life cycle of locally manufactured solar-powered coolers. Such insights will be instrumental in enhancing the sustainability of these products.

1. Introduction

Preserving vaccines and perishable food in Sub-Saharan Africa is a challenging task due to a combination of factors, including unreliable energy sources (Blimpo and Cosgrove-Davies, 2019), insufficient storage facilities (Makule et al., 2022), elevated operational expenses (McCarney et al., 2013), and fluctuating temperatures (Raihan Uddin et al., 2021). This serious challenge threatens the continuity of the vaccine cold chain (Sinnei et al., 2023). Inadequate vaccine storage conditions decrease efficacy, increasing disease risk and causing financial losses (Hong et al., 2023; Sinnei et al., 2023; Syed et al., 2023). Specifically, Sub-Saharan Africa experiences a substantial toll of child deaths due to inadequate immunization rates. Moreover, the lack of access to proper storage facilities places an additional 19.5 million children in a dangerous situation (Raihan Uddin et al., 2021).

Many countries in sub-Saharan Africa depend on electrically powered cooling systems to store vaccines and perishable foods. However, the unreliability of the national electricity grid, especially in rural areas/regions, poses significant challenges (Mandelli et al., 2016). In areas lacking grid access, the situation worsens. Among other nations, Tanzania struggles with inadequate and irregular energy supply in its rural areas (SDG, 2021; Tonini et al., 2022).

Using generators powered by fossil fuels like gasoline or diesel presents an alternative but becomes expensive for low-income individuals. Furthermore, this approach contributes to the emission of greenhouse gases like carbon dioxide, sulfur dioxide and nitrous oxide (Adebayo, 2022; Coady et al., 2017; Hassan et al., 2021), thus leading to global warming (Letcher, 2021), ozone layer depletion (Holtsmark, 2014), air pollution (Bekun et al., 2019), acidic rain (Martins et al., 2019), climate change (Plantinga and Scholtens, 2021). To tackle these energy and environmental concerns, solar power generation technologies emerge as a promising solution (Sadi et al., 2021).

In the past two decades, the cost of conventional energy has risen, while solar photovoltaic (PV) technology has advanced significantly, leading to 20–25 % increase in worldwide solar PV installations (Fu et al., 2018; Ren et al., 2020). Among all renewable sources, solar energy

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emerges as the most abundant and widely accessible globally (da Silva et al., 2018; Pillot et al., 2019).

This technology is increasingly recognized as the most favourable alternative, particularly for small cooling systems used to store food and vaccines (Del Pero et al., 2015; McCarney et al., 2013). Due to its proximity to the equator, Sub-Saharan Africa possesses significant solar energy potential, exceeding that of other renewable sources such as wind energy (Baye et al., 2021; Mohammed et al., 2013). Solar energy is free; the only expenses are associated with the installation, batteries, and purchasing of solar PV modules (Silveira et al., 2013). A solar-powered cooler reduces its contribution to global warming (Pillot et al., 2019), and this impact can be further reduced by using alternative refrigerants, such as R134a that have a lower global warming potential (Ren et al., 2020).

Numerous studies have conducted in-depth investigations into the life cycle and cost analysis of solar-powered coolers in developed countries (Ikram et al., 2021; Kishor Verma and Dondapati, 2017; Qi et al., 2021; Rossetti et al., 2022; Verma and Dondapati, 2017; Xiao et al., 2015), especially those utilized for advanced cooling applications of vaccines and perishable food items. However, these systems often come with a substantial price tag that makes them unaffordable for some developing countries, such as Tanzania.

Despite global solar refrigeration advancements, few studies have addressed the unique economic and environmental challenges of locally produced solar-powered coolers in developing countries like Tanzania. To ensure the effective implementation of innovative technologies like solar-powered coolers, conducting a comprehensive life cycle assessment (LCA) and cost analysis (CA) is crucial. LCA and CA are crucial tools for evaluating the balance between a specific technology's, economic feasibility and environmental impact. While LCA examines the potential environmental impact associated with the product's complete life cycle, ranging from raw material extraction to its final disposal (Finnveden and Potting, 2014; Gilmore, 2016), CA assesses the economic feasibility of the technology (Giacomella, 2021).

To address this knowledge gap, the main objective of this research was to assess the life cycle dimensions and cost analysis of a locally manufactured solar-powered cooler designed for the storage of vaccines and perishable food in Tanzania. The results obtained from this study can provide a crucial basis for future development projects focused on solar cooling systems in Tanzania and other parts of the world.

2. Material and methods

2.1. Design of the system

The solar-powered cooler, designed with a 30 L capacity, has dimensions of 89 cm (height), 56 cm (length), and 52 cm (width), as shown in Fig. 1. The design accounts for optimal cooling efficiency, using aluminium for the inner lining and galvanized steel for the outer casing. The insulation thickness was calculated to maintain internal temperatures below −15 °C in ambient conditions, with material properties sourced from ASHRAE standards. Factors considered when sizing the solar-powered cooler were the temperature required, the amount required to be stored by the cooler, and portability. Its construction included an interior made of aluminium and an exterior made of galvanized steel. The thermal conductivities for steel, aluminium, and insulation were sourced from ASHRAE standards. The values are 48.5 W/(m·K) for steel and 229 W/(m·K) for aluminium. The refrigerant selected for the solar-powered cooler is R134a, chosen for its non-toxic and non-flammable properties and its zero-ozone depletion potential (ODP) (Ren et al., 2020). R134a also offers efficient thermodynamic performance, making it suitable for low-temperature cooling applications.

The solar photovoltaic (PV) system comprises a solar module, a charge controller, and a battery. The cooling system comprises a compressor, expansion valve, evaporator, and condenser. Table 1 provides detailed specifications for the solar panel, charge controller, and battery used in the solar-powered cooler. These components were carefully selected to meet the cooling system's energy demands, ensuring consistent performance in off-grid conditions. For example, the monocrystalline solar panel can generate 200 W at standard test conditions (STC), while the deep-cycle lead battery provides a 200 Ah capacity suitable for long-term energy storage. The sizing of the PV system was carefully determined, considering various factors, such as ambient temperature, since higher temperature may reduce power output and increase thermal stress on materials. Low temperature potentially increases efficiency but may limit production due to shorter daylight hours.

This analysis ensures that the PV system is designed to meet the cooler's requirements and operate efficiently in different environmental conditions. Furthermore, the evaluation of the cooler's dimensions

Fig. 1. Design of the Solar-Powered Cooler (locally made in Tanzania).

Table 1
The parameters of solar panel, charge controller and battery.

Items	Parameters/unit
Parameters of solar panel	
Solar Cell	Monocrystalline silicon
Dimensions	(Length 435 mm, Width 395 mm)
Area	0.171 8m^2
Open circuit voltage	18 V
Short circuit current	11.1 V
Maximum power at STC (Pmax)	200 W
Parameters of charge controller	
Battery input voltage	12V
Charging current	20A
Parameters of solar battery	
Type of battery	Deep cycle-Lead
Nominal voltage	12V
Rated capacity	200Ah

STC: Standard Test Condition (temperature is 25 °C, solar irradiation is 1000 W/m^2)

involved assessing critical factors, including its storage capacity and the precise temperature needed for preserving vaccines and perishable food items. This analysis ensures that the cooler is suitably sized to meet the demands of its intended use, effectively maintaining the desired temperature settings for the stored items. Moreover, this system operates with lower electricity requirements because it is designed to power a DC cooler, making it both portable and cost-efficient. Detailed data on the design and performance analysis of the cooler is provided by Marwa et al. (2024).

2.2. Life cycle assessment

The Life Cycle Assessment (LCA) was conducted using SimaPro software (version 9.3.0.3) (Kruhak et al., 2022), following the ISO 14040 standard. The functional unit was defined as the complete life cycle of an 80 kg solar-powered cooler with a 30 L capacity. The study included all stages, from raw material extraction to end-of-life disposal. Key assumptions, such as using data from the Ecoinvent database (Fernández-Marchante et al., 2024) for material inputs, were made to ensure consistency in environmental impact assessments. It is a comprehensive methodology that enables the identification and measurement of material and energy consumption, as well as waste production, throughout the entire life cycle of a product (Ciacci and Passarini, 2020). LCA provides a holistic evaluation of all environmental aspects and their impacts (Guinee et al., 2011). This study focuses on the LCA of a solar-powered cooler's life cycle. The study adhered to the concepts outlined in the LCA standards of the ISO 14040 series established by the International Organization for Standardization. The LCA methodology involved goal and scope definition, inventory analysis, impact assessment, and interpretation of the results.

10.2.1. Goal and scope definition

This LCA study aimed to assess the environmental impact of the solar-powered cooler's operation through the entire life cycle and environmental emissions. This study also identifies environmental hotspots and investigates potential opportunities for improvement. Following the international standards ISO 14040 and 14044, the analysis employed a cradle-to-grave life cycle assessment, including raw material extraction, production, transport, use, and end-of-life considerations. The LCA focused on key environmental impact categories associated with materials used in the cooler's construction, including: (i) Global warming potential (GWP) - evaluates the total greenhouse gas emissions, primarily CO_2, from materials like steel and refrigerants, (ii) Stratospheric ozone depletion (SOD) - measures the potential for substances like refrigerants (R134a) to deplete the ozone layer, (iii)

Human toxicity (HT) - assesses the impact of toxic emissions, particularly aluminium and steel production, on human health. These categories provide a comprehensive evaluation of the cooler's environmental footprint, from material extraction to disposal. The study's primary goal was to assess the environmental implications of the solar-powered cooler's life cycle and identify components with the most substantial environmental impacts.

2.2.1.1. Functional unit.

The functional unit was defined as the complete life cycle of an 80 kg solar-powered cooler with 30 L of cooling space made in Tanzania. This cooler can achieve a cooling temperature as low as −15 °C for vaccine/food storage for 25 years of cooler use. The selection of this function unit is based on the life span of the components used in fabricating the cooler.

2.2.1.2. System boundary.

The life cycle of a solar-powered cooler is divided into four stages following the ISO 14040 standard and specific research objectives: production (including raw material extraction, part manufacturing, and assembly), transportation, usage, and disposal. The life span of the solar-powered cooler is defined based on literature, with the lifespan of solar PV set at 25 years (Hocine and Mounia Samira, 2019) and the cooler within the range of 10–15 years (Xiao et al., 2015). The system boundary is illustrated in Fig. 2.

10.2.2. Inventory analysis

The inventory analysis aimed to collect data on material inputs and energy consumption associated with the solar-powered cooler. Data were obtained from production sites and relevant literature, including material weights (e.g., steel, aluminium, and polyurethane foam) and energy use during the cooler's fabrication. This data was used as inputs into SimaPro software, where background information was supplemented using the Ecoinvent v3 database. The analysis quantified air, water, and soil emissions, focusing on key pollutants like CO_2, NOx, and heavy metals. Data for the manufacturing process of the solar-powered cooler (Table 2), including material weights (steel, aluminium, and wheels, and quantities for components like the solar panel, battery, and compressor), information on the fabrication of components like solar PV and battery, and total energy consumption during the cooler's fabrication were collected from production sites. This data forms the basis for the Life Cycle Impact Assessment (LCIA), allowing for an accurate calculation of environmental burdens associated with each component, from production to disposal. In addition, background information was sourced from databases, particularly the Ecoinvent libraries within SimaPro software version 9.3.0.3, as well as relevant literature. The environmental impact of the materials used in constructing the solar-powered cooler was assessed from cradle to grave, considering all stages from raw material extraction to disposal. The resulting inventory provides a detailed list of substance emissions to various environmental components, including soil, water, and air, with a breakdown of specific substances and their respective emissions to these environmental compartments.

10.2.3. Life cycle impact assessment (LCIA)

The study employed SimaPro software version 9.3.0.3 to manage inventory data and perform impact assessments. SimaPro was selected for its high accuracy, transparency, and extensive adoption in various LCA software platforms. The ReCiPe2016 midpoint methodology was used because it is widely used for developing phases in various processes. It stands out for several reasons: it includes 18 midpoint impact categories, considers future extraction consequences in inventory analysis, adopts a global impact perspective instead of focusing on specific continents like Europe, reflects the current state of scientific knowledge, provides best practices for both midpoint and endpoint assessments, and integrates considerations from CML2001 and Eco-Indicator 99, making it the successor of both models (Hischier et al., 2010). The analysis considered the following impact categories (IM) relevant to the life cycle of the refrigerator: Global warming, Human ecotoxicity, Stratospheric

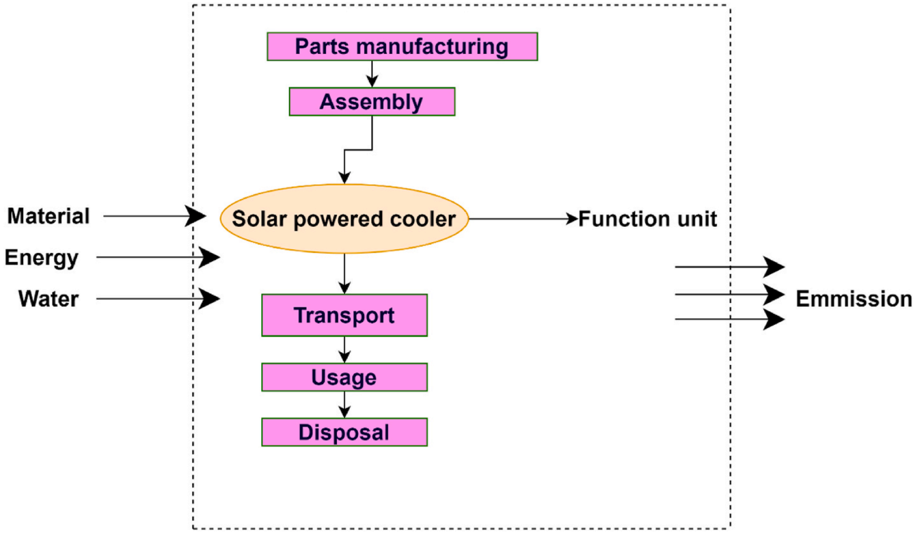

Fig. 2. System boundary for complete life cycle of solar powered cooler.

Table 2
Inventory data for the 80 kg solar-powered cooler.

INDICATOR	QUANTITY	WEIGHT (kg)
Wheel	4	1.000
Solar Panel	1	8.000
Battery	1	40.000
Refrigerant	1	0.125
Galvanized Steel Outer Cover	1	22.640
Aluminium Sheet Inner Cover	1	1.270
Polyurethane Foam	1	1.230
Compressor	2	5.000

ozone depletion, Ionization radiation, Ozone formation (Human health), Fine particulate matter formation, Ozone formation (Terrestrial ecosystem), Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Human carcinogenic toxicity, Human non-carcinogenic toxicity, Land use, Mineral resource scarcity, Fossil resource scarcity, and Water consumption. These categories were chosen for their significant relevance to the environmental impact of the cooler throughout its life cycle.

10.3. Cost analysis

Cost analysis is a systematic method of understanding the total expenses associated with a project. It involves evaluating the costs associated with a project (Prosser et al., 2024). This analysis can help organizations understand the economic feasibility of projects and assess profitability, allowing stakeholders to make informed financial decisions. Cost analysis accounts for expenses related to raw materials and additional equipment needed to manufacture the solar-powered cooler. The manufacturer supplied these costs, consisting of various component prices such as solar panels, inverters, batteries, compressors, refrigerants, and other materials.

3. Result and discussion

3.1. Life cycle impact assessment results

Table 3 presents the Life Cycle Impact Assessment (LCIA) results for the solar-powered cooler, calculated using the ReCiPe2016 Midpoint (H) V1.08/World (2010) H/A method. The table shows that the highest environmental impacts are observed in the categories of TEC and HNCT, driven primarily by battery manufacturing. These findings suggest that battery production significantly affects the overall environmental footprint of the cooler. The solar-powered cooler had the greatest impact on TEC, followed by HNCT and GW. The battery component of the solar-powered cooler significantly contributes to environmental impact across various categories, so there is a need to explore alternative batteries with lower environmental impact.

Table 3
LCIA results for a solar powered cooler using the ReCiPe2016 midpoint method.

Impact category (IM)	Unit	Total
Global warming (GW)	kg CO_2 eq	230.5540
Stratospheric ozone depletion (SOD)	kg CFC11 eq	0.0001
Ionizing radiation (ID)	kBq Co-60 eq	17.5322
Ozone formation, Human health (OF, HH)	kg NO_x eq	0.8026
Fine particulate matter formation (FPMF)	kg PM2.5 eq	0.6935
Ozone formation, Terrestrial ecosystems (OF, TE)	kg NO_x eq	0.8351
Terrestrial acidification (TA)	kg SO_2 eq	1.2417
Freshwater eutrophication (FEU)	kg P eq	0.1314
Marine eutrophication (MEU)	kg N eq	0.0092
Terrestrial ecotoxicity (TEC)	kg 1,4-DCB	2815.8300
Freshwater ecotoxicity (FEC)	kg 1,4-DCB	53.1308
Marine ecotoxicity (MEC)	kg 1,4-DCB	72.3929
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	83.2484
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB	1923.2800
Land use (LU)	m^2a crop eq	6.3210
Mineral resource scarcity (MRS)	kg Cu eq	9.9076
Fossil resource scarcity (FRS)	kg oil eq	51.9687
Water consumption (WS)	m^3	3.1896

3.1.1. Production of solar-powered cooler

The production assessment of the solar-powered cooler focused on key components, including the battery, refrigerant, solar panel, galvanized steel outer cover, aluminium sheet inner cover, polyurethane foam, compressor, and wheels. Fig. 3 illustrates the relative contributions of various components of the solar-powered cooler to different environmental impact categories. The battery component shows the highest contribution across most categories, particularly in TA (75.36 %) and HNCT (80.60 %). In comparison, the solar panel contributes significantly to GW (27.52 %) and SOD (27.55 %). This visualization highlights the critical areas for improvement, especially in battery and solar panel materials. Battery manufacturing was the dominant contributor to environmental impacts, accounting for 50 % of the total mass of the solar-powered cooler. It contributed most to categories such as terrestrial ecotoxicity (75 %) and human non-carcinogenic toxicity

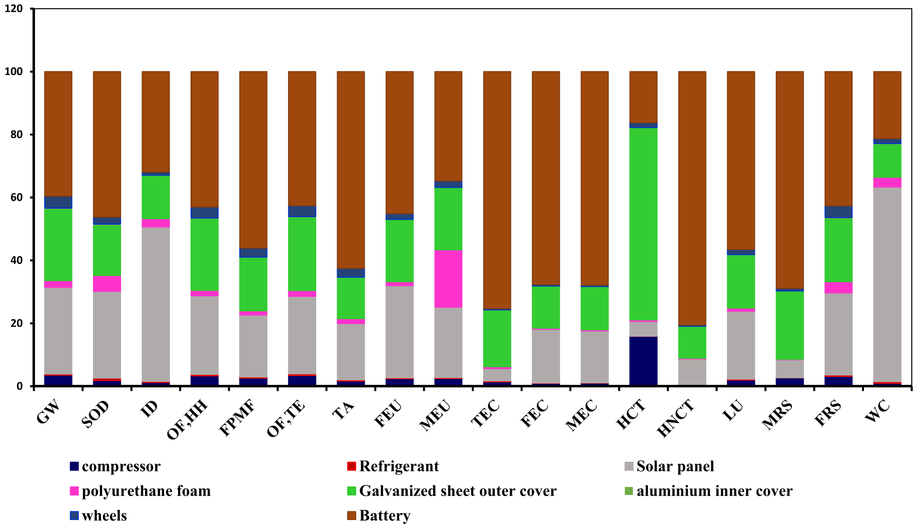

Fig. 3. Relative contributions of production process to each impact category.

(80 %). This contributes to the release of harmful gases, such as carbon dioxide, during its production. The solar panel ranks as the second most significant contributor after the battery. As shown in Table 4, the battery contributes 39.63 % to GW and 75.36 % to TEC, making it the largest contributor to environmental impacts. The galvanized steel outer cover and solar panel contribute largely to GW, at 22.71 % and 27.52 %, respectively. These results suggest that future improvements should focus on reducing the environmental burden of these components, particularly the battery.

The primary factors influencing the environmental impact category are as follows; In terms of TEC, the battery accounts for 75.36 %, followed by the galvanized steel outer cover at 17.89 % and the solar panel at 3.90 %. Regarding HNCT, the main contributors include the battery (80.60 %), galvanized steel outer cover (10.12 %), and solar panel (8.26 %). Lead (II) is the primary contributor to human non-carcinogenic toxicity.

In the context of GW within the life cycle of the solar-powered cooler, the major contributors are the battery (39.63 %), galvanized steel outer cover (22.71 %), and solar panel (27.52 %). The predominant factor driving global warming is greenhouse gases, particularly carbon dioxide (CO_2), emitted during battery manufacturing. The leading contributors to MEC in the analyzed product are the battery (68.5 %), galvanized steel outer cover (13.8 %), and solar panel (15.6 %). The primary agents responsible for marine ecotoxicity are zinc (II) and copper ions.

The minor contributors to the environmental impact category are as follows:

In the FPMF, the major contributors are the battery (56.11 %), galvanized steel outer cover (16.90 %), and the solar panel (19.67 %). Sulfur dioxide stands out as the largest contributor to fine particulate matter formation. Regarding FEU, key contributors include the battery (67.73 %), galvanized steel outer cover (17.02 %), and the solar panel (13.33 %). The primary factor driving freshwater eutrophication is phosphate. In MEU, significant contributors are the battery (34.77 %), galvanized steel outer cover (18.22 %), and solar panel (22.37 %). Nitrate and ammonium are the major contributors to marine eutrophication. For SOD, major contributors are batteries (46.26 %), followed by galvanized steel outer cover (15.93 %), and solar panels (27.55 %). Dinitrogen monoxide is the main contributor to stratospheric ozone depletion, followed by methane, tetrachloro, and CFC-10.

3.1.2. *Disposal*

During the disposal of a solar-powered cooler, certain components, such as the galvanized steel outer cover and aluminium inner cover, will be reused. These parts, along with the compressor, wheels, and some sections of the battery, solar panel, and Polyurethane Foam, can be recycled, reused, or disposed of in municipal solid waste. This study emphasizes the reuse of many parts of the solar-powered cooler, the recycling of others, and the disposal of a few components, ultimately

Table 4
Contribution of parts of solar-powered cooler to the environmental impact category in percentage form.

IM	Unit	compressor	Refrigerant	Solar panel	polyurethane foam	Galvanized steel outer cover	aluminium inner cover	wheels	Battery
GW	%	3.56	0.35	27.52	2.12	22.71	0.35	3.75	39.63
SOD	%	1.82	0.78	27.55	5.04	15.93	0.40	2.21	46.26
ID	%	1.21	0.36	49.70	2.62	13.79	0.03	0.97	31.94
OF, HH	%	3.32	0.46	24.98	1.70	22.68	0.31	3.48	43.06
FMPF	%	2.60	0.37	19.67	1.32	16.90	0.18	2.84	56.11
OF, TE	%	3.43	0.5177	24.64	1.84	23.18	0.31	3.44477	42.63
TA	%	1.71	0.35	17.88	1.56	12.95	0.22	2.77	62.56
FEU	%	2.44	0.26	29.33	1.20	19.76	0.05	1.83	45.14
MEU	%	2.48	0.29	22.37	18.22	19.72	0.1	2.04	34.77
TEC	%	1.44	0.27	3.90	0.62	17.89	0.17	0.35	75.36
FEC	%	0.93	0.14	17.02	0.38	13.33	0.06	0.39521	67.73
MEC	%	0.98	0.17	16.47	0.36	13.68	0.06	0.40	67.91
HCT	%	15.87	0.06	4.67	0.50	61.11	0.03	1.47	16.23
HCNT	%	0.36	0.08	8.26	0.21	10.12	0.02	0.34	80.60
LU	%	2	0.31	21.58	0.96	16.85	0.17	1.61	56.53
MRS	%	2.67	0.05	5.74	0.13	21.68	0.02	0.79	68.92
FRS	%	3.17	0.42	26.06	3.57	20.00	0.39	3.72	42.67
WS	%	0.97	0.52	61.84	3.10	10.40	0.32	1.56	21.29

reducing environmental impact during the disposal phase. The relative contribution of each phase to each impact category in the disposal stage is shown in Fig. 4. The reuse of solar-powered coolers brings benefits to all of the environmental impact categories. Reusing several components, such as the galvanized steel outer cover and compressor, leads to significant reductions in global warming and terrestrial ecotoxicity. Recycling the solar panel and other parts further mitigates environmental impacts. This analysis highlights the importance of incorporating reuse and recycling strategies in the cooler's lifecycle to minimize its environmental footprint.

3.2. *Cost analysis*

The manufacturing cost of the solar-powered cooler (unit cost for the production) was specified at USD 2682, covering the expenses associated with raw materials and labour. Among the components of the solar-powered cooler, the cost of the solar panel was very high because it is a folded solar panel, followed by a solar battery and then a compressor. Table 5 provides a detailed breakdown of the costs for materials and labour associated with constructing the solar-powered cooler. Solar panels and batteries represent the highest costs, at USD 644 and USD 421, accounting for nearly 40 % of total capital expenditure. The solar-powered cooler project exhibits a favourable economic outlook. This indicates the project's feasibility as the initial investment is USD 2682.

Table 5
Manufacturing cost of solar-powered cooler.

Item	Unit price (USD)	Quantity	Total price (USD)
Solar panel	644	1	644
Solar battery	421	1	421
Charge controller	32	1	32
Digital AKO thermostat	206	1	206
Compressor	301	1	301
Condenser	13	1	13
Evaporator	21	1	21
Refrigerant	52	1′	52
Polyurethane foam spray	19	5	95
Plate sheet galvanized	129	1	129
Plate sheet aluminium	86	1	86
Fridge stand	21	2	42
Twin cable, plastic	1	5	5
Flexible plastic	2	5	10
Power plug	2	1	2
Socket power	2	1	2
Capillary tube	13	1	13
External temperature sensor	64	1	64
Fridge door handle	3	1	3
Data logger	193	1	193
Fridge door gasket	13	1	13
Fridge door key	21	2	42
Araldite and polyamine resin	36	1	36
Countersunk screw stainless steel	9	¼	9
Rivet (aluminium)	26	1	26
Total labour charge	215		215
Total			2682

3.3. *Comparison of the present study with other studies*

There is a limited number of studies that comprehensively assess both the life cycle and cost analysis of solar-powered coolers. Previous research has often focused on specific cooler components, conducting separate analyses for life cycle assessments and cost analysis considerations. Only a few studies have integrated life cycle assessments and cost analysis in a single paper. The existing life cycle assessment studies often center on larger coolers powered by electricity from the national grid; a mix of energy sources, unlike the solar-powered cooler considered in this study. Additionally, the coolers discussed in these studies tend to be larger in size compared to the ones under examination. The study conducted by Xiao et al. (2015) focused on the LCA of a cooler, excluding discussions on the battery and solar panel. The cooler in their study was powered by electricity sourced from the national grid. Their result for GW was 1670 kg CO_2 eq, nearly five times that of the solar-powered cooler presented in this study, which emitted only 230.5540 kg CO_2 eq, but also the result of TA was 12.3 kg SO_2 eq nearly nine times that of the solar-powered cooler presented in this study which emitted only 1.24 kg SO_2. This means that the solar-powered cooler presented in this study has low CO_2 and SO_2 emissions. Despite being small in size compared to the cooler examined by Xiao et al. (2015), at 30 L capacity, this solar-powered cooler offers more advantages due to its minimal CO_2 and SO_2 emission and portability. Since the impact categories selected for this study are different, we have compared the results using approximate indicators. Table 6 summarizes the comparison between

Table 6
Comparison with other studies.

Category	Current study	Xiao et al. (2015)
Database	Ecoinvent	Ecoinvent
Weight	80 kg	61 kg
Refrigerant	R134a	R600a
Capacity	30 L	200 L
Methodology	ReCiPe	CML 2001
Result; (GWP)	230.5540 kg CO_2 -eq	1670 kg CO_2 - eq
(TA)	1.24 kg SO_2 -eq	12.3 kg SO_2 -eq

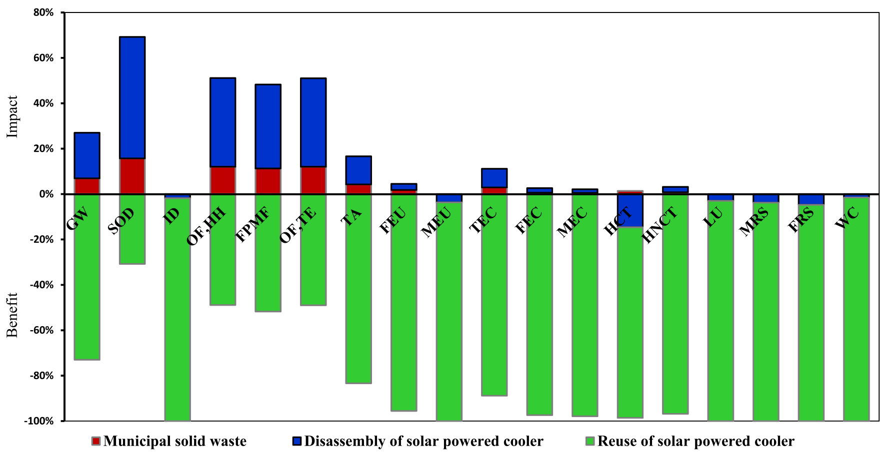

Fig. 4. Contributions of different disposal scenarios to various environmental impact categories.

the current study and those by Xiao et al. (2015). The solar-powered cooler in this study has significantly lower CO_2 emissions (230.55 kg CO_2-eq) compared to the cooler analyzed by Xiao et al. (2015) (1670 kg CO_2-eq)). Additionally, this study's cooler emits only 1.24 kg SO_2-eq, much lower than the 12.3 kg SO_2-eq reported in Xiao et al. (2015) study. The solar-powered cooler in our study has a slightly higher mass of 80 kg compared to coolers in other studies. This is due to the inclusion of the solar PV battery, which constitutes 50 % of the total weight of the solar-powered cooler. The cooler itself weighs 32 kg. These differences highlight the environmental advantages of using a smaller, solar-powered system, especially in terms of global warming and terrestrial acidification reduction.

Within the context of cost analysis, numerous studies have focused on sophisticated and expansive cooling systems, frequently neglecting the element of portability evident in the solar-powered cooler examined in this study. For instance, study by Sadi et al. (2021) done in India revealed an initial investment of nearly USD 7000. In a study by Gill--Wiehl et al. (2023) done in Rwanda, the solar-powered cooler had an initial investment of USD 22,500 and was fabricated in Italy. The coolers in these studies are generally larger in size compared to the portable solar-powered cooler considered in our study. Furthermore, the current study focuses on the storage of vaccines, distinguishing it from systems in other studies that are often used for perishable food storage.

3.4. Limitation

Given the scarcity of available data, this study relied on extrapolations derived from existing literature, introducing a degree of uncertainty to the results. Our data set includes the Ecoinvent v3 database, while some data are actual data from the fabricated solar-powered cooler. This approach in the study differs from methodologies like CML 2001, which only considers 11 environmental impact categories, where most of those environmental impact categories differ. The absence of data on the manufacturing processes of outsourced components, such as electronic components, could result in an underestimation or overestimation of the environmental impacts associated with the solar-powered cooler. Future studies should aim to obtain comprehensive data to address this limitation. It is important to note that the cooler investigated in this study is predominantly smaller in size compared to those analyzed in previous research. This size discrepancy may impact the applicability and generalizability of the study's findings, particularly in contexts involving larger-scale cooling systems.

3.5. Sensitivity analysis

Sensitivity analysis was conducted to examine how variations in one or more input parameters affect the results of the LCA and technical economy. The sensitivity analysis revealed significant variations in environmental impact categories based on the materials used in fabricating the solar-powered cooler. For example, switching from lead to lithium batteries increased global warming potential (GWP) by 20 % and MEU by 50 %. Table 7 compares the environmental impact of using lead versus lithium batteries. While lithium batteries are more energy-efficient, they contribute to a GWP (343 kg CO_2-eq) than lead batteries (284.28 kg CO_2-eq). However, lead batteries have a higher TEC impact. These findings suggest that choosing between battery types involves a trade-off between environmental categories, and future research should focus on improving battery technologies to minimize overall impacts. The impact categories depend significantly on the materials selected for constructing the solar-powered cooler. Lithium batteries are costlier and more portable, weighing approximately 65 kg, and have a slightly higher environmental impact than lead batteries, as shown in Table 7. In contrast, lead batteries are less expensive, have a mass of nearly 40 kg, and pose a lower environmental impact compared to lithium batteries which have a mass of 15 kg.

Table 7
A sensitivity analysis of important parameters.

Impact category	Units	When using lead battery	When using lithium battery
GW	kg CO_2 eq	284.2761	343
SOD	kg CFC11 eq	9.85E-05	0.00014
ID	kBq CO-60 eq	25.2476	25.8
OF, HH	kg NO_x eq	0.791925	1.01
FMPF	kg PM2.5 eq	0.707778	1
OF, TE	kg NO_x eq	0.824958	1.05
TA	kg SO_2 eq	1.633946	2.96
FEU	kg P eq	0.184001	0.262
MEU	kg N eq	0.013393	0.0247
TEC	kg 1,4-DCB	3817.087	8220
FEC	kg 1,4-DCB	75.03299	109
MEC	kg 1,4-DCB	102.4709	143
HCT	kg 1,4-DCB	127.5105	136
HCNT	kg 1,4-DCB	2709.386	1880
LU	m^2 a crop eq	9.150676	11.5
MRS	kg Cu eq	14.39804	10.7
FRS	kg oil eq	75.86702	87.7
WS	M^3	4.587215	5.17

4. Conclusion

This study utilized both life cycle and cost analysis approaches to evaluate the environmental consequences and cost analysis of solar-powered coolers, providing insights into their sustainability and economic viability. The life cycle analysis clearly showed the benefits of using solar energy to power a cooler, especially in reducing CO_2 and SO_2 emissions. Hence, the solar-powered cooler would be less harmful to the environment. Hotspots were identified in the production stages of the solar-powered cooler. TEC emerged as the highest impact category, primarily driven by battery manufacturing and solar panel production. Future research should explore alternative materials and technologies to mitigate environmental impacts. The cost analysis results showed a positive outcome, with the initial investment of USD 2682.

Future studies should emphasize optimizing the production process of solar-powered coolers, focusing on reducing environmental impacts, especially during the manufacturing phase. This could involve exploring alternative materials and technologies with lower environmental footprints. Additionally, future optimization efforts should consider the selection of materials used in manufacturing solar-powered coolers to ensure holistic sustainability improvements.

Generally, the proposed solar-powered cooler is a promising investment. It is an alternative compared to commercial refrigerators powered by the national electricity grid and fossil fuels, in addition to being attractive to be used in remote areas where electricity is limited.

CRediT authorship contribution statement

Milton Mbugano: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Juma Rajabu Selemani:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Baraka Kichonge:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Grite Nelson Mwaijengo:** Writing – review & editing, Writing – original draft, Investigation. **Mwema Felix Mwema:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

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Data availability

All data are within this article. However, additional data, if any, will be made available on request.

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