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Research article

Life cycle assessment of metallic vs. wooden structured solar dryers: Insights into the environmental sustainability

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Abstract: Solar drying has emerged as a viable alternative drying method to fossil fuel–based methods, extending the shelf life of agricultural products, reducing post-harvest loss, ensuring food security, improving the livelihood of the people, and minimizing environmental impacts. While the thermal efficiency of solar dryers has been studied by many researchers, their environmental sustainability remains mostly understudied. This study attempted to fill this gap by comparing an indirect metallic structured solar dryer (ISDM) and a wooden structured dryer (ISDW), both equipped with thermal energy storage (TES) materials. The study employed the cradle-to-grave method of life cycle assessment, whereby the midpoint and endpoint characterization values were calculated using the ReCiPe 2016 (H) model. Primary data for the assessment of the dryers was collected from the owners and manufacturers of the two types of solar dryers, supplemented by some secondary data from the ecoinvent database. The life cycle of ISDM shows endpoint single-score impact values of 2.15, 19.6, and 414.26 pt on resources, ecosystem, and human health, respectively. ISDW shows endpoint single-score impact values of 1.99, 17.49 and 289.32, respectively, for the same factors. These findings suggest that ISDW has a lower environmental impact than ISDM; hence, it is recommended for small-scale farmers in developing countries like Tanzania. The findings further demonstrate that not all solar dryers have equal sustainability benefits and that not all solar drying technologies have the same environmental impact. This calls for further investigation into proper material selection and end-of-life management strategies in order to reduce environmental impacts. Policymakers should prioritize the development and implementation of policies that promote the widespread adoption of environmentally sustainable solar dryers (such as the ISDW model) by providing support to small-scale farmers through incentives and investments in research and development. Furthermore, national renewable energy strategies should incorporate end-of-life (EoL) management strategies to mitigate resource depletion and promote circular economy practices in the design and disposal of solar drying components and materials. Future research should focus on identifying alternative, low-impact materials for solar dryer construction and adopting a holistic sustainability assessment approach that integrates environmental, economic, and social dimensions in the assessment. In addition, further LCA studies should explore viable EoL options for solar dryer materials such as recycling, safe disposal (land filling), repair or refurbishment, and new manufacturing. These measures will contribute to extending the shelf life of crops, particularly perishables, reducing post-harvest losses, enhancing food security, and promoting environmental sustainability. Ultimately, such efforts will contribute to the realization of Sustainable Development Goals (SDGs) 2, 13, and 15, which emphasize zero hunger, climate action, and sustainable ecosystems, respectively.

Keywords: Life cycle assessment; solar dryers; environmental impact; sustainability; small-scale farmers; post-harvest loss

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1. Introduction

Tanzania is an agricultural nation in which more than 75% of the population depends on subsistence crop farming for their living [1]. The climatic condition in the country favors the cultivation of different crops[2], where some of them, especially perishable crops, have a high risk of spoilage[3]. Different scholars agree that food waste and loss (FWL) is estimated to be about one-third of the total food produced globally [4]; furthermore, FWL occurs at the consumption stages in developed nations, while in developing nations it occurs at the farm-to-retail store stage [5,6]. Some of the factors leading to food waste during consumption were noted by [7] as poor quality of the food and poor post-harvest processing include drying. In Tanzania, estimates suggest that FWL ranges from 20% to 60% of harvested crops annually, depending on the type of crop [7]. This highlights the need for an effective drying method to minimize or completely eliminate post-harvest loss (PHL). Traditional drying methods, including open sun drying (OSD) and fossil fuel–based drying, are widely used but have significant drawbacks [8]. OSD is inefficient and can compromise product quality[9]. Fossil fuel dryers, which co-fire with biomass, natural gas, and electricity, contribute to greenhouse gas (GHG) emissions [10]. Despite their economic benefits, fossil fuels drive climate change and global warming.

FWL is a pressing global issue, leading to significant economic, environmental, and food security concerns. Conventional food preservation methods are often energy-intensive, contributing significantly to environmental degradation through increased greenhouse gas (GHG) emissions. In contrast, solar drying offers a sustainable alternative by harnessing renewable energy to extend the shelf life of food while simultaneously reducing FWL[11]. Recent research highlights its effectiveness in reducing food spoilage, minimizing carbon footprints [12], and even repurposing waste into valuable by-products such as animal feed and biofertilizers [13]. By optimizing drying kinetics and energy efficiency, solar drying emerges as a practical, eco-friendly method to mitigate FWL and support sustainable food-processing systems.

Solar dryers are classified based on design and drying mode [14]. They include direct, indirect, and hybrid (mixed-mode) dryers [14–16]. In direct dryers, products are exposed to solar radiation [17], while indirect dryers use a solar air heater (SAH) to transfer heat to a drying chamber, leading to increased efficiency [18]. Hybrid dryers may incorporate additional energy sources like electricity, biomass, or gas [19]. To improve efficiency and reduce dependence on non-renewable energy, solar dryers are integrated with TES materials, allowing them to operate even when solar energy is unavailable (at night) [20,21]. TES materials may be in solid (rock or sandstone) or liquid forms (water or mineral oils) [22]. This study focuses on solar dryers utilizing the natural TES material soapstone, which is cost-effective and environmentally friendly [23]. Furthermore [24] found that soapstone rock outperformed other rocks such as granite as a TES material in solar drying applications.

Solar dryers have a lower environmental impact than conventional drying methods during operation because they use solar energy, which is free of charge. However, from the life cycle perspective, including raw material processing, assembly, utilization, and end of life, reveals potential environmental impacts [25,26]. Assessing their sustainability requires the use of Life Cycle Assessment (LCA), a tool that was adopted in this study to evaluate environmental impacts from raw material acquisition to end-of-life treatment of solar dryers [27]. While environmental sustainability assessments, particularly those employing LCA, have increasingly been applied across various sectors such as waste management, agriculture, energy systems, and food processing, solar dryers have received comparatively little attention. Given their potential and broad implications, the environmental sustainability of solar dryers remains significantly underexplored in academic literature. Previous studies have primarily focused on technical aspects, including dryer design, thermal efficiency [28,29], and optimization through mathematical modeling [30,31] and computational simulations [32]. Similarly, aspects such as hygiene and product quality during the drying process have been addressed in details [33,34]. However, LCA studies that assess the environmental impacts of solar dryers are limited, and those that do exist have largely been conducted in developed countries, particularly in Europe and Asia. This has resulted in a geographical imbalance and a lack of context-specific data for developing regions. This study, conducted in Tanzania, seeks to address this knowledge gap by providing a localized LCA of solar dryers, thereby contributing to the broader understanding of their environmental performance in Sub-Saharan Africa (SSA). Additionally, Tanzania’s agriculture and industrialization policies, aligned with Vision 2025, underscore the importance of adopting renewable energy-based technologies, such as solar dryers, to promote sustainable development, thereby reinforcing the relevance of this research.

Recognizing the fact that the materials used in the fabrication of solar dryers significantly influence environmental sustainability [30], this study aims to evaluate and compare the life cycle environmental performance of metallic and wooden indirect solar dryers utilized by small-scale farmers in Tanzania. This assessment will be conducted using LCA, a widely accepted tool for evaluating the environmental impacts of products, processes, and technologies throughout their life cycle [35].

2. Literature review

The increased demand for sustainable agriculture practices has attracted high research interest in the application of sustainable technologies, including solar dryers. Several studies have been conducted in different parts of the world to evaluate the environmental sustainability of solar dryers. This literature review began with a global assessment, before focusing on region-specific studies in Africa. Finally, reviewed studies were synthesized, and a proposed way forward was outlined. Some studies evaluated the thermal performance of solar dryers using metrics such as embodied energy (Ee), energy efficiency, energy payback period, CO_2 mitigation, and carbon credits earned. In addition, some LCA studies applied life cycle impact assessment (LCIA) methods, including ReCiPe (2016), CML2 baseline, and IMPACT 2002+, to assess environmental impacts such as global warming potential, acidification, eutrophication, and human toxicity.

The cradle-to-gate LCA study of phase change material-based solar dryers (PCMBSDs) vs. cylindrical solar-assisted dryers (CSADs) was done by [36]. This study, which utilized the ReCiPe (2016) as the LCIA method, found that PCMBSDs have a significantly higher environmental impact, except in human carcinogenic toxicity and fossil resource scarcity. PCMBSDs impact human health by 40% more (DALY) and ecosystems by 37.04% more (species/year) than CSADs, while CSADs have a 14.18% greater resource impact ($). The single-score assessment shows CSADs (37.04%) outperform PCMBSDs (40%) in overall environmental impact. In this study, it was concluded that CSADs are the better choice for drying agricultural products with lower environmental impacts, whereas PCMBSDs offer faster drying, making it preferable when speed is the priority. This study aids in selecting optimal solar drying systems for agriculture. A comparative energy-exergy and environmental analysis of passive indirect solar dryers (ISDs) with and without thermal energy storage systems (TESSs) was done by [37] in India. The ISD with TESSs had a higher embodied energy (1008.67 vs. 563.75 kWh) and greater CO_2 emissions but provided better CO_2 mitigation and credit. Overall, the TESS-equipped dryer outperformed the non-TESS version in energy and environmental efficiency, except for CO_2 emissions.

A study on the thermal, environmental, and economic performance of solar dryers using three types of solar air heaters (SAHs): the evacuated tube (ETSAH), modified evacuated tube (METSAH), and finned plate evacuated tube (FPSAH) was done by [38]. The results indicate that METSAH outperformed the others with a 27.48 °C temperature difference, 67.92% thermal efficiency, and 2.97% energy efficiency. METSAH reduced CO_2 emissions by 237.08 kg/year for grapes and 1573.58 kg/year for eggplants, earning $3.44 and $22.82 in carbon credits, respectively. The energy payback periods were 8.41 years for grapes and 1.27 years for eggplants. Both systems were found to be sustainable, making them suitable for large-scale applications. A comparative economic and environmental performance analysis of phase-change material-based solar dryer (PCMSDs) vs. OSD was done by [39] in India. The economic feasibility was assessed via annualized costs, savings, and the payback period method, while environmental analysis was assessed by taking into account potential carbon credits, embodied energy (Ee), annual CO_2 emissions, and CO_2 mitigation. The findings revealed that PCMSDs were economically feasible with a shorter payback period due to low operation costs and annual revenue, despite the higher capital cost of the devices. Moreover, PCMSDs have high Ee, but annual CO_2 emissions, mitigation, and the possibility of carbon credits show positive effects on the environment. It is evident that PCMSDs are more economically feasible than OSD with lower energy consumption and environmental impact. A life cycle assessment of an indirect cabinet solar dryer equipped with PCM loaded at the bottom, middle, and upper trays was done by [26]. Authors used the IMPACT 2002+ as a life cycle impact assessment (LCIA) model to compare the LCA results of an indirect solar dryer with the 1000 W electric thermal dryer. LCIA results indicated a significant difference between the solar dryer (3.55 mPt) and the electric thermal dryer (11.36 mPt) in all four endpoint indicators. The reason for such a difference may be due to the fact that the energy used in a solar dryer is renewable and generated from sunlight, whereby environmental pollution is avoided. Conversely, because electric heat dryers typically draw power from non-renewable energy sources, they have a negative impact on resources, ecosystem quality, climate change, and human health. As a result, it was recommended to replace electric thermal dryers with solar dryers in order to minimize environmental impacts.

A comparison was made between passive and active indirect solar dryers (PISDs and AISDs) for drying carrot slabs by [40], evaluating both environmental and economic impacts. Environmental factors considered included embodied energy (Ee), CO_2 emissions, carbon mitigation, and carbon credits. Economic factors evaluated include capital, annuity, material and labor costs, payback periods, and lifetime savings. Results showed AISDs had lower environmental impacts and better CO_2 mitigation and carbon credits than PISDs. Economically, AISDs had a shorter energy payback period (1.33 years for PISDs vs. 1.78 years for AISDs) and a reduced economic payback period (0.622 years for AISDs vs. 1.02 years for PISDs). Overall, AISDs outperformed PISDs in both environmental and economic assessments. A study on the 4E i.e. (energy, exergy, economic, and environmental) analysis of indirect solar dryers for drying sweet potatoes was done by [41] . The drying system had a 35-year lifespan, an energy payback period of 8.8 years, and a CO_2 mitigation of 20.2 tons, which generated carbon credits worth 56,700 RMB. The techno-economic study also revealed that the PBP was 29.24 months, the yearly total revenue was 8464 RMB, and the return on investment was 0.7 RMB. The drying system is environmentally and economically friendly and was recommended for drying varieties of crops.

A study by [42] focused on a forced convection mixed-mode solar dryer (MSD) to assess its economic and environmental impact using the net present value (NPV), payback period (PBP), life cycle savings, internal rate of return (IRR), and embodied energy (Ee). Results showed an exceptionally short PBP of 0.9 years and an IRR of 130%, with the total NPV reaching Rs. 9,48,892 against an initial investment of Rs. 75,000. Environmentally, the MSD reduced CO_2 emissions by 8.4t over its lifespan, with an energy payback time (EPBT) of 3.75 years. A greenhouse solar dryer was developed by [43], who analyzed its environmental and financial viability under forced and natural convection. Results showed higher CO_2 mitigation in forced convection (36.34t) compared to natural convection (33.04t), along with greater carbon credits. Economically, revenue from bitter gourd flakes ranged from INR 12,173 to 48,695 under forced convection and INR 11,068 to 44,273 under natural convection. Overall, forced convection proved to be the more efficient drying method.

A life cycle impact assessment (LCIA) was done by [44] to compare a photovoltaic-assisted solar dryer (PVDD) and a grid electricity dryer. It was found that energy source selection significantly affects the environment. The PVDD had lower environmental impacts, especially in aquatic ecotoxicity and global warming potential. Since agricultural production contributes over 60% of the total impact, even with PV use, it was further recommended that sustainability efforts must consider the entire production chain, covering both cultivation and drying phases. An LCA of hybrid photovoltaic/thermal (PV/T) solar systems for domestic use was done by [45] to analyze the environmental impacts from production to disposal. Results showed high energy consumption during fabrication and installation, mainly due to significant silicon use in PV module production. Additionally, extensive use of steel alloys in water tanks and pumps further increased the system's ecological impacts.

A cradle-to-grave LCA study was done by [25] on two solar dryers, direct mode (DMTD) and indirect mode (MMTD), using the ReCiPe method. The study assessed the environmental sustainability of the two dryers covering fabrication and recycling phases. Results showed MMTD had higher impact scores than DMTD across human health (15.5 vs. 7.14 pts), ecosystems (25.99 vs. 15.48 pts), and resources (16.5 vs. 7.14 pts). This suggests DMTD is a more environmentally friendly option, highlighting the need for investing in renewable energy-based drying facilities. An experimental study was conducted on a cylindrical solar dryer for drying maize in Udaipur, India, by [46] analyzing thermal and environmental performance in comparison with conventional dryers, which use electricity and fuel. Results showed that a moisture reduction from 28% to 12.64% (wb) was achieved in just 11 hours. This incredible performance of the dryer saved 1352.97 kWh of electricity, 128.18 L of diesel, and reduced CO_2 emissions by 1.22 tons annually, demonstrating its environmental benefits over conventional drying methods.

A life cycle optimization study of a solar-assisted hybrid drying system to analyze its environmental impacts, focusing on global warming potential (GWP), respiratory effect potential (REP), and acidification potential (AP) was done by [47]. Results showed GWP as the most significant factor, with the operating phase contributing 98% of total CO_2-eq emissions. SO_2-eq and PM2.5-eq emissions averaged 82% and 67%, respectively. The top energy-consuming phases after operation were raw material acquisition, transportation, and plant construction. A life cycle assessment was conducted on a solar dryer for converting food waste into animal feed by [13]analyzing its construction and operational impacts. The study utilized CML2 baseline 2000 as the LCIA model for impact assessment. The key notable environmental concerns during construction were human toxicity, freshwater and marine aquatic ecotoxicity, and abiotic depletion. During operation, marine aquatic ecotoxicity was the most significant impact. The process had a total carbon footprint of 217.45 kg CO_2-eq per ton of food waste processed. The overall carbon footprint of the process could be reduced by utilizing electricity generated from renewable energy sources.

A study was done by [48] investigating on a hybrid biomass-solar energy drying system, analyzing its environmental impact across manufacturing, operation, maintenance, disassembly, and recycling stages. Results showed that manufacturing had the highest impact, with acidification (AP) and eutrophication (EP) accounting for over 90% of emissions. Manufacturing impacts were 28.71 times higher than disassembly and recycling. The present hybrid solar-biomass energy supplying system, therefore, provides a promising solution to reduce environmental impacts in the food waste processing industry. A study was performed on a hybrid greenhouse solar dryer (HGSD) with an evacuated solar collector by [49] in India. The results found out that it reduced drying times by 47.36% for tomatoes, 61.9% for bottle gourd, and 34.09% for ginger compared to conventional drying. The payback period was 0.18 years for bottle gourd and 5.5 years for ginger. HGSD also mitigated significantly more CO_2 emissions over its lifespan than conventional drying. It was concluded that conventional drying had advantages in capital cost and CO_2 emissions; HGSD performed better in carbon mitigation, drying time, and payback period.

A comparison of the performance and environmental impact of four drying systems: solar cabinet dryer (SCD), solar greenhouse dryer (GHD), fluidized bed dryer (FBD), and conventional hot air dryer (HAD) was done by [50]. The study assessed drying performance, CO_2 emissions, energy payback periods, and life cycle conversion efficiencies. Results indicated that FBD had the highest drying rate and superior heat and mass transfer, but consumed the most energy, raising sustainability concerns. In contrast, SCD and GHD demonstrated significant environmental and economic benefits, achieving CO_2 mitigation of 76.56 kg and 9.1 kg, with payback periods of 2.31 and 1.5 years, respectively. The study highlights the potential of solar drying technologies in reducing post-harvest losses, enhancing food security, and mitigating climate change. The life cycle economic and environmental assessment of hybrid passive mode/active mode solar dryers in comparison to the conventional open-sun-drying (OSD) method was done in Uganda by [51]. The analysis focused on drying time, energy used, and the energy payback period (EPTB). In terms of drying time, the study found that solar dryers reduced drying time from 30 (OSD) to 10 hours (for hybrid solar dryers). Energy savings were higher in solar-assisted dryers than in conventional methods. Also, the payback period was significantly lower, making hybrid solar drying a cost-effective and sustainable alternative.

A numerical study of the solar drying of timber in different geographical and climatic conditions of central Africa was done by [52]. Key findings included that solar energy consumption per cubic meter of wood ranged from 2 to 4.3 GJ/m^3. Thermal efficiency varied between 12% and 47%, depending on climate conditions. Ndjamena's climate is unsuitable for solar drying due to its low absolute humidity, which causes a rapid decrease in moisture content, ultimately compromising the quality of wood boards. In contrast, Bangui, Brazzaville, Douala, Kinshasa, Libreville, and Yaoundé provide favorable drying conditions with the tested solar dryer. The study confirmed the feasibility of solar drying for timber in specific central African regions while recommending solar collector improvements for enhanced drying efficiency. A social life cycle assessment (S-LCA) study was done in Tanzania by [53] to assess a solar dryer house used for postharvest loss management. Unlike the traditional LCA method, which uses LCIA methods, this study integrated environmental, economic, and social sustainability factors analysis. The study found that solar dryer technology significantly improved food security, reduced postharvest losses, and created employment opportunities for local farmers. Additionally, the use of solar dryers reduced dependency on fossil fuels, lowering the carbon footprint of agricultural drying processes.

From the above literature, it can be noted that a large number of research investigations have been conducted to evaluate the thermal efficiency and effectiveness of different solar drying systems. Top priority has been given to performance assessment variables such as drying time and energy consumption, efficiency, and payback period, among others. Environmental impacts have equally been researched by considering embodied energy parameter (Ee), using parameters such as energy payback period, CO_2 emitted, CO_2 mitigation, and carbon credits earned. Few studies have evaluated the environmental impacts based on the LCA ISO 140040:2006 guidelines. An example is [26], which took into account the entire life cycle of the product from cradle to grave. Few LCA studies on solar dryers have been conducted on dryers made of metallic materials, which have a higher impact on resources e.g., [25,27,46]. Hence, this study employed an LCA approach to compare the environmental impacts of solar dryers made of metallic and wooden materials. In addition, available LCA studies on solar dryers have been concentrated in the Asian and European countries, while studies conducted in Africa, particularly Sub-Saharan Africa (SSA) countries, remain inadequate. From this review, it is evident that future research should focus on scaling LCA methodologies across different regions, improving solar dryer efficiency, addressing economic feasibility, and developing region-specific policies for broader implementation. Therefore, this study was conducted in Tanzania to extend the geographical coverage of LCA studies in SSA and compare the findings with previous studies.

3. Materials and methods

This study utilized the LCA method to assess the environmental impacts of indirect solar dryers with metallic (ISDM) and wooden structures (ISDW) installed in the Morogoro and Arusha regions in Tanzania. The LCA was conducted following the standards outlined in the ISO14040, which provides credibility to the results obtained [48]. Usually, the LCA study comprises four distinct steps, namely goal and scope statement, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [56]. The goal and scope phase defines the objective, system boundaries, unit flow, and study functional unit. The LCI phase involves data collection for the LCA, while the LCIA includes the modeling of environmental impact indicators. The interpretation stage integrates the findings from LCI and LCIA to provide crucial information about improvements to be made on the system for sustainability. The ISDW included some metallic components such as the solar air heater (SAH), drying trays, and ventilators. Dryers were designed, fabricated, installed, and in use at the Tanzania Horticultural Association (TAHA) in Arusha and the Sokoine University Graduate Entrepreneurs Cooperatives (SUGECO) in Morogoro, Tanzania. Both dryers consist of support structures, a drying chamber with drying trays, solar collectors, air circulation systems, some insulation materials, and a TES system.

The ISDM consists of a 50 × 50 × 2.5 mm mild steel angle iron painted in black to prevent rusting. Additionally, the structure includes a combination of some flat bar materials with 25 mm × 2.5 mm in size and small joining material components like bolts, nuts, and rivets. The drying chamber is approximately 2.3 m (L) × 1.2 m (W) × 1.5 m (H). The inner part of the chamber consists of an aluminum sheet with 1.5 mm thickness, while the outer surface is composed of a mild steel sheet of 1.5 mm thickness. The two walls of the drying chamber are separated by a 2.5 mm-thick fiberglass, which is a thermal insulating material that prevents heat transfer. The drying trays are composed of 1.5 mm aluminum sheets with 1000 mm (L) × 700 mm (W). Approximately 15 trays were made with a capacity of 3.5 kg of fruits or vegetables, making the total capacity of the dryer 52.5 kg. Below the drying chamber is a small chamber of approximately 2.4 m (L) × 1.2 m (W) × 0.5 m (H) to allow other sources of energy such as biomass or liquefied petroleum gas (LPG) when the solar radiation is not enough or is unavailable for drying, especially during the night. The air-circulating system consists of a standard wind turbine ventilator of 200 mm installed at the top of the dryer.

The dryer consists of three SAH or solar collectors to capture solar radiation during the day. Collectors are made of flat plate solar collectors approximately 1.5 m long and 1.0 m wide. The absorber plate is made of aluminum (0.5 mm thickness), while the receiver is made of flat glass (5 mm thickness). The inner part of the collectors is coated with black paint to enable effective capture of solar radiation and thermal energy storage. The TES materials used are soapstone, placed inside the solar collectors. The heated air is blown into the drying chamber with a copper tube of 16 mm in diameter.

The ISDW is composed of treated structural timber of different sizes, including 2 × 4 × 10, 2 × 3 × 10, and 2 × 2 × 10 inches. The wood was cut into pieces and joined together using nails, bolts, and nuts. The drying chamber is 2 m (L) by 2 m (W). The inner part of the chamber is covered with an aluminum sheet 1.5 mm thick, while the outer structure of the dryer is covered with polycarbonate sheets. Inside the drying chamber, drying trays made of aluminum sheet are placed. The size of the drying trays is 600 m × 600 m. Up to 2.5 kg of fruits or vegetables can be placed in one tray; in total, 20 trays can be placed inside the drying chamber, making the overall capacity of the dryer 50 kg. The dryer also consists of a solar thermal collector of 176 mm (H) × 115 mm (W). The inner part of the collector is coated with black paint to facilitate effective capture of solar radiation. TES materials (soapstone) are placed inside the collectors, and heated air is delivered into the drying chamber by galvanized steel tubes.

The components used for each dryer were purchased from a local market and transported to the site using waterways (for imported parts) and land transport systems. In the use stage, the dryer may require some maintenance to ensure its smooth functioning. At the end of its life, dryers are dismantled, whereby some components are landfilled, incinerated, or recycled. A cradle-to-grave LCA approach was employed to evaluate the environmental impacts involving transportation, fabrication/assembly, use, and disposal. The four stages involved in LCA studies are goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

3.1. Goal and scope definition

The goal of the present study was to assess and compare the environmental impacts of ISDM vs. ISDW. The system boundary includes processing, transportation of materials, dryer assembly, use, and disposal or recycling, as indicated in the dotted lines of Figure 1. However, the preparation and transportation of the crops to the site is excluded in this study because this should be accounted for in a separate LCA study specifically for horticultural crop production. The functional unit (FU) is defined as the drying of 50 kg of vegetables or fruits per day. The lifespan of the ISDM solar dryer is estimated to be 20 years, while that of ISDW is 15 years. The lifespan of equipment such as the blower and solar collectors is about 10 years.

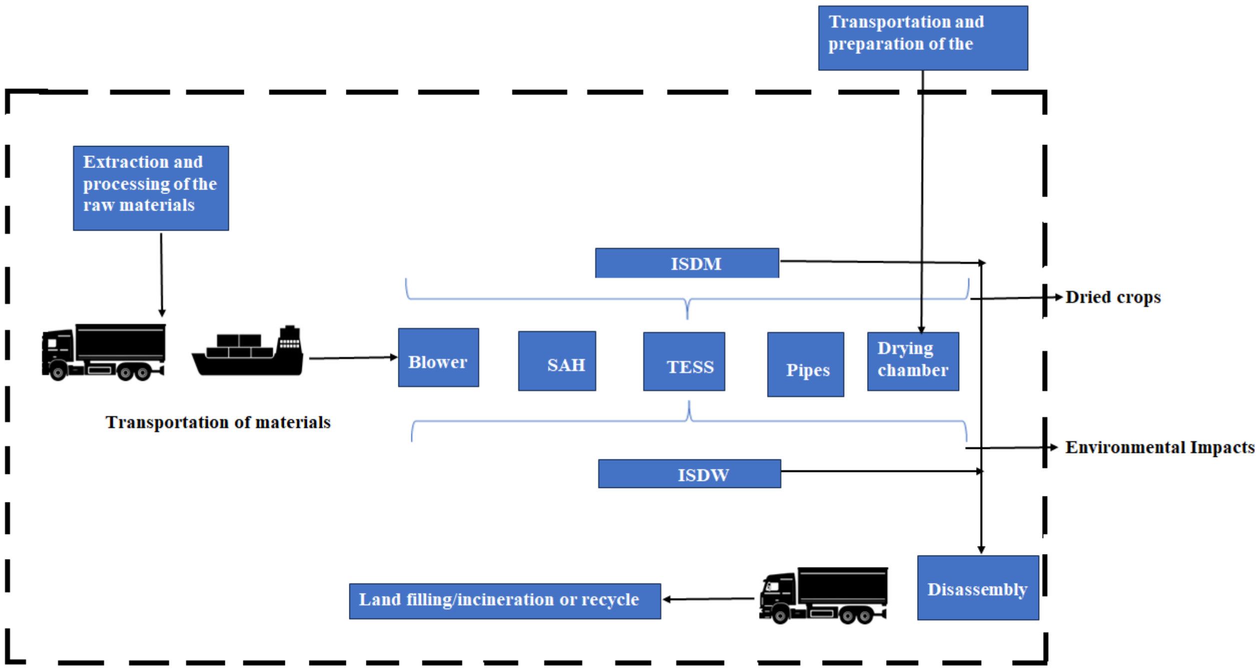

Figure 1. System boundary for LCA of solar dryers (ISDM and ISDW).

3.2. Life cycle inventory (LCI) analysis

The life cycle inventory analysis phase of LCA involves the collection of data on all the inputs (i.e., materials, energy, and resources) and outputs (emissions and wastes) for the entire life of the solar dryer (i.e., the entire cradle-to-grave process of the product system is examined and quantified). LCI data used in this study was categorized into the following five major groups: raw material extraction and processing, transportation and distribution, assembly and installation, operations, and end of life and recycling. During the extraction and processing phase, the materials quantified include metals, plastics, glass, and insulation materials. Most of these materials are extracted and processed outside Tanzania; thus, the data for energy used for their processing is sourced based on the ecoinvent database for those countries. During the installation and assembly phase, data include the materials used for site preparation (e.g., cement, sand, and water) and the energy used in the assembly of structural components, such as trays, drying chambers, solar collectors, and eventually, the assembly of the entire solar dryer. All these datasets were obtained from the local dryer manufacturers. During the transportation of the raw materials and semi-finished components, data collected included the distance traveled, fuel consumed, and emissions associated with the transportation process. These data were sourced from the ecoinvent database, which is embedded in the SimaPro software. During the operation phase, additional sources of energy such as LPG or biomass might be used to supplement solar energy when needed. Finaly, during the end-of-life phase, data collected included the distance covered to transport materials like metals and plastics to the recycling point and/or land filling/incineration point for the non-recycled components. Some data were obtained through documentation and interviews from the local manufacturers of the two solar dryers under study, i.e., ISDM and ISDW. Furthermore, additional data were obtained from literature reviews (including scientific studies) and databases such as ecoinvent data. All materials used for the dryers could be recycled, with the exception of materials like glue, paint, and glass. These could not be recycled due to the lack of recycling facilities in the area; therefore, data for their recycling phase cannot be easily obtained.

Solar dryer designs are beyond the scope of this study, since the solar dryers being assessed had already been designed and installed and had started operating. The inventories used on SimaPro software to map the environmental impacts were quantified based on the different parts used while assembling the dryers, as provided by the owners or designers. For example, the quantity of materials used for the steel angle iron used for ISDM solar dryers was estimated considering the manufacturers' specifications, which state that the 50 × 50 × 2.5 mm angle iron is supplied with a standard length of 9 m with 1.81 kg/m. Therefore, for making the ISDM support structure, 25 m long angle irons were used (data obtained from the installed dryers). Thus, the total weight of the angle iron bars of the ISDM is 25 m × 1.81 kg/m = 45.25 kg. Other dimensions of the angle iron are known, and thus, the cross-sectional area and volume can be calculated. Also, since the density of iron is known, the weight of the angle iron can be obtained by multiplying the density and the volume of the bar. In a similar way, other materials were quantified.

Both ISDM and ISDW were installed on a concrete floor and covered an area of 6 and 4 m^2, respectively. Typical materials used to construct the concrete floor are cement, gravel, sand, and water. The thickness of the slab was 0.1 m, which is a standard slab thickness for lightweight applications. A standard concrete mix ratio of 1:2:3 for cement, sand, and gravel was used; knowing their densities, their amounts can be quantified. Additionally, a water-to-cement ratio of 0.4–0.6 is recommended for different cement grades. The quantity of water used was obtained by multiplying the amount of cement used by the ratio. The wind ventilator consisted of stainless-steel materials with 200 mm (D1) × 300 mm (D2) × 240 mm (H) with a standard weight of 0.75 kg, as per the manufacturer's specifications. Table 1 provides details of the components used in the assembly of ISDM and ISDW dryers for mapping environmental impacts in SimaPro software.

Table 1. LCI of ISDM and ISDW.

ISDM	ISDW	Quantity	Unit
Aluminum alloy	Aluminum alloy	43.5/32.6	kg
Stainless steel		40.2	kg
Iron angle bar		45.25	kg
	Structural timber	1.5	m^3
Flat glass	Flat glass	40.8/26.56	kg
Glass wool		4	kg
Urea formaldehyde resin	Urea formaldehyde resin	5/8	kg
	Alkyd paint	2.2	kg
	Polycarbonate	3.8	kg
Polyvinylchloride		1.8	kg
	Polystyrene	2	kg
Sawn wood	Sawn wood	64	Pcs
	Plywood	16	kg
	Wire mesh	4	kg
Flat glass	Flat glass	29/24	kg
Reinforcing steel		19.2	kg
Copper	Galvanized steel	2.5/3	kg
Alkyd paint		2	kg
Insulation foam		10.2	kg
PVC pipes	PVC pipes	2/1	kg
Ventilator	Ventilator	0.75/0.5	kg
Cement	Cement	123.8	kg
Gravel	Gravel	514.4	kg
Water	Water	0.0619	m^3
Sand	Sand	274	kg
Soapstone	Pebble	220/198	kg

3.3. Life cycle impact assessment (LCIA)

This study used SimaPro software version 9.6.0.1, integrated with the ecoinvent database, to conduct LCIA. The ReCiPe 2016 (H) method was selected to evaluate both midpoint and endpoint environmental impacts. ReCiPe 2016 is a widely used and contemporary LCIA method that provides a harmonized approach to measuring environmental impacts at two levels: midpoint indicators (e.g., climate change, eutrophication) represent specific environmental problems, while endpoint indicators reflect broader areas of protection such as human health, ecosystem quality, and resource availability [56]. Among the various LCIA methods available, which include CML2 baseline, IMPACT 2002+, TRACI, EPS2000, and Eco-Indicator 99, the ReCiPe 2016 (H) is considered superior due to its ability to integrate both midpoint and endpoint categories. In contrast, methods like CML2 and TRACI are limited to midpoint indicators, while EPS2000 and Eco-Indicator focus solely on endpoint damage categories. The choice of ReCiPe 2016 is further supported by its frequent application in prior research assessing the environmental performance of solar dryers [25,46].

SimaPro software supports comprehensive and up-to-date environmental data, enabling detailed evaluation of the impacts associated with each material or process. In the context of LCA, LCIA results from tools like ReCiPe are interpreted alongside economic and social metrics to holistically evaluate the sustainability of a product or system. For instance, when assessing solar dryers, LCIA can quantify impacts such as GHG emissions, resource depletion, or land use, facilitating the comparison of environmental trade-offs between alternative technologies or material choices. Using the ReCiPe (2016) model, 18 midpoint impact categories are linked with 3 endpoint categories. The 18 midpoint indicators and their units of measurement are listed in Table 2. The three endpoint categories are the quality of the ecosystem (species·yr), resource depletion ($), and human health (DALY). The endpoint categories are normalized and combined into a single score for decision-making (Figure 2). The impacts on human health are expressed in DALYs (disability-adjusted life years), which describe the damage to health or loss of life caused by climate change as a result of the negative environmental impacts of a process or product [57]. For the quality of the ecosystem, damage is measured in terms of species·yr, which describes the number of species that have vanished as a result of climate change due to the negative impacts of a product on the environment. Finally, resource depletion is expressed in $ to describe the reduction in natural resources due to their extraction and consumption in the product life cycle.

LCA characterization involves quantifying the potential environmental impacts of a product or process by translating the inventory data (e.g., emissions, resource use) into comparable impact indicators. It involves allocating the contributions of life cycle inventory data to the corresponding impact categories within the life cycle assessment. Each component contributing to a particular impact category is multiplied by its respective characterization factor [58]. In the ReCiPe midpoint method, midpoint-level characterization is calculated using Equation 1 below [59,60]

$$I_m = \sum Q_{mi} m_i \tag{1}$$

Here, m_i represents the amount of substance i released (in kg), Q_m is the characterization factor that links the quantity of the substance to the specific impact category (e.g., kilograms of substance i per kg of CO_2 for climate change), and I_m is the resulting value indicating the substance's contribution to that impact category (e.g., in kg of CO_2 for the climate change category).

ReCiPe also allows impact aggregation to endpoint levels, which translates midpoint results into damage to areas of protection presented by equation 2 [56].

$$I_k = \sum_i (I_i CF_{ik}^{endpoint}) \tag{2}$$

where I_k is the total damage score for endpoint category k (e.g., damage to human health, ecosystem quality, or resource scarcity). It expresses the potential long-term impact of all relevant midpoint categories on a specific area of protection. Units vary by category; for example, for human health, it is disability-adjusted life years (DALYs); for the quality of the ecosystems, it is species loss over time (species·yr); for resource depletion, it is the extra cost required for future resource extraction (USD). I_i is the midpoint impact result for impact category i (e.g., kg CO_2-eq for climate change, kg SO_2-eq for acidification). These are calculated in the midpoint LCIA phase. $CF_{ik}^{endpoint}$ is the endpoint characterization factor that links the midpoint category i to the endpoint category k. It expresses how much a unit of impact from i contributes to the damage in k; the unit depends on the endpoint.

Table 2. Midpoint impact categories and their unit of measurement.

Impact category	Unit
Global warming	kg CO_2 eq
Stratospheric ozone depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation, human health	kg NOx eq
Fine particulate matter formation	kg PM2.5 eq
Ozone formation, terrestrial ecosystems	kg NOx eq
Terrestrial acidification	kg SO_2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Terrestrial ecotoxicity	kg 1,4-DCB
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Land use	m^{2a} crop eq
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq
Water consumption	m^3

4. Results and discussion

This section presents and interprets the findings of the LCA conducted to compare the environmental sustainability performance of ISDM and ISDW dryers. The analysis follows the ReCiPe 2016 (H) method and covers multiple impact levels. The results are organized and discussed across four key dimensions: midpoint characterization values, which represent specific environmental impact categories (e.g., climate change, ozone depletion); endpoint characterization values, which aggregate impacts into broader damage categories (human health, ecosystem quality, and resource availability); endpoint damage assessment, which evaluates the severity of environmental damage across these protection areas; and single score values, which provide a normalized and weighted overall environmental impact score for each system. This comprehensive assessment facilitates a holistic comparison of the two dryer types, highlighting the environmental trade-offs associated with material choice in solar dryer fabrication. Additionally, ReCiPe (2016) introduces novel damage pathways, including the impacts of water use on human health and ecosystems, and the effects of climate change on freshwater ecosystems, reflecting advancements in scientific understanding and supporting informed decision-making in sustainability evaluations. Furthermore, it comprises a broader and newer set of impact categories like land use and marine ecotoxicity. Normalized results are usually perceived as relevant for understanding the extent of the damage for informed decision-making [61].

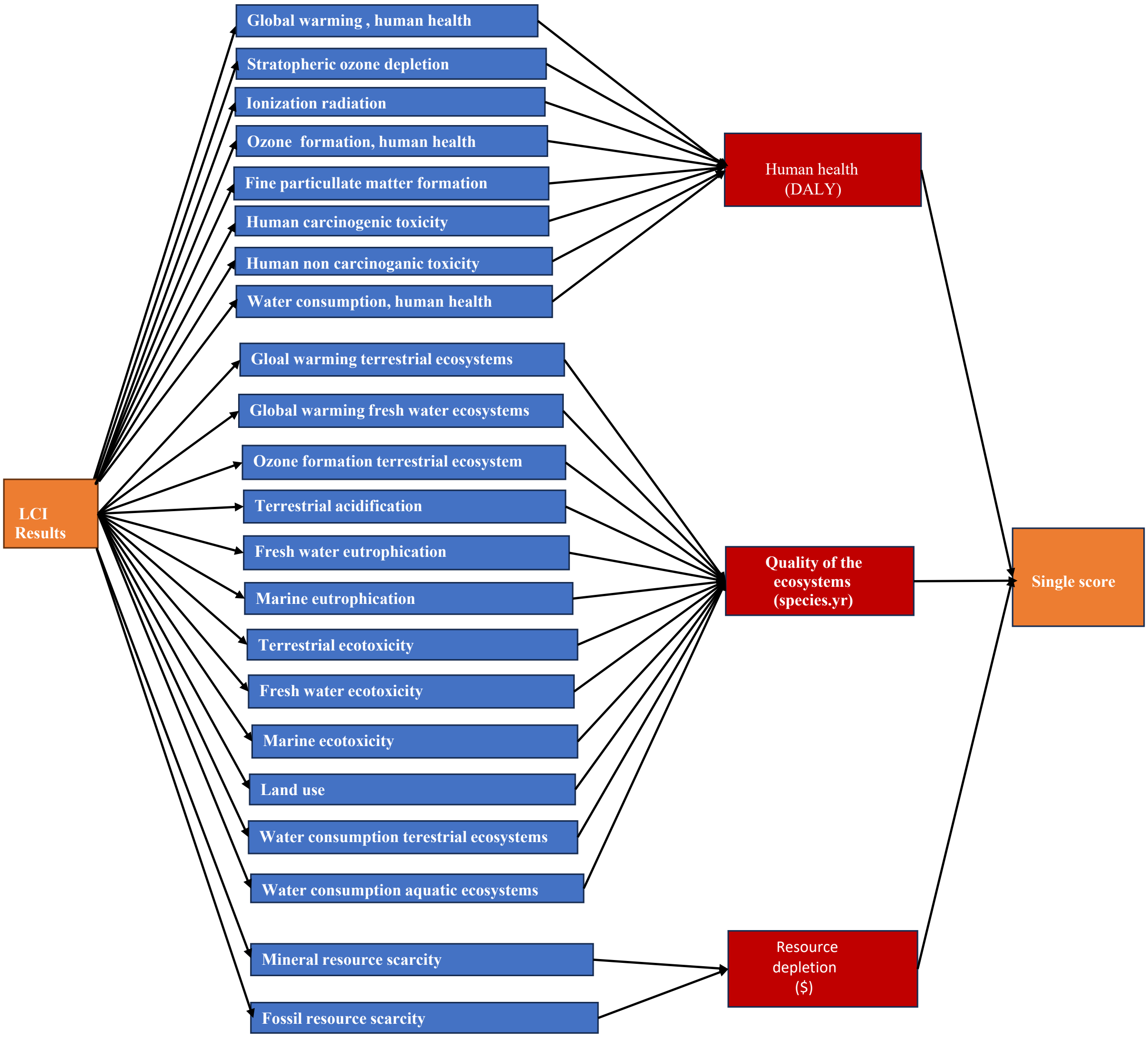

Figure 2. Midpoint and endpoint impact categories used to assess the solar dryers.

4.1. Midpoint characterization values

The purpose of midpoint characterization values is to quantify environmental impacts at a more specific level; for example, the product's GHG emission is quantified in terms of the global warming potentials measured in kg of CO_2 equivalents. Figure 3 shows a comparison of the midpoint characterization values of ISDM and ISDW extracted from SimaPro software. The results show that the environmental impacts of ISDM exceed those of ISDW by a significant margin.

In the terrestrial acidification category, the ISDM shows a 61.2% higher environmental impact than the ISDW. This substantial difference suggests that the ISDM system might be more vulnerable to acidifying chemical substances that cause soil and water acidification, such as sulfur oxide (SOx), nitrogen oxide (NOx), or ammonia. This suggests that the materials or energy sources utilized in the ISDM process may be linked to an elevated acidification potential. This emphasizes the need to increase efforts to lower acidifying emissions, perhaps by using cleaner energy sources or better process design. ISDM has a 55.4% greater impact on terrestrial ecotoxicity compared to ISDW. This implies that ISDM is linked to increased concentrations of toxic substances discharged into terrestrial ecosystems, which have an impact on biodiversity, plant life, and soil organisms. This inference aligns with broader findings in environmental assessments, where differences in industrial processes and material usage can lead to varying levels of ecotoxicological toxicity, as observed in [64,65]. Improving waste management procedures or investigating the use of less hazardous materials during the ISDM dryer's construction and operation stages could be two ways to address this problem. The impact of mineral resource scarcity for ISDMs is 54.2% greater than that of the ISDW. This indicates that ISDMs rely more heavily on the extraction and use of non-renewable mineral resources (such as metals or minerals), contributing to a higher scarcity potential. General research in LCIA supports the notion that processes with higher demands for mineral resources can lead to increased scarcity potential, as observed in [45,64,65]. This suggests that the extraction and construction phase of ISDM is more resource-intensive, and efforts should aim to optimize material choices or move toward more sustainable, renewable alternatives to reduce the impact on mineral resource availability. The land use category exhibits a slight difference, with ISDM having a 1.2% smaller impact than ISDW, in contrast to the previous impact categories, where ISDM had higher impacts than ISDW. This small difference in impact implies that ISDM's land footprint is marginally more effective than that of ISDW. Optimizing land use is nevertheless crucial for both systems to lower their overall environmental impact, even though the impact difference is minimal. Finally, the ISDM has a 14% higher global warming potential (GWP) than ISDW, with an average GWP of 1.3×10^{-3} as opposed to 1.1×10^{-3} for ISDW. This difference implies that ISDM is linked to higher greenhouse gas emissions, most likely as a result of energy use during the extraction of the materials used. Even though the difference in the impact of global warming is not significant, an improvement in this area, such as the use of renewable energy sources or system energy efficiency optimization to lower carbon emissions, could be of great benefit. Overall, the LCA midpoint characterization results indicate that the ISDM has an average environmental impact that is 32.3% higher than that of the ISDW in a number of important impact categories assessed. These results imply that although both dryers had some environmental impacts, ISDM has a greater environmental impact in most of the areas assessed.

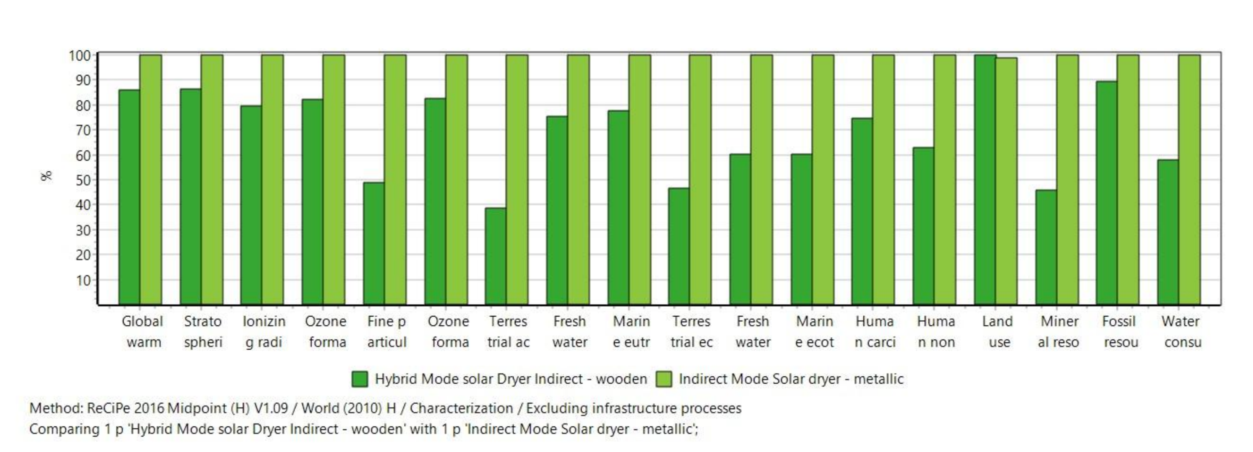

Figure 3. Midpoint characterization values of ISDM and ISDW dryers.

4.2. Endpoint characterization values

Endpoint characterization values translate the midpoint impacts into final consequence effects to human health, damage to ecosystems, or depletion of resources. For the purpose of overall decisions, the endpoint characterization values for each category for the life cycle of ISDM and ISDW were calculated. The impacts on human health are expressed in DALY (disability-adjusted life years), which describe the damage to health or loss of life brought on by climate change as a result of negative environmental impacts of a process or product [53]. For the quality of the ecosystem, the damage is measured in terms of species.yr, which describes the number of species that have vanished as a result of climate change due to the negative impacts of a product on the environment. Finally, the resource depletion is expressed in $ to describe the reduction of natural resources due to their extraction and consumption in the product life cycle.

Table 3. Endpoint characterization values of ISDM and ISDW.

Impact category	Unit	ISDM	ISDW
Global warming, human health	DALY	0.003992454	0.003407235
Global warming, terrestrial ecosystems	species.yr	1.20495E-05	1.02831E-05
Global warming, freshwater ecosystems	species.yr	3.29054E-10	2.80822E-10
Stratospheric ozone depletion	DALY	7.23673E-07	6.19218E-07
Ionizing radiation	DALY	1.96405E-06	1.55472E-06
Ozone formation, human health	DALY	1.16409E-05	9.45576E-06
Fine particulate matter formation	DALY	0.008806685	0.004227615
Ozone formation, terrestrial ecosystems	species.yr	1.71648E-06	1.40465E-06
Terrestrial acidification	species.yr	7.59627E-06	2.85811E-06
Freshwater eutrophication	species.yr	1.41942E-06	1.05493E-06
Marine eutrophication	species.yr	3.57683E-10	2.7606E-10
Terrestrial ecotoxicity	species.yr	1.06882E-06	4.42535E-07
Freshwater ecotoxicity	species.yr	2.32791E-07	1.22576E-07
Marine ecotoxicity	species.yr	5.311E-08	2.82752E-08
Human carcinogenic toxicity	DALY	0.010343809	0.007549624
Human non-carcinogenic toxicity	DALY	0.00159952	0.000948514
Land use	species.yr	4.76919E-05	4.82615E-05
Mineral resource scarcity	USD2013	31.79683674	14.13886433
Fossil resource scarcity	USD2013	268.701571	264.7050781
Water consumption, human health	DALY	7.91533E-05	3.31266E-05
Water consumption, terrestrial ecosystem	species.yr	5.24598E-07	2.29343E-07
Water consumption, aquatic ecosystems	species.yr	6.29385E-11	4.63653E-11

In the human health damage category, the endpoint values for the impacts of ISDM were higher than those of ISDW. The ISDM and ISDW impacts on human health (DALY) are maximum for the human carcinogenic toxicity impact category (i.e., 0.0103 and 0.00755 DALYS, respectively), and minimum for the stratospheric ozone depletion category (i.e., 7.24E-7 and 6.19E-7 DALYS, respectively). Similarly, the impacts of ISDM surpasses those of ISDW for almost all categories of ecosystems quality, except for the land use category, which had impacts of 4.77E-5 and 4.88E-7 species, respectively (Table 3). In terms of resource depletion, the endpoint values for ISDM and ISDW in the mineral resource scarcity category are 31.8$ and 14.1$, respectively (Table 3). Furthermore, for the fossil resource scarcity, the impacts are 269$ and 265$, respectively (Table 3). Therefore, the impacts of ISDM are higher than those for ISDW in this category.

The endpoint characterization results indicate that the ISDM has generally higher environmental impacts than the ISDW across the damage categories of human health, ecosystem quality, and resource depletion. Notably, ISDM shows greater contribution to human health risks and resource scarcity, while ISDW performs slightly worse only in the land use category under ecosystem impacts. In conclusion, the findings suggest that the wooden solar dryer (ISDW) is environmentally more sustainable than the metallic version (ISDM), making it a preferable option for small-scale farmers seeking low-impact drying technologies.

Table 4. Endpoint damage values of ISDM and ISDW.

Damage category	**Unit**	**ISDM**	**ISDW**
Human health	DALY	0.024836	0.016178
Ecosystems	species.yr	7.24E-05	6.47E-05
Resources	USD2013	300.4984	278.8439

4.3. Endpoint damage assessment values

The endpoint damage assessment values quantify the total damage of a product at the endpoint to show the long-term actual consequences of a product on human health, ecosystems, and resources. The purpose of endpoint damage assessment values in the LCA of solar drying technologies is to provide a simplified, high-level understanding of the overall environmental damage associated with the entire technology life cycle. These values help translate complex environmental impacts into more interpretable categories that reflect real world consequences. The details of the damage occurring at the endpoint for the ISDM and ISDW are shown in Table 4 and Figure 4, respectively. According to the findings of the LCA endpoint damage assessment, the ISDM has a greater environmental impact than the ISDW in each of the following three areas: resource depletion ($), ecosystem quality (species.yr), and human health (DALY). Findings indicate that ISDM has 34.9% greater impact on human health than ISDW, pointing to the possibility that ISDM is linked to increased risks of carcinogenic toxicity or other health hazards, possibly as a result of increased emissions or resource use throughout its life cycle. In the ecosystem category, findings show that ISDM has a 10.6% higher impact than ISDW. This is possibly due to emissions, waste, or resource extraction that may cause more ecosystem degradation, including habitat disruption or biodiversity loss. Finaly, for the category of resource depletion, ISDM also has 7.2% greater impacts than ISDW. This suggests that ISDM is more dependent on limited resources, especially fossil fuels and non-renewable minerals, which may present problems for its long-term viability. In totality, ISDM outperforms ISDW by 34.9% in terms of ecosystem quality, 10.6% in terms of human health, and 7.2% in terms of resource depletion. These results clearly demonstrate that ISDM generally has a greater negative impact on the environment than ISDW.

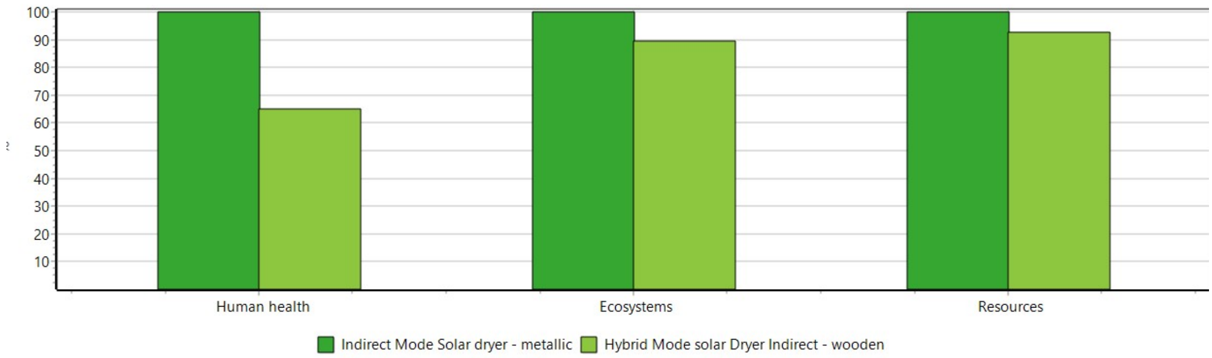

Figure 4. Endpoint damage values of ISDM and ISDW.

4.4. Single-score value

Single-score assessment values simplify decision making by aggregating all the impact categories at both levels (midpoint and endpoint) into a single value that represents the overall environmental performance of a product or process. The single-score results (Table 5 and Figure 5) show that the ISDM solar dryer had a generally higher environmental impact than the ISDW; this difference is most noticeable in the human health category. Although ISDM has a greater impact on the quality of the ecosystem and resource depletion, the differences are relatively smaller. These results indicate that ISDM may benefit from improvements aimed at reducing its human health risks (e.g., minimizing toxic emissions), minimizing harm to ecosystems (e.g., lowering pollution and disturbance of habitat), and optimizing the use of resources (e.g., employing more sustainable materials and renewable energy). By addressing these issues, the ISDM system's overall environmental impacts could be decreased, increasing its sustainability compared with ISDW. From Table 5, it is clearly seen that in all the endpoint impact categories, ISDM aggregates a total of 435.9736 points, compared to 289.3267 points for the ISDW. These results confirm that ISDW has a lower impact on the environment than ISDM in all the damage categories. Hence, as per this study, ISDW can be a better option for drying agricultural products without causing as much danger to the environment.

Policy makers aiming to mitigate human health impacts associated with solar drying technologies should consider the following strategies: Material selection should prioritize the use of non-toxic, sustainable materials in the construction of solar dryers to reduce harmful emissions during both the manufacturing and operational phases. Also, enhancing the energy efficiency of solar dryers is recommended, for example through the use of TESS to minimize reliance on auxiliary energy sources that may contribute to environmental pollution and associated health risks.

Table 5. Endpoint single-score values of ISDM and ISDW.

Damage category	Unit	ISDM	ISDW
Total	Pt	435.9736	289.3267
Human health	Pt	414.2637	269.8448
Ecosystems	Pt	19.56441	17.49098
Resources	Pt	2.145559	1.990946

The decision to prioritize wooden solar dryers should be based on a comprehensive assessment of their environmental and health impacts compared to alternative materials, like the current study. Other similar studies have shown that certain solar dryer designs can have environmental impacts across various categories that are significantly lower than those of traditional dryers. For instance, a previous LCA study revealed that a new solar wood-dryer prototype had environmental impacts in all analyzed categories that were 5% or lower than those of the traditional dryer [66]. However, it is essential to consider factors such as the source and treatment of the wood, durability, and potential emissions during the dryer's lifecycle. While similar studies on solar drying are limited, the few available works using LCA found similar results [25,45,46]. In this case [46] compared direct-mode (DMTD) and indirect-mode (MMTD) solar dryers and concluded that MMTD, which was resource-intensive, had higher environmental impacts than DMTD, which included fewer resources in its construction. On the other hand, [25] compared phase-change material-based (PCMB) solar dryers against cylindrical material-based dryers (CSD), in which the PCMB had higher impacts due to its composition. Also [45] established that a hybrid PV/T solar drying system had significant environmental impacts due to its material use like silicon used in PV module production and steel alloys used in water tank and pumps fabrication. Policymakers should also weigh the benefits of wooden dryers against other sustainable materials that may offer similar or superior environmental performance. Conclusively, it can be stated that wooden solar dryers may present certain environmental advantages; the decision to prioritize them should be informed by detailed life cycle assessments and considerations of local environmental conditions, resource availability, and health impact mitigation strategies.

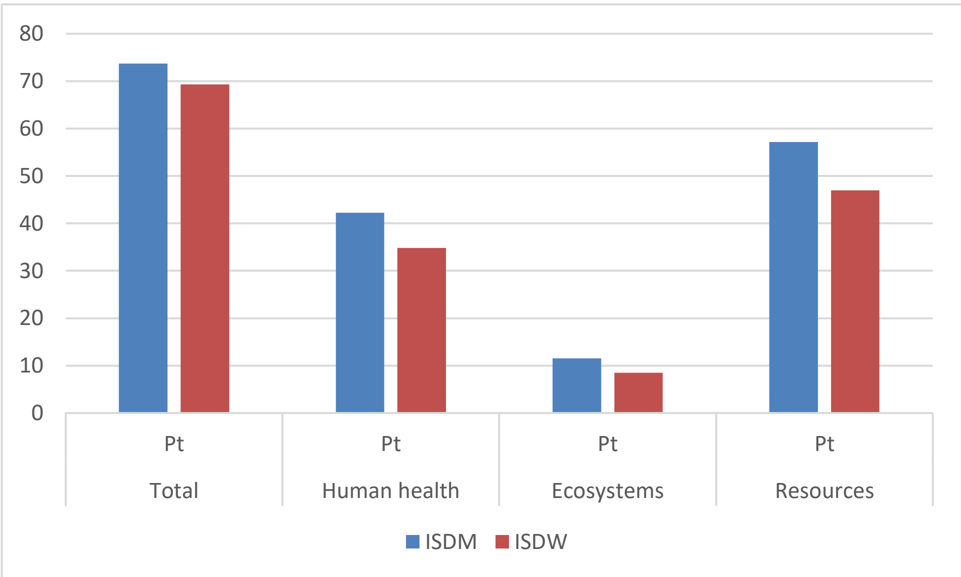

Figure 5. Single-score values of ISDM and ISDW.

5. Conclusions and future directions

The cradle-to-grave LCA was performed comparing ISDM and ISDW. The results of the LCA indicate that ISDM has a higher environmental impact compared to ISDW across both midpoint characterization and endpoint damage categories. The midpoint characterization values show that the ISDM has an average environmental impact 32.3% higher than the ISDW in several important impact categories. Furthermore, the endpoint damage assessment reveals that the ISDM exceeds the ISDW by 34.9% in human health, 10.6% in ecosystem quality, and 7.2% in resource depletion. The single-score assessment further reinforces these findings, with the ISDM accumulating a total of 435.97 points, compared to 289.33 points for the ISDW. This confirms that the ISDW has a lower overall environmental impact across all assessed damage categories. Therefore, based on these results, the ISDW is a more environmentally sustainable option for drying agricultural products, as it causes less harm to human health, ecosystems, and natural resources.

These findings have several key policy implications. First, policymakers should create policies focusing on scaling up and encouraging small scale farmers (SSFs) to use environmentally sustainable technologies like ISDW (the most sustainable dryer in this case) to reduce environmental impacts. This can be done by providing incentives, for example, subsidies, tax exemption on solar dryers' equipment, or provisions of support grants to enable SSFs and other stakeholders in the agro-industries to adopt and use sustainable drying technologies.

Second, end-of-life (EoL) strategies should be integrated into national renewable energy policies. This is key for material recovery and recycling programs, whereby local authorities should monitor and regulate the establishment of formal systems for collecting, dismantling, and recycling components, especially the metallic parts (e.g., aluminum, steel) used in ISDMs. This reduces resource depletion and diverts waste from landfilling. Additionally, producer responsibility should be extended, especially regarding EoL responsibility, including return schemes, take-back programs, or safe disposal solutions. This will help to repurpose some materials like metals, glass, and plastics. In line with this, the use of modular and repairable components will enhance circular economy practices of solar dryer components.

Future life cycle sustainability studies on solar dryers should focus on the following specific sustainability aspects, which remain unexplored.

- Further investigations on the environmental sustainability of alternative materials for solar dryers in order to decrease environmental impacts. For example, the use of biodegradable, recyclable, or bio-based materials to replace high-impact materials like metals and synthetic insulation.
- Future studies should also include other dimensions of sustainability, i.e., life cycle costing (LCC), to compare the economic viability of various disposal and recovery strategies, as well as analyze the energy and environmental costs of recycling vs. producing new materials. Also, the social dimension of sustainability, i.e., social life cycle assessment (SLCA), should be studied, for example, assessing social factors associated with solar dryers, such as job creation, user health and safety, gender equity, and technology accessibility, which influence the social acceptance and long-term success of solar drying technologies. This will enable more informed decisions based on all three dimensions of sustainability.
- More research on EoL strategies on solar dryer materials is needed. This may include evaluation of different EoL scenarios, such as landfilling, incineration, recycling, reuse, and biodegradation, using LCA.

In summary, future research on the LCA of solar dryers should prioritize three key areas. First, exploring the use of alternative, low-impact materials to reduce overall environmental burdens. Second, expanding the sustainability assessment beyond a single-dimensional (environmental) focus to incorporate economic and social dimensions, enabling a more holistic evaluation. Third, conducting in-depth studies on end-of-life strategies for solar dryer materials to support circularity and minimize long-term environmental impacts.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflict of interest.

Authors contributions

Ashiraf Abeid performed the Conceptualization, literature review, methodology, data collection, analysis, drafting of the manuscript and prepare the final version of the manuscript. Felichesmi Lyakurwa provided guidance on research design and methodology. Additionally, he provided critical feedback on the work by ensuring academic accuracy and alignment with the study objectives. Eliaza Mkuna offered expertise in the design of the framework, reviewed the manuscript, offer suggestions for improvement and ensure compliance with ethical standards.

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