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Research Article

Evaluating the Environmental Impact of a Home Appliances: A Life Cycle Assessment with a New Green Product Design Framework

Mohd Tayyab[1*], Ranganath M Singari[2], Peer M Sathikh[3]

[1*,2]epartment of Design, Delhi Technological University, India. [*]mdtayyab7809@gmail.com
[3]School of Art, Design & Media, Nanyang Technological University, Singapore.

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ARTICLE INFO **ABSTRACT**

The objective of this research is to verify the proposed innovative green product design (GPD) framework by conducting a case study that compares and contrasts the environmental impacts of two juicers manufactured by different companies but possessing identical power ratings and capacities. In accordance with the ISO 14044 standard, the research examines the complete life cycle of the household appliance by utilizing life cycle inventory data acquired from a prior publication (Shaukat et al., 2021). The validity of the proposed GPD framework is established through a comparison of its outcomes with those of a prior study that also utilized the life cycle assessment method (Shaukat et al., 2021). A life-cycle analysis reveals that the environmental impacts of the two juicers are notably dissimilar. The first juicer's energy consumption and environmental impact are lower in comparison to the second juicer. Furthermore, the proposed GPD framework's performance is comparable to the method described in the cited article. This study introduces a novel GPD framework for assessing the environmental sustainability of other products and enhances knowledge about the environmental impact of home appliances.

Keywords: Life cycle assessment, Citrus juicer, Green Product Design(GPD), Framework, Environmental impact.

I.Introduction:

Background and Motivation

Exponential growth in the use of home appliances is a result of rapid urbanisation. In 2020, the market for home appliances was expected to be worth around 283 USD billion. (Priyanka Bisht 2015).
The production, use, and disposal of these appliances, however, are responsible for a number of environmental problems. The demand for environmentally friendly products has increased as people's awareness of the effects of climate change and the depletion of natural resources has grown. Understanding how these appliances affect the environment throughout their entire life cycle is crucial.

A widely used method for calculating the environmental effects of products and processes is life-cycle assessment (LCA). Since its introduction in the 1990s, it has become widely embraced. (Allen and Shonnard 2001). Using life cycle assessment (LCA), potential effects of a product are determined throughout all stages of production, including raw material extraction, manufacturing, transportation, use, and final disposal. LCA helps to prevent the shifting of environmental impacts from one life-cycle stage to another by providing incredibly detailed information about the various environmental impacts produced by each stage of the product life cycle. (Bohm et al. 2010; Cooper 2005). The environmental performance of various products, including refrigerators, coffee makers, hand dryers, etc., has also been compared by a number of researchers using LCA. The manufacturing processes that are employed in the creation of a product are greatly influenced by its design. Consequently, a product's design plays a role in determining how it will affect the environment. Different manufacturers use various design methodologies to create products with the same functionality (Shaukat et al., 2021).

Objectives of this research are:

To verify the suggested framework's accuracy by contrasting its findings with earlier LCA research that was published.

To advance knowledge of how household appliances affect the environment and to recommend the new GPD framework as a helpful resource for assessing other items' environmental sustainability.

To assess how two different manufacturers' citrus juicers affect the environment.

To determine which phase of a juicer's life cycle results in the greatest environmental impact.

II. Literature Review

The application of LCA is regulated by the standards of the International Standards Organization (ISO) 14040 series (ISO 14044:2006, 2014). In general, two varieties of LCAs are employed: those with multiple figures and those with single figures, such as the proposed framework. Multiple-figure LCA computes a product's ecological repercussions across a variety of impact categories. When comparing two or more product systems, calculations are performed for each of these multiple impact categories. This can be a voluminous, costly, and perplexing procedure that surpasses the capabilities of the majority of seasoned designers.

The environmental effects of various products, including air conditioners (Grignon-Massé, Rivière, and Adnot 2011), cooking appliances (Favi et al. 2018), domestic boilers (Vignali 2017), domestic solar water heaters (Uctug and Azapagic 2018), and refrigerators (Ma et al. 2012), have all been examined by several researchers using LCA. Subassemblies of these products have also been examined by some researchers. Elduque et al. (2014), for instance, performed a life cycle analysis on the electronic boards of an induction hob. The following is a summary of a few key studies on the LCA of home appliances.

Pina et al., (2015) performed a thorough life cycle analysis (LCA) of five distinct induction hob generations. They discovered that newer induction hob generations had less of an impact on the environment than older ones. This discovery was attributed to the more recent induction hob models' effective use of materials and components.

In a different study, a domestic cooker hood's LCA was carried out by Bevilacqua et al., (2010) The majority of the environmental effects, they discovered, were caused by the manufacturing and use phases. The electricity mix used during the use phase, they added, significantly affected the outcomes. In order to lessen the negative effects on the environment, their study also included a modified design that used LED lamps and a three-phase motor.

LCA was used by Hawthorne and Ameta (2012) to assess the environmental effects of blenders. They came to the conclusion that during the entire life of blenders, the manufacturing phase caused the most environmental harm. Additionally, they came to the conclusion that the overall environmental impacts were primarily determined by the materials used to make these blenders. Using LCA, Favi et al. (2018) compared two types of stoves sold in Italy: induction and gas. They discovered that the induction hob had greater negative effects on the environment than the gas hob.

Similarly, several other studies have compared and analyzed the environmental impacts of various products and/or processes using LCA. An examination of two distinct streetlight technologies was conducted in rural Lebanon by Tannous et al. (2018). Hischier (2015) analyzed numerous display technologies using LCA. Scharnhorst, Hilty, and Jolliet conducted a comparative analysis of multiple mobile phone networks in their 2006 study. Rubin et al. (2014) investigated different techniques for copper recovery from printed circuit boards using LCA. A comparative analysis of the environmental impacts of packaging alternatives composed of polymers and glass was conducted by Dhaliwal et al. (2014). In order to further comprehend the ramifications, the LCA methodology facilitated the incorporation of supplementary environmental effects associated with health services. Twenty-23 (Hernández-de-Anda et al.).

In conclusion, the literature review demonstrates that LCA has been used to assess the environmental effects of numerous goods and procedures. The overall environmental effects of these products depend on the design, materials, and manufacturing techniques used to create them. Reduced environmental impact can also be achieved through efficient energy use during the usage phase.

This paper compares two different methods of life cycle assessment and also compares juicers made by two different manufacturers that have the same functionality and power rating, adding to the body of existing literature. This study will highlight how these juicers' various environmental performances differ and relate those differences to their various designs.

III.Methodology

In this study, ISO14040 was used to perform LCA of citrus juicer. This section discusses goal and scope, life-cycle inventory, and life-cycle effect assessment method which is a proposed novel GPD framework. The study's assumptions and sources of inventory data are also explained. According to the ISO standard, an LCA study consists of four steps: objective and scope definition, life-cycle inventory compilation, life-cycle assessment, and outcome interpretation. (ISO 2006).

A Life Cycle Assessment (LCA) study commences by establishing a well-defined scope, functional unit, and system boundaries. Subsequently, a comprehensive record of the resources and energy consumed at every phase of the product's life cycle is compiled. The inventory is subsequently utilized to conduct the impact assessment and calculate various environmental impacts, such as global warming potential.

In pursuance with the objectives of this research, the subsequent procedures were executed:

a. Information Collection From previous publication for life cycle inventory compilation.
b. Define and implement the Proposed GPD Framework for home appliance life cycle assessment.
c. Validation and Analysis of Data.

Information Collection From previous publication

- The functional unit for this study was extraction of a half-litre of juice per day. The life of each juicer was assumed to be 3 years (given three-year warranty by each manufacturer) (Shaukat et al., 2021).
- First juicer (J1) was produced in Slovenia and the second juicer (J2) was produced in China (Shaukat et al., 2021).
- It is postulated that the two juicers were conveyed from the port of Dammam to the retail establishment via vehicle after coming via sea. Both juicers are presumed to be disposed of via landfilling (Shaukat et al., 2021).
- Simapro software was used for modelling life-cycle inventory.

Figure 1, demonstrates the system boundary for the LCA study of both juicers, and Tables 1 demonstrate the weight of various material used for both the juicers.

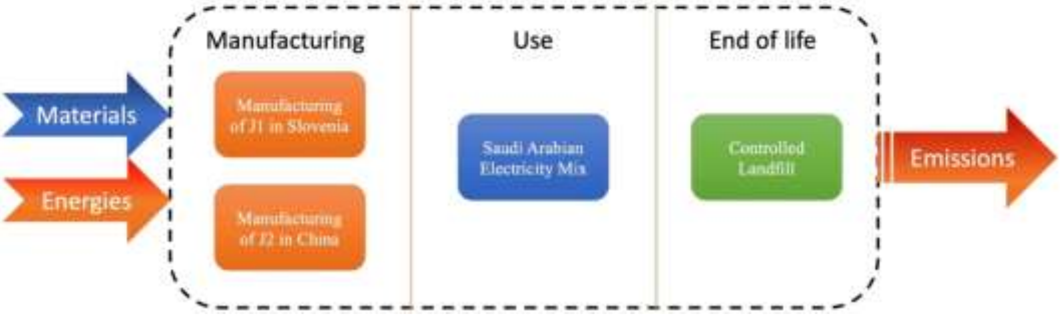

Fig. 1: System boundary for both juicers.

Table1: Life Cycle Inventory for both juicers (Shaukat et al., 2021).

Material	**J1**	**J2**
Printed paper (g)	19	12
Cardboard for packaging(g) (corrugated board)	141	117
Polypropylene (g)	336	185
Polyethylene (g) (high density)	29	33
Polystyrene (g)	0	4
Styrene-acrylonitrile (g)	0	186
Steel unalloyed (g)	71	72
Permanent magnet (g)	19	15
Cast Iron (g)	2	2
Copper (g)	27	26
Chromium steel (g)	2	4
Cable (g)	76	114
Transportation, Energy consumption and manufacturing processes		
Transportation by road (kg.km)	18.175	19.275
Transportation by sea (t.km)	9.46	9.885
Electricity usage (MJ)	1.675	2.76
Steel processing (g) (sheet rolling)	69	70
Plastic bag production (g)	0	6
Polystyrene Foam production (g)	0	4
Injection molding of different plastic parts (g)	366	398
Copper wire drawing for motor (g)	26	24

MJ = Mega Joules; g = gram; t.km = tones-kilometre

Proposed GPD Framework

A growing awareness of environmental issues such as material scarcity, high energy consumption, rising atmospheric CO2 levels, ozone depletion, population growth, depletion of natural resources, and so forth contributed to the rise in popularity of "green product design (GPD)" during the late 1980s and early 1990s (Toktas-Palut, P., et al., 2022). The term "sustainable" was initially defined during the Oslo Roundtable in 1994

(Aerais, 2010). Subsequently, a multitude of GPD definitions have been presented, accompanied by illustrations of their application across diverse domains.

Vinodh and Rajanayagam (2010) argue that the main objective of a green production system is to minimize the environmental impact by integrating product and process design with process planning and control. This integration allows for environmental waste flow identification, measurement, evaluation, and management. Green product design provides economic and social benefits to customers, stakeholders, and enterprises, while also serving as a realistic and effective method to counteract environmental degradation (Fuller and Ottman, 2004). The GPD framework also encompasses the concept of eco-design, which aims to harmonize environmental considerations with design objectives that are directed towards economic goals (Karlsson and Luttropp, 2006). Howarth and Hadfield (2006) argue that organizations and designers should prioritize the selection of "environmentally friendly" raw materials. This should be followed by implementing suitable manufacturing and distribution systems, as well as specifying the use and disposal of the final product in a way that minimizes its impact on the environment and society. In the present global context, GPD is extensively advocated as a strategy that can yield substantial advantages. Consequently, numerous scholars have made significant contributions to the advancement and study of unexplored domains within the GPD discipline, with the aim of furthering GPD research.

The proposed Green Product Design (GPD) framework is a design-oriented framework that offers a single-figure score for Life Cycle Assessment (LCA) aspects. This score is significantly more efficient and user-friendly compared to using many categories for LCA. The simplicity of this framework allows for easy implementation using only pencil and paper. Designers who employ this approach develop a deep understanding of the facts, which greatly influences their design process.

This proposed GDP framework (Mohd Tayyab et al., 2024) used similar approach which is used by Philip White (White et al., 2013), which were created with modifications to the TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) impact characterization method that was developed by scientists at the US Environmental Protection Agency (EPA). The factors combine ten environmental impact categories in one single-figure score.

This framework categorizes the product life cycle into three distinct stages: manufacture, usage, and end of life. Figure 2 illustrates this division and provides the carbon emission value for each stage. A lower value indicates a greener product.

The GPD framework can be utilized in several ways to comprehend the environmental efficacy of a design concept, spanning from rapid preliminary assessment to comprehensive examination of the entire product system. Various methodologies can be advantageous, depending on the circumstances and the types of questions the designer aims to address. The primary strategy to utilizing this framework is doing a comprehensive life cycle assessment (LCA) of the entire system. However, it can also be employed for simpler screening purposes and for comparing subassemblies (Mohd Tayyab et al., 2024).

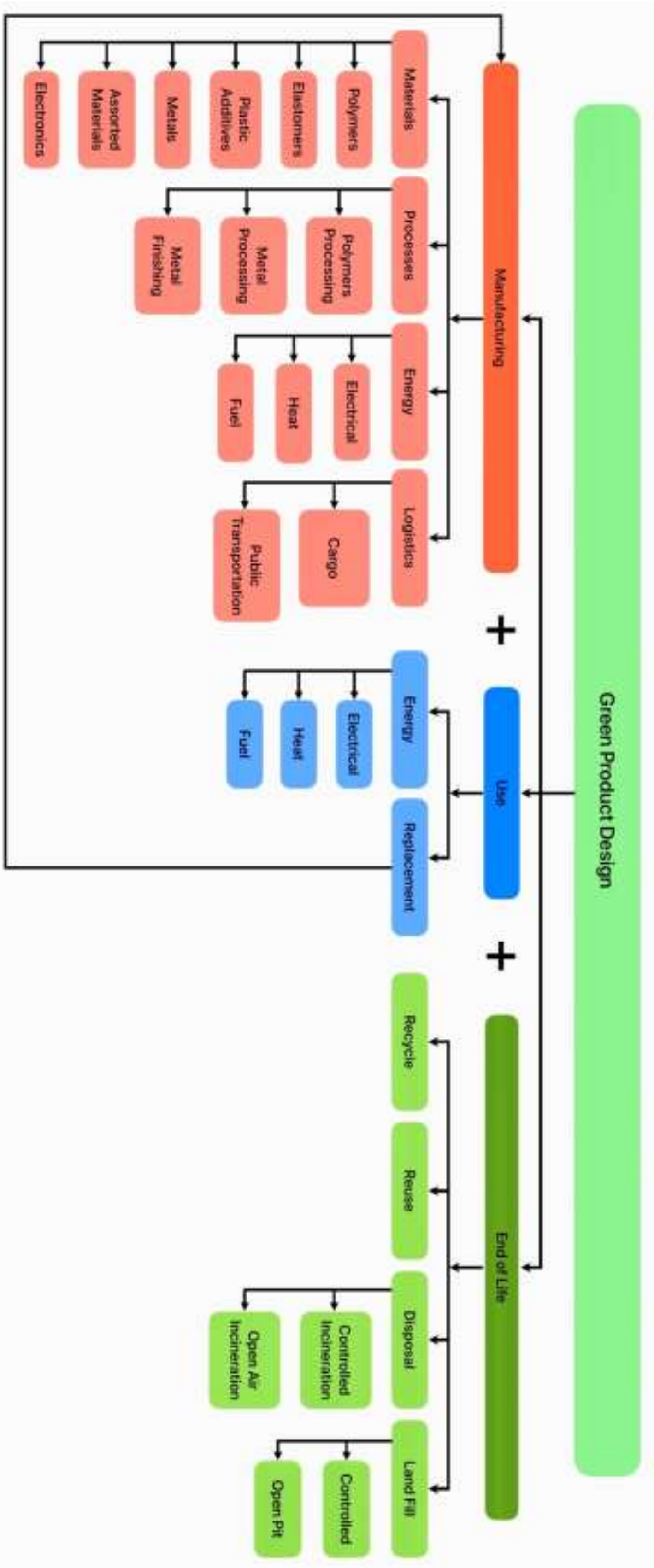

Fig 2: Proposed Framework GPD

The following steps are involved during the life cycle assessment of the product:
Step1: Define lifetime, function unit and system boundaries.
Step2: Make bill-of-materials
Step3: Calculation of estimated impacts

Data Validation and Analysis

The functional unit for this study was extraction of a half-litre of juice per day. The life of each juicer was assumed to be 3 years (given three-year warranty by each manufacturer).

Juicer J1 used an average of 7.5W and J2 used an average of 14W during juice extraction.

Assumed controlled landfill at the end of the life cycle

1. Define lifetime, function unit and system boundaries.

Juicer J1		**Juicer J2**	
Lifetime J1	24 x 365 x 3 = 26,280 hours	Lifetime J2	24 x 365 x 3 = 26,280 hours
Functional Unit	Impacts/life	Functional Unit	Impacts/ life
System boundary	Excludes cleaning during use	System boundary	Excludes cleaning during use

2. Make bill-of-materials

	Juicer J1			**Juicer J2**	
Materials	Printed paper (g)	19	**Materials**	Printed paper (g)	12
	Cardboard for packaging(g) (corrugated board)	141		Cardboard for packaging(g) (corrugated board)	117
	Polypropylene (g)	336		Polypropylene (g)	185
	Polyethylene (g) (high density)	29		Polyethylene (g) (high density)	33
	Polystyrene (g)	0		Polystyrene (g)	4
	Styrene-acrylonitrile (g)	0		Styrene-acrylonitrile (g)	186
	Steel unalloyed (g)	71		Steel unalloyed (g)	72
	Permanent magnet (g)	19		Permanent magnet (g)	15
	Cast Iron (g)	2		Cast Iron (g)	2
	Copper (g)	27		Copper (g)	26
	Chromium steel (g)	2		Chromium steel (g)	4
Manufacturing	Steel processing (g) (sheet rolling)	69	**Manufacturing**	Steel processing (g) (sheet rolling)	70
	Plastic bag production (g)	0		Plastic bag production (g)	6
	Polystyrene Foam production (g)	0		Polystyrene Foam production (g)	4
	Injection molding of different plastic parts (g)	366		Injection molding of different plastic parts (g)	398
	Copper wire drawing for motor (g)	26		Copper wire drawing for motor (g)	24
Use	Electricity usage (MJ)	1.675	**Use**	Electricity usage (MJ)	2.76
Transport	Transportation by road (kg.km)	18.175	**Transport**	Transportation by road (kg.km)	19.275
	Transportation by sea (t.km)	9.46		Transportation by sea (t.km)	9.885
Disposal	landfill		**Disposal**	landfill	

3. Calculations:

Input	**Amount**	**x CO_2 eq** *(kg)*	**= Value** *(kg)*	**Input**	**Amount**	**x CO_2 eq** *(kg)*	**= Value** *(kg)*
Printed paper	0.019(kg)	0.68	0.01292	Printed paper	0.012(kg)	0.68	0.00816
Cardboard for packaging (corrugated board)	0.141(kg)	0.44	0.06204	Cardboard for packaging (corrugated board)	0.117(kg)	0.44	0.05148
Polypropylene	0.336(kg)	1.68	0.56448	Polypropylene	0.185(kg)	1.68	0.3108
Polyethylene (high density)	0.029(kg)	1.50	0.0435	Polyethylene (high density)	0.033(kg)	1.50	0.0495
Polystyrene	0	2.22	0	Polystyrene	0.004(kg)	2.22	0.00888
Styrene-acrylonitrile	0	1.86	0	Styrene-acrylonitrile	0.186(kg)	1.86	0.34596
Steel unalloyed	0.071(kg)	2.13	0.15123	Steel unalloyed	0.072(kg)	2.13	0.15336
Cast Iron	0.002(kg)	0.54	0.00108	Cast Iron	0.002(kg)	0.54	0.00108
Copper	0.027(kg)	1.86	0.05022	Copper	0.026(kg)	1.86	0.04836
Chromium steel	0.002(kg)	2.04	0.00408	Chromium steel	0.004(kg)	2.04	0.00816

Steel processing (sheet rolling)	0.069(kg)	0.16	0.01104
Plastic bag production	0	0.25	0
Polystyrene Foam production	0	1.18	0
Injection molding of different plastic parts	0.366(kg)	0.59	0.21594
Copper wire drawing for motor	0.026(kg)	0.21	0.00546
Transportation by road	18.175 (kg.km)	0.27	4.90725
Transportation by sea	9.46 (t.km)	0.027	0.25542
During Use			
Electricity usage	1.675(MJ)	4.25	7.11875
Controlled landfill			
Printed paper	0.019(kg)	0.43	0.00817
Cardboard for packaging (corrugated board)	0.141(kg)	0.54	0.07614
Polypropylene	0.336(kg)	0.045	0.01512
Polyethylene (high density)	0.029(kg)	0.049	0.001421
Polystyrene	0	0.054	0
Styrene-acrylonitrile	0	0.27	0
Steel unalloyed	0.071(kg)	0.006	0.000426
Cast Iron	0.002(kg)	0.006	0.000012
Copper	0.027(kg)	0.006	0.000162
Chromium steel	0.002(kg)	0.006	0.000012

Steel processing (sheet rolling)	0.070(kg)	0.16	0.0112
Plastic bag production	0.006(kg)	0.25	0.0015
Polystyrene Foam production	0.004(kg)	1.18	0.00472
Injection molding of different plastic parts	0.398(kg)	0.59	0.23482
Copper wire drawing for motor	0.024(kg)	0.21	0.00504
Transportation by road	19.275 (kg.km)	0.27	5.20425
Transportation by sea	9.885 (t.km)	0.027	0.266895
During Use			
Electricity usage	2.76(MJ)	4.25	11.73
Controlled landfill			
Printed paper	0.012(kg)	0.43	0.00516
Cardboard for packaging (corrugated board)	0.117(kg)	0.54	0.06318
Polypropylene	0.185(kg)	0.045	0.008325
Polyethylene (high density)	0.033(kg)	0.049	0.001617
Polystyrene	0.004(kg)	0.054	0.000216
Styrene-acrylonitrile	0.186(kg)	0.27	0.05022
Steel unalloyed	0.072(kg)	0.006	0.000432
Cast Iron	0.002(kg)	0.006	0.000012
Copper	0.026(kg)	0.006	0.000156
Chromium steel	0.004(kg)	0.006	0.000024

Total impact/life Juicer J1: 13.50kg CO_2 eq | **Total impact/life Juicer J2: 18.57kg CO_2** eq

The process is only accurate to 2 significant figures, so we calculate the impacts per functional unit and round to two significant figures.
*Due to unspecified cable and magnet, the environmental impact of these is not included.

Figure 3(a) and 3(b) shows the environmental impact of both juicer during the three main life cycle stages. It is a graphical representation of proposed GPD framework.

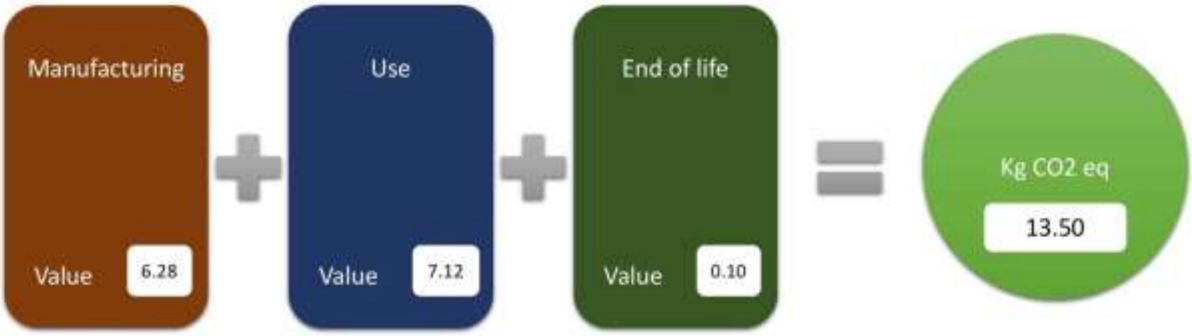

Fig 3(a): Environmental impact of juicer J1 at different stages

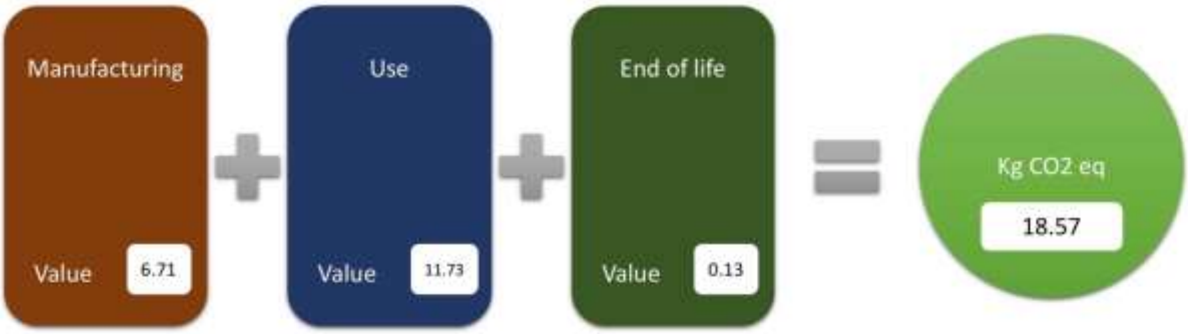

Fig 3(b): Environmental impact of juicer J2 at different stages

IV. Results and discussion

Table 2 presents the characteristics of both juicers, whereas Figure 4 illustrates the respective contributions of different life cycle stages to the environmental impacts of these two juicers. The outcome was determined utilizing the GPD framework and subsequently compared to the outcome of a previously published article that employed the ReCiPe impact assessment technique to ascertain the outcome.

As it is cleared from the result that the juicer J2 which is produced in China having higher environmental impact with compared to juicer J1 which is produced in Slovenia, and it is also cleared from the result that the use phase for both the juicers have majority of environmental impact. On the other hand, the manufacturing phase has second highest environmental impacts during the life cycle of both the juicers, as shown in table 3.

The study also discovered some interesting differences between the two juicers' motors. Compared to the motor used by J2, J1's motor is more effective and uses less power while in use, that's why during use phase juicer J1 impacts lesser than the juicer J2 environmentally.

Table 2: Environmental impact of bicycle at different stages.

Stages	**J1 *(Kg CO_2 Eq)***	**J2 *(Kg CO_2 Eq)***
During manufacturing	6.28	6.71
During use (for 26,268hr life)	7.12	11.73
At the end of life	0.10	0.13

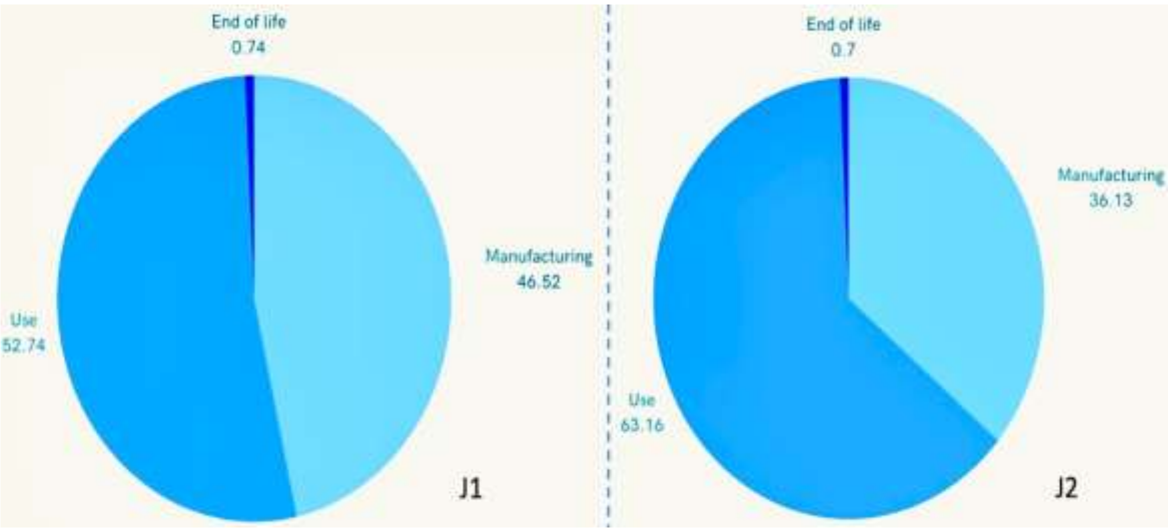

Fig 4: shows the impacts over the entire life cycle of the juicer J1 and Juicer J2.

V. Conclusion

The purpose of this case study was to validate the novel green product design (GPD) framework by assessing the environmental impact of household appliances. The LCI information gathered from a study that was previously published (Shaukat et al., 2021). The research developed a novel GPD framework for life cycle assessment in order to evaluate the ecological consequences of household appliances. Through a comparison of life cycle assessments, it was ascertained that the manufacturing phase had the second-highest environmental impact, trailing only the use phases. The findings revealed that the juicer J2, manufactured in China, exhibited a greater ecological footprint in comparison to the juicer J1, manufactured in Slovenia. This contrast underscores the notion that identically powered and functional products can manifest divergent environmental impacts. The study validated that the results of the revised GPD framework align with those of the previously published framework, indicating that the impacts of transportation and end-of-life phases are inconsequential. The research, which was carried out in Saudi Arabia, encountered obstacles including the scarcity of dependable local datasets, the absence of direct communication with manufacturers, and information regarding supply chain organizations and component transportation from suppliers to final assembly. The results of this study have the potential to contribute to the development of environmentally friendly consumer products by demonstrating that the life-cycle impacts of appliances can be diminished by incorporating energy-efficient motors, optimizing component design, and exercising judicious material selection. This research will help to identify and maintain optimal management and manufacturing practices in the production of household appliances.

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