Environmental Payback Periods of Reusable Alternatives to Single-Use Plastic Kitchenware Products

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Abstract

Many consumers are transitioning away from single-use plastic products and turning to reusable alternatives. Oftentimes this change is being made with the assumption that these alternatives have fewer environmental impacts; however, reusable products are frequently made from more environmentally-intensive materials and have use phase impacts. This study used LCA to examine the GWP, water consumption and primary nonrenewable energy use associated with reusable alternatives for single-use plastic kitchenware products, and determined environmental payback periods. Payback periods are calculated for each reusable alternative and defined as the number of times a consumer must re-use an alternative in order for the environmental impact per use to be equivalent to the environmental impact for the single-use product. The research explored the sensitivity of the results to different consumer washing and reuse behaviors, as well as local conditions such as overall transportation distances and the carbon intensity of different electricity grids. Product types studied included straws (4 reusable, 2 single-use), sandwich storage (2 reusable, 3 single-use), coffee cups (3 reusable, 2 single-use) and forks (1 single-use, 3 reusable).

Environmental impacts associated with the reusable alternatives were highly dependent on the use phase due to dishwashing, making payback period sensitive to washing frequency and method, and for GWP, carbon intensity of the energy grid (used for water heating). For single-use products, the material/manufacturing phase was the largest contributor to overall impacts. It was found that nine of the twelve reusable alternatives were able to breakeven in all three environmental indicators. The coffee cup product type was the only product type to have one reusable alternative, the ceramic mug, have the shortest payback period for all three impact categories. Both the bamboo straw and beeswax wrap were unable to breakeven in any scenario due to high use phase impacts from manual washing. The research found that reusable alternatives can payback the environmental impacts of GWP, water consumption, and energy use associated with their more resource intensive materials, but it is dependent on number of uses, consumer behavior and for GWP, carbon intensity of the energy grid. A key takeaway is that consumer behavior and use patterns influence the ultimate environmental impact of reusable kitchenware products.

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Table of Contents

1.0 Introduction

Reusable alternatives have quickly become a popular solution for replacing single-use products and combatting the ubiquity of disposable plastic (European, 2018; Schnurr et al., 2018; UNEP, 2018; Godfrey, 2019). Although reusable alternatives have the potential to reduce end of life waste, they also come with their own environmental impacts (Herberz et al., 2020), as reusable items can be made with more resource intensive materials and have use-phase impacts, such as water consumption and energy use, associated with washing (Blanca-Alcubilla et al., 2020; Milà-i-Canals, L. et al., 2020). This study compares the use of reusable and single-use products, and determines the number of re-uses necessary to payback the environmental impacts associated with reusable alternatives.

Additionally, forecasted markets for alternatives to single-use plastic reflect this shift in consumer behavior. One study valued the market for sustainable packaging at ~$225 billion in 2018 and forecasted a compound annual growth rate (CAGR) of 5.7% from 2019-2024 (MarketInsightsReport, 2019). Another report looking at the drinking straw market also expects a CAGR of ~6%, with a shift in consumer preference for reusable or biodegradable products (Budholiya, 2019). Additionally, certain reusable products have gained increased media attention, such as straws, sandwich bags and travel utensils (Ro, L., 2020; Englishman, K. O., 2020; Kitts, K. & Conti, M., 2020).

While many consumers are transitioning to reusable alternatives with the hopes of being more sustainable, research has shown that consumer perception of what makes a product sustainable does not always reflect actual life cycle assessment (LCA) results (Boesen & Niero, 2019; Steenis et al., 2017). This means some consumers might be inaccurately thinking they are making the most sustainable choices when another alternative is environmentally preferable. Currently, there are many LCA studies on everyday consumer products such as plastic carrier bags (Edwards, 1998; Greene, 2011; Kimmel et al., 2014; Bisinella, 2018), disposable cups (Openbare, 2006; Ligthart & Ansems , 2007; Van der Harst & Potting, 2013, Cottafava, D. et al., 2020), plates (Postacchini et al., 2016), milk bottles (Keoleian & Spitzley, 1999), take-away containers (Madival, S. et al., 2009; Accorsi et al., 2014; Bortolini, M. et al., 2018; Gallego-Schmidt et al., 2019) and other food packaging options (Franklin Associates, 2018). These papers demonstrate the complexity of product sustainability, the nuances of the environmental impact of reusable items, and the number of factors and behaviors results are dependent on. These contingencies for environmental favorability are further explored in recent research identifying common misperceptions associated with single-use plastic solutions (Miller, 2020).

In order to better communicate the environmental impact per use of reusable products to consumers, this study looks at popular and highly advertised reusable alternatives and uses the concept of payback period to communicate the environmental impact. In this paper, payback period is defined as the number of uses required to have equivalent environmental impacts per use between the reusable and single-use product on a life cycle basis, which includes resource extraction, manufacturing, transportation, use and disposal (Cherif & Belhadj, 2018). Payback period is calculated as a ratio between overall emissions of single-use products versus a reusable alternative for the same number of uses. Some advantages of using payback period is that it is both easily understandable to the average consumer (Alton & Underwood, 2003; Saoutert & Andreasen, 2006) and provides a specific action that can be taken (Jensen & Schnack, 1997; Breiting & Mogensen, 1999; Robelia et al., 2011).

Payback period is commonly associated with a monetary calculation, but previous research has used environmental payback to optimize scenarios such as air conditioner, refrigerator, freezer, and automobile replacement (De Kleine, 2009; Horie, 2004; Spitzley et al., 2005). Many of these studies have shown how environmental favorability is highly contingent on product lifetime, consumer behaviors and local conditions. An example of the impact of consumer behavior on optimal replacement was presented in a 2006 study on washing machines where payback calculations resulted in recommendations on washer replacement that varied between replacing only once to three times within a 35 year period depending on the user's choice to wash their clothes with cold or hot water, and the choice to hang-dry versus machine-dry (Bole, 2006). A meta-analysis conducted by the UN Environment Programme showed that local conditions such as land-use change from production and extraction stages, and local waste management practices affected the environmental payback of reusable bags. The report found that GHG emission payback period of a reusable polyethylene bag varied between 4 – 20 uses when compared to a traditional single-use plastic bag (UNEP, 2020). With this in mind, the current study assesses how consumer behavior and local condition factors impact the number of uses before environmental payback for reusable products might occur.

The overall objectives of this research are:

(1) Identify the number of re-uses necessary to payback the environmental impacts associated with reusable products,
(2) Determine consumer behaviors and local conditions which impact payback period.

Using LCA, this paper analyzes single-use and reusable alternatives for four common kitchenware product groups: drinking straws, sandwich storage, coffee cups, and utensils. These alternatives were selected due to media and consumer popularity (Brown, N., 2019; Leighton, M., 2019; Wells, K., 2019). Although some LCA studies have been done on these products (Razza, F. et al., 2009, Takou, V. et al., 2019; Chitaka, T.Y. et al., 2020), many are location specific or evaluate few alternatives. This analysis compares a wide variety of products using the lens of environmental payback rather than standard comparative LCA to help put environmental impacts of product alternatives into better context.

This study compares reusable and single use products on the basis of global warming potential, water consumption and primary nonrenewable energy use. Different scenarios are used to investigate how assumptions can impact the payback period for each product group. The payback period is determined for each reusable item and sensitivity analysis is conducted with respect to changes in material emissions, transportation distance, consumer behavior during the use phase, disposal scenarios, and local conditions such as carbon intensity of the energy grid and type of water heater in the home. In some scenarios, a payback period cannot be calculated since the environmental impacts of the reusable item are unable to break even with the environmental impacts of a single-use item, which occurs when the use phase impacts associated with washing the reusable item are greater than the total life cycle impact of the single-use item.

2.0 Materials and Methods

This study utilized an LCA framework and followed the standard four-step approach defined in ISO14040/14044 (International Organization for Standardization [ISO], 2006). Simapro v9.1.0.11 was used to obtain inventory and impact assessment data, supplemented with literature data as appropriate. Specific assumptions and methodological choices for each of the four stages of the LCA are detailed in each section.

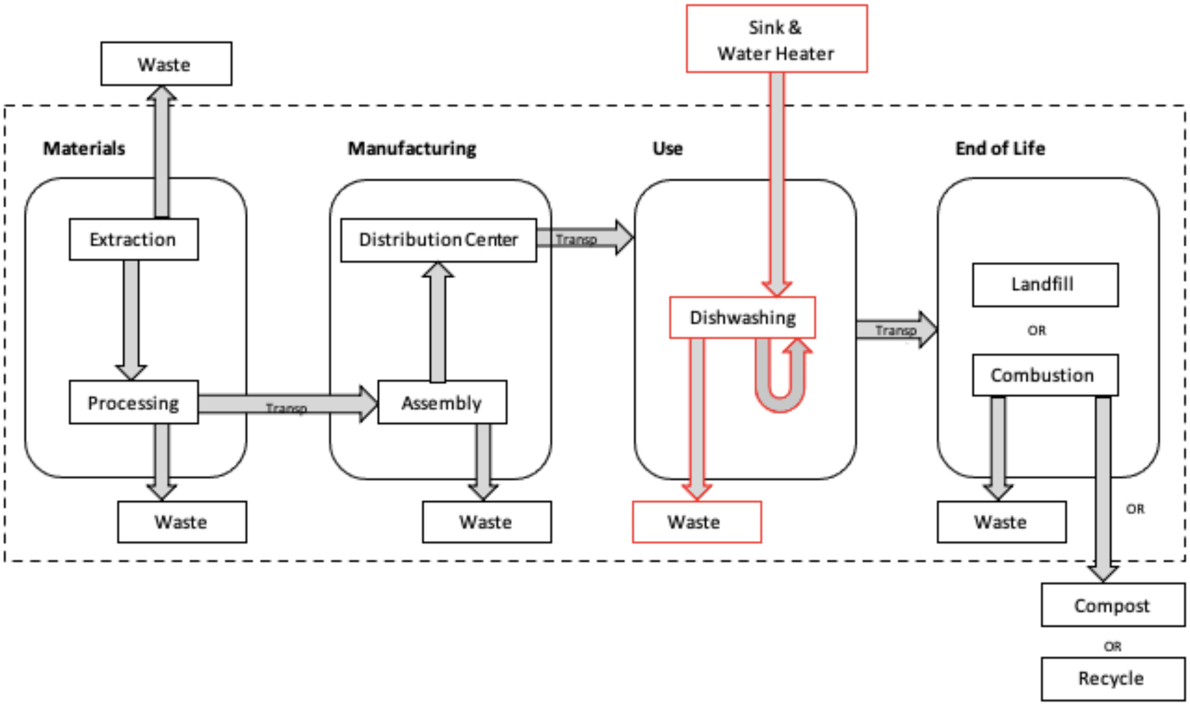
2.1 Goal and Scope Definition

The goal of the study is to estimate the life cycle global warming potential (GWP), water consumption, and primary nonrenewable energy use associated with single-use kitchenware products and their reusable alternatives and determine the environmental payback period in each impact category for the reusable alternatives. Payback period is defined as the number of times a consumer must re-use an alternative in order for the environmental impact per use to be equivalent to the environmental impact for the single-use product. GWP, water consumption, and primary nonrenewable energy use were selected as the most appropriate environmental indicators for this suite of products. It was decided that the calculation of environmental payback period would not be appropriate for impact categories where the type of impact is a significant issue for one product yet non-existent or negligible in others (i.e. land use in bio-based products, physical marine damage for plastics) since it can be assumed that no payback exists in these circumstances. In lieu of calculating a payback period for these impacts, inherent tradeoffs of impact categories for different types of products are included in the discussion section.

The environmental impact of reusable products change with respect to the number of uses, so for example with GWP, kg CO2-eq/one use is different than the kg CO2-eq/1000 uses. Although the purpose of the paper is to calculate the environmental payback period which identifies the number of uses for the reusable and single use products to have equivalent environmental impact, illustrative functional unit scenarios of 1 use, 1 year, and 5 years are calculated to demonstrate the general trend in results with increased number of uses. These scenarios correspond to using a product a single time, using it five times per week for a year, and using it five times per week for five years. The analysis also explores how different consumer behaviors may impact results.

Figure 1 depicts a generic system boundary diagram for each of the products. Production and disposal of transportation vehicles and other capital equipment is not included. For the use phase, dishwasher production, energy, detergent and water consumed by washing reusable products are included in the analysis (Porras et al., 2020). Impacts associated with dishwasher disposal, sink and water heater are excluded. Lastly for the end-of-life phase, Ecoinvent v3.6 system model – allocation cut-off by classification was followed ("Allocation").

Figure 1: System boundary of single-use and reusable products. Processes highlighted in red are only associated with reusable products.



2.2 Product Selection

Four common consumer product categories were compared, each of which have commercial reusable alternatives available: drinking straws (5 alternatives), sandwich storage (4 alternatives), coffee cups (4 alternatives), and forks (3 alternatives). Product types are included in Table 1 below. Specific brands or models used to calculate product characteristics, such as mass or surface area, are listed in supplemental material Table S1. Comparative analysis is conducted within each product type.

Table 1: Product Types

Drinking Straws	Sandwich Storage	Coffee Cups	Forks
• Bamboo Straw • Glass Straw • Metal Straw • Paper Straw • Plastic Straw • Silicone Straw	• Beeswax Wrap • Plastic Wrap • Plastic Bag • Silicone Bag • Aluminum Foil	• Paper Coffee Cup with Plastic Lid • Metal Mug • Reusable Plastic Mug • Foam Coffee Cup with Plastic Lid • Ceramic Mug	• Plastic Fork • Bamboo Fork • Reusable Plastic Fork • Metal Fork

2.3 Life Cycle Inventory and Impact Assessment

The following section outlines the assumptions associated with the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA). For the LCI, the majority of product characteristics, such as materials used, were found on product websites, or through publicly available internet sources describing an industry. The mass of materials used was either found on product websites or measured using an analytical balance. Expert judgment was used to define the industrial processes used to manufacture raw materials into their final products. Process assumptions are that all metal products followed average product manufacturing for their material type, while plastic products were either extruded, moulded or thermoformed, depending on material and shape of the final product.

For data pertaining to the LCI for the transportation, use, and EoL life cycle stages, data was collected from peer-reviewed studies and product websites as documented in the supporting information. This includes method of transportation, transportation distance, dishwashing method, lifespan and EoL disposal methods.

Environmental impact was determined using Ecoinvent v3.6 – Allocation, cut off by classification – system, accessed via Simapro v9.1.0.11, along with data obtained through literature review. For GWP, values are reported in kg CO_2 equivalent (kg CO_2e) with a 100-year timeframe based on the 2013 Intergovernmental Panel on Climate Change (IPCC) report, except for dishwashing data, which used the 2001 IPCC report, due to disaggregated emissions data being unavailable. Biogenic carbon is balanced for all bio-based products. No temporal adjustments to carbon emissions were included due to the relatively short time frame of this analysis (5 years or less).

ReCiPe 2016 Midpoint (H) was used to calculate water consumption (Huijbregts, M.A.J., et al., 2017), which is the amount of off stream water that is used and not returned (Owens, J.W., 2001), and reported in m^3 water-eq consumed. To keep the study generalizable, water consumption was not characterized with respect to regional scarcity. For modeling of primary nonrenewable energy use, IMPACT2002+ was used (Jolliet, O. et al., 2003). In order to calculate payback period and perform sensitivity analysis, data from Simapro was transferred to Microsoft Excel, where it was further analyzed.

2.3.1 Material and Manufacturing

A summary of the materials and amounts used to model each product can be found in the supplemental material Table S3. For all products, dyes were not included due to insufficient data surrounding the type, amount, and environmental impact of the dye used during the specific manufacturing process. Additional manufacturing process step(s) were incorporated for the majority of products and can also be found in the supplemental material Table S8. The average emissions, water consumption and primary nonrenewable energy use factors associated with the majority of both the materials and manufacturing steps were quantified using Ecoinvent v3.6 , cut off by classification – system. Due to data availability, academic literature was used to supplement inventory data for bamboo culm and poles (Escamilla & Habert, 2014) and the World Food Life Cycle Database was used to model honey. For both the bamboo and honey models, inputs also came from Ecoinvent, resulting in minimal systemic error in the context of other products in the study. Beeswax wrap was modeled using cotton, beeswax, resin and jojoba oil, but due to lack of emission factors on these specific materials, the emissions factor for honey was used in place of beeswax, epoxy resin was used in place of resin and cottonseed oil was used in place of jojoba oil as the closest reasonable proxies for which data were available.

2.3.2 Transportation

The researchers chose an average overall transportation distance of 250 miles or 402.33 km using a transport, freight lorry >32 metric ton for the base case scenarios. This distance was selected based off of research showing that most goods in the U.S. are transported less than 250 miles (U.S. DOT, 2017). Trucking was selected as the transportation method in the model because it is responsible for moving ~66% of goods in the U.S. (U.S. DOT, 2017). Environmental impact was estimated using the same Ecoinvent 3- Allocation, cut off by classification – system.

2.3.3 Use

In order to estimate the environmental burden from washing reusable products, values from Porras et al., 2020 were used. The results of the study are based on primary data from the Whirlpool Corporation, with plant-level data coming from their Findlay, Ohio facility. System boundaries from Porras et al., 2020 are reflected in this study (Figure 1) with the sink, water heater and recycled material being outside the scope. Environmental impacts were reported with a functional unit of 2150 loads, but researchers of this study were able to calculate GWP, water consumption and primary nonrenewable energy use for both machine dishwashing and manual washing on an in^2 dish basis. With this allocation, the average GWP values of 0.00016 kg CO_2e/in^2 dish for dishwashers and 0.000431 kg CO_2e/in^2 dish for manual washing were found. Emission values from this study were consistent with other academic literature (Vivian et al., 2011). Values for water consumption and primary nonrenewable energy use for both machine dishwashing and manual washing can be found in supplemental material Table S15.

2.3.4 End-of-Life (EoL)

The EPA Advancing Sustainable Materials Management: 2017 Fact Sheet was used to determine the average disposal rates for material types (EPA, 2019). The model bases the percentage of waste going towards each disposal method (sanitary landfill, combustion, compost, recycle) off of these figures. Ecoinvent v3.6 system model – allocation cut-off by classification was used for end of life modeling, meaning waste treatment such as landfill or combustion is included, but burdens or credits from the recycle or compost process are attributed to the production of secondary material, not the primary ("Allocation").

2.4 Sensitivity Analysis

A Monte Carlo simulation was conducted on the GWP results including relevant parameter distributions for manufacturing emissions, transportation distances, dishwashing emissions, and product end-of-life, using triangular distributions defined in Table 2. The majority of products in the analysis are comprised of one or two materials. Therefore, correlations within the inventories were not included due to the relative simplicity of the product inventories and lack of expected impact on results. Sensitivity analysis was confined to GWP due to lack of distribution data for the other impact categories. To supplement the Monte Carlo simulation, an additional one at a time sensitivity analysis was conducted and the material emission factor, manufacturing emission factor, transportation emission factor, transportation distance, dishwashing emission factor and disposal emission factor were varied by +/- 50%.

For the Monte Carlo simulation, 10,000 trials were run. Table 2 shows the key parameters, their distribution types and the ranges. Because ranges were not available for all materials and manufacturing processes, a range of +/- 10% was used for all materials/manufacturing in order to maintain uniformity between products. For transportation, a triangular distribution was modeled and a range of 160.93 – 1609.34 miles was used (U.S. DOT, 2017). Changes in dishwashing emission factors reflect changes in carbon intensity of the grid, and the use of an electric versus natural gas water heater (Porras et al., 2020). Calculations for these different dishwashing emission factor scenarios can be found in supplemental material Table S18. Lastly, EoL models show disposal rates ranging from 0 – 100% for all applicable disposal scenarios per material (landfill, combustion, compost, recycle).

Table 2: Monte Carlo Parameters, Distribution Types and Ranges

Key Parameters	Distribution Type	Ranges
Material/Manufacturing Emission Factor	Triangular Distribution	+/- 10% for both material and manufacturing emission factors
Transportation Distance		Most common: 402.34 miles Range: 160.93 – 1609.34 miles
Use Phase – Machine Dishwashing Emission Factor		Most common : 1.60*10-4 Range: 1.09 - 2.98*10-4 (Unit: kg CO_2e /in2 dish)
Use Phase – Manual Dishwashing Emission Factor		Most common: 4.31*10-4 Range: 2.67 - 8.96*10-4 (Unit: kg CO_2e /in2 dish)
EoL Disposal Scenario Percentage		Most common disposal percentages: Varied by material Range: 0 -100% of each disposal scenario

3.0 Results

Initial modeling of both the single-use and reusable products looked at the resource intensity of the material and manufacturing phases. Results showed that although in some instances reusable products use more resource intensive materials (on a per kg basis) than single-use, this is not always the case. Looking specifically at straws in Table 3, the materials with lowest GWP (bamboo), water consumption (glass) and primary nonrenewable energy use (bamboo) are all used for reusable products. On the other hand, plastic was the largest consumer of primary nonrenewable energy. This is due to the fact one of the main feedstocks of polypropylene is crude oil or natural gas.

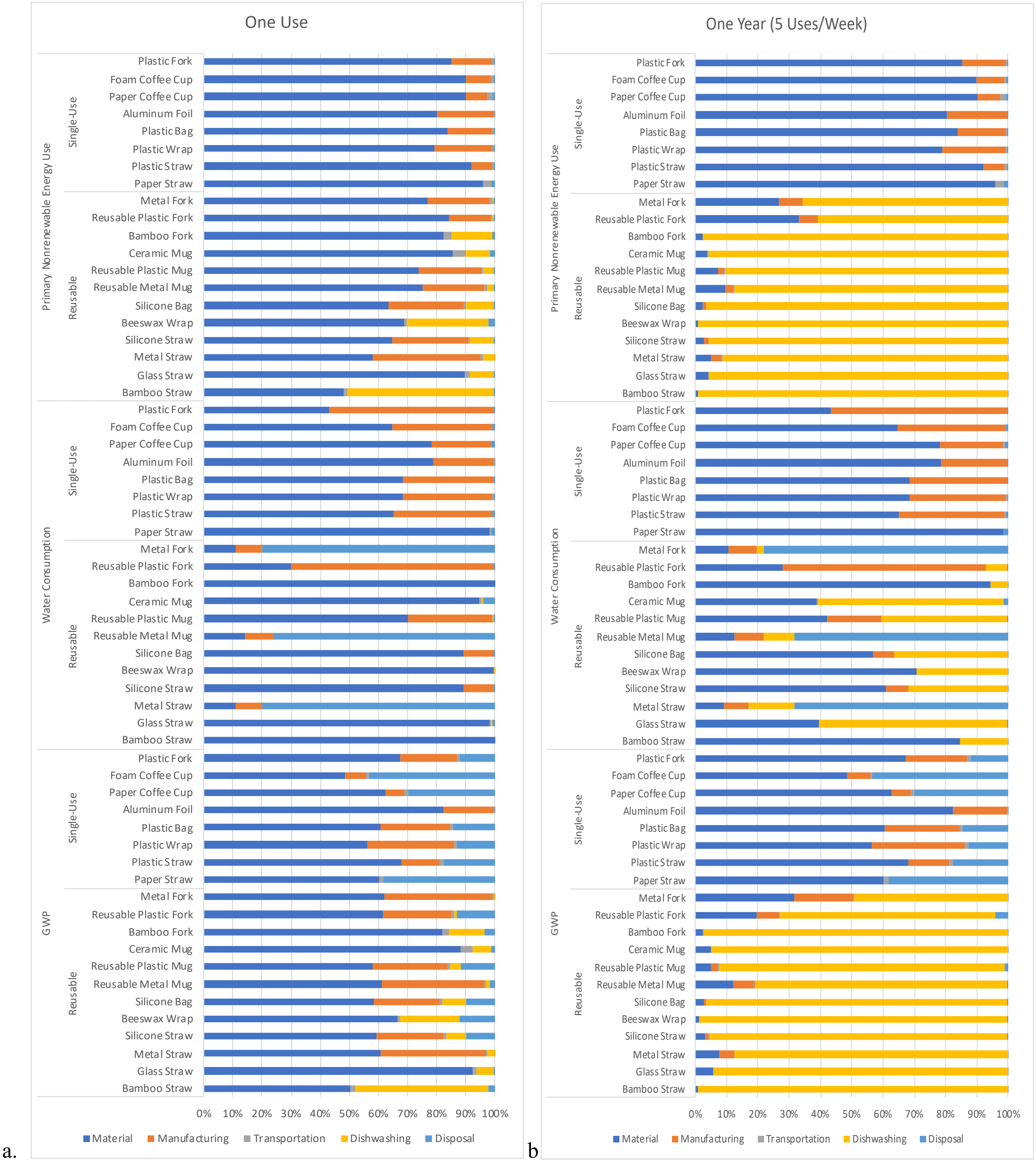
There was no product type where materials for reusable or single-use products always fared better or worse than the other. For the coffee cups, ceramic had the lowest impacts in all three environmental indicators. This was the only instance where one material performed best in all three impact categories.

Table 3: Comparison of the resource intensity of the material and manufacturing phase inputs on a per kg basis. Product types in the most category had the highest impact per kg material manufactured, whereas product types in the least category had the lowest impact per kg material manufactured. This table does not reflect total impacts of the material and manufacturing phase for each product, rather the resource intensity of each on a per kg basis.

	Straws		**Sandwich Bags**		**Coffee Cups**		**Forks**	
	Most	**Least**	**Most**	**Least**	**Most**	**Least**	**Most**	**Least**
GWP	Metal	Bamboo	Aluminum	Plastic	Metal	Ceramic	Metal	Bamboo
Water Consumption	Bamboo	Glass	Beeswax Wrap	Plastic	Foam Cup	Ceramic	Bamboo	Metal
Energy Use	Plastic	Bamboo	Aluminum	Silicone	Reusable Plastic	Ceramic	Plastic	Bamboo

Next overall impacts, which include all life cycle phases, were analyzed. It was found different phases were responsible for the majority of impacts in single-use and reusable products. Figure 2 breaks down the overall impacts of each product into the four life cycle phases for two different use scenarios, 1 Use and 1 Year. Average impact factors, disposal rates and transportation distance were used in both use scenarios. Figure 2a shows the impacts using functional unit of one use for both the reusable and single-use options. Figure 2b depicts a functional unit of 1 Year, or 260 uses, which corresponds to 260 single-use products and reusable products that are used 260 times, with the exception of the bamboo straw. Because the bamboo straw has a life expectancy of only 6 months or ~183 uses, Figure 2b includes upstream emissions for 2 reusable bamboo straws.

Figure 2: Breakdown of percent contributed to overall impacts by each life cycle phase. A) Functional Unit: 1 Use; B) Functional Unit: 1 Year (5 Uses/Week)



It can be seen that for single-use products, the material and manufacturing phase dominates impact regardless of number of uses. This is supported by another study which found the majority of impact to occur in the production stage for disposable items (Blanca-Albubilla et al., 2020). The results of the Blanca-Albubilla study found on average, 53% of the impact occurred during the production stage, which is slightly lower than results calculated in this study. This is partially because the Blanca-Albubilla study was specifically focusing on tableware used in the aviation sector, and therefore incorporated impacts associated with airport transport and the flight.

On the other hand, the majority of reusable products are initially dominated by the material and manufacturing phase for the first use, but as they are used at a higher frequency, such as in the 1 Year scenario, the upstream impacts become less of a factor and the use phase quickly becomes the largest contributor. This is further supported by the 5 Year scenario, found in supplemental material Table S28, which showed the use phase continuing to dominate. Multiple other studies have found similar results on the influence of dishwashing on the overall environmental impact (Ligthart & Ansems, 2007; Woods & Bakshi, 2014). A 2007 study on reusable cups concluded that as number of uses increased, the overall importance of washing also increases. The study also found that other life cycle stages were negligible compared to fabrication and washing of reusables (Garrido & del Castillo, 2007).

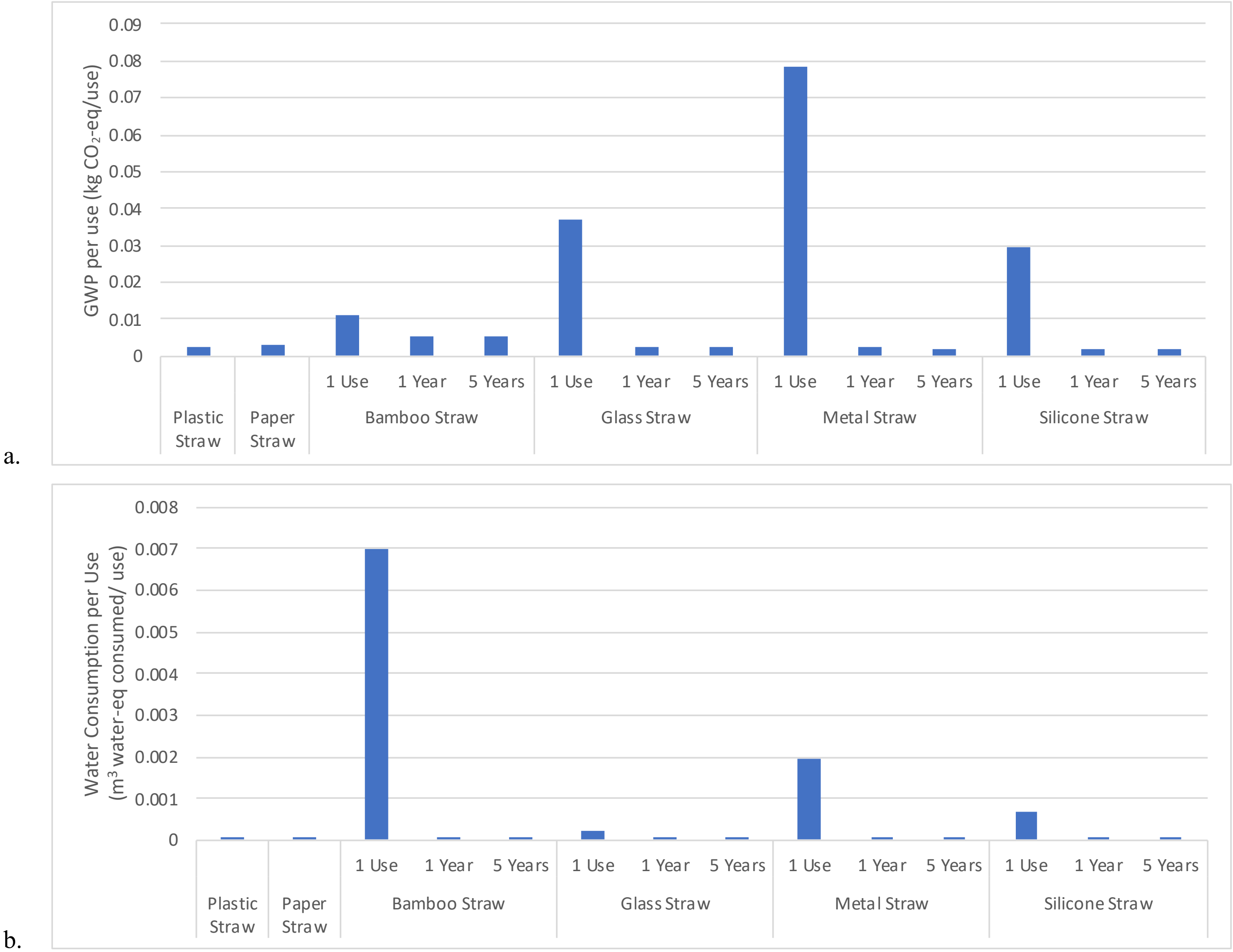
The bamboo straw has a higher contribution to GWP and primary nonrenewable energy use from the use phase for the single-use scenario than the other reusable alternatives, because impacts from handwashing before using the first time are similar in scale to total material and manufacturing impacts of growing and processing the bamboo. All products with stainless steel (metal straw, metal mug, metal fork) saw high contributions from the disposal phase for water consumption due to sanitary landfilling's water consumption factor being an order of magnitude larger per kg material than the material/manufacturing phase.

To further demonstrate the effect of re-using products, Figure 3 shows the data for straws in absolute terms of kg CO_2e/use, m^3/use and MJ primary/use for scenarios of 1 use, 1 Year and 5 Years. It is important to emphasize that because the y-axis unit for this graph is impact per use instead of total environmental impact, the single-use product's impacts per use remain constant while the reusable product impact change with the number of uses. If the graph were total overall impact, using 1300 (5 Year scenario) plastic straws would have much higher impacts than using one plastic straw. Impact per use was selected as the most appropriate y-axis functional unit in order to show that as you use reusable products, even though total impacts increase due to washing, impacts per use decrease.

Before diving into individual results for each product type, it should be noted that these findings reflect typical washing behavior (Porras et al., 2020). If consumers were to follow washing best practices, payback periods for reusables would be reduced. In some instances, following washing best practices could make reusable alternatives that do not breakeven in this study more favorable than single-use products.

Looking at Figure 3a, which shows GWP per use for straws, the plastic straw was found to have the lowest GWP when used only once, but is outperformed by the glass, metal and silicone straws by the 1 Year scenario. This means three of the four reusables are favorable in terms of GWP to the single-use plastic straw if used for 1 Year. Emissions for the bamboo straws were unable to reach a payback period within 5 Years because their use phase emissions in the average scenario increased more rapidly than the overall emissions of the plastic straw. In Figure 3b it can be seen that three of the reusable alternatives (glass, metal, and silicone) breakeven by the 1 Year scenario for water consumption, whereas bamboo does not reach a payback period due to higher water consumption from hand washing. Lastly, in Figure 3c, paper straws were found to have the lowest primary nonrenewable energy use per use. Similar to the results for GWP, the glass, metal and silicone straws had lower primary nonrenewable energy use per use than the plastic straw by the 1 Year scenario, whereas the bamboo straw was not able to reach a payback period.

Figure 3: Environmental impact per use for straw products at functional units of 1 Use, 1 Year (5 uses/week) and 5 Years (5 uses/week). A) GWP B) Water Consumption C) Primary Nonrenewable Energy Use



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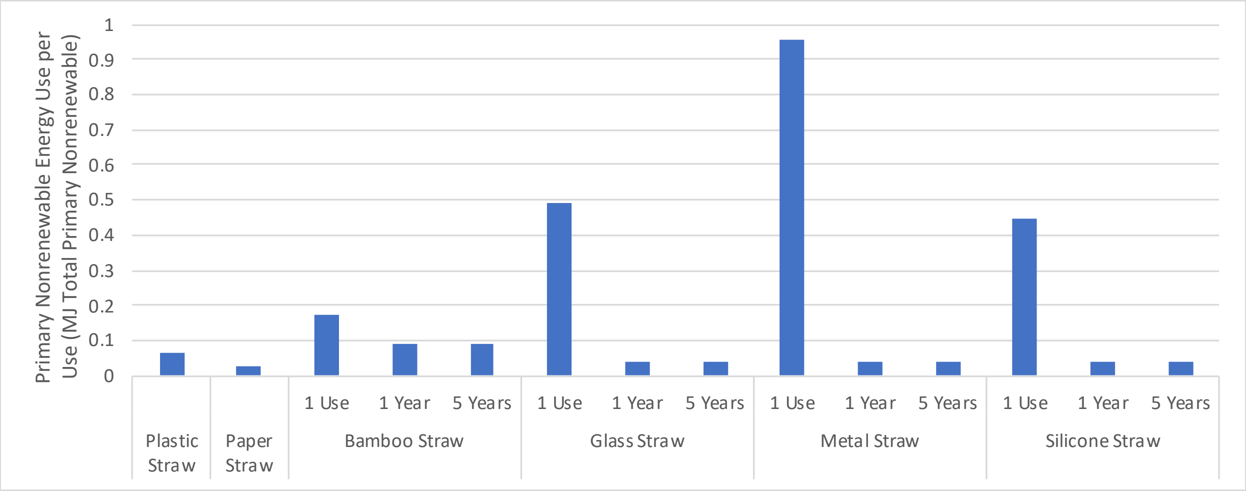


Equivalent analysis and graphs for the three other product types can be found in the supplemental material tables S29, S30 and S31. For the sandwich bag category, a few main takeaways were found. On the single-use side, aluminum foil had the largest impact in all three environmental categories. When comparing the plastic bag and plastic wrap, it could be seen that results were mostly driven by mass. Because the mass of the plastic bag was two times that of plastic wrap, the impacts were also approximately double. Looking at the reusable sandwich bag alternatives, it could be seen that impacts were driven by high use phase impacts associated with large washing surface areas. This resulted in neither sandwich bag alternative reaching a payback period for GWP or primary energy use within the 5 Year scenario. It is important to remember that washing impacts were allocated on an in^2 basis, and that environmental burden from this phase can be minimized with certain behavior changes such as using cold water or a two-basin washing technique.

Looking at the single-use coffee cup products, the foam cup had the lowest impacts for all three indicators. This is supported by other studies which also found foam cups to have lower impacts than paper cup variations (Franklin Associates, 2011; Jung et al., 2011). The single-use paper cup was favorable to all reusable products when used only once, but by the 1 Year scenario, all three reusable products had lower GWP per use and water consumption per use than the paper cup. By the 5 Year scenario, all three reusable products had lower primary nonrenewable energy use per use than the paper cup. Of the reusables, the ceramic mug had the lowest impacts for all scenarios and indicators, and the metal cup the highest.

Lastly, when looking at the fork products, the bamboo fork has lower GWP per use and primary nonrenewable energy use per use than the plastic fork with just a single use. The water consumption per use for the bamboo fork became less than the plastic fork by the 1 Year scenario. Both the reusable plastic and metal forks become favorable to the plastic fork in GWP per use, water consumption per use, and primary nonrenewable energy use per use by the 1 Year scenario.

Evaluating all of the single-use products shows that one of the key factors in overall impacts is the mass of the product. For the three product types with more than one single-use product (straws, sandwich bags, and coffee cups), the single-use product with the lower mass had lower GWP, water consumption and primary nonrenewable energy use. The only exception to this was the plastic straw used more energy than the paper straw. A review of ten studies also found that the impact of disposable cups was highly influenced by cup mass (van der Harst & Potting, 2013).

Key factors for reusable products are the cleaning surface area and the washing method (manual vs. auto). Products that had to be manually washed, such as the bamboo straw and beeswax wrap, had higher impacts than those that could be placed in a dishwasher. These results are supported by another study, which found for reusable cups, dishwashing was the highest contributor to overall impacts, whereas for disposable cups, impacts from production were one of the largest contributors (Ligthart & Ansems, 2007).

Using base case values for impact factors, transportation distance and EoL disposal method percentages, initial results for payback period of each reusable product was calculated, shown in Table 4. It was found that 9 of the 12 reusable alternatives reached a payback period for all three environmental impact categories when typical washing behavior was used. The bamboo straw, and beeswax wrap did not breakeven in any category, due to high washing emissions from either hand washing or large surface areas. The silicone bag reached a payback period for water consumption when compared to the plastic bag but did not break even in either GWP or energy use.

For the straws, the silicone straw had the shortest payback period for both GWP and primary nonrenewable energy use (70 and 16 uses, respectively), while the glass straw had the shortest payback period for water consumption (12 uses). The metal straw on the other hand had the longest payback period for all three impact categories.

The coffee cup product type was the only product type to have one alternative dominate all three impact categories. The ceramic mug had a payback period of 16 uses for GWP, 4 uses for water consumption and 32 uses for primary nonrenewable energy use. The metal coffee cup had the longest payback periods for all three categories. All three products reached a payback period for all three impact categories.

This trend continued for the forks. The bamboo fork was more favorable than the plastic fork with just a single use for GWP and primary nonrenewable energy use, but had to be used 34 times before it broke-even for water consumption. The payback period for the reusable plastic fork was 4-5 uses for all three categories. Lastly, the metal fork broke even in 8 uses for GWP, 11 uses for water consumption and 4 uses for primary nonrenewable energy use.

Table 4. Payback period for GWP, Water Consumption and Primary Nonrenewable Energy Use of Reusables Alternatives.

Straws: Compared to Plastic Straw

	Bamboo	Glass	Metal	Silicone
GWP	Did Not Breakeven	163	229	70
Water Consumption	Did Not Breakeven	12	93	34
Energy Use	Did Not Breakeven	20	37	16

Sandwich Bags: Compared to Plastic Bag

	Beeswax Wrap	Silicone
GWP	Did Not Breakeven	Did Not Breakeven
Water Consumption	Did Not Breakeven	102
Energy Use	Did Not Breakeven	Did Not Breakeven

Coffee Cups: Compared to Paper Cup with Plastic Lid

	Metal	Reusable Plastic	Ceramic
GWP	111	43	16
Water Consumption	60	10	4
Energy Use	288	210	32

Forks: Compared to Plastic Fork

	Bamboo	Reusable Plastic	Metal
GWP	1	4	8
Water Consumption	34	4	11
Energy Use	1	5	4

Analysis of these results showed a few interesting details. The authors hypothesized the payback periods for forks and straws would be similar, due to similar materials being used. In reality the forks broke even much faster than the straws, especially for GWP and energy use, because the ratio of mass between the single-use and reusable product was much lower. The reusable straws were 6.18 – 21.28 times the mass of the plastic straw, whereas the reusable forks were 1.75 – 4.75 times the mass of the plastic fork. Additionally, the results found that the metal reusable alternative of each product type (straw, coffee cup, and fork) had to be used the most in order to breakeven.

Other studies had varying results for payback periods of similar products. A recent study on straws in South Africa showed glass and metal reusable straws to have payback periods of 23 and 37 uses for GWP, respectively, when compared to a polypropylene straw produced in South Africa (Chitaka & von Blottnitz, 2020). These results are considerably lower for two main reasons. The first is that polypropylene production in South Africa is significantly more carbon intensive than in North America and Europe. In South Africa, coal is the primary feedstock for polypropylene (9.67 kg CO_2e/kg PP), whereas in North America and Europe crude oil and natural gas are used (1.82 – 1.97 kg CO_2e/kg PP) (Chitaka & von Blottnitz, 2020). Secondly, the study assumed users were washing in cold water. The use of hot water saw a 38% and 42% increase in emissions for glass and steel straws respectively

(Chitaka & von Blottnitz, 2020). This shows that there are many factors, including local conditions, that may impact payback period. These will be explored further in the sensitivity analysis.

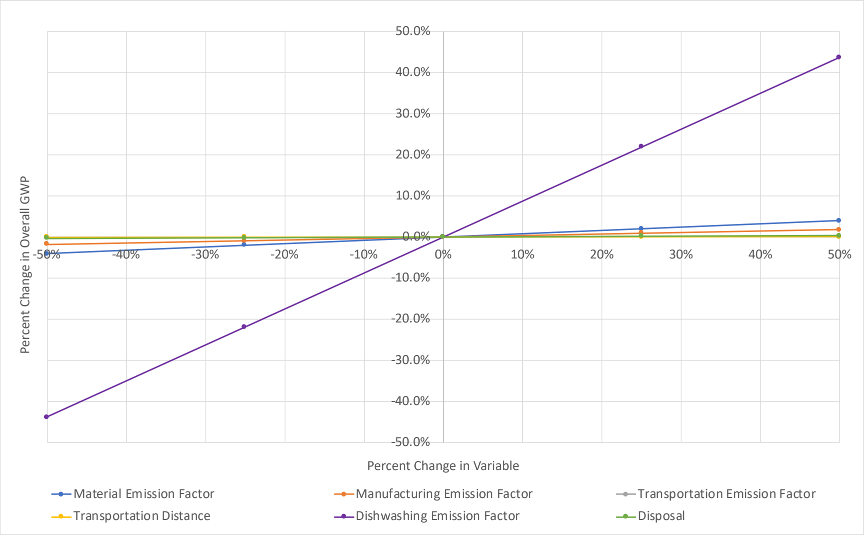
4.0 Sensitivity Analysis

A sensitivity analysis was conducted in order to determine the drivers of the overall impact. Due to limited data, the researchers chose to focus on GWP. Variables that were considered include the transportation distance, and material, manufacturing, transportation, dishwashing and disposal emission factor of the reusable product. For both the sensitivity analysis and the Monte Carlo simulation conducted later on, variations in the dishwashing emission factor reflect changes in the typical washing behavior system, such as grid carbon intensity and what energy source is being used for water heating. Further variations in the emission factor would be found if washing best practices were modeled and included.

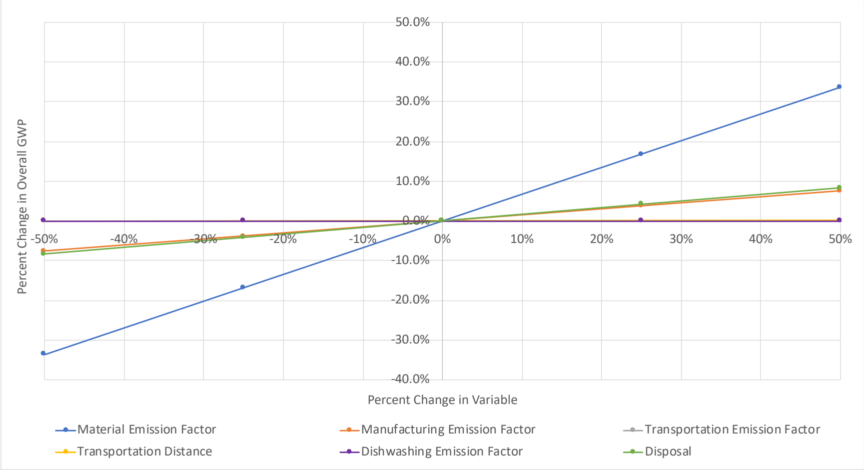
The average change for reusable products and single-use products can be seen in Figure 4. Analysis was done on the 1 Year (260 uses) scenario, and showed that on average, for the reusable product, GHG emissions were highly sensitive to dishwasher emission factor, shown in Figure 4a. This is consistent with results from Figure 2, where the use phase was the highest contributor to overall emissions. Looking at individual products it can be seen that when the dishwashing emission factor was varied by +/- 50%, overall emissions were impacted by 25% - 50%. On the other hand, the model was not sensitive to either transportation emission factor, disposal emission factor, or distance transported. On average, when disposal emission factor was varied by +/-50%, results were only impact by 0.3%. Emissions were even less sensitive to distance transported, with a +/-50% variance only resulting in an average change of 0.05%.

For the single-use products and a 1 Year (260 products) scenario, shown in Figure 4b, overall emissions were most sensitive to the material emission factor, again consistent with findings from Figure 2. When varied by +/- 50%, emissions for plastic single-use products were impacted by 28% - 48%. Single-use products were also fairly sensitive to manufacturing and disposal emission factor, with a +/-50% change resulting in ~8% increase or decrease in emissions. The model was least sensitive to transportation emission factor and distance transported, with an average change of only 0.47% when varied by 50%.

Figure 4: Sensitivity analysis showing percent changes in overall GWP for products in 1 Year (260 use) scenario when variables were ranged by +/- 50% A) Reusable Products B) Single-Use Products



a)



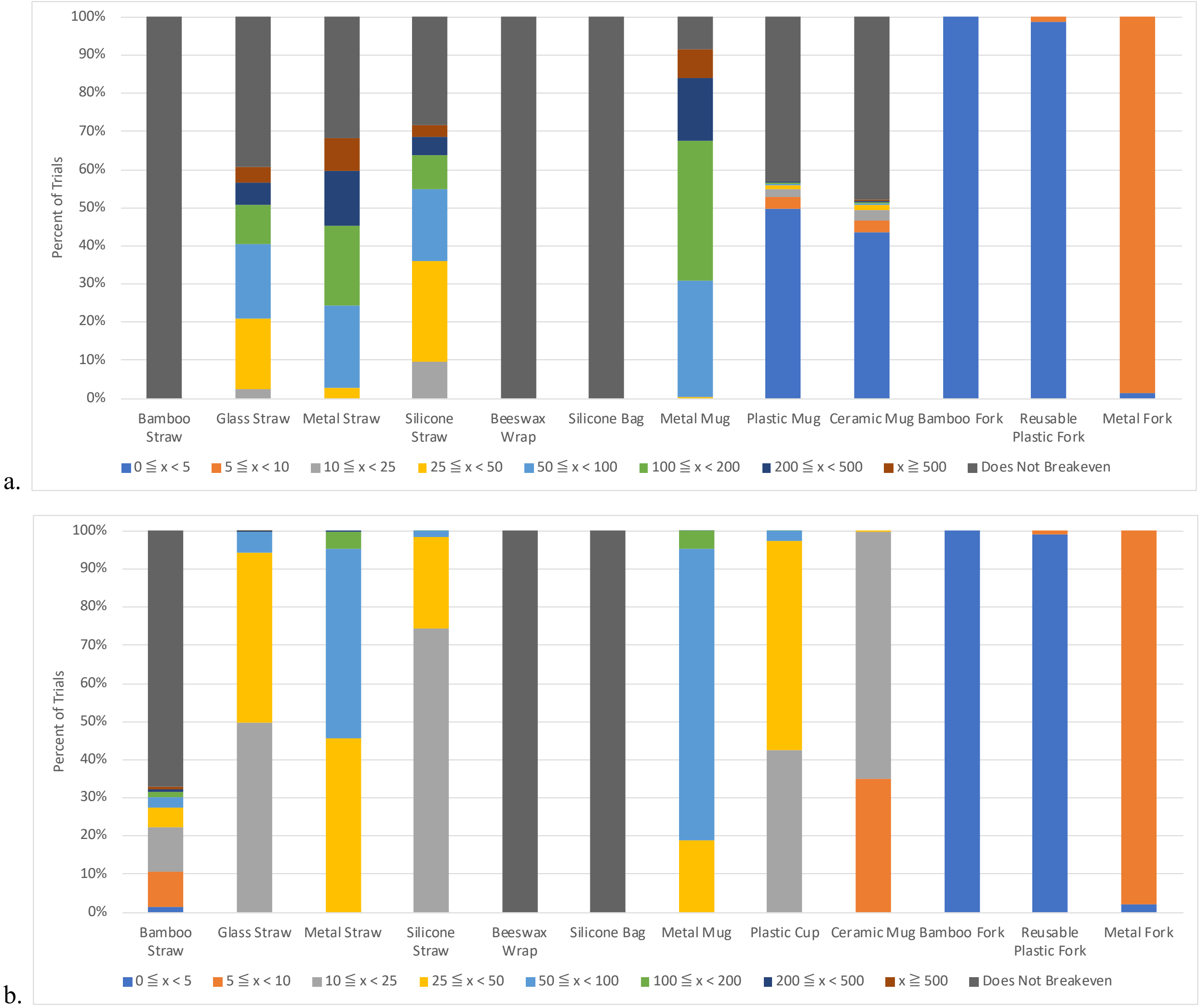
b)

In addition, Monte Carlo analysis was completed in order to determine the payback periods for a range of conditions varied at the same time, with results reported in Figure 5. The reusable products were compared to the plastic straw, plastic bag, paper cup and plastic fork, as the researchers determined these were the most common single-use products in their area. In addition, for the straw and fork product types, the single-use product selected had the lowest emissions of all single-use options, which allows the more conservative break even scenario to be calculated. Seen in Figure 5a, when washed after every use, a payback period is unable to be calculated for the bamboo straw, silicone bag and beeswax wrap since the GHG emissions during a single wash are greater than the total life cycle GHG emissions of the relevant disposable product. Products with large surface areas or that had to be manually washed were more likely to not breakeven. The silicone straw, glass straw, metal straw, metal mug, plastic cup and ceramic mug all had trials where the reusable product did not breakeven. The reusable fork options always broke-even, with the payback period for the bamboo fork and reusable plastic fork being between 0 – 5 uses for 100% and

98% of the trials, respectively. The metal fork had a payback period between 5 – 10 uses for almost 99% of the trials.

When washed every other use, seen in Figure 5b, silicone bags and beeswax wrap are still unable to reach a payback period. Bamboo straws now are able to breakeven for 33% of trials. All other reusable alternatives breakeven for 100% of trials. The most common payback period range for these reusable products are: 10-25 uses (glass straw), 50-100 uses (metal straw), 10-25 uses (silicone straw), 50-100 uses (metal mug), 25-50 uses (plastic mug), 10-25 uses (ceramic mug), 0-5 uses (bamboo fork), 0-5 uses (reusable plastic fork) and 5-10 uses (metal fork).

Figure 5: Monte Carlo analysis results when reusable alternatives are washed after every use (Figure 5a) and when the alternatives are washed after every other use (Figure 5b). The legend depicts the various payback period categories, and represents the range of uses necessary to reach a breakeven point. Each figure shows the percent of trials in each payback period category.



These results show that payback period is highly sensitive to use phase emissions. When switching from washing every use to every other use, many of the reusable products (silicone straw, glass straw, metal straw, metal mug, plastic cup and ceramic mug) went from having trials not reaching a payback period to having all 10,000 trials reach payback periods of under 200 uses.

In this Monte Carlo Analysis, the silicone straw, ceramic mug, and bamboo fork had the fastest average payback periods for their respective product types, while the bamboo straw, metal mug and metal fork had the longest on average. Both the silicone straw and ceramic mug had the smallest surface area being washed of the products in their respective product type being machine washed. Neither sandwich storage alternative reached a payback period due to high use phase impacts.

5.0 Discussion

Results from this study can impact how producers and consumers move forward and reduce the environmental impacts associated with these common kitchenware products. The findings of this research should be used to understand what variables drive overall impact for both reusable and single-use products, and how these variables can influence payback period for reusable alternatives. The goal of this study was not to determine if single-use or reusable products were better or worse, and should not be used in this way. Reusable alternatives and single-use products both have their strengths and weaknesses, and in any situation, environmental tradeoffs will have to be made.

This is also true when looking within the two categories of reusable and single-use. Not all reusable and not all single-use goods are created equally. Some products outperformed others in different environmental categories. For many product types, tradeoffs would have to be made when selecting which product to use.

This study only calculates the environmental payback periods associated with GWP, primary energy use and water consumption. Additional environmental impacts are associated with the production and use of kitchenware products. Notably, concerns surrounding single use plastic pollution are one of the main drivers associated with an increased emphasis on reusable kitchenware products. Incorporation of marine plastic pollution represents numerous challenges and impacts to the LCA community (Andrady, A. L., 2011; Vince, J. & Hardesty, B. D., 2017) and the first methodological approach to including marine litter of microplastics into LCA is being developed (Saling et al., 2020). In the case of microplastic pollution, only plastic products are responsible for this particular impact, resulting in an inherent tradeoff between plastics and other materials with respect to physical damage to marine systems; therefore, attempts to calculate a payback period for microplastic pollution would be unproductive since there will never be a breakeven point for this impact category, by definition. Similarly, for land-use, bio-based products such as paper straws or beeswax wrap would have disproportionally large payback periods compared to those made from other materials and calculation of payback period is not ultimately useful. The tradeoffs of these kinds of impacts must ultimately be evaluated against one another.

Future research should focus on modeling processes for different environmental indicators, such as the amount of waste to landfill, ecotoxicity, eutrophication and acidification potential, in order to better understand the overall environmental impact. For consumers in water stressed regions, it may be desirable to include additional calculations of water availability and criticality, which will likely highlight the importance of dishwashing in the payback period of water impact.

For the single-use products, it can be seen that overall impacts, especially GWP, are sensitive to the material and manufacturing phase. For these products, a large part of sustainability efforts should be manufacturers focusing on optimization of the production process. After the material and manufacturing phase, the second largest contributor was EoL disposal. Improving this phase to minimize impacts will take a joint effort between producers and consumers. Producers should research which disposal option will reduce their product's lifetime impact, and then assure that this disposal method is accessible for consumers. It is then up to consumers to properly dispose of these products. This study did not consider leakage of products to the ecosystem, which can occur when locations do not have appropriate solid waste management infrastructure.

One of the main findings of this research is that the use phase is the key driver of overall impact of reusable alternatives, especially when discussing GWP. Producers of reusable alternatives should advocate for integration of renewables into the energy grid, and for innovation on efficiency of dishwashers in order to reduce their product's lifetime impact. Throughout this study, typical washing behavior for both machine and manual washing was modeled. Other research has suggested that use phase impacts associated with dishwashing can be minimized by practicing optimal loading, using rinse aid and high-quality detergent packs, and cleaning the interior of the machine periodically. Best practices for manual washing include using a two-basin method, where dishes are soaked and scrubbed in hot water, then rinsed in cold water, and lastly air dried (Porras et al., 2020). Producers should help to educate the public on the environmental impact of these behavior changes, while consumers should focus on adopting these best practices.

Additionally, results showed that not washing after every use can have a large impact on payback period, and makes reusable alternatives more favorable. Although there might be hesitation due to societal perception of personal cleanliness of washing less frequently, a study actually found that average washing frequency in an office ranged from one to ten mug uses, with four uses being the average (Ligthart & Ansems, 2007). This study did not explore hygienic implications of not washing products after every use, but recognizes choosing not to wash is dependent on the amount of food particulate matter that is leftover on the product and therefore, is not always feasible.

Similar logic can also be applied to the single-use products. Reusing items intended for single-use without washing in between would effectively cut emissions per use in half. This would cause the payback period for reusable alternatives to significantly increase, and would make it more difficult for these alternative products to be favorable.

It is also important to point out that the study assumes that consumers use the product until the end of its useful life. If a consumer loses or replaces the reusable before the requisite number of uses to break even, this will also increase impact.

Consumers should also determine the actual need for the product. In terms of the 3Rs, with reduce being the most important, if a consumer can reduce overall consumption of a specific kind of product, they can also reduce overall environmental impacts. For example, while some people need and benefit from straws, other consumers could consider not using a straw whatsoever.

In terms of consumer choice between reusable and single-use, this research found that although some reusable alternatives were able to have lower impacts per use than their single-use counterpart, not all broke even within their lifetime. As a consumer, this means reusable is not always the best option and that there is more nuance to single-use products than a default assumption that reusable is always better (Miller, 2020). Doing research before you purchase a new alternative can reduce your personal environmental impact, though relative to food consumption choices, transportation emissions, and overall household energy use, the environmental impacts of the kitchenware products analyzed in this study are likely small.

Additionally, because the dishwashing emission factor was the largest driver of the GWP, it is important to recognize that researchers of this study chose to model typical washing behavior, and found allocation on an in^2 dish being washed to be the most representative. These assumptions inherently influence overall results. Other options for allocation could be by mass, footprint in the dishwasher, or time it takes to wash. Each of these allocation factors might favor one product type. For example, both sandwich storage alternatives had surface areas of over 200 in^2, compared to the average coffee cup size of 136 in^2, average straw size of 12.7 in^2 and average fork size of 3.2 in^2. Both of these alternatives generally had the most difficulty reaching a payback period. Allocating on a different factor unit such as time to wash may reduce use phase impacts for sandwich storage, but increase use phase impacts for straws, since it can be difficult to wash the inside. Future studies could explore how modeling best practices or changing allocation factor impact overall results.

6.0 Conclusion

Overall the study concludes that reusable alternatives have the ability to pay back the environmental impacts associated with their more environmentally-intensive materials and use phase impacts, but it is highly dependent on number of uses, consumer behavior, product material, and dishwashing. These results were consistently seen in initial impact calculations, the Monte Carlo Analysis and sensitivity analysis, as well as supported by other peer-reviewed studies. The findings from this study should be used to minimize environmental impacts associated with these product types.

For the single-use products, it was determined that the material and manufacturing phase was the largest contributor to overall impact. Further analysis also showed that GWP specifically was most sensitive to the material and manufacturing emission factor, followed by disposal emission factor. Other studies on single-use products have also found similar results on the factors that influence the GWP.

On the other hand, impacts for reusable products were initially dominated by the material and manufacturing phase, but after usage increased, the use phase quickly became the largest contributor. The large impact of the use phase could be seen when determining payback period for GWP, which was found to decrease significantly as frequency of washing was also decreased. Additionally, during the sensitivity analysis, results showed that emissions for reusable products were highly sensitive to changes in dishwashing emission factor.

A key takeaway from this study is that consumer behavior does have an impact and can help minimize overall environmental impacts associated with kitchenware products. For reusable products, many of the most impactful behavior changes will occur in the use phase. The list below quickly summarizes actions consumers can take to reduce their footprint associated with reusable products:

1) Don’t always assume reusable is the best option. There is a great deal of nuance to the perception that reusable products have less impact than single-use products. In some cases, the impact of washing a reusable product is greater than the life cycle impacts of a single-use product.
2) For products that do breakeven, extend product lifetime. The more times you use a product, the smaller your footprint.
3) Research products before purchase, since not all reusable alternatives are equal. Some have larger impacts than others.
4) In the case of typical washing behavior, give preference to machine washing over manual washing. Best practice behaviors that can reduce use phase impacts for machine washing include completely filling the dishwasher, buying energy efficient appliances, and not pre-rinsing dishes. For manually washing, try using a two-basin dishwashing method.
5) Try not to wash products after every use if practical. For example if you are having plain black coffee or tea, do a quick rinse of your mug/cup and use again the next day.
6) Advocate for integration of renewables into your local energy grid. The lower the carbon intensity and primary nonrenewable energy use of the grid, the lower the environmental impact of dishwashing.

And lastly, the best consumption is no consumption. Minimizing consumer purchasing minimizes overall environmental footprint.

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Figures

Figure 1: System boundary of single-use and reusable products. Processes highlighted in red are only associated with reusable products.

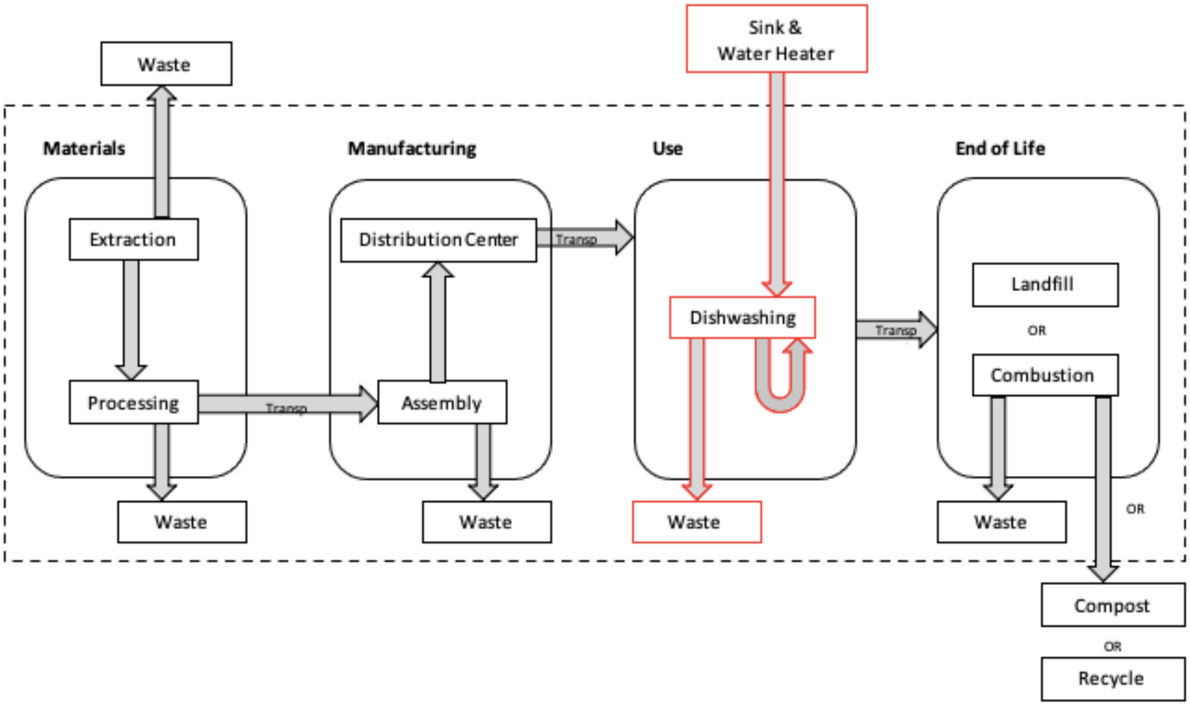


Table 1: Product Types

Drinking Straws	**Sandwich Storage**	**Coffee Cups**	**Forks**
• Bamboo Straw • Glass Straw • Metal Straw • Paper Straw • Plastic Straw • Silicone Straw	• Beeswax Wrap • Plastic Wrap • Plastic Bag • Silicone Bag • Aluminum Foil	• Paper Coffee Cup with Plastic Lid • Metal Mug • Reusable Plastic Mug • Foam Coffee Cup with Plastic Lid • Ceramic Mug	• Plastic Fork • Bamboo Fork • Reusable Plastic Fork • Metal Fork

Table 2: Monte Carlo Parameters, Distribution Types and Ranges

Key Parameters	Distribution Type	Ranges
Material/Manufacturing Emission Factor	Triangular Distribution	+/- 10% for both material and manufacturing emission factors
Transportation Distance		Most common: 402.34 miles Range: 160.93 – 1609.34 miles
Use Phase – Machine Dishwashing Emission Factor		Most common : 1.60*10-4 Range: 1.09 - 2.98*10-4 (Unit: kg CO_2e /in2 dish)
Use Phase – Manual Dishwashing Emission Factor		Most common: 4.31*10-4 Range: 2.67 - 8.96*10-4 (Unit: kg CO_2e /in2 dish)
EoL Disposal Scenario Percentage		Most common disposal percentages: Varied by material Range: 0 -100% of each disposal scenario

Table 3: Comparison of the resource intensity of the material and manufacturing phase inputs on a per kg basis. Product types in the most category had the highest impact per kg material manufactured, whereas product types in the least category had the lowest impact per kg material manufactured. This table does not reflect total impacts of the material and manufacturing phase for each product, rather the resource intensity of each on a per kg basis.

	Straws		**Sandwich Bags**		**Coffee Cups**		**Forks**	
	Most	**Least**	**Most**	**Least**	**Most**	**Least**	**Most**	**Least**
GWP	Metal	Bamboo	Aluminum	Plastic	Metal	Ceramic	Metal	Bamboo
Water Consumption	Bamboo	Glass	Beeswax Wrap	Plastic	Foam Cup	Ceramic	Bamboo	Metal
Energy Use	Plastic	Bamboo	Aluminum	Silicone	Reusable Plastic	Ceramic	Plastic	Bamboo

Figure 2: Breakdown of percent contributed to overall impacts by each life cycle phase. A) Functional Unit: 1 Use; B) Functional Unit: 1 Year (5 Uses/Week)

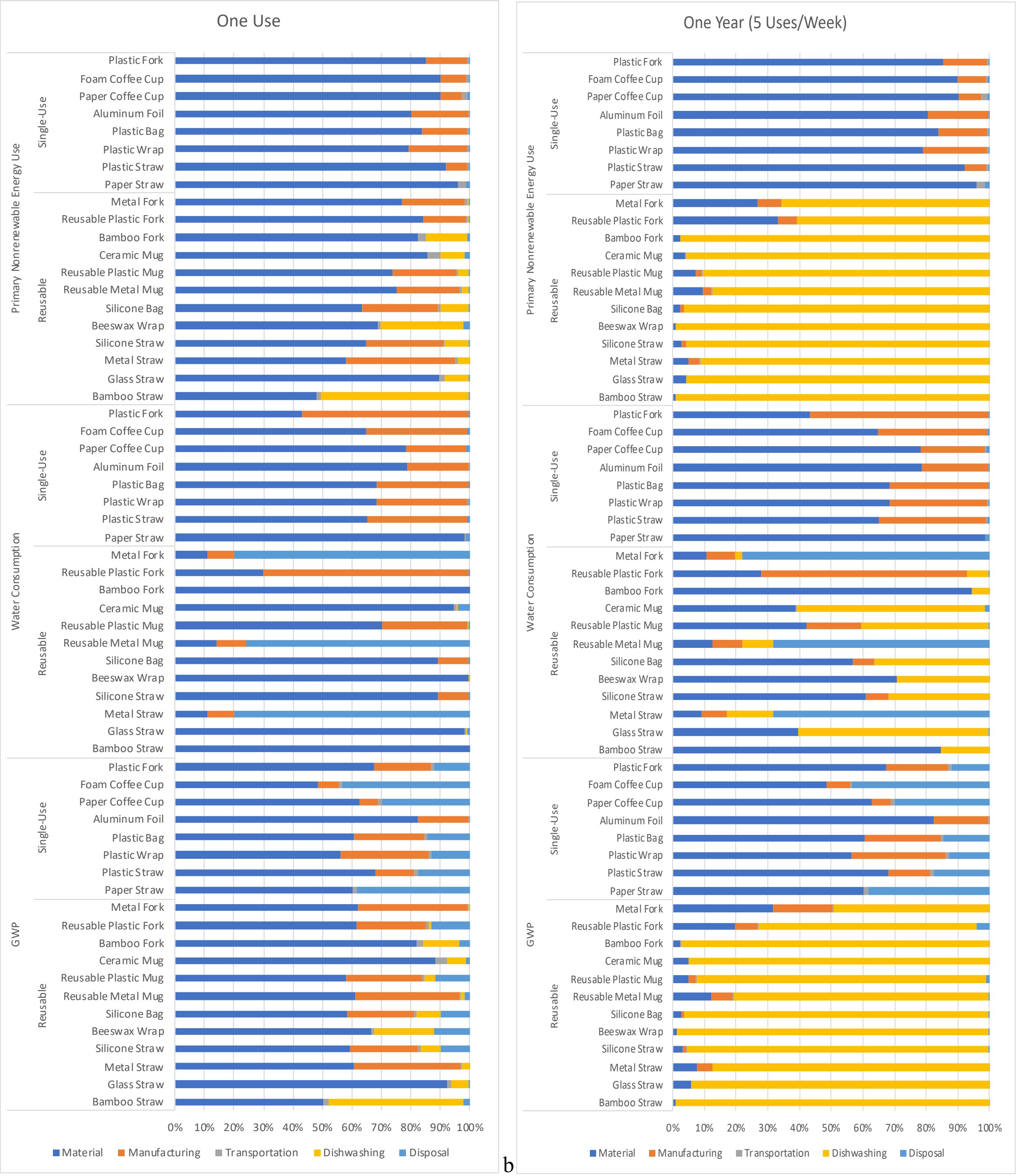


Figure 3: Environmental impact per use for straw products at functional units of 1 Use, 1 Year (5 uses/week) and 5 Years (5 uses/week). A) GWP B) Water Consumption C) Primary Nonrenewable Energy Use

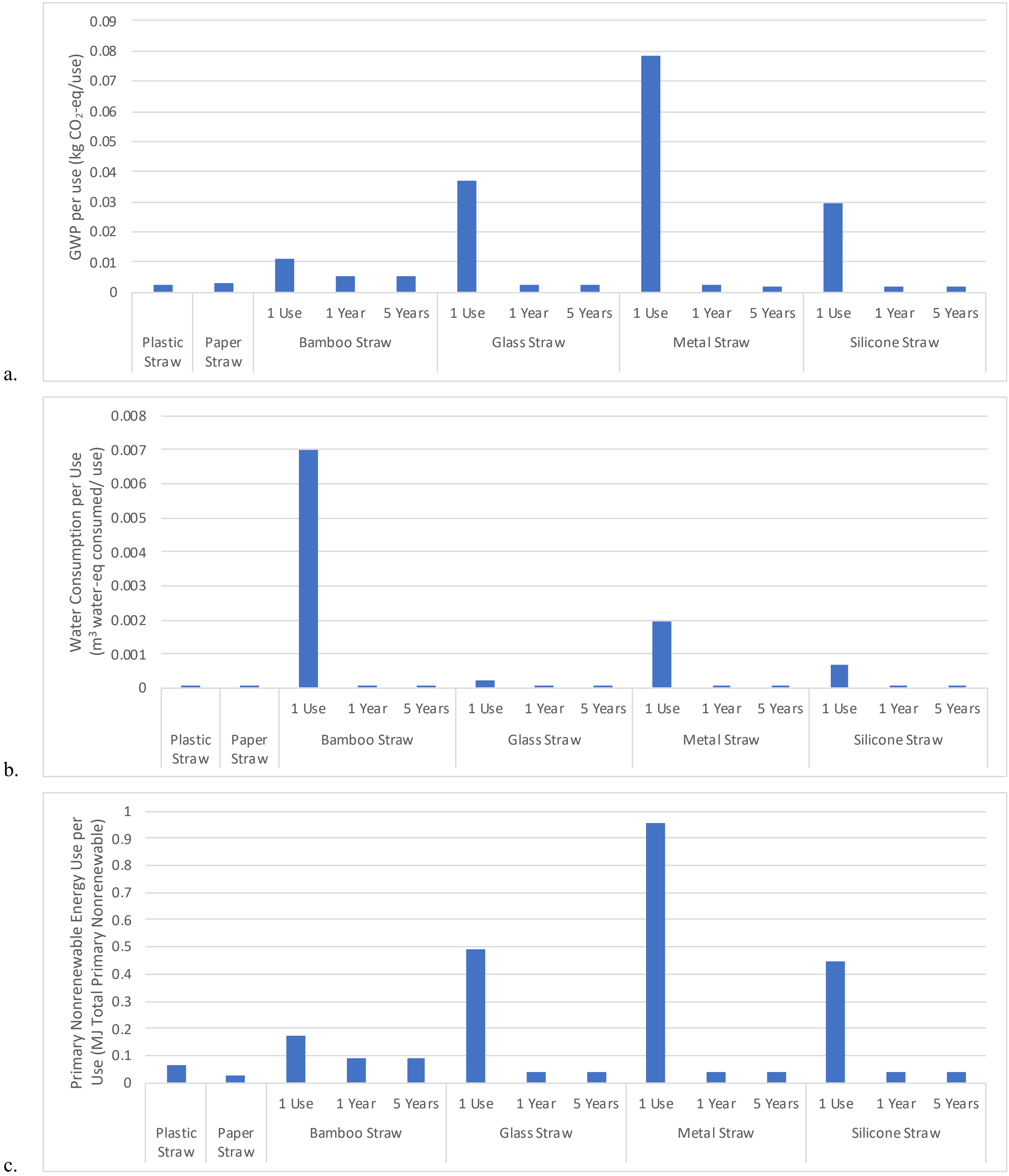


Table 4. Payback period for GWP, Water Consumption and Primary Nonrenewable Energy Use of Reusable Alternatives.

Straws: Compared to Plastic Straw

	Bamboo	**Glass**	**Metal**	**Silicone**
GWP	Did Not Breakeven	163	229	70
Water Consumption	Did Not Breakeven	12	93	34
Energy Use	Did Not Breakeven	20	37	16

Sandwich Bags: Compared to Plastic Bag

	Beeswax Wrap	**Silicone**
GWP	Did Not Breakeven	Did Not Breakeven
Water Consumption	Did Not Breakeven	102
Energy Use	Did Not Breakeven	Did Not Breakeven

Coffee Cups: Compared to Paper Cup with Plastic Lid

	Metal	**Reusable Plastic**	**Ceramic**
GWP	111	43	16
Water Consumption	60	10	4
Energy Use	288	210	32

Forks: Compared to Plastic Fork

	Bamboo	**Reusable Plastic**	**Metal**
GWP	1	4	8
Water Consumption	34	4	11
Energy Use	1	5	4

Figure 4: Sensitivity analysis showing percent changes in overall GWP for products in 1 Year (260 use) scenario when variables were ranged by +/- 50% A) Reusable Products B) Single-Use Products

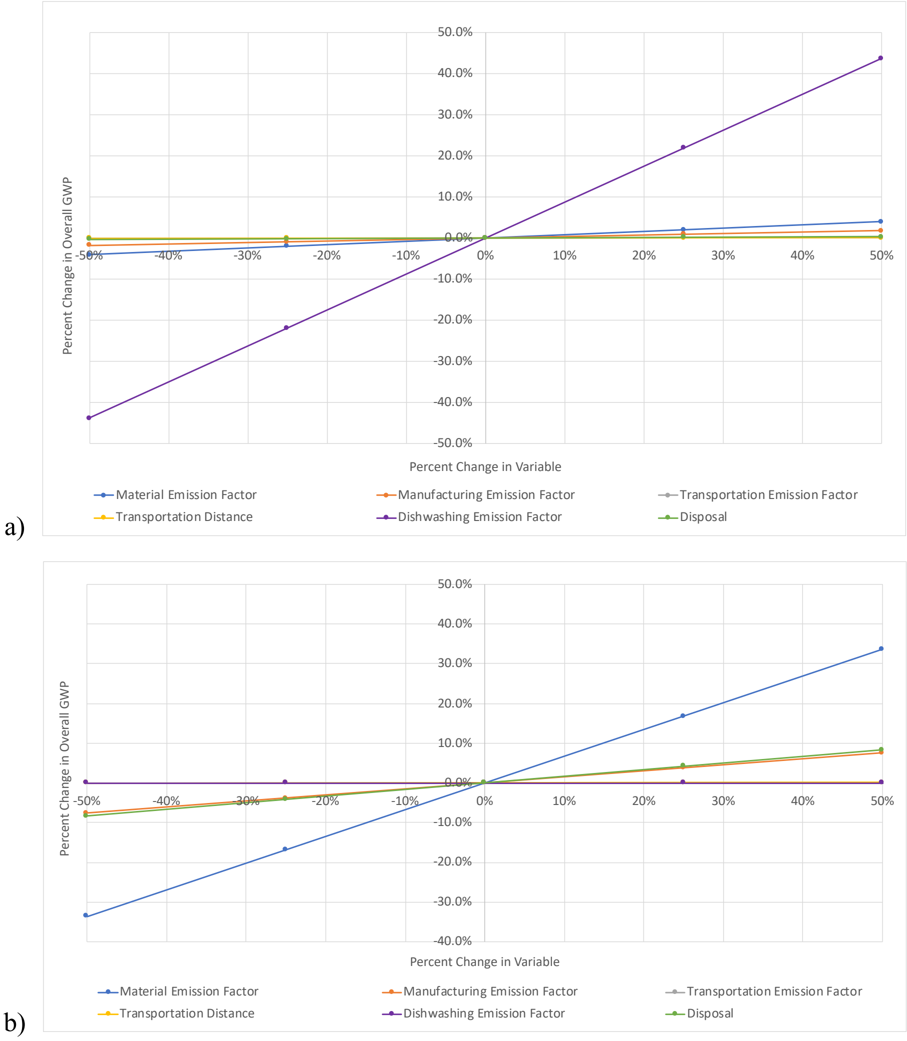
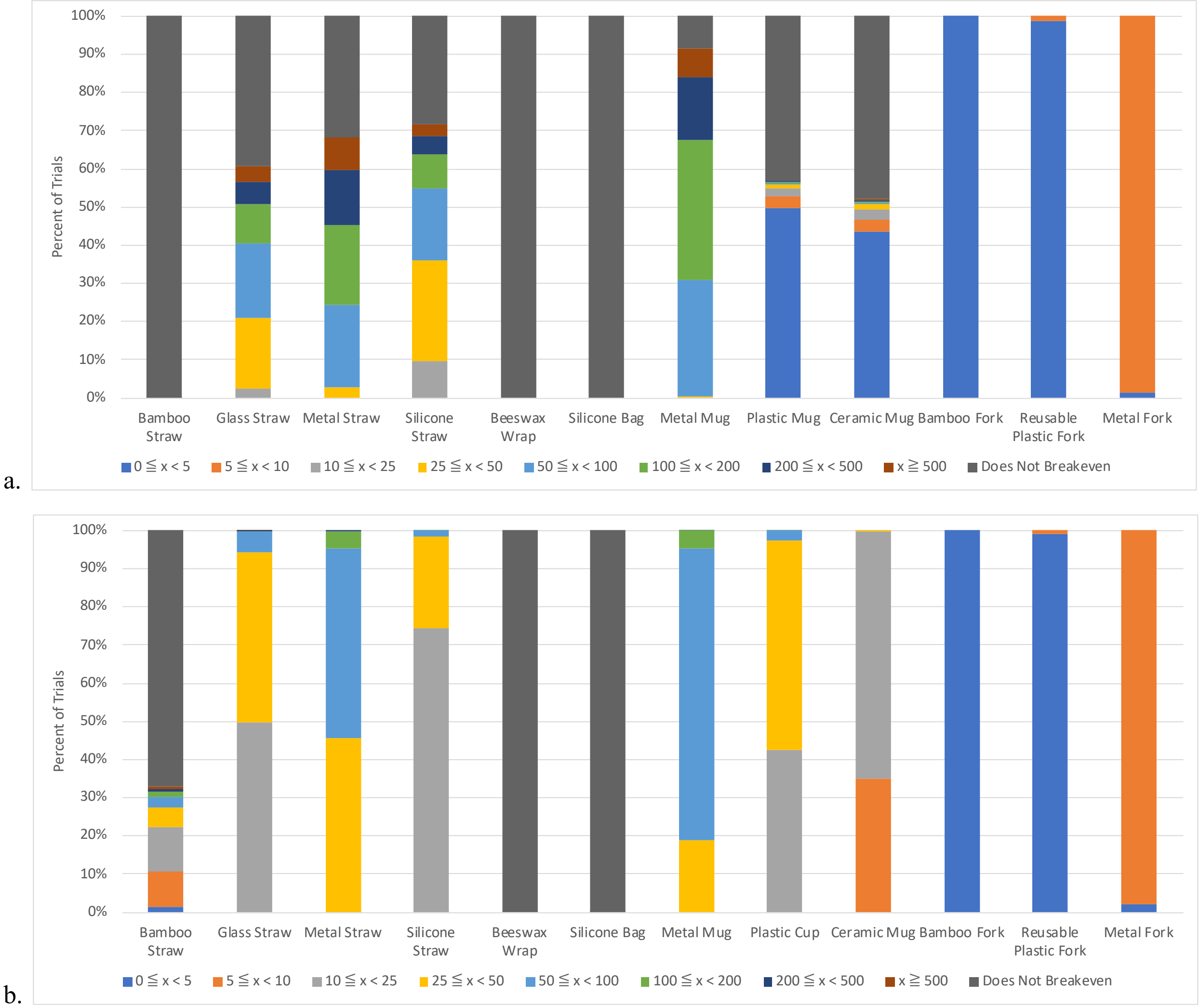


Figure 5: Monte Carlo analysis results when reusable alternatives are washed after every use (Figure 5a) and when the alternatives are washed after every other use (Figure 5b). The legend depicts the various payback period categories, and represents the range of uses necessary to reach a breakeven point. Each figure shows the percent of trials in each payback period category.



Supplemental Material

S1. Product List

Straws	• **Bamboo Straw:** Jungle Straws – Organic 8” Reusable Bamboo Drinking Straws • **Glass Straw:** One Ocean Straw Kit – 9” Regular Glass Straw • **Metal Straw:** Manna Stainless Steel Straw – 9.5” • **Paper Straw** • **Plastic Straw** • **Silicone Straw:** 8.25” Softy Silicone Straw – Slender Size BPA Free Non-Rubber Silicon Reusable
Sandwich Bags	• **Beeswax Wrap:** Chef Sous Chef Homemade Reusable Beeswax Wraps (14” x 14”) • **Plastic Wrap:** • **Plastic Bag:** Ziploc Brand Sandwich Bags – Easy Open Tabs • **Silicone Bag:** Stasher reusable silicone sandwich bag • **Aluminum Foil:**
Coffee Cups	• **Paper Coffee Cup** • **Metal Mug:** Yeti 14 oz Rambler Mug • **Reusable Plastic Mug:** Tervis Clear and Colorful 16 oz Mug with Tervis Travel Lid • **Foam Coffee Cup** • **Ceramic Mug**
Forks	• **Plastic Fork:** Up & Up Premium Plastic Fork • **Bamboo Fork:** BlueApeBlades Zero Waste Wooden Utensil Set (Fork) • **Reusable Plastic Fork** • **Metal Fork**

S2. Product Lifespans

Product	Lifespan
Bamboo Straw	6 months
Glass Straw	Lifetime
Metal Straw	Lifetime
Paper Straw	Single Use
Plastic Straw	Single Use
Silicone Straw	Lifetime
Beeswax Wrap	1 year
Plastic Wrap	Single Use
Plastic Bag	Single Use
Silicone Bag	Lifetime
Aluminum Foil	Single Use
Paper Coffee Cup	Single Use
Metal Mug	Lifetime
Reusable Plastic Mug	Lifetime
Foam Coffee Cup	Single Use
Ceramic Mug	Lifetime
Plastic Fork	Single Use
Bamboo Fork	3 years
Reusable Plastic Fork	Lifetime
Metal Fork	Lifetime

S3. Material Allocation

Life Cycle Inventory of Input Material Flow (unit: kg)

Straws	**Bamboo Straw**	**Glass Straw**	**Metal Straw***	**Paper Straw**	**Plastic Straw***	**Silicone Straw***
Bamboo Pole	0.0044					
Borosilicate Glass Tube		0.015				
Chromium Steel 18/8			0.011			
Kraft Paper				0.0011		
Polypropylene					0.00071	
Silicone						0.0053

Sandwich Bags	**Beeswax Wrap**	**Plastic Wrap***	**Plastic Bag***	**Silicone Bag***	**Aluminum Foil***
Cotton	0.026				
Beeswax[1]	0.075				
Resin[2]	0.020				
Jojoba Oil[3]	0.028				
LDPE		0.001	0.001		
LLDPE			0.001		
Silicone				0.073	
Aluminum					0.006

Coffee Cups	**Paper Coffee Cup***	**Metal Mug***	**Reusable Plastic Mug***	**Foam Coffee Cup***	**Ceramic Mug**
Packaging Board	0.0097				
HDPE	0.0004				
Polystyrene	0.0026			0.0026	
Chromium Steel 18/8		0.18			
PET		0.038	0.12		
Polystyrene EPS				0.0015	
Ceramic Tile					0.32

Forks	**Plastic Fork***	**Bamboo Fork**	**Reusable Plastic Fork***	**Metal Fork***
Bamboo Pole		0.007		
Chromium Steel 18/8				0.019
Polypropylene	0.002		0.017	
Polystyrene	0.002			

*Additional manufacturing process step(s) were included in the model

Due to lack of emission factor data on specific materials:

[1] Emissions factor for honey is used for Beeswax

[2] Emissions factor for Epoxy Resin is used for Resin

[3] Emissions factor for Cottonseed Oil is used for Jojoba Oil

S4. Material Sources

Material	**Source**	**Item**
Bamboo	Escamilla & Habert, 2014	Bamboo Pole
Glass	Ecoinvent 3 - allocation, cut off by classification, system	Glass tube, borosilicate {RoW} production, cut-off, S
Steel	Ecoinvent 3 - Allocation, cut-off by classification - system	Steel, chromium steel 18/8 {GLO} market for Cut-off, S
Paper	Ecoinvent 3 - Allocation, cut-off by classification - system	Kraft paper, bleached {GLO} market for cut off, s
Polypropylene	Ecoinvent 3 - Allocation, cut-off by classification - system	Polypropylene, granulate {GLO} market for Cut-off, S
Silicone	Ecoinvent 3 - Allocation, cut-off by classification - system	Silicone product {RoW} market for silicone product cut-off, S
Cotton	Ecoinvent 3 - Allocation, cut-off by classification - system	Textile, woven cotton {GLO} market for cut-off, s
Honey	World Food LCA Database	Honey, raw, large-scale production, unpackaged, at farm (WFLDB)/US U
Epoxy Resin	Ecoinvent 3 - Allocation, cut-off by classification - system	Epoxy resin, liquid {RoW} market for epoxy resin, liquid cut-off, s
Cottonseed Oil	Ecoinvent 3 - Allocation, cut-off by classification - system	Cottonseed Oil, refined {GLO} market for Cut-off, S
LDPE	Ecoinvent 3 - Allocation, cut-off by classification - system	Polyethylene, low density, granulate {GLO} market for cut-off, S
LLDPE	Ecoinvent 3 - Allocation, cut-off by classification - system	Polethylene, linear low density, granulate {GLO} market for cut-off, S
Aluminum	Ecoinvent 3 - Allocation, cut-off by classification - system	Aluminum, primary, cast alloy slab from continuous casting {GLO} market for cut-off, s
Paperboard	Ecoinvent 3 - Allocation, cut-off by classification - system	Solid bleached board {GLO} market for cut-off s
HDPE	Ecoinvent 3 - Allocation, cut-off by classification - system	Polyethylene, high density, granulate {GLO} market for cut-off, s
Polystyrene	Ecoinvent 3 - Allocation, cut-off by classification - system	Polystyrene, general purpose {GLO} market for cut-off, S
PET	Ecoinvent 3 - Allocation, cut-off by classification - system	Polyethylene terephthalate, granulate, bottle grade {GLO{ market for Cut-off, S
Polystyrene EPS	Ecoinvent 3 - Allocation, cut-off by classification - system	polystyrene, expandable {GLO} market for cut-off, s
Ceramic Tile	Ecoinvent 3 - Allocation, cut-off by classification - system	Ceramic tile {GLO} market for cut-off S
Nylon	Ecoinvent 3 - Allocation, cut-off by classification - system	Nylon 6-6 {RoW} market for nylon 6-6 cut-off s

S5. Material GWP Emissions Factors

Units: KG	Emissions	Unit
Bamboo	1.31	kg CO_2e / kg bamboo pole
Glass	2.25	kg CO_2e / kg glass tube
Steel	4.4	kg CO_2e / kg stainless steel
Paper	1.46	kg CO_2e / kg paper
Polypropylene	2.3	kg CO_2e / kg PP
Silicone	3.28	kg CO_2e / kg silicone
Cotton	10.9	kg CO_2e /kg textile
Honey	0.971	kg CO_2e / kg honey
Epoxy Resin	5.15	kg CO_2e / kg resin
Cottonseed Oil	3.25	kg CO_2e / kg oil
LDPE	2.5	kg CO_2e/ kg LDPE
LLDPE	2.3	kg CO_2e / kg LLDPE
Aluminum	18.5	kg CO_2e / kg aluminum
Paperboard	1.26	kg CO_2e / kg paperboard
HDPE	2.32	kg CO_2e / kg HDPE
Polystyrene	3.76	kg CO_2e /kg polystyrene
PET	2.9	kg CO_2e / kg PET
Polystyrene EPS	3.64	kg CO_2e / kg EPS
Ceramic Tile	0.797	kg CO_2e / kg ceramic tile
Nylon	8.34	kg CO_2e / kg nylon

S6. Material Water Use Factors

Material	**Water Use**	**Unit**
Bamboo	1.6	m^3 / kg bamboo
Glass	0.0155	m^3/ kg glass tube
Steel	0.0198	m^3/ kg steel
Paper	0.0458	m^3/ kg paper
Polypropylene	0.0207	m^3/ kg PP
Silicone	0.118	m^3/ kg silicone
Cotton	5.51	m^3/ kg cotton
Honey	0.0608	m^3/ kg honey
Epoxy Resin	0.0654	m^3/ kg epoxy resin
Cottonseed Oil	1.82	m^3/ kg cottonseed oil
LDPE	0.0321	m^3/ kg LDPE
LLDPE	0.0471	m^3/ kg LLDPE
Aluminum	0.104	m3/ kg aluminum
Paperboard	0.0333	m^3/ kg paperbaord
HDPE	0.0238	m^3/ kg HDPE
Polystyrene	0.0525	m^3/ kg PS
PET	0.034	m^3/ kg PET
Polystyrene EPS	0.065	m^3/ kg EPS
Ceramic Tile	0.00642	m^3/ kg ceramic
Nylon	0.226	m^3/ kg nylon

S7. Material Energy Use Factors

Material	**Energy**	**Unit**
Bamboo	19.3	MJ primary/ kg bamboo stem
Glass	29.3	MJ primary/ kg glass tube
Steel	51.2	MJ primary/ kg stainless steel
Paper	21.9	MJ primary/kg paper
Polypropylene	81.2	MJ primary/ kg PP
Silicone	55	MJ primary/ kg silicone
Cotton	116	MJ primary/ kg textile
Honey	13.9	MJ primary/ kg honey
Epoxy Resin	104	MJ primary/ kg resin
Cottonseed Oil	28.7	MJ primary/ kg oil
LDPE	81.7	MJ primary/ kg LDPE
LLDPE	78.9	MJ primary/ kg LLDPE
Aluminum	189	MJ primary/ kg aluminum
Paperboard	17.6	MJ primary/ kg paperboard
HDPE	79.4	MJ primary/ kg HDPE
Polystyrene	88.8	MJ primary/ kg polystyrene
PET	74.1	MJ primary/ kg PET
Polystyrene EPS	90.4	MJ primary/ kg EPS
Ceramic Tile	11.6	MJ primary/ kg ceramic
Nylon	137	MJ primary/kg nylon

S8. Manufacturing Allocation

	Metal Straw	Plastic Straw	Silicone Straw	Plastic Wrap	Plastic Bag	Silicone Bag	Aluminum Foil	Paper Cup	Metal Mug	Reusable Plastic Mug	Foam Cup	Plastic Fork	Reusable Plastic Fork	Metal Fork
Steel Product Manufacturing	X								X					X
Plastic Extrusion (PP)		X												
Injection Molding (Silicone)			X			X								
Blow Molding (LDPE)				X	X									
Extrusion (LLDPE)					X									
Aluminum Product Manufacturing							X							
Thermoforming (PS)								X			X	X		
Injection Molding (PET)									X	X				
Thermoforming (PP)												X	X	

S9. Manufacturing Sources

Process	Source	Item
Steel Product Manufacturing	Ecoinvent 3 - Allocation, cut-off by classification - system	Metal working, average for chromium steel product manufacturing {GLO} market for, cut-off S
Plastic Extrusion (PP)	Ecoinvent 3 - Allocation, cut-off by classification - system	Extrusion, plastic pipes {GLO} market for cut-off, s
Injection Molding (Silicone)	Ecoinvent 3 - Allocation, cut-off by classification - system	Injection Moulding {GLO} market for cut-off, s
Blow Molding (LDPE)	Ecoinvent 3 - Allocation, cut-off by classification - system	Blow Moulding {GLO} market for cut-off, S
Extrusion (LLDPE)	Ecoinvent 3 - Allocation, cut-off by classification - system	Extrusion, plastic film {GLO} market for, cut-off S
Aluminum Product Manufacturing	Ecoinvent 3 - Allocation, cut-off by classification - system	Metal working, average for aluminum product manufacturing {GLO} market for, cut-off S
Thermoforming (PS)	Ecoinvent 3 - Allocation, cut-off by classification - system	Thermoforming, with calendering {GLO} market for cut-off, s
Injection Molding (PET)	Ecoinvent 3 - Allocation, cut-off by classification - system	Injection Moulding {GLO} market for cut-off, s
Thermoforming (PP)	Ecoinvent 3 - Allocation, cut-off by classification - system	Thermoforming, with calendering {GLO} market for cut-off, s
Blow Molding (LLDPE)	Ecoinvent 3 - Allocation, cut-off by classification - system	Blow Moulding {GLO} market for cut-off, S

S10. Manufacturing GWP Emission Factors

Process	Emissions	Unit
Steel Product Manufacturing	2.61	kg CO_2e / kg steel processed
Plastic Extrusion (PP)	0.439	kg CO_2e / kg plastic extruded
Injection Molding (Silicone)	1.29	kg CO_2e / kg silicone moulded
Blow Molding (LDPE)	1.33	kg CO_2e / kg LDPE moulded
Extrusion (LLDPE)	0.571	kg CO_2e / kg LLDPE extruded
Aluminum Product Manufacturing	3.91	kg CO_2e / kg aluminum processed
Thermoforming (PS)	0.876	kg CO_2e / kg PS processed
Injection Molding (PET)	1.28	kg CO_2e / kg PET processed
Thermoforming (PP)	0.876	kg CO_2e / kg PP processed
Blow Molding (LLDPE)	1.33	kg CO_2e / kg LLDPE processed

S11. Manufacturing Water Use Factors

Process	**Water Use**	**Unit**
Steel Product Manufacturing	0.0165	m^3 / kg steel processed
Plastic Extrusion (PP)	0.0108	m^3/ kg plastic extruded
Injection Molding (Silicone)	0.014	m^3/ kg silicone moulded
Blow Molding (LDPE)	0.0144	m^3/ kg LDPE moulded
Extrusion (LLDPE)	0.0217	m^3/ kg LLDPE extruded
Aluminum Product Manufacturing	0.028	m3/ kg aluminum processed
Thermoforming (PS)	0.0478	m^3/ kg PS processed
Injection Molding (PET)	0.0139	m^3/ kg PET processed
Thermoforming (PP)	0.0478	m^3/ kg PP processed
Blow Molding (LLDPE)	0.0144	m^3/ kg LLDPE processed

S12. Manufacturing Energy Use Factors

Process	**Energy**	**Unit**
Steel Product Manufacturing	33.1	MJ primary/ kg steel processed
Plastic Extrusion (PP)	6.15	MJ primary/ kg plastic extruded
Injection Molding (Silicone)	22.2	MJ primary/ kg silicone moulded
Blow Molding (LDPE)	20.8	MJ primary/ kg LDPE moulded
Extrusion (LLDPE)	8.31	MJ primary/ kg LLDPE extruded
Aluminum Product Manufacturing	45.2	MJ primary/ kg aluminum processed
Thermoforming (PS)	13.9	MJ primary/ kg PS processed
Injection Molding (PET)	22	MJ primary/ kg PET processed
Thermoforming (PP)	13.9	MJ primary/ kg PP processed
Blow Molding (LLDPE)	20.8	MJ primary/ kg LLDPE processed

S13. Transportation Environmental Impact Factors, Distance and Sources

Transport	Source	Item
Freight	Ecoinvent 3 - Allocation, cut-off by classification - system	Transport, freight lorry >32 metric ton, euro4 {RoW} market for, transport, freight, lorry >32 metric ton, euro4 cut-off, S

Transport	Emissions	Unit
Freight	9.23E-05	kg Co2e/ kgkm

Transport	Water Use	Unit
Freight	1.74E-07	m^3 / kgkm

Transport	Energy	Unit
Freight	0.00152	MJ primary/ kgkm

Transport	Source	Distance
Freight	U.S. DOT, 2017	402.336 km

S14. Use Phase Allocation

Product	Dishwashing Method
Bamboo Straw	Manual
Glass Straw	Machine
Metal Straw	Machine
Paper Straw	N/A
Plastic Straw	N/A
Silicone Straw	Machine
Beeswax Wrap	Manual
Plastic Wrap	N/A
Plastic Bag	N/A
Silicone Bag	Machine
Aluminum Foil	N/A
Paper Coffee Cup	N/A
Metal Mug	Machine
Reusable Plastic Mug	Machine
Foam Coffee Cup	N/A
Ceramic Mug	Machine
Plastic Fork	N/A
Bamboo Fork	Manual
Reusable Plastic Fork	Machine
Metal Fork	Machine

S15. Use Phase Source and Environmental Impact Factors

Dishwashing Method	Source
Machine	Porras et al., 2020
Manual	Porras et al., 2020

Dishwashing Method	GWP	Unit
Machine	0.000160137	kg CO_2e /in^2
Manual	0.000430608	kg CO_2e /in^2

Dishwashing Method	Water Use	Unit
Machine	0.000000100644	m^3 /in^2
Manual	0.000000809214	m^3/in^2

Dishwashing Method	Energy Use	Unit
Machine	0.00292147	MJ primary /in^2
Manual	0.007263028	MJ primary /in^2

S16. Product Surface Area Calculations

Product	Surface Area (in^2)
Bamboo Straw	12.06
Glass Straw	13.57
Metal Straw	12.81
Silicone Straw	12.44
Beeswax Wrap	392
Silicone Bag	210
Metal Mug	144.51
Reusable Plastic Mug	144.51
Ceramic Mug	119.38
Bamboo Fork	3.16
Reusable Plastic Fork	3.3
Metal Fork	3.12

Product	Equation	R (in)	H (in)	X (in)	Y (in)	Assumptions
Bamboo Straw	2PIRH*2	0.12	8			No difference between inner and outer radius
Glass Straw	2PIRH*2	0.12	9			No difference between inner and outer radius
Metal Straw	2PIRH*2	0.12	8.5			No difference between inner and outer radius
Silicone Straw	2PIRH*2	0.12	8.25			No difference between inner and outer radius
Beeswax Wrap	2*XY			14	14	www.chefsouschef.com
Silicone Bag	2*XY			7	7.5	www.stasherbag.com
Metal Mug	(2*(2PIR^2+2PIRH))	2	3.75			www.yeti.com
Reusable Plastic Mug	(2*(2PIR^2+2PIRH))	2	3.75			Assumed same size as Yeti
Ceramic Mug	2PIR^2+(2*2PIRH)	2	3.75			Assumed same size as Yeti (minus lid)

Bamboo Fork	2*(Handle+Neck+Tines)	Handle (4in x .2in), Neck (1in x .9in), Tines (1.1in x .15in)
Reusable Plastic Fork	2*(Handle+Neck+Tines)	Handle (4in x .25in), Neck (.8in x .8in), Tines (1.1in x .15in)
Metal Fork	2*(Handle+Neck+Tines)	Handle (4in x .2in), Neck (1in x .9in), Tines (1in x .155in)

S17. Use Phase Emission Factor Calculation

Estimation of Dishes Used in Porras et al., 2020 Study

Dish Type	Quantity	Surface Area (in^2)
Dinner Plate	8	157.08
Bread and Butter Plate	8	71.57
Fruit Bowl	8	59.69
Cup	8	43.39
Saucer	8	56.55
Serving Bowl	1	70.69
Platter	2	462.60
Glass – Iced Tea	8	110.04
Flatware- Knife	8	8.76
Flatware – Dinner Fork	4	7.3
Flatware – Salad Fork	3	5.54
Flatware - Teaspoon	7	20.54
Flatware – Serving Fork	1	10.13
Flatware – Serving Spoon	1	95.98
Plastic Bowl	2	123.84
Spatula	1	34.4
Baking Dish	1	440
TOTAL	79	6070.37

	Manual Dishwashing	Machine Dishwashing
Total Emissions for 2150 loads (kg CO_2e)	5620	2090
Emissions Factor (kg CO_2e /in^2 dish)	0.000430608	0.000160137

	Manual Dishwashing	Machine Dishwashing
Total Water Use for 2150 loads (m^3)	347	2790
Water Use Factor (m^3/in^2 dish)	0.000000100644	0.000000809214

	Manual Dishwashing	Machine Dishwashing
Total Energy Use for 2150 loads (MJ primary)	94792	38129
Energy Use Factor (MJ primary /in^2 dish)	0.007263028	0.00292147

S18. Use Phase Alternate Scenario GWP Emission Factor Calculations

	Washing Type	**Grid**	**Water Heater Type**	**Percent Change**	**Emissions (kg CO_2e per 2150 loads)**	**Emissions (kg CO_2e /in^2)**
Base Case	Machine	Average US Electric Grid	natural gas heater	N/A	2090	0.00016014
Base Case	Manual	Average US Electric Grid	natural gas heater	N/A	5620	0.00043061
Cleaner Grid	Machine	NYUP Grid	natural gas heater	-29%	1483.9	0.0001137
Cleaner Grid	Manual	NYUP Grid	natural gas heater	0%	5620	0.00043061
Dirty Grid	Machine	MROE Grid	natural gas heater	26%	2633.4	0.00020177
Dirty Grid	Manual	MROE Grid	natural gas heater	0%	5620	0.00043061
Electric heater	Machine	Average US Electric Grid	electric heater	30%	2717	0.00020818
Electric heater	Manual	Average US Electric Grid	electric heater	38%	7755.6	0.00059424
Clean grid electric heater	Machine	NYUP Grid	electric heater	-32%	1421.2	0.00010889
Clean grid electric heater	Manual	NYUP Grid	electric heater	-38%	3484.4	0.00026698
Dirty grid electric heater	Machine	MROE Grid	electric heater	86%	3887.4	0.00029786
Dirty grid electric heater	Manual	MROE Grid	electric heater	108%	11689.6	0.00089567

S19. Use Alternate Scenario Water Use Factor Calculations

	Washing Type	Grid	Water Heater Type	Percent Change	Water Use (m^3 per 2150 loads)	Water Use (m^3 /in^2)
Base Case	Machine	Average US Electric Grid	natural gas heater	N/A	347	0.000000100644
Base Case	Manual	Average US Electric Grid	natural gas heater	N/A	2790	0.000000809214
Cleaner Grid	Machine	NYUP Grid	natural gas heater	-29%	246.4	0.00000007147
Cleaner Grid	Manual	NYUP Grid	natural gas heater	0%	2790	0.0000008092
Dirty Grid	Machine	MROE Grid	natural gas heater	26%	437.2	0.0000001268
Dirty Grid	Manual	MROE Grid	natural gas heater	0%	2790	0.0000008092
Electric heater	Machine	Average US Electric Grid	electric heater	30%	451.1	0.0000001308
Electric heater	Manual	Average US Electric Grid	electric heater	38%	3850.2	0.000001117
Clean grid electric heater	Machine	NYUP Grid	electric heater	-32%	236	0.00000006845
Clean grid electric heater	Manual	NYUP Grid	electric heater	-38%	1729.8	0.0000005017
Dirty grid electric heater	Machine	MROE Grid	electric heater	86%	645.4	0.0000001872
Dirty grid electric heater	Manual	MROE Grid	electric heater	108%	5803.2	0.000001683

S20. Use Alternate Scenario Energy Use Factor Calculations

	Washing Type	**Grid**	**Water Heater Type**	**Percent Change**	**Energy Use (MJ primary per 2150 loads)**	**Energy Use (MJ primary /in^2)**
Base Case	Machine	Average US Electric Grid	natural gas heater	N/A	38129	0.00292147
Base Case	Manual	Average US Electric Grid	natural gas heater	N/A	94792	0.007263028
Cleaner Grid	Machine	NYUP Grid	natural gas heater	-29%	27072	0.00207428
Cleaner Grid	Manual	NYUP Grid	natural gas heater	0%	94792	0.00726303
Dirty Grid	Machine	MROE Grid	natural gas heater	26%	48043	0.00368109
Dirty Grid	Manual	MROE Grid	natural gas heater	0%	94792	0.00726303
Electric heater	Machine	Average US Electric Grid	electric heater	30%	49568	0.00379793
Electric heater	Manual	Average US Electric Grid	electric heater	38%	130813	0.01002298
Clean grid electric heater	Machine	NYUP Grid	electric heater	-32%	25928	0.00198662
Clean grid electric heater	Manual	NYUP Grid	electric heater	-38%	58771	0.00450307
Dirty grid electric heater	Machine	MROE Grid	electric heater	86%	70920	0.00543394
Dirty grid electric heater	Manual	MROE Grid	electric heater	108%	197167	0.01510707

S21. EoL Average Percentages

Item	**% Landfilled**	**% Recycled**	**% Composted**	**% Combusted**
Organic Matter	75.31%	N/A	6.30%	18.37%
Glass	60.37%	26.60%	N/A	13.01%
Steel (or stainless steel)	55.21%	32.70%	N/A	12.12%
Paper	27.38%	65.90%	N/A	6.70%
Polypropylene	75.83%	8.40%	N/A	15.80%
Silicone	72.67%	N/A	N/A	27.33%
Polyethylene	75.83%	8.40%	N/A	15.80%
Polystyrene	75.83%	8.40%	N/A	15.80%
PET	75.83%	8.40%	N/A	15.80%
General Plastic	75.83%	8.40%	N/A	15.80%
Ceramic	100.00%	N/A	N/A	N/A
Textile	66.02%	15.20%	N/A	18.77%
Aluminum	69.19%	16.20%	N/A	14.62%

Source - Advancing Sustainable Materials Management: 2017 Fact Sheet

S22. EoL Source

Disposal	Source	Item
Compost Biowaste	Ecoinvent 3 - Allocation, cut-off by classification - system	Compost {CH} treatment of biowaste, industrial composting cut-off, S
Sanitary Landfill - Wood	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste wood, untreated {RoW} treatment of, sanitary landfill, cut-off, S
Incineration - Wood	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste wood, untreated {RoW} treatment of waste wood, untreated, municipal incineration, cut-off, S
Recycle - Glass	Ecoinvent 3 - Allocation, cut-off by classification - system	Packaging glass, white (waste treatment) {GLO} recycling of packaging glass, white cut-off, S
Sanitary Landfill - Glass	Ecoinvent 3 - Allocation, cut-off by classification - system	Inert waste {RoW} treatment of, sanitary landfill, cut-off, S
Incineration - Glass	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste glass {RoW} treatment of waste glass, municipal incineration cut-off, S
Recycle - Steel	Ecoinvent 3 - Allocation, cut-off by classification - system	Steel and iron (waste treatment) {GLO} recycling of steel and iron, cut-off, S
Sanitary Landfill - Steel	Ecoinvent 3 - Allocation, cut-off by classification - system	Inert waste {RoW} treatment of, sanitary landfill, cut-off, S
Incineration - Steel	Ecoinvent 3 - Allocation, cut-off by classification - system	Scrap Steel {CH} treatment of, municipal incineration, cut-off, S
Sanitary Landfill - Paperboard	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste paperboard {RoW} treatment of, sanitary landfill cut-off, S
Incineration - Paperboard	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste paperboard {RoW} treatment of, municipal incineration, cut-off, S
Recycle - PP	Ecoinvent 3 - Allocation, cut-off by classification - system	PP (waste treatment) {GLO} recycling of PP cut-off, s
Sanitary Landfill - PP	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polypropylene {RoW} treatment of waste polypropylene, sanitary landfill, cut-off, S
Incineration - PP	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polypropylene {RoW} treatment of waste polypropylene, municipal incineration, cut-off, S
Sanitary Landfill - Silicone	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste plastic, mixture {RoW} treatment of waste plastic, mixture, sanitary landfill, cut-off, S
Incineration - Silicone	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste plastic, mixture {RoW} treatment of waste plastic, mixture, municipal incineration, cut-off, S
Landfill - Textile	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste textile, soiled {RoW} market for waste textile, soiled, cut-off, S
Incineration - Textile	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste textile, soiled {RoW} treatment of, municipal incineration, cut-off, S
Recycle - PE	Ecoinvent 3 - Allocation, cut-off by classification - system	PE (waste treatment) {GLO} recycling of PE, cut-off, S
Sanitary Landfill - PE	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polyethylene {RoW} treatment of waste polyethylene, sanitary landfill, cut-off, S
Incineration - PE	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polyethylene {RoW} treatment of waste polyethylene, municipal solid waste, cut-off, S

Recycle - Aluminum	Ecoinvent 3 - Allocation, cut-off by classification - system	Aluminum (waste treatment) {GLO} recycling of aluminum, cut-off, S
Landfill - Aluminum	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste aluminum {RoW} treatment of waste aluminum, sanitary landfill, cut-off, S
Incineration - Aluminum	Ecoinvent 3 - Allocation, cut-off by classification - system	Scrap aluminum {RoW} treatment of, municipal incineration, cut-off, S
Recycle - PS	Ecoinvent 3 - Allocation, cut-off by classification - system	PS (waste treatment) {GLO} recycling of PS, cut-off, S
Landfill - PS	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polystyrene {RoW} treatment of waste polystyrene, sanitary landfill, cut-off, S
Incineration - PS	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polystyrene {RoW} treatment of waste polystyrene, municipal incineration, cut-off, S
Recycle - PET	Ecoinvent 3 - Allocation, cut-off by classification - system	PET (waste treatment) {GLO} recycling of PET, cut-off, S
Landfill - PET	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polyethylene {RoW} treatment of waste polyethylene, sanitary landfill, cut-off, S
Incineration - PET	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste polyethylene {RoW} treatment of waste polyethylene, municipal incineration, cut-off, S
Landfill - Ceramic	Ecoinvent 3 - Allocation, cut-off by classification - system	Inert waste {RoW} treatment of, sanitary landfill, cut-off, S
Incineration - EPS	Ecoinvent 3 - Allocation, cut-off by classification - system	Waste expanded polystyrene {RoW} treatment of, municipal incineration, cut-off, S

S23. EoL Emission Factors

Disposal	Emissions	Unit
Compost Biowaste	0	kg CO_2e / kg composted
Sanitary Landfill - Wood	0.0748	kg CO_2e / kg landfilled
Incineration - Wood	0.0138	kg CO_2e / kg incinerated
Recycle - Glass	0	kg CO_2e / kg recycled
Sanitary Landfill - Glass	0.0104	kg CO_2e / kg landfilled
Incineration - Glass	0.0177	kg CO_2e / kg incinerated
Recycle - Steel	0	kg CO_2e / kg recycled
Sanitary Landfill - Steel	0.0104	kg CO_2e / kg landfilled
Incineration - Steel	0.00987	kg CO_2e / kg incinerated
Sanitary Landfill - Paperboard	1.52	kg CO_2e / kg landfilled
Incineration - Paperboard	0.0307	kg CO_2e / kg incinerated
Recycle - PP	0	kg CO_2e / kg recycled
Sanitary Landfill - PP	0.11	kg CO_2e / kg landfilled
Incineration - PP	2.55	kg CO_2e / kg incinerated
Sanitary Landfill - Silicone	0.102	kg CO_2e / kg landfilled
Incineration - Silicone	2.37	kg CO_2e / kg incinerated
Landfill - Textile	0.729	kg CO_2e / kg landfilled
Incineration - Textile	0.733	kg CO_2e / kg incinerated
Recycle - PE	0	kg CO_2e / kg recycled
Landfill - PE	0.128	kg CO_2e / kg landfilled
Incineration - PE	3.02	kg CO_2e / kg incinerated
Recycle - Aluminum	0	kg CO_2e / kg recycled
Landfill - Aluminum	0.0391	kg CO_2e / kg landfilled
Incineration - Aluminum	0.0142	kg CO_2e / kg incinerated
Recycle - PS	0	kg CO_2e / kg recycled
Landfill - PS	0.135	kg CO_2e / kg landfilled
Incineration - PS	3.19	kg CO_2e / kg incinerated
Recycle - PET	0	kg CO_2e / kg recycled
Landfill - PET	0.128	kg CO_2e / kg landfilled
Incineration - PET	3.02	kg CO_2e / kg incinerated
Landfill - Ceramic	0.0104	kg CO_2e / kg landfilled
Incineration - EPS	3.18	kg CO_2e / kg incinerated

S24. EoL Water Consumption Factors

Disposal	Water Consumption	Unit
Compost Biowaste	0	m^3 / kg composted
Sanitary Landfill - Wood	0.000262	m^3/ kg landfilled
Incineration - Wood	-0.000212	m^3/ kg incinerated
Recycle - Glass	0	m^3/ kg recycled
Sanitary Landfill - Glass	0.00026	m^3/ kg landfilled
Incineration - Glass	-0.000119	m^3/ kg incinerated
Recycle - Steel	0	m^3/ kg recycled
Sanitary Landfill - Steel	0.263	m^3/ kg landfilled
Incineration - Steel	0.000594	m^3/ kg incinerated
Sanitary Landfill - Paperboard	0.000333	m^3/ kg landfilled
Incineration - Paperboard	0.00124	m^3/ kg incinerated
Recycle - PP	0	m^3/ kg recycled
Sanitary Landfill - PP	0.000262	m^3/ kg landfilled
Incineration - PP	0.000163	m^3/ kg incinerated
Sanitary Landfill - Silicone	0.000265	m^3/ kg landfilled
Incineration - Silicone	0.000352	m^3/ kg incinerated
Landfill - Textile	0.00138	m^3/ kg landfilled
Incineration - Textile	0.00139	m^3/ kg incinerated
Recycle - PE	0	m^3/ kg recycled
Landfill - PE	0.000262	m^3/ kg landfilled
Incineration - PE	0.000274	m^3/ kg incinerated
Recycle - Aluminum	0	m^3/ kg recycled
Landfill - Aluminum	0.000424	m^3/ kg landfilled
Incineration - Aluminum	-0.000206	m^3/ kg incinerated
Recycle - PS	0	m^3/ kg recycled
Landfill - PS	0.000262	m^3/ kg landfilled
Incineration - PS	0.000271	m^3/ kg incinerated
Recycle - PET	0	m^3/ kg recycled
Landfill - PET	0.000262	m^3/ kg landfilled
Incineration - PET	0.000274	m^3/ kg incinerated
Landfill - Ceramic	0.00026	m^3/ kg landfilled
Incineration - EPS	0.000811	m^3/ kg incinerated

S25. EoL Energy Use Factors

Disposal	Energy	Unit
Compost Biowaste	0	MJ primary/ kg composted
Sanitary Landfill - Wood	0.266	MJ primary/ kg landfilled
Incineration - Wood	0.000424	MJ primary/ kg incinerated
Recycle - Glass	0	MJ primary/ kg recycled
Sanitary Landfill - Glass	0.263	MJ primary/ kg landfilled
Incineration - Glass	0.369	MJ primary/ kg incinerated
Recycle - Steel	0	MJ primary/ kg recycled
Sanitary Landfill - Steel	0.263	MJ primary/ kg landfilled
Incineration - Steel	0.185	MJ primary/ kg incinerated
Sanitary Landfill - Paperboard	0.397	MJ primary/ kg landfilled
Incineration - Paperboard	0.24	MJ primary/ kg incinerated
Recycle - PP	0	MJ primary/ kg recycled
Sanitary Landfill - PP	0.266	MJ primary/ kg landfilled
Incineration - PP	0.259	MJ primary/ kg incinerated
Sanitary Landfill - Silicone	0.272	MJ primary/ kg landfilled
Incineration - Silicone	0.47	MJ primary/ kg incinerated
Landfill - Textile	1.68	MJ primary/ kg landfilled
Incineration - Textile	1.65	MJ primary/ kg incinerated
Recycle - PE	0	MJ primary/ kg recycled
Landfill - PE	0.267	MJ primary/ kg landfilled
Incineration - PE	0.298	MJ primary/ kg incinerated
Recycle - Aluminum	0	MJ primary/ kg recycled
Landfill - Aluminum	0.599	MJ primary/ kg landfilled
Incineration - Aluminum	0.282	MJ primary/ kg incinerated
Recycle - PS	0	MJ primary/ kg recycled
Landfill - PS	0.268	MJ primary/ kg landfilled
Incineration - PS	0.293	MJ primary/ kg incinerated
Recycle - PET	0	MJ primary/ kg recycled
Landfill - PET	0.267	MJ primary/ kg landfilled
Incineration - PET	0.298	MJ primary/ kg incinerated
Landfill - Ceramic	0.263	MJ primary/ kg landfilled
Incineration - EPS	0.309	MJ primary/ kg incinerated

S26. EoL Allocation

	Bamboo Straw	Glass Straw	Metal Straw	Paper Straw	Plastic Straw	Silicone Straw
Compost Biowaste	X					
Sanitary Landfill - Wood	X					
Incineration - Wood	X					
Recycle - Glass		X				
Sanitary Landfill - Glass		X				
Incineration - Glass		X				
Recycle - Steel			X			
Sanitary Landfill - Steel			X			
Incineration - Steel			X			
Sanitary Landfill - Paperboard				X		
Incineration - Paperboard				X		
Sanitary Landfill - PP					X	
Incineration - PP					X	
Sanitary Landfill - Silicone						X
Incineration - Silicone						X

	Beeswax Wrap	Plastic Wrap	Plastic Bag	Silicone Bag	Aluminum Foil
Compost Biowaste	X				
Sanitary Landfill - Silicone				X	
Incineration - Silicone				X	
Landfill - Textile	X				
Incineration - Textile	X				
Recycle - PE		X	X		
Landfill - PE		X	X		
Incineration - PE		X	X		
Recycle - Aluminum					X
Landfill - Aluminum					X
Incineration - Aluminum					X

	Paper Coffee Cup	Metal Mug	Reusable Plastic Mug	Foam Cup	Ceramic Mug
Recycle – Steel		X			
Sanitary Landfill – Steel		X			
Incineration – Steel		X			
Sanitary Landfill – Paperboard	X				
Incineration - Paperboard	X				
Landfill – PE	X				
Incineration – PE	X				
Recycle – PS	X			X	
Landfill – PS	X			X	
Incineration – PS	X			X	
Recycle – PET		X	X		
Landfill – PET		X	X		
Incineration – PET		X	X		
Landfill – Ceramic					X
Incineration - EPS				X	

	Plastic Fork	Bamboo Fork	Reusable Plastic Fork	Metal Fork
Compost Biowaste		X		
Sanitary Landfill – Wood		X		
Incineration - Wood		X		
Recycle – Steel				X
Sanitary Landfill – Steel				X
Incineration – Steel				X
Recycle - PP	X		X	
Sanitary Landfill – PP	X		X	
Incineration – PP	X		X	
Recycle – PS	X			
Landfill – PS	X			
Incineration - PS	X			

S27. Environmental Impact and Payback Period Calculations

The procedure for calculating GHG emissions for reusable and single-use products, and the payback period is summarized below.

$$E_O = E_M + E_T + E_U + E_E \tag{1}$$

where E_O is the overall emissions (kg CO_2e) associated with the product(s) necessary to reach the functional unit usage requirements defined in each scenario.

E_M is the overall material emissions (kg CO_2e) associated with material extraction and manufacturing of the product(s). It is defined as follows:

$$E_M = \sum M_{EN} * MA_N * X \tag{2}$$

where M_E is the material emissions factor for N material $\left(\frac{kg\ CO2e}{kg\ material}\right)$, MA_N is the mass of N material per product $\left(\frac{kg\ N\ material}{product}\right)$, and X is the number of products being used in the scenario.

E_T is the transportation emissions (kg CO_2e) for moving the product system. This is determined by:

$$E_T = T_E * MA_T * X * D \tag{3}$$

where T_E is the transportation method emissions factor $\left(\frac{kg\ CO2e}{kg*km}\right)$, MA_T is total mass per product $\left(\frac{kg}{product}\right)$, X is number of products being transported, and D is distance traveled (km).

E_U is the use phase emissions (kg CO_2e) associated with the washing of the reusable product. For single-use products, the emissions from this life cycle stage will be zero. Use phase emissions can be calculated:

$$E_U = DW_E * X * U * SA \tag{4}$$

where DW_E is the dishwashing emissions factor per square inch of dish $\left(\frac{kg\ CO2e}{in^2 dish}\right)$, X is the number if products, U is the number of times a product is used (and therefore washed), and SA is the surface area per product $\left(\frac{in^2}{product}\right)$.

E_E is the end-of-life emissions (kg CO_2e). Products may be landfilled, composted, combusted or recycled. This is found by doing a summation of the impact of the different applicable disposal methods:

$$E_E = \sum DE_{ZN} * MA_N * X * \overline{DM_{ZN}} \qquad (5)$$

where DE_Z is disposal method emissions factor for Z disposal scenario of N material $\left(\frac{kg\ CO2e}{kg\ N\ material}\right)$, MA_N is the mass of N material per product $\left(\frac{kg\ N\ material}{product}\right)$, X is the number of products, and $\overline{DM}$ is the average percentage of material that goes towards Z disposal method.

Using these equations payback period can be calculated. The subscript R is used to designate reusables, and S is used for single-use.

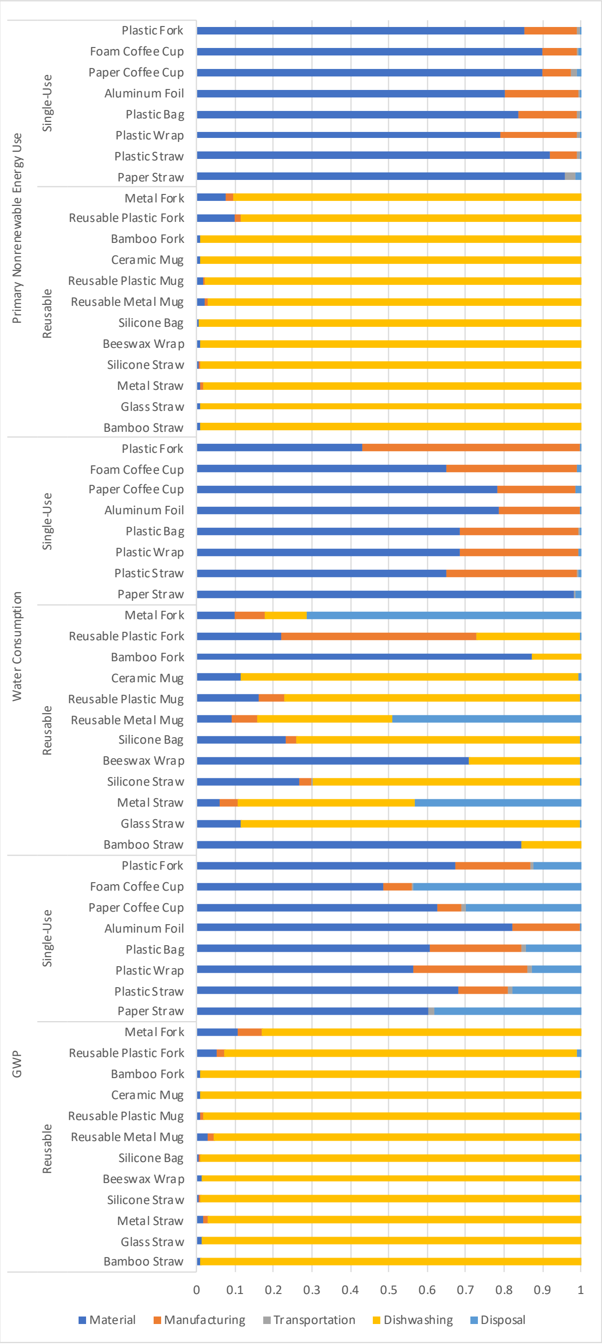
1. $E_{RM} + E_{RT} + E_{RU} + E_{RE} = E_{SM} + E_{ST} + E_{SE}$
2. $M_{RE} * MA_R + T_E * MA_R * D + DW_E * U * SA_R + DE_R * MA_R * DM_R = M_{SE} * MA_S * U + T_E * MA_S * D * U + DE_S * MA_S * DM_S * U$

where M_{RE} is the material emissions factor for the reusable product $\left(\frac{kg\ CO2e}{product}\right)$; MA_R is the mass of the reusable product $\left(\frac{kg}{product}\right)$; T_E is transportation method emissions factor $\left(\frac{kg\ CO2e}{kg*km}\right)$; D is the distance transported (km); DW_E is the dishwasher emissions factor per inch squared of renewable product $\left(\frac{kg\ CO2e}{in^2 dish}\right)$; U is the number of uses or the payback period (uses); SA_R is the surface area of the renewable product $\left(\frac{in^2}{product}\right)$; DE_R is the disposal method emissions factor for the renewable product $\left(\frac{kg\ CO2e}{product}\right)$; DM_R is the average disposal method percentages for the reusable product; M_{SE} is the material emissions factor for the single-use product $\left(\frac{kg\ CO2e}{product}\right)$; MA_S is the mass per single-use product $\left(\frac{kg\ N\ material}{product}\right)$; DE_S is the disposal method emissions factor for the single-use product $\left(\frac{kg\ CO2e}{product}\right)$; and DM_R is the average disposal method percentages for the single-use product.

Then solve for U.

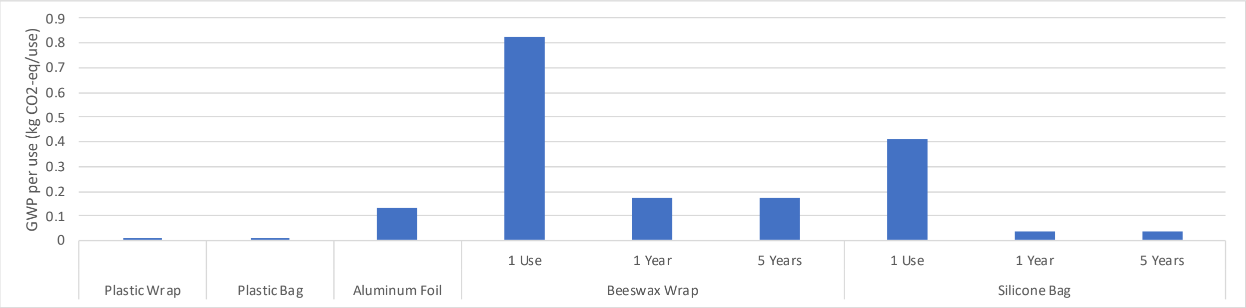
$$U = \frac{M_{RE}*MA_R+T_E*MA_R*D+DE_R*MA_R*DM_R}{M_{SE}*MA_S+T_E*MA_S*D+DE_S*MA_S*DM_S-DW_E*SA_R} \qquad (6)$$

S28. Breakdown of percent contributed to overall impacts by each life cycle phase. Functional Unit: 5 Years (5 uses/week)

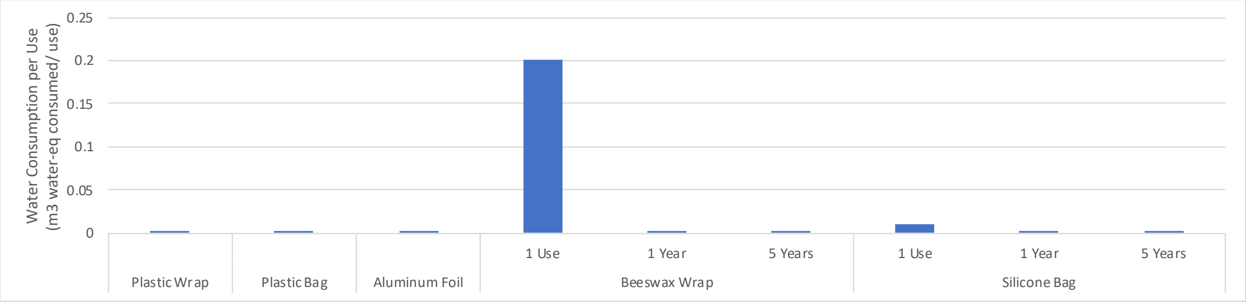


S29. Sandwich Bag Environmental Impact Per Use Results

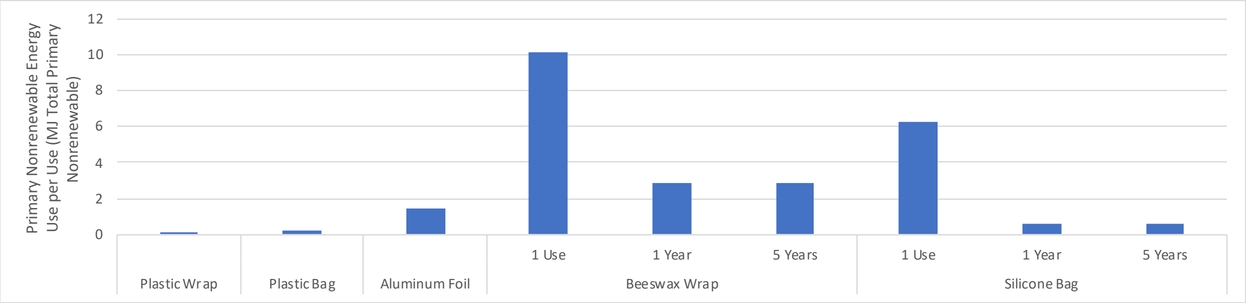
a) GWP



b) Water Consumption

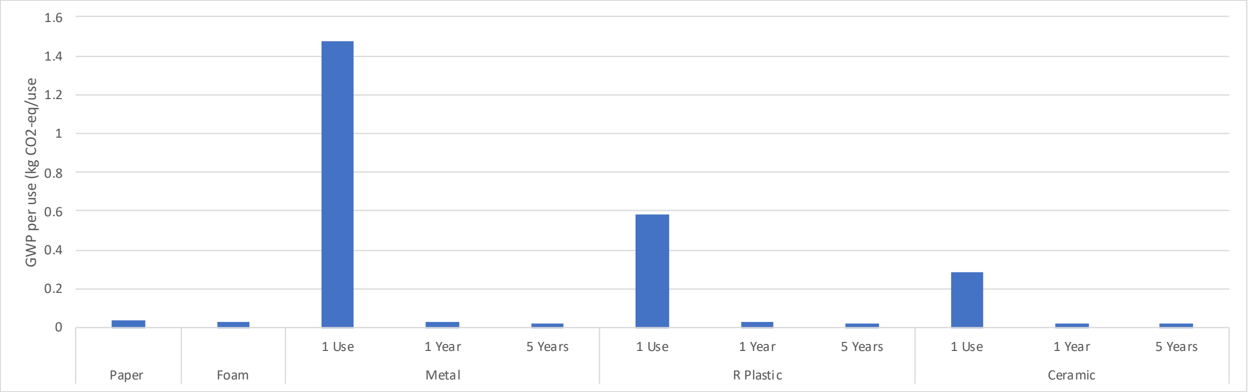


c) Primary Nonrenewable Energy Use

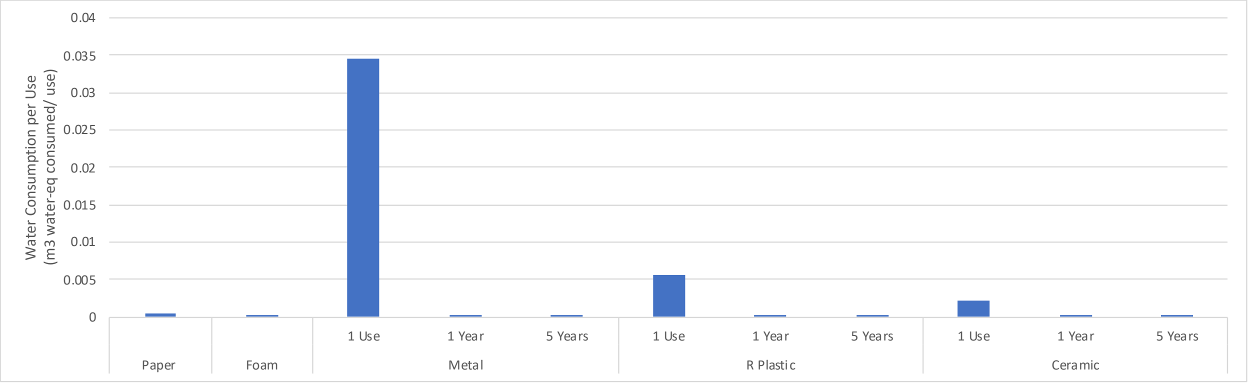


S30. Coffee Cup Environmental Impact Per Use Results

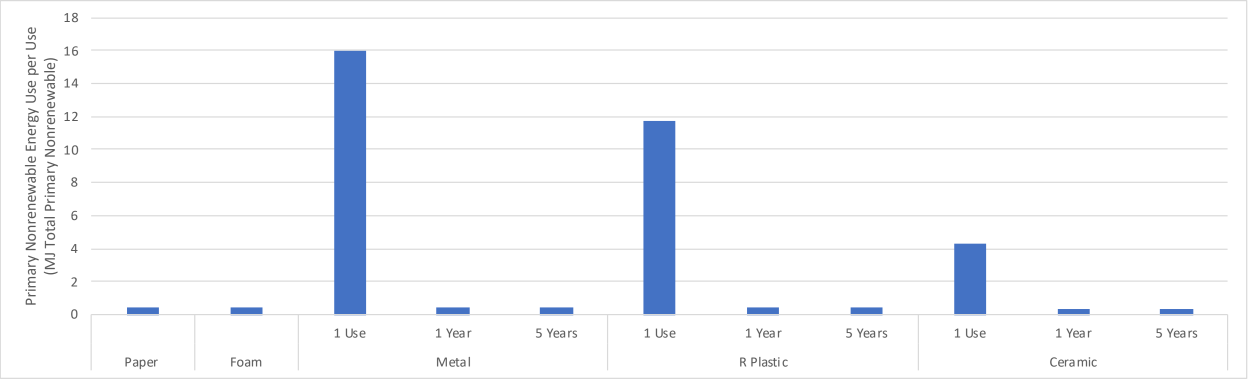
a) GWP



b) Water Consumption

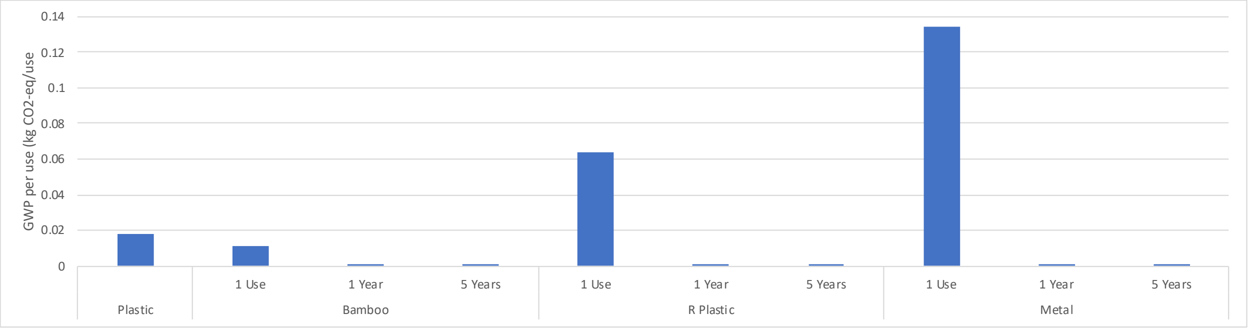


c) Primary Nonrenewable Energy Use

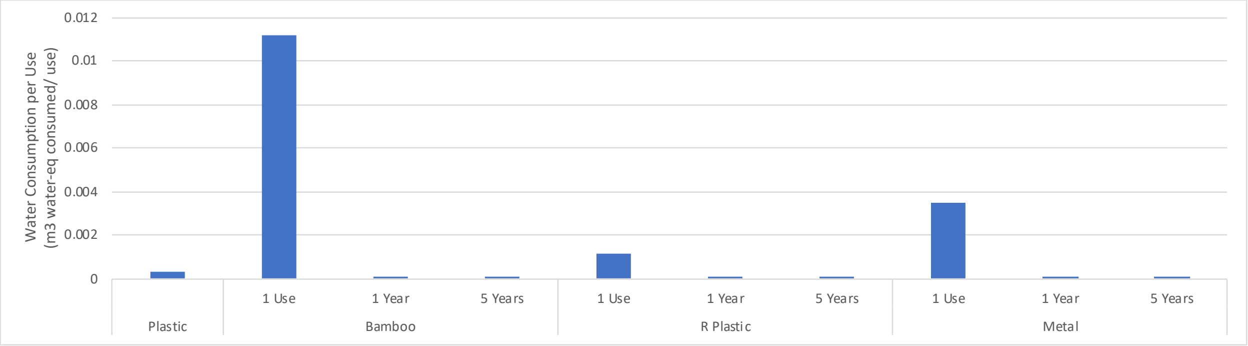


S31. Fork Environmental Impact Per Use Results

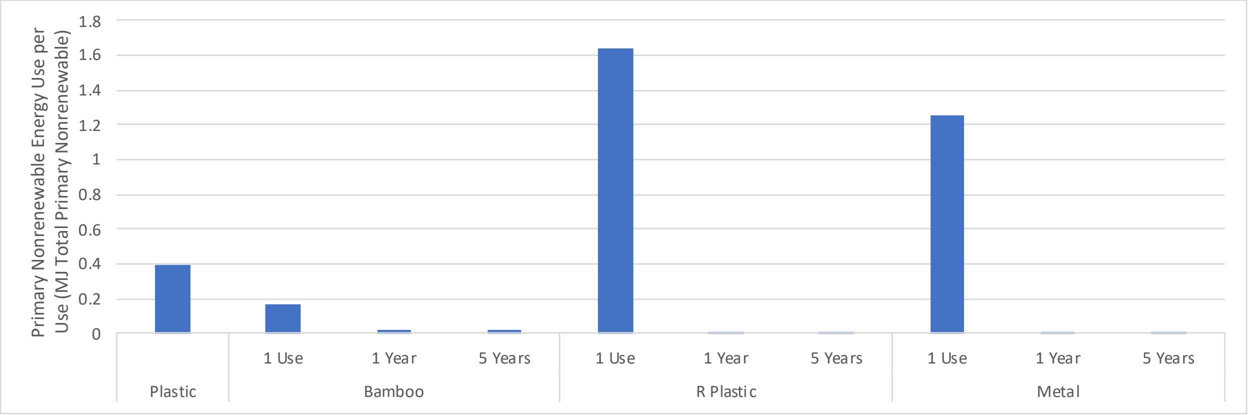
a) GWP



b) Water Consumption



c) Primary Nonrenewable Energy Use



S32. Monte Carlo Material Ranges

	Low Emissions Factor Value	Average Emissions Factor Value	High Emissions Factor Value	Emissions Unit
Bamboo	1.179	1.31	1.441	kg CO_2e/kg bamboo
Glass	2.025	2.25	2.475	kg CO_2e/kg glass
Steel	3.96	4.4	4.84	kg CO_2e/kg steel
Paper	1.314	1.46	1.606	kg CO_2e/kg paper
Polypropylene	2.07	2.3	2.53	kg CO_2e/kg PP
Silicone	2.952	3.28	3.608	kg CO_2e/kg silicone
Cotton	9.81	10.9	11.99	kg CO_2e/kg cotton
Honey	0.8739	0.971	1.0681	kg CO_2e/kg honey
Epoxy Resin	4.635	5.15	5.665	kg CO_2e/kg resin
Cottonseed Oil	2.925	3.25	3.575	kg CO_2e/kg oil
LDPE	2.25	2.5	2.75	kg CO_2e/kg LDPE
LLDPE	2.07	2.3	2.53	kg CO_2e/kg LLDPE
Aluminum	16.65	18.5	20.35	kg CO_2e/kg aluminum
Paperboard	1.134	1.26	1.386	kg CO_2e/kg paperboard
HDPE	2.088	2.32	2.552	kg CO_2e/kg HDPE
Polystyrene	3.384	3.76	4.136	kg CO_2e/kg PS
PET	2.61	2.9	3.19	kg CO_2e/kg PET
Polystyrene EPS	3.276	3.64	4.004	kg CO_2e/kg EPS
Ceramic Tile	0.7173	0.797	0.8767	kg CO_2e/kg ceramic
Nylon	7.506	8.34	9.174	kg CO_2e/kg nylon

*Because ranges were not available for all materials, a range of +/- 10% was ran for all materials in order to maintain uniformity between products.

S33. Monte Carlo Manufacturing Ranges

	Low Emissions Factor Value	Average Emissions Factor Value	High Emissions Factor Value	Emissions Unit
Steel Product Manufacturing	2.349	2.61	2.871	kg CO_2e/kg steel
Plastic Extrusion (PP)	0.3951	0.439	0.4829	kg CO_2e/kg PP
Injection Molding (Silicone)	1.161	1.29	1.419	kg CO_2e/kg silicone
Blow Molding (LDPE)	1.197	1.33	1.463	kg CO_2e/kg LDPE
Extrusion (LLDPE)	0.5139	0.571	0.6281	kg CO_2e/kg LLDPE
Aluminum Product Manufacturing	3.519	3.91	4.301	kg CO_2e/kg aluminum
Thermoforming (PS)	0.7884	0.876	0.9636	kg CO_2e/kg PS
Injection Molding (PET)	1.152	1.28	1.408	kg CO_2e/kg PET
Thermoforming (PP)	0.7884	0.876	0.9636	kg CO_2e/kg PP
Blow Molding (LLDPE)	1.197	1.33	1.463	kg CO_2e/kg LLDPE

S34. Monte Carlo Transportation Distance Ranges

	Low Distance	Average Distance	High Distance	Unit
Transportation Distance	160.93	402.34	1609.34	km

Source: U.S. Department of Transportation (DOT) & Bureau of Transportation Statistics (2017). Freight Facts and Figures.

S35. Monte Carlo EoL Ranges

	Low Emissions Factor Value	Average Emissions Factor Value	High Emissions Factor Value	Emissions Unit
Bamboo Straw	0	0.05886694	0.0748	kg CO_2e/kg disposed
Glass Straw	0	0.00858125	0.0177	kg CO_2e/kg disposed
Metal Straw	0	0.006938084	0.0104	kg CO_2e/kg disposed
Silicone Straw	0.102	0.7218444	2.37	kg CO_2e/kg disposed
Plastic Straw	0	0.486313	2.55	kg CO_2e/kg disposed
Beeswax Wrap	0	0.683662	0.733	kg CO_2e/kg disposed
Silicone Bag	0.102	0.7218444	2.37	kg CO_2e/kg disposed
Plastic Bag	0	0.5742224	3.02	kg CO_2e/kg disposed
Metal Mug	0	0.105822506	0.535009174	kg CO_2e/kg disposed
Reusable Plastic Mug	0	0.5742224	3.02	kg CO_2e/kg disposed
Ceramic Mug	0.104	0.104	0.104	kg CO_2e/kg disposed
Paper Coffee Cup	0.027618909	0.85700467	1.904545455	kg CO_2e/kg disposed
Bamboo Fork	0	0.05886694	0.0748	kg CO_2e/kg disposed
Reusable Plastic Fork	0	0.486313	2.55	kg CO_2e/kg disposed
Metal Fork	0	0.006938084	0.0104	kg CO_2e/kg disposed
Plastic Fork	0	2.186611	2.87	kg CO_2e/kg disposed