LIFE CYCLE ASSESSMENT (LCA) OF ANTIOXIDANT ACTIVE PACKAGING: FINDING A BREAKEVEN POINT

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by

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ABSTRACT

To combat the food waste problem, active packaging technologies have been developed to extend the shelf life of food products at the consumer level. Non-migrative packaging, in which active compounds are immobilized on the food-contact surface, could also provide advantages in the clean label. Although active packaging could reduce food waste, it produces more environmental impacts because it requires additional raw material and processing steps, compared to conventional packaging. This study uses life cycle assessment (LCA) to gain an understanding of the sustainability performance of PET-Curcumin packaging that contains oil vinaigrette. The eco profile of the food-packaging system was calculated and presented in 8 impact categories. Overall, the additional impacts generated from the active packaging are small. A food waste reduction of 2% of the total amount contained in the packaging could offset the additional impacts of active packaging, except for freshwater eutrophication and fossil resource scarcity, which require 11.6% and 6.5%, respectively. Additionally, when developing active packaging for oil vinaigrette products, researchers need to pay particular attention to keeping fossil resource scarcity and human carcinogenic toxicity under acceptable levels.

BIOGRAPHICAL SKETCH

Xueqi was born in Shijiazhuang, China. She received her bachelor’s degree from the University of Wisconsin-Madison where she in Food Science and Nutritional Sciences. After completing a research and development internship and a food market insights internship, she decided to further her education in food science and sustainability. She joined the MFS program in the Fall of 2021. Since then, she has collaborated with Dr. Julie Goddard to evaluate the sustainability of active food packaging by conducting life cycle assessments. After graduation, she is looking forward to working in the food industry.

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I would like to thank Halle Redfearn, who provided me with technical information regarding the curcumin active package film she develops. I would also like to thank everyone in the Goddard Research Group, I will remember the wonderful time we shared.

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1. INTRODUCTION

1.1 Global & US food waste

The global food system is a major energy consumer and carbon emitter, accounting for about 30% of all energy consumed (FAO, 2011) and 34% of total carbon emissions (Crippa et al., 2021). One-third of the world's annual food output, over 1.3 billion tons, is lost or wasted, resulting in an estimated $1 trillion in economic losses, making food waste one of the most urgent global concerns (UN, 2022). The raw materials, fuel, and other resources used in the supply chain disappear with every discarded food item. According to the U.S. Environmental Protection Agency (EPA) estimation, more than half of the food waste in the U.S. occurs at the retail and consumer levels. Additionally, compared to industrial food waste, a higher proportion of food waste generated at the consumer end goes directly to landfills (EPA, 2020a). Therefore, reducing food waste at the consumer level is crucial for slowing climate change.

1.2 Oxidation in food products

Much of the food spoilage are caused by microbial degradation, oxidation, and change of moisture. Oxidation can alter the flavor, texture, and appearance of food products, rendering them unacceptable to consumers (Resconi et al., 2012). Products of oxidation include off-flavors and toxic compounds that have adverse health effects (Guillen & Goicoechea, 2008) To combat oxidation in food, the food industry has widely adopted antioxidants, such as EDTA, in the form of direct additives. However, in recent years, artificial additives are increasingly unwelcomed by consumers as the demand for natural food ingredients increases (Maruyama et al., 2021). Therefore, there is a compelling need to remove artificial antioxidants from food formulations without significantly reducing shelf life.

1.3 Active Packaging

Active packaging is an alternative approach to food additives for extending shelf life. Active compounds, such as antimicrobials and antioxidants, are incorporated into the food-contact surface of the packaging. Those active compounds are linked to the packaging material through non-covalent bonds, in migrative active packaging, or through covalent bonds, in non-migrative packaging. Numerous previous studies have reported that migrative food packaging, which depends on the controlled diffusion of active compounds into the food, is effective against food spoilage (Barbosa-Pereira et al., 2014; Fiore et al., 2021). However, the migration of active compounds may alter the sensory qualities of the food product enclosed (Muriel-Galet et al., 2013). Additionally, the active compounds that migrate into food matrix may make the product no longer qualify for organic or clean labels, and present a complicated pathway for regulatory approval, since they are direct additives as any other ingredient.

Non-migrative packaging, on the other hand, has the advantage over migrative packaging in the regulatory aspect. Because active compounds are immobilized onto the packaging material, they are not regulated as direct additives (21CFR101.100). Studies have demonstrated that the migration rates of the active agents in nonmigratory active packaging are below regulation limits while the functionality was maintained. (Doshna et al., 2022; Tian et al., 2013; Tovar et al., 2005). The effectiveness of antioxidative nonmigratory active packaging has been investigated in earlier studies. The active films were examined in aqueous solutions of various pH, competing ion concentrations, and viscosities. It was demonstrated that polyhydroxamic acid-grafted polypropylene (pp-g-PHA) film successfully retarded the oxidative degradation of ascorbic acid, showing the potential for use of nonmigratory active packaging for liquid food (Zhu et al., 2019).

Except technical performance, its performance in sustainability also needs to be thoroughly evaluated.

1.4 Life Cycle Assessment

Life Cycle Assessment (LCA) is a powerful tool that measures the environmental impacts generated by a product or service throughout its life cycle. It calculates impacts such as carbon emission, non-renewable energy consumption, eutrophication potential, and acidification potential. The scopes of LCA are often cradle-to-grave or cradle-to-cradle. The two terms indicate raw material extraction to disposal and raw material extraction to re-utilization of waste materials, respectively. LCA allows researchers to identify points of improvement, helps policymakers to make decisions, and informs the public about the sustainability of the product or service (ISO 14044). By reviewing past LCA studies on active packaging, we found that, due to the difference in the choice of active compounds, base materials, and processing methods, the results are highly variable.

Notably, whether an active package is sustainable not only depends on the packaging itself but also on the food product it contains (Williams & Wiskström, 2011). For example, for high-impact foods like beef, a small percentage of shelf-life extension could compensate for the additional emissions generated by active packaging (Zhang et al., 2015). Although the production of fresh-cut fruits and vegetables has fewer environmental impacts, these foods are the most perishable and require packaging to extend their shelf life (Vigil et al., 2020).Therefore, a balance between reduced food waste and additional processes must be found based on the selected combination of active packaging and food products.

1.5 Choice of food and packaging materials

In this work, we chose a lemon basil vinaigrette product as the food matrix because of its susceptibility to oxidation and its low viscosity. The ingredients and product characteristics are extrapolated from a product found in a local supermarket. The main ingredients are canola oil and olive oil that are rich in unsaturated fats. The product does not contain artificial food additives, rendering a significantly shorter shelf life than vinaigrette products with artificial antioxidants. The shelf life is 6 months, versus 18 months for conventional products. The difference provides opportunity for shelf-life extension with active packaging. The reason we chose a vinaigrette instead of a mayonnaise-like salad dressing is that vinaigrettes have lower viscosity. According to a previous study, the efficacy of antioxidant active packaging decrease with increasing viscosity of the fluid (Zhu et al., 2019). Thus, a model product with low viscosity is more suitable for this study.

The packaging material we chose is PET with curcumin grafted on the food contact surface. Curcumin is a yellow-colored polyphenolic compound that naturally presents in the rhizome of *Curcuma longa*, the plant commonly known as turmeric. Research has reported the antioxidant property of curcumin (Jayaprakasha et al., 2006). Recently, the application of curcumin in active packaging has been explored. Curcumin demonstrated antioxidant and/or antimicrobial effects in various polymers, including gelatin (Roy & Rhim, 2020), Thermoplastic Cassava Starch/poly(butylene adipate-*co*-terephthalate (TPCS/BPAT) (Iqdiam, 2021), cellulose/chitosan (Xu et al., 2021). This study uses polyethylene terephthalate-Curcumin (PET-Cur) as the packaging material, considering both mechanical properties of PET and antioxidant capabilities of curcumin.

1.6 Purpose of the study

In this study, the environmental impacts of a model system consisting of a PET-Cur nonmigratory active bottle and an all-natural lemon basil vinaigrette are calculated. Breakeven points between the impacts of active packaging and food waste reduction are identified. Additionally, the study displays the distribution of environmental impacts along the stages of the supply chain for the PET-Cur active food package. Suggestions are given to future research based on the findings of this LCA study.

2. METHODS

2.1 Goal and scope

This LCA study quantifies the environmental impacts generated from the life cycle of the food and its conventional PET packaging or PET-Cur active packaging. The objective is to investigate the relationship between the use of active packaging and the reduction of food waste in terms of various environmental impacts including terrestrial acidification, fine particulate matter formation, freshwater eutrophication, fossil resource scarcity, ozone formation- human health, global warming, marine ecotoxicity, and human carcinogenic toxicity. The food product system of choice is a lemon basil vinaigrette product with canola oil, olive oil, and balsamic vinegar as main ingredients. The vinaigrette is chosen because of its high susceptibility to lipid oxidation and its low viscosity. This study also identifies potential processes that needs future improvements and provides active packaging scientists with suggestions.

2.2 Software, databases, and frameworks

OpenLCA 1.11.0 (Green Delta, Berlin, Germany) is an open source, specialized software that is built to conduct LCA and life cycle impact assessment (LCIA) calculations. It could carry a wide range of databases, as well as manual inputs of input/output data. The calculations and analysis accords to the framework defined by ISO 14040 and 14044. In this study, the databases used are Ecoinvent 3.8 (Ecoinvent, Zurich, Swizerland) and Agribalyse 3.0.1 (French Agency for Ecological Transition; France's National Research Institute for Agriculture, Food, and Environment, France). Ecoinvent is one of the most used databases in LCA studies with recognized reliability, and coverage of wide range of sectors. Agribalyse is developed by French Agency for Ecological Transition to provide a life cycle inventory database specialized in agricultural and food products. The inventories in Agribalyse are built based on data from Ecoinvent. As a result, using Agribalyse in conjunction with Ecoinvent does not affect the consistency of inventory data. The algorithm used for impact calculations is "Allocation, cut-off". The algorithm is used in attributional LCA studies in which the inputs and emissions are allocated based on either economic value or physical relationship. Under this algorithm, the system only carries the burdens of the recycling/disposal processes but does not receive credits from them. For example, the heat generated from incineration and the recycled products from recycling process are not converted to negative inputs, but the energy spent in the processes are carried by the system. The LCIA method is ReCiPe 2016 Midpoint (H) (PRé Sustainability, Amersfoort, the Netherlands), which translates emissions to mid-point environmental impact factors that are equivalent amounts of reference substances (Huijbregts et al., 2017). The impact categories selected for analysis are presented in section 2.6.

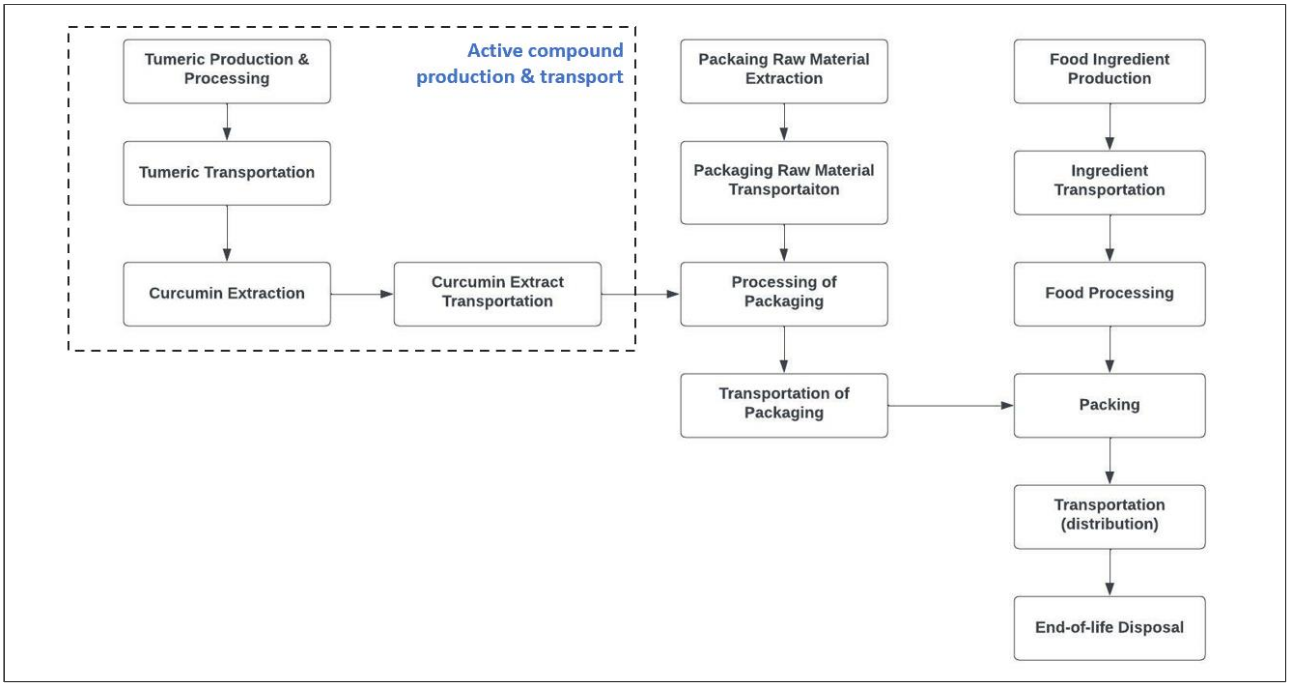
2.3 Functional Unit

In this study, the functional unit is defined as 1000 items. For food + packaging analysis, the functional unit is made up of 1000 bottles of product. The product characteristics are determined based on a lemon basil vinaigrette product that is purchased from a supermarket. Each bottle is comprised of 50g PET/PET-Cur bottle and a 7g PP cap. The weight of vinaigrette contained in each bottle is 460g. The weight of the paperboard boxes used to distribute 1000 bottles of product from the manufacturer to the retailers is 12kg. For analysis on food production alone, 1000 items equal 460 kg of lemon basil vinaigrette.

2.4 System boundary

Figure 1 illustrates the system boundary of the LCA. This study is a cradle-to-grave study, i.e. from raw material extraction to end-of-life, with certain stages excluded. The excluded stages are retail store display, consumer storage and consumption, and end-of-life disposal of vinaigrette. Retail store display is excluded because the difference in emissions generated from the store display stage of the two products are minimal since they are unlikely affected by the type of packaging used for the product. The other stages are excluded because the food waste and storage data at consumer end are largely unavailable and difficult to collect (Heller et al., 2019). The end-of-life of packaging is included because of existence of official data. No specific geographical boundaries are set in the analysis because this study aimed to imitate the situation in North America while geographically specific data is lacking in this region. The providers of the inventory data are either European, Canadian, or global average. The transportation distances are mapped assuming the processing sites are in the U.S. except that the Turmeric powder are assumed to be sourced from India.

Figure 1. System boundary and key life cycle stages of food product and conventional, active bottles. Stages in the dashed rectangle are exclusive to active packaging



2.5 Life cycle inventory

The data source and assumptions for the life cycle processes in this study are presented in table1. When available, inventory data from Ecoinvent and Agribalyse databases are preferred. When the inputs are not directly found in the databases, data are extracted from scientific literature and converted to reference flows.

Table 1. Life cycle processes, data sources, and assumptions

Life cycle Process	Data source	Assumptions
Plastic granulate production	Ecoinvent	PP cap, PET bottle
Injection molding	Ecoinvent	Cap, 2% loss rate
Blow molding	Ecoinvent	Conventional bottle, 3% loss rate
Co-extrusion	Ecoinvent	Active bottle, 3% loss rate, 10% PET-Cur + 90% PET, 2% curcumin in active material; radical initiator DCP converted to the amount of cumene needed to make DCP (Nowacka et al., 2019)
Transport, freight train	Ecoinvent	
Transport, fright lorry	Ecoinvent	16-32 metric ton, EURO5
Transport, freight, sea, container ship	Ecoinvent	India to USA
Turmeric powder	Agribalyse, literature	11.5% dry matter from fresh turmeric (Borah et al., 2017)
Curcumin extraction	Literature, Ecoinvent	Powder: acetone (w/v) = 1:3 (Wakte et al., 2011)
Lemon basil vinaigrette production	Ecoinvent, Agribalyse	

As presented in Table 2, the assumptions on end-of-life scenarios for packaging material are extrapolated from EPA 2018 data with a slight twist for simplicity of calculations (EPA, 2020b). The recyclability of PET-Cur bottle is assumed to be inferior to that of PET bottles since few studies has examined the recyclability of active packaging. Therefore, PET-Cur bottles are either combusted for energy recovery or landfilled.

Table 2. End-of-life assumptions for conventional and active packaging materials

PP packaging material	landfill	80%
	combustion	20%
PET bottle	landfill	60%
	recycling	27%
	combustion	13%
PET-Cur bottle	landfill	80%
	combustion	20%
Cardboard	recycling	97%

2.6 Environmental impact categories

As stated above, eCiPe 2016 Midpoint (H) is employed as the LCIA method in this study. Although endpoint categories are more straightforward for the general public to interpret, midpoint environmental impact factors allow scientists to examine the impacts in greater details. Out of the 17 midpoint impact categories provided, the following 8 were selected based on relevance and importance:

- Terrestrial acidification

  The factor represents this impact category is Acidification potential (AP). The atmospheric pollutant, including NO_x, NH_3, and SO_2, and soil pollutant are quantified and expressed in kg SO_2 eq. The factor indicates acid deposition in the soil.

- Fine particulate matter formation

  The emission of precursor compounds, including NH_3, NO_x, SO_2, and primary $PM_{2.5}$ are quantified and converted to $PM_{2.5}$ eq. The factor is considered for the influences of human intake of $PM_{2.5}$ on the risk of cardiopulmonary disease and lung cancer (van Zelm et al., 2016)

- Freshwater eutrophication

The emission of phosphorous forms into freshwater are quantified and expressed in kg P equivalence. In the calculation, it is assumed that 10% of phosphorus emissions to agricultural soil migrate to freshwater (Bouwman et al., 2009)

- Fossil resource scarcity

  Fossil resource use is quantified into Fossil Fuel Potential, and expressed as kg oil eq. The factor is defined as the ratio of the fossil resource's higher heating value to the energy content of crude oil (Jungbluth & Frischknecht, 2010).

- Ozone formation, human health

  The release of a precursor (NO_x) or non-methane volatile organic compounds (NMVOC) lead to changes in the ambient concentration of ozone; the change is predicted and represented in kg NO_x eq (van Zelm et al., 2016). For ozone formation, human health category, the factor indicates the amount that concerns human population intake of ozone, which leads to adverse health effects.

- Global warming

  Emissions of greenhouse gases are quantified and converted to global warming potential (GWP), expressed in kg CO2 eq. GWP is widely used in climate analysis and reports, including IPCC report (Stocker, 2014).

- Marine ecotoxicity

  The impact of toxic substances on the marine ecosystem is quantified and expressed in kg 1,4 dichlorobenzene (1,4-DCB eq). 1,4-DCB is commonly found in pesticides, fragrances and chemical fibers in daily use. 1,4-DCB is genotoxic and it is carcinogenic in multiple tissues of animals (Igarashi et al., 2020)

- Human carcinogenic toxicity

  The carcinogenic effect of toxic pollutants on human health is quantified and converted in 1,4-DCB eq. (Huijbregts et al., 2005)

2.7 Evaluation of tradeoff between additional impacts and food waste reduction

To determine the target amount of food waste reduction, the difference between vinaigrette with conventional package and vinaigrette with active packaging was converted to a factor that representing the proportion of food that could generate the equivalent amount of impact. For each impact category, the food waste reduction equivalence factor was calculated following the equation:

$$\text{Food Waste Reduction equivalence (FWR eq)} = \frac{Impact_{V+active\ packaging} - Impact_{V+conventional\ packaging}}{Impact_{vinaigrette}} \quad (1)$$

Another approach to explore the relationship between the impact of packaging and food is food to packaging (FTP) impact ratio (Heller et al., 2019; Williams & Wikström, 2011). The equation used in this study to calculate follows Heller et al. (2019):

$$FTP = \frac{Impact_{agricultural\ production\ per\ kg\ food} + Impact_{food\ processing\ per\ kg\ food}}{Impact_{packaging\ materials\ per\ kg\ food}} \quad (2)$$

3. RESULTS & DISCUSSIONS

3.1 Eco-profile of vinaigrette and vinaigrette-packaging systems

The environmental impacts were calculated using 1000 items as the functional unit. The respective impacts of food products (Vinaigrette), food product with conventional packaging and outer packaging (V+ conventional), and food product with active packaging and outer packaging

(V+ active) were determined. Table 2 presents a summary of the results. As expected, products with active packaging exhibited greater environmental impacts compared to products with conventional packaging. The additional impacts came from the agricultural production, processing, transportation, and incorporation of the active compound curcumin.

Table 2. Eco-profile of vinaigrette, vinaigrette + conventional packaging, and vinaigrette + active packaging; functional unit = 1000 items

Impact category	Vinaigrette	V+ conventional	V+ active	Unit
Terrestrial acidification	9.579	10.28	10.33	kg SO2 eq
Fine particulate matter formation	1.735	2.059	2.065	kg PM2.5 eq
Freshwater eutrophication	0.1812	0.232	0.2531	kg P eq
Fossil resource scarcity	130	243.5	251.9	kg oil eq
Ozone formation, human health	2.273	2.837	2.859	kg NOx eq
Global warming	559.1	829.8	839.8	kg CO2 eq
Marine ecotoxicity	25.23	38.45	38.51	kg 1,4-DCB eq
Human carcinogenic toxicity	15.89	29.98	30.05	kg 1,4-DCB eq

3.2 Relative proportion of vinaigrette, vinaigrette with conventional packaging, and vinaigrette with active packaging

It has been widely recognized in LCA studies that, for high-impact foods such as meat and cheese, the production of food accounts for the majority of the environmental impact in the life cycle of food-packaging systems due to high consumption and emissions in the animal fattening phase and/or the food processing phase (Williams & Wikström, 2011; Zhang et al., 2015). Oil vinaigrette products are less impactful than meat and cheese since they are not derived from animal sources. Nonetheless, it is more impactful than low-impact foods such as minimally processed fruits and vegetables. Since there is no consensus on how medium-impact foods would affect the food-packaging interplay, it is crucial to determine in this study the proportion of impacts generated by the food-packaging system can be attributed to the food product itself.

Figure 2 depicts the relative proportion of vinaigrette, vinaigrette with conventional packaging, and vinaigrette with active packaging for each environmental impact category. The environmental impact values of vinaigrette and vinaigrette with active packaging were corrected by the values of vinaigrette with conventional packaging, which was set to 100%.

In the categories of terrestrial acidification, fine particulate matter formation, freshwater eutrophication, and ozone formation-human health categories, food production dominated due to the high impacts of agricultural processes. The impacts generated by food and packaging are nearly equal in terms of fossil resource scarcity and human carcinogenic toxicity. The additional impacts generated by the additional processes for active packaging are not significant in most categories. This is consistent with previous findings in LCA studies that the production and incorporation of active compounds usually accounts for a small portion of the total impacts (Lorite et al., 2017; Vigil et al., 2020). The greatest increase is observed in freshwater eutrophication because the curcumin used in this study is extracted from turmeric plant, the production of which involves agricultural processes. It is worth noting that although the freshwater eutrophication increased by 9.09%, the value of the increase is 0.0211 kg P equivalent.

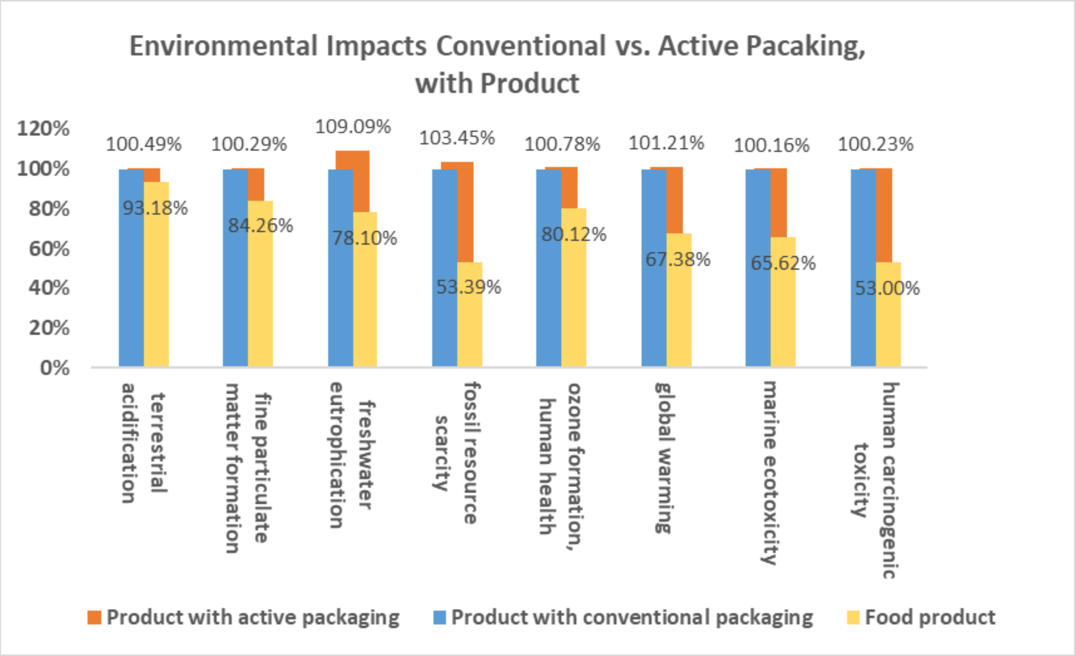


Figure 2. the % contribution of food product, product with conventional packaging, and product with active packaging to various environmental impacts. The contributions of product with conventional packaging are set at 100%

3.3 Factors depicting tradeoff between food and packaging impacts

Food waste reduction equivalence (FWR eq)

Due to the difficulty in collecting consumer-end food waste data, scientists have developed factors and models to examine the balance between the environmental impact of novel packaging and the environmental impact of reduced food waste. In this study, two factors were calculated to demonstrate the relationship between the environmental impacts of food and packaging. The first factor, food waste reduction equivalence (FWR eq), converts the additional impacts generated by active packaging to an equivalent percentage of food that is contained in the package. The results are presented in Table 3. FWR eq indicates the amount of food waste reduction that must be achieved by the active packaging to offset the additional impacts. For terrestrial acidification, fine particulate matter formation, ozone formation – human health, marine toxicity, and human carcinogenic toxicity, a food waste reduction of 1% of total weight can compensate for additional environmental burdens. Approximately 2% of food waste reduction is required to reach the breakeven point on global warming potential. To offset the additional freshwater eutrophication potential, the PP-Cur active packaging needs to reduce the amount of food waste by 11.6% of total packaged food. The number is 6.5% for fossil resource scarcity.

Food to packaging (FTP) ratio

The other factor is food to packaging (FTP) ratio. FTP ratio shows the potential additional impacts that are permitted in the novel packaging technology. A high FTP ratio indicates an ample room for increase in environmental impact in the new food packaging technology. In this case, even though the application of advanced active packaging technology generates greater environmental impacts, it is likely that a small portion of food waste reduction could counteract the effects. The greatest FTP ratio is observed in the terrestrial acidification category (Table 3). The terrestrial acidification potential from vinaigrette is 16.8 times that from PET package for each unit of product. Other categories with relatively high tolerance are fine particulate formation, freshwater eutrophication, and ozone formation-human health. In the development of active packaging technology, special attention is needed to restrict the fossil resource scarcity and human carcinogenic toxicity within acceptable levels.

Table 3. Additional impacts converted to food waste reduction equivalence (FWR eq), FTP ratio by category

	Terrestrial acidification	**Fine particulate formation**	**Freshwater eutrophication**	**Fossil resource scarcity**	**Ozone, human health**	**Global warming**	**Marine ecotoxicity**	**Human carcinogenic toxicity**
FWR eq.	0.5%	0.3%	11.6%	6.5%	1.0%	1.8%	0.2%	0.4%
FTP ratio	16.08	6.73	4.28	1.28	5.21	2.75	2.20	1.28

3.4 Distribution of impact contribution of processes in the life cycle of PET-Cur active packaging

As shown in figure 3, the production of PET pellet, which includes the acquisition of raw material, is the top 1 contributor in the life cycle of PET-Cur active packaging across all environmental impact categories. To alleviate the negative impacts of plastics, researchers have attempted to develop active packaging with base materials of plant sources. One of the materials that draw the most attention is polylactic acid (PLA). PLA is currently the most used biodegradable polymer because its advantages in cost, availability, transparency, and thermal processability (Zhong et al., 2020). Previous studies have attempted to construct active packaging with PLA as the base material (Fiore et al., 2021; Kay et al., 2022). However, LCA study has found that currently, PLA is more impactful than PET in terms of ecotoxicity, acidification, and human health impacts due to use of fertilizer and pesticides in growing sugar cane crop, the raw material for PLA production (Desole et al., 2022). Future substitution of PET with PLA or other biopolymers requires advancements in agricultural technology and recycling/composting infrastructure (Desole et al., 2022; Mendes & Pedersen, 2021). Thus, PET remains a good choice for the base material of active packaging before the advances in agricultural technology and PLA recycling/composting infrastructures are achieved.

The production of curcumin, which encompasses the cultivation of turmeric, post-harvest processing, and extraction of curcumin from turmeric plant, has substantial influence on freshwater eutrophication (figure 3). To reduce the additional impact from active compounds, consideration could be given to the use of synthetic active compounds. Another option is to use curcumin derived from turmeric residue. With the pressing concerns on both food waste and negative environmental impacts, scientists have connected the concepts of bioeconomy and circular economy, proposing upcycling of waste stream into value added products (Mak et al., 2020). Previous research has explored the use of turmeric residue from dye extraction in bioactive packaging film (Maniglia et al., 2015). Studies have also been conducted to find novel technologies to extract other bioactive compounds from food waste (Mouratoglou et al., 2016). Utilizing agri-food waste as the source of active compounds could not only save the environmental impact generated from the agricultural process to produce active compounds, but also recapture and recycle the waste streams of other production systems.

Notably, for marine ecotoxicity and human carcinogenic toxicity, co-extrusion, the processing method for PET-Cur nonmigratory active packaging, was identified as one of the top contributors, despite having a negligible effect on other impact categories (Figure 2). Previous studies have demonstrated that, compared to other reagent-dependent grafting methods, co-extrusion has the advantages of being solvent-free and single-step (Doshna et al., 2022). Thus, future efforts could focus on improving the productivity and reducing waste stream of the co-extrusion process.

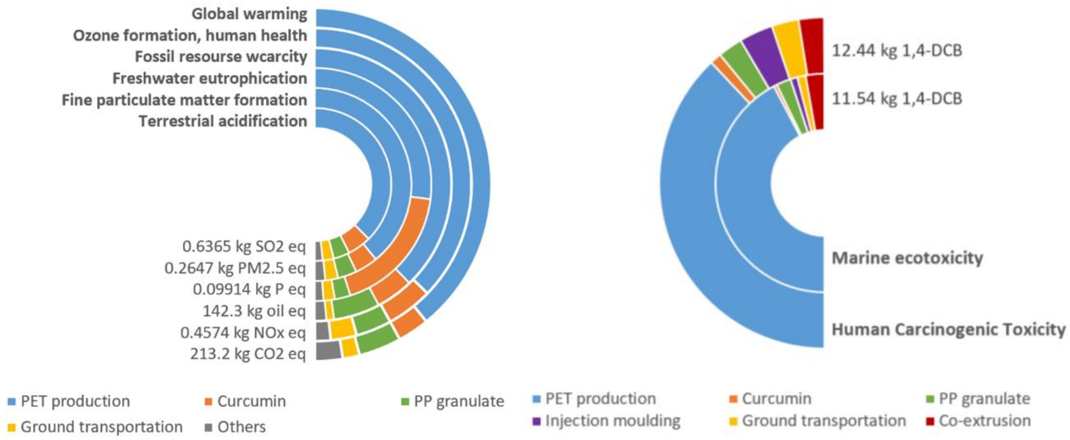


Figure 3. the distribution of environmental impacts of the top contributor categories

3.5 Limitation of current study

There are several limitations in this study and LCA studies in general. First, this study is a not a regionalized analysis due to lack of geographically specific data retrieved from North America. While data from EU countries are abundant, life cycle inventory data in North America are yet to be collected. This requires collaborative efforts of the private sector, academic institutions, and government agencies. Secondly, in this study, the majority of the life cycle inventory data are retrieved from databases. To improve accuracy, it would be ideal to obtain on-site manufacturing data or to consult industry experts.

In literature review, it was noticed that many LCA studies did not publish inventory data at a level of detail that could be easily repeated by other scientists. The results of LCA studies are highly dependent on the choice of system model, algorithm, and assumptions. While replicability is well addressed in the laboratory protions of the studies, it is frequently overlooked in LCA analysis. Also, most studies did not specify whether they are consequential or attributional study. In practive, it was found that the choice of using attributional or consenquential algorithms leads to differences in magnitude of the results. Notably, although researchers may choose either algorithm, the selection should match the design of the system model (Weidema et al., 2018). For example, in cradle-to-cradle LCA studies in which recycled energy and materials are fed back into the system, attribution-cutoff algorithm is unlikely a good fit for the analysis due to the inconsistency between the logics of the system design and that of the attributional algorithm.

3.6 Future research

Before the commercialization of the non-migrative active packaging technology, the following need to be considered. First is the recyclability of active packaging materials. A few studies have investigated the effect of active compounds on the performance of recycled active packaging material. A study tested the mechanical properties of materials recycled from nano-particle-reinforced active packaging, concluding that the nanoparticles compromised the color and elongation at break of PET (Sánchez et al., 2014). Few study has examined the recyclability of non-migrative active packaging. Caution should be taken on the accumulation of active compounds in the recycling system. Moreover, without closed-loop recycling infrastructure to remove active compounds, the material can only be downcycled instead of recycled because recycling requires very low level of contaminants (Franz & Welle, 2022). According to current FDA regulations, active packaging may only eligible for tertiary recycling (FDA, 2021). However, closed-loop recycling of active packaging is difficult to execute and will require specialized equipments. Therefore, caution should also be taken when setting end-of-life assumptions for future senarios: a high rate of recycling may be unrealistic for active packaging.

To obtain a more accurate estimation of shelf-life extension, a shelf-life study using PET-Cur packaging film and oil vinaigrette product should be conducted. The effective concentration of curcumin in the active film could also be determined from the shelf life study. For the interpretation of LCA analysis reuslts, researchers could explore other parameters that may better demonstrate the interplay between active packaging and food waste reduction.

To better understand the sustainability performance of non-migrative active packaging, LCA could be conducted on active packaging in different scenarios. For example, the effect of PET-Curcumin on shelf life extension of other food product could be investigated. The change in impacts when substituting the base material with biopolymers could also be explored.

4 CONCLUSIONS

An LCA study was carried out to quantify the eco-profile of lemon basil vinaigrette product and its PET or PET-Cur active packaging. The relationship between the additional environmental impacts and food waste reduction generated by active packaging was also explored. The food production generates the most environmental impacts in the food-packaging system; the production of plastic pellets generates the most environemntal impacts in active packaging. Overall, the Points of breakeven between the two was identified for each impact category. To offset the additional impacts of terrestrial acidification, fine particulate matter formation, ozone formation – human health, marine toxicity, and human carcinogenic toxicity, a food waste reduction as small as 1% is needed. For the impact of global warming, a breakeven point was achieved at 2% food waste reduction. The aims of food waste reduction are higher for freshwater eutrophication and fossil resource scarcity, the values are 6.5% and 11.6% respectively. In the future development of active packaging, scientists should pay attention to limiting additional impacts of fossil resource scarcity and human carcinogenic toxicity within acceptable levels.

For LCA studies, researchers should put more emphasis on replicability. Publishing inventory data and assumptions in supplementary material would help fellow researchers to assess the quality of the analysis. The results of LCA studies depend heavily on assumptions, model design, and choice of algorithm. Thus, researchers should state clearly whether the study used attributional or consequential algorithm, and whether a cut-off is applied in the calculations of impacts. For prospective LCA studies, researcher need to be cautious about end-of-life assumptions as high level of recycling may be difficult to achieve for active packaging.

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