COMPARING THE ENVIRONMENTAL IMPACTS OF PET, PP, COATED PAPERBOARD, AND MOLDED FIBER FROZEN MEAL TRAYS: A REVIEW

By

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ABSTRACT

COMPARING THE ENVIRONMENTAL IMPACTS OF PET, PP, COATED PAPERBOARD, AND MOLDED FIBER FROZEN MEAL TRAYS: A REVIEW

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Increased public awareness of environmental impacts associated with packaging has caused companies to seek out more sustainable materials to package their goods. Investigation into the comparative environmental impact of frozen meal trays was conducted due to a perceived environmental benefit associated with a switch from traditional plastics to fiber packaging materials. Life cycle assessment (LCA) provides a highly defensible method for comparing the full life cycle impact of alternatives, but consumer perception of packaging sustainability largely focuses on material attributes associated with the end of life phase, such as recyclability and compostability. A preliminary review of published life cycle literature and a detailed look at the end of life section of the life cycle with a specific focus on consumer access to waste management infrastructure in the United States were used to better understand the comparative environmental impact of frozen meal trays produced from polyethylene terephthalate (PET), polypropylene (PP), coated paperboard, and molded fiber. General trends in comparative impact between plastic and fiber alternatives were identified in published literature, but the lack of studies focused on the target package and materials indicates a need for further life cycle assessment to elucidate the comparative impact of the frozen meal trays. Analysis of consumer access to waste management showed that the ability of a package to be handled by an end of life option deemed preferable does not automatically imply associated environmental benefits will be achieved.

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CHAPTER 1 – INTRODUCTION

Increased awareness of the environmental impacts associated with the production and disposal of packaging has caused companies to seek out more sustainable means to package their goods. This has included shifting away from traditional, oil-derived plastics to materials produced from renewable resources, a move catalyzed by highly visible issues such as plastic litter in marine environments and a perceived environmental benefit associated with the use of biobased materials. The perception of environmental friendliness is also becoming increasingly important to consumers and can positively influence views of product quality [1]. Specifically, consumer perception of packaging sustainability focuses on features associated with the end of life, such as recyclability, biodegradability, or compostability, which are commonly seen as indicators of reduced environmental impact, whether or not that is actually the case [2]–[4].

On average, U.S. consumers spent $67.41 on frozen meals in 2017, up approximately 11% from the previous year [5]. Frozen meals have also been found to reduce food waste in the home compared to fresh and ambient food equivalents [6]. Traditionally, polypropylene (PP) and a crystallized polyethylene terephthalate (CPET) have been used within the frozen meal space due to application-specific material requirements and plastic's ability to create a contrasting background used to accentuate the product [7]. Paperboard coated with plastic has also been used as a means to incorporate renewable material into the packaging while maintaining the required package properties. Most recently, molded fiber has been utilized as a way to fully move away from the traditional plastics in favor of an entirely fiber-based, renewable package. Pictures of trays produced from each material are shown in Figure 1.

Figure 1: Frozen meal trays

Although there is commonly a perceived environmental benefit associated with replacing plastic packaging with fiber alternatives, in-depth analysis is required to elucidate the validity of that perception. This is particularly important for a material such as molded fiber, which is entering the frozen meal space due to a desire for reduced environmental impact. Life cycle assessment (LCA) is a methodology commonly used to evaluate the environmental impact of a product or package system through its life cycle. The International Organization for Standardization (ISO) published the 14044 standard in 2006, standardizing the approach to life cycle assessment into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [8].

The strength in LCA is that, through its standardized process, it allows for the comparison between alternatives, making it useful in helping to understand the comparative impact of the frozen meal trays produced from different materials. Full life cycle assessment is an involved process, making an initial review of published life cycle assessment literature useful to determine if any comparative analysis focused on the package forms and materials included in this study has already been conducted. Further, a review of previous literature can shed light on what knowledge gaps exist and guide continued study.

This research is split into two sections: a preliminary review of published life cycle literature and a detailed look at the end of life section of the life cycle with a specific focus on consumer access to waste management infrastructure in the United States. The research aims to better understand the comparative environmental impact of the frozen meal trays in two ways: through a focus on life cycle assessment, a highly defensible method for comparing environmental impact, and through a focus on end of life, a life cycle section commonly associated with material attributes seen as indicators of reduced environmental burden by consumers. This paper will be split into 5 chapters. Chapter 2 includes a literature review focused on life cycle assessment and end of life options in the United States. Chapter 3 presents information on the package form and materials in focus for this study and life cycle assessment literature related to each. Chapter 4 includes information on access to end of life options in the United States with additional discussion of the opportunity for the frozen meal trays to be handled by waste management options from which environmental benefits can be realized. Finally, conclusions and recommendations for future work are provided in Chapter 5.

CHAPTER 2 – LITERATURE REVIEW

2.1 – Life Cycle Assessment

Life cycle assessment is a methodology used to quantify the environmental impacts associated with a product or service from the raw material acquisition, through production, to disposal at end of life [9]. This is done by quantifying and translating inputs and outputs associated with each section of a product or service's life cycle to environmental and health impacts [10]. For example, greenhouse gases such as carbon dioxide and methane emitted during the production of PP resin can be measured and subsequently translated into the global warming potential of the production process using a consistent unit. This process can then be applied to other inputs and outputs, as well as other sections of the life cycle. LCA is standardized by the ISO 14040 and 14044 standards [8]. The process has many applications, including product development and improvement, government policy development and industry decision making, and justification for environmentally-focused marketing [8]. Further, the standardized approach to LCA allows for comparisons between alternatives [10].

Life cycle analysis was first used in the late 1960s to account for environmental releases and use of natural resources in the production of beverage containers [11]. The concept was initially referred to as resource and environmental analysis, which focused on quantifying emissions and energy demand without translation to impacts on human and ecosystem health [11]. Oil shortages in the 1970s and an increased focus on landfill availability in the 1980s were causes for continued use of life cycle inventorying of energy demands and waste production, but no standardized approached was utilized in published studies [12], [13]. In the early 1990s, the Society of Environmental Toxicology and Chemistry (SETAC) released technical guidelines attempting to standardize the process of life cycle assessment, identifying three separate, but interconnected steps; the life cycle inventory, life cycle impact analysis, and life cycle improvement analysis [12]. A scoping step was later added to the SETAC guidance, creating a structured framework for the LCA process similar to that used today [13]. ISO released its first LCA standard in 1997, with additional iterations in 1998 and 2000 prior to the 2006 version still used today [8], [14]. Most recently, the European Commission's Joint Research Centre – Institute for the Environment and Sustainability released The International Reference Life Cycle Data System (ILCD) handbook, which provides additional guidance in conducting LCAs in accordance with ISO standards [10].

LCA described by the ISO 14044 standard is broken down into four main sections: definition of the study goal and scope, development of the life cycle inventory (LCI) data, translation of the life cycle inventory data into associated environmental and health impacts during the life cycle impact assessment (LCIA), and interpretation of the results [8]. Figure 2 shows the framework as described by the ISO 14044 standard as well as applications for life cycle assessment.

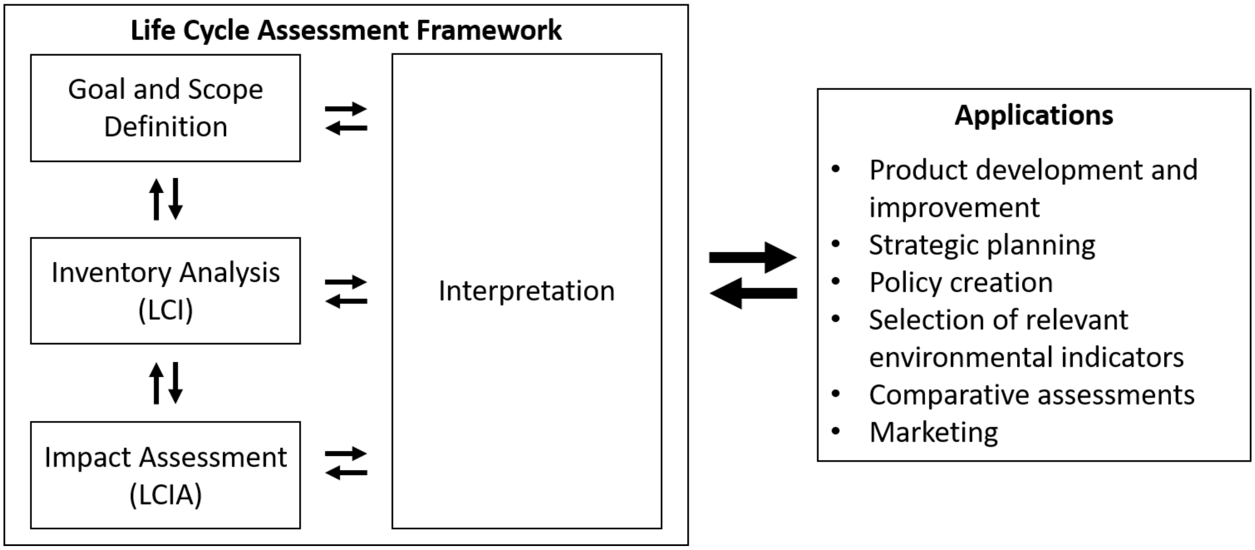

Figure 2: Life cycle assessment framework and applications (adopted from ILCD Handbook [10])

The first step of a life cycle assessment is the definition of the goal and scope of the study. The goal provides the reasoning for conducting the study and the intended applications of the study. The scope outlines details pertinent to how the study will be conducted, including the systems being studied, the functions of the systems and the associated functional unit, the system boundaries, LCIA methodologies, and how the results will be interpreted [8]. Once the function of the systems being studied is defined, the functional unit acts as a reference for the normalization of the input and output data collected during the life cycle inventory [8]. For example, the function of a frozen meal tray could be described as the containment, delivery, and proper cooking of a single-serve, frozen meal. Based on the function, the functional unit for a LCA study focused on the comparative assessment of frozen meal trays could be defined as the amount of packaging material required to contain, deliver, and cook 1000 servings of frozen meal. Inventory data and category impacts can then be understood in the context of 1000 frozen meal trays. The system boundaries define the sections of the life cycle, referred to as unit processes, that will be included within the study [8]. System boundaries are commonly defined through the use of flow diagrams and can range from the full life cycle (i.e. cradle-to-grave) to a section of the life cycle (i.e. cradle-to-gate).

Following the definition of study goal and scope, input and output data for the processes included within the system boundaries is collected during the life cycle inventory. Many LCA utilize previously generated datasets housed within LCI databases such as Europe's EcoInvent or the United States' National Renewable Energy Laboratory LCI Database [9], [15]. The datasets contain aggregated unit process data, making them more widely representative in comparison to data collected from a specific site.

Input and output data collected during the life cycle inventory phase is translated into environmental and health impacts during the life cycle impact assessment phase. During the LCIA, impact categories are selected, the LCI data is assigned to relevant categories (classification), and category indicators are calculated and converted into common units based on the classification (characterization) [8]. Different methodologies for LCIA exist, some utilizing midpoint methods where LCI data is translated only into impact categories such as global warming potential, acidification, or carcinogens, while others utilize endpoint methods where impact categories are consolidated into broad endpoint categories such as damage to human health or ecosystems. Following characterization, normalization can also be used to illustrate differences in magnitude of impact between selected indicator categories. Further, subjective weighting can also be used to convert or aggregate indicator categories to weighted factors based on the intended audience [8].

Throughout each phase of LCA, interpretation is carried out to ensure the study is consistent with the defined goal and scope. Interpretation is also used to identify issues based on the results of the LCI and LCIA phases [8]. Although robust in nature, life cycle assessment also has limitations. In a review of LCA methodology and application, Curran identifies a number of aspects important to the interpretation of LCA results [9]. The aspects most relevant to a review of life cycle literature focused on frozen meal trays include a general lack of readily available, high quality inventory data, the rarity of LCA in actually showing a clear-cut "winner" in comparative analyses, and, in some cases, the inability of comparative LCA to articulate a better alternative at all [9]. In a study on data quality issues for bioplastic feedstocks, Grabowski et al. also make note of the limited availability of inventory data for some biobased materials, such as bioplastics [16]. Ayres also identifies the "pro vs. con" nature of evaluating alternatives in comparative analyses, stating that many LCAs only show tradeoffs in environmental impact between alternatives based on the wide range of considerations inherent in the LCA process [13].

2.2 – End of Life Options

All of the frozen food trays at end of life can be defined as municipal solid waste (MSW), the category of waste generally produced within households, businesses and institutional locations [17]. It includes durable goods, non-durable goods, packaging, and other organic wastes [18]. The United States Environmental Protection Agency produces a yearly report titled "Advancing Sustainable Materials Management" within which waste statistics and trends from waste produced within the U.S. are reported [17]. The report focuses on the generation and handling of MSW. The most recent EPA Advancing Sustainable Materials Management report provides municipal solid waste numbers from 2015 [17]. In 2015, 262 million tons of MSW was generated, containers and packaging accounting for 30% of total generation at 78 million tons [17]. Waste generation and handling figures by end of life option for paper and paperboard, plastics, and organic wastes are shown in Table 1.

Table 1: 2015 paper and paperboard, plastics, and ancillary organic waste generation and waste handling statistics (data from United States Environmental Protection Agency [19])

	Thousands of tons *(% of generation)*			
	Generated	**Landfilled**	**Combusted w/ energy recovery**	**Recycled or Composted**
Container or Package	77, 440	29,400 *(38.0)*	7,190 *(9.3)*	41,330 *(40.3)*
Paper and Paperboard				
Corrugated Boxes	31,330	1,930 *(6.2)*	470 *(1.5)*	28,930 *(92.3)*
Other Paper and Paperboard	8,590	5,080 *(59.1)*	1,240 *(14.4)*	2,270 *(26.4)*
Total Paper and Paperboard	39,920	7,010 *(17.6)*	1,710 *(4.3)*	31,200 *(78.2)*
Plastics				
PET Bottles and Jars	2,980	1,680 *(56.4)*	410 *(13.8)*	890 *(29.9)*
HDPE Natural Bottles	760	430 *(56.6)*	100 *(13.2)*	230 *(30.3)*
Other Containers	1,940	1,270 *(65.5)*	310 *(16.0)*	360 *(18.6)*
Bags, Sacks, and Wraps	4,130	2,890 *(70.0)*	710 *(17.2)*	530 *(12.8)*
Other Plastics	4,870	3,800 *(78.0)*	930 *(19.1)*	140 *(2.9)*
Total Plastics	14,680	10,070 *(68.6)*	2,460 *(16.8)*	2,150 *(14.6)*
Other Organic Wastes				
Food	39,730	30,250 *(76.1)*	7,380 *(18.6)*	2,100 *(5.3)*
Yard Trimmings	34,720	10,800 *(31.1)*	2,630 *(7.6)*	21,290 *(61.3)*
Total Other Organic Wastes	74,450	41,050 *(55.1)*	10,010 *(13.4)*	23,390 *(31.4)*

For non-hazardous materials such as MSW, the U.S. EPA has developed a schematic for the various methods of available waste management, titled the Waste Management Hierarchy [20]. Figure 3 orders the various methods of waste management within the United States based on preference, starting with the waste management methods deemed the least environmentally impactful at the top. When considering the management of packaging at the end of life, recycling, composting, and combustion with energy are all seen as preferential and less impactful waste management strategies compared to final disposal.

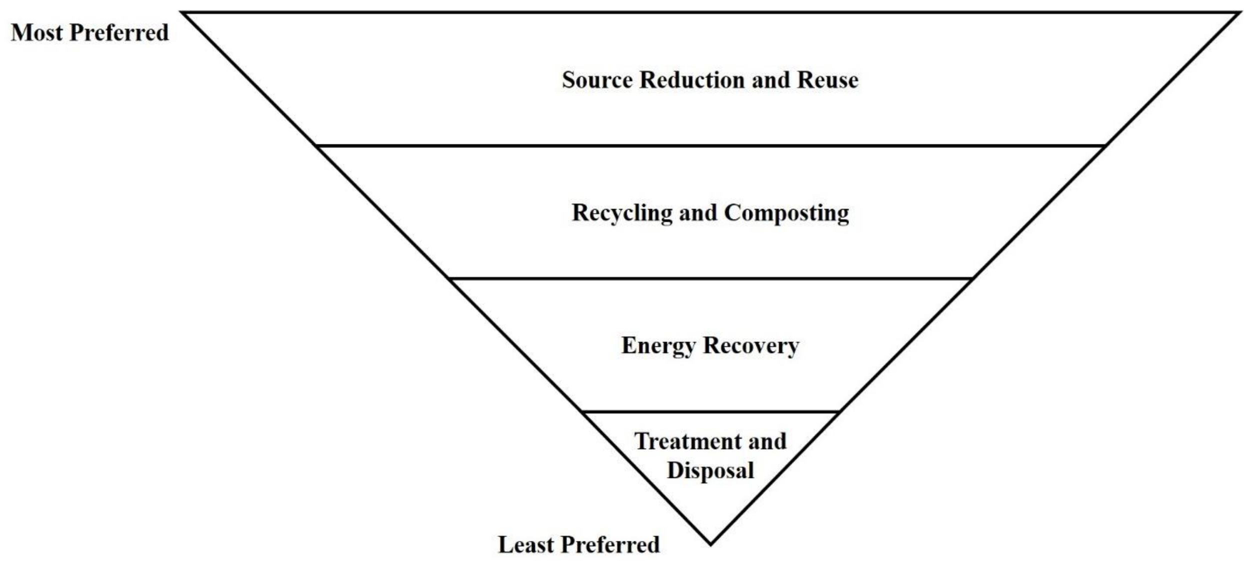

Figure 3: Non-hazardous waste management hierarchy (adopted from United States Environmental Protection Agency [20])

2.2.1 – Recycling

Recycling is the process of reusing diverted materials to produce new products. The recycling process consists of four steps: collection of diverted material, sorting of the materials into specific streams, reprocessing of the sorted material into a usable feedstock, and reusing the diverted material in the creation of a new product or package [21]. Many materials commonly found in the MSW stream can be recycled, including plastics, paper, glass, and metal [22].

Recycling is a preferred waste management strategy due to reducing impacts associated with final disposal and offsetting associated impacts through the displacement of virgin material [23]. In comparison to final disposal, the extent to which environmental impacts are mitigated is dependent on the material being recycled, but environmental benefits associated with recycling both fiber materials and plastic have been shown [24]. For materials with a large amount of biogenic carbon like paper, recycling is beneficial as it limits methane emissions associated with anaerobic degradation of the material in a landfill setting and displaces the impacts associated with the production of virgin paper. Additionally, the use of recycled paper creates the potential for forests to sequester carbon due to decreased virgin material demand for wood to be used as an energy source that can displace the use of fossil fuels [22], [25], [26]. Recycling of plastics can result in a large reduction of emissions of greenhouse gases, particulate matter, and heavy metals through the displacement of impacts associated with the manufacturing of virgin material [27].

In a review of life cycle assessment literature focused on waste management, the United Kingdom’s Waste and Resources Action Programme (WRAP) sought to determine how recycling compared with other waste management options using depletion of natural resources, climate change potential, cumulative energy demand, and water consumption as indicator categories [22]. In that study, paper recycling was found to be preferable to landfill in climate change potential due to offset disposal and primary production emissions, energy demand due to avoided primary production energy, and water consumption due to a net reduction compared to water needs for primary fiber production [22]. Mechanical recycling of plastic was found to be the best waste management system in all reported indicator categories, benefits maximized by good collection and a high level of displacement of virgin material [22]. The benefit of offset primary production is illustrated further in research by Turner, Williams, and Kemp, in which avoided greenhouse gas emissions associated with primary production were found to be the major contributor to net greenhouse gas emission reductions associated with recycling [28].

In a review of life cycle assessment literature focused on waste management of paper conducted by Villanueva and Wenzel, a general consensus of the environmental benefits of recycling paper over incineration or disposal in landfill was found, despite geographic location [29]. Merrild, Damgaard, and Christenen found that, if the production of fossil fuel energy is substituted by the production of energy utilizing biomass saved from the use of recycled paper, recycling performs better than incineration in terms of global warming potential [30]. Studies by Foolmaun and Ramjeeawon [31] and Chilton, Burnley, and Nesaratnam [27] used life cycle assessment to investigate recycling of post-consumer PET in comparison to final disposal in landfill and incineration with energy recovery. Foolmaun and Ramjeeawon found increased flake production for recycling to be the least impactful option compared to landfill and incineration for human health categories, climate change potential, and acidification/eutrophication potential [31]. Increased flake production for recycling was found to be the most impactful option for the land use and ecotoxicity categories [31]. Chilton, Burnley, and Nesaratnam also found recycling of post-consumer PET bottles to produce less environmental emissions and pollutants compared to incineration with energy recovery used to displace thermal energy production [27]. This was due to the ability of the recycled PET to displace the impacts associated with the manufacturing of virgin PET

2.2.2 – Biological Treatment of Organic Waste

Biological treatment of MSW consists of the degradation of organic material by microorganisms in controlled environments, resulting in the production of gases (CH_4, CO_2, N_2O), water, and residual solids [32]. Biodegradation can be done aerobically through a composting process and anaerobically through a digestion process. In the United States, the majority of anerobic digestion systems are liquid operations used for the treatment of sewage sludge or animal manure while composting is used for a variety of solid organic materials, including food waste, yard trimmings, and agricultural residues [33]. Composting can be done both at an industrial scale and in at-home operations. Industrial composting is the biological decomposition of organic waste under managed, primarily aerobic conditions that allow for thermophilic conditions (50 – 60 °C) to be produced from biologically generated heat [34], [35].

At-home composting utilizes the same biological decomposition processes, but due to the smaller scale, results in lower psychrophilic (0 – 20 °C) and mesophilic (20 – 45 °C) temperature ranges [34], [36].

Composting of organic MSW has benefits similar to those associated with recycling, namely the avoidance of impacts associated with final disposal and the potential to displace impacts associated with the production of other materials. Compost can be used as a substitute for fossil-carbon derived soil amendments such as peat, a soil conditioner extracted from wetland areas, and act as a source of organic nitrogen, limiting the need for additional fertilizer application and offsetting impacts associated with fertilizer production, such as N_2O [32], [37], [38]. Further, the use of finished compost as a soil amendment can improve soil quality, build soil structure, and sequester carbon [33], [37].

In a study focused on hotspot identification for a food waste composting operation, Saer et al. found a net reduction in all indicator categories when comparing the impacts associated with composting operations and the offset impacts associated with peat mining when using compost as a soil amendment [37]. Similarly, WRAP found that benefits associated with the use of compost are derived from the ability to displace products such as soil conditioners and fertilizers [22]. Composting of food packaging is also appealing because it eliminates the need to separate the packaging from residual food material, which can cause issues during the recycling process, and eliminates emissions associated with the anaerobic degradation of both materials in the landfill [32].

2.2.3 – Incineration

The thermal treatment of municipal solid waste, referred to as incineration, is a waste management process that reduces the volume of residual waste through a combustion process prior to disposal in landfill [39]. Additionally, incineration produces bottom ash, consisting of non-combusted material, fly ash, consisting of contaminants, acid gases, and other products of incomplete combustion, and high pressure steam, which can generate electricity or produce thermal energy directly [40], [41]. As such, some incineration operations are referred to as waste-to-energy.

In comparison to final disposal, the benefit of incineration with energy recovery is production of electricity and heat, which can replace energy production from fossil fuel sources [39]. Although methane gas capture for energy purposes is done at landfills, a much higher amount of energy is produced in incineration operations, making the process preferable if waste is to be used as an energy source [42].

Merrild, Larsen, and Christensen have shown that incineration can be environmentally better than recycling for waste fractions including paper and plastic, but this requires a high level of energy recovery and is dependent on the indicator categories used [25]. Results from WRAP were inconclusive comparing paper recycling and incineration in climate change potential, cumulative energy demand, and depletion of natural resources due to location-specific assumptions related to energy mix (i.e. high portion of CO_2 free energy sources) and the level of virgin material required to supplement recycled material [22]. That same study did find incineration of both paper and plastic to be preferable to landfill in the energy demand category due to increased levels of energy recovery associated with incineration operations [22]. Assamoi and Lawryshyn found incineration without consideration of offset thermal power plant energy production to be worse than landfill for residual waste in terms of global warming potential, acidification potential, and eutrophication potential [42]. If offset energy production at a thermal power plant is considered, incineration outperformed landfill by a wide margin in all three indicator categories [42].

CHAPTER 3 – LIFE CYCLE ASSESSMENT FOR FROZEN MEAL TRAYS

3.1 – Package Descriptions

Four materials used to produce frozen meal trays were the focus of this research. The materials include polyethylene terephthalate (PET), polypropylene (PP), PET-coated paperboard, and molded fiber. PET, PP, and coated paperboard are all materials commonly used within the frozen meal space. Molded fiber can be considered an emerging material. Molded fiber current utilization for frozen meal applications is low, but perceived environmental benefits associated with the material have catalyzed its use in the space. Because the package is used for food contact, it will be assumed that all trays are produced using virgin materials. A simplified flow diagram for all of the trays is shown in Figure 4.

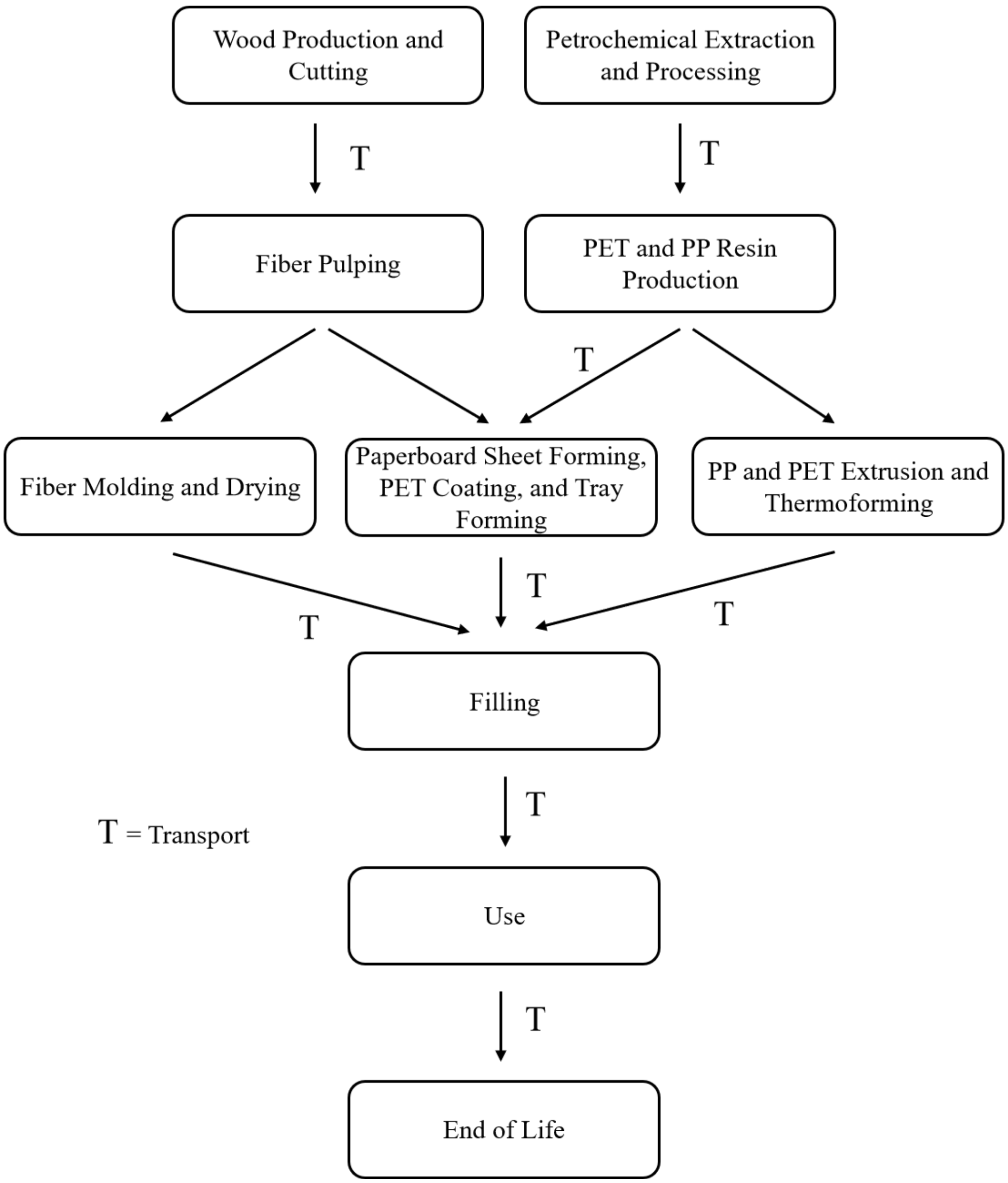

Figure 4: Simplified flow diagram for frozen food trays

Both plastic trays are converted from extruded sheets using a thermoforming process following petrochemical extraction and conversion into the respective resin. Both trays are commonly colored black due to the contrasting background black plastic provides for the product [7]. Translucent, colorless versions of the PP tray are also used. The PET tray uses a crystalline version of the polymer referred to as CPET, which allows the material to withstand temperature ranges from freezer to cooking in a conventional oven [43]. PP trays are only used for lower temperature cooking applications, such as cooking in the microwave.

Unbleached kraft paperboard produced from wood fibers is commonly used to produce frozen meal trays [44]. Following the acquisition of raw materials, the fibers are pulped using a kraft process, washed, screened, and converted into a paperboard sheet [45]. PET resin is then extruded onto the paperboard sheet. Besides providing a high level of moisture barrier, PET is used specifically for frozen meal applications due to its high melting temperature, which allows the frozen meal to be cooked in package [45]. Following resin application, the trays are formed by pressing and deep-drawing the coated paperboard sheets [45].

Molded fiber packaging can be produced from a wide range of materials, including virgin wood, recycled paper, or alternative sources of fibers such as bamboo fibers or sugarcane bagasse [46]. For this research, it is assumed that the molded fiber tray is produced from wood fibers similar to those used to produce the paperboard tray, as the use of virgin wood fiber is common for foodservice molded fiber packaging [45].

Following raw material acquisition, the fiber is turned to pulp, a mold featuring the negative of the package is submerged in the pulp, and the fibers are drawn onto the mold through vacuum suction [46]. For frozen meal tray applications where a high level of control over package dimensions and thickness is required, a precision molding system is use. This presses the captured fibers between two matching molds, during which it is heated and dried [45], [46]. The precision molding process allows for the production of trays that match the appearance thermoformed plastics trays [45]. Although not currently included, the use of plastic coating on a similar fiber package indicates that the application of some sort of barrier coating will likely be required for the molded fiber tray. Whether or not compostable or conventional plastic would be used is uncertain.

3.2 – Identified Life Cycle Literature

In an attempt to better understand the comparative impact of the four materials utilized to produce the frozen food trays, an initial review of literature focused on comparative life cycle assessment and inventory was conducted. The review took a qualitative approach similar to that described by Zumsteg, Cooper, and Noon, focused on grouping and discussing relevant published literature [47]. The literature search was conducted using Michigan State University's library access to databases including peer-reviewed journals and through a general search of publicly available information from governmental bodies, nongovernmental organizations, and businesses.

No literature was identified that compared the impact of PET, PP, coated paperboard, and molded fiber within the same study. Further, no studies were found that identified frozen meal packaging as the specific system being studied. Below is a description of identified literature that can provide some insight into an understanding of the materials used for the production of the frozen food trays or, at a higher level, a comparison of plastics to fiber materials used for similar packaging applications. The identified literature generally included one or both of the following: the comparison of two materials in focus for this study or packaging similar to that used for frozen meals. The literature presented below is not intended to be completely exhaustive and should not be viewed as such.

Zabaniotou and Kassidi studied the comparative impact of egg cups produced from polystyrene (PS) and molded fiber [48]. In the study, the molded fiber was produced from recycled newspaper and cardboard as the feedstock material. The polystyrene tray was produced using an extrusion and thermoforming process following the production of the polystyrene resin. For the molded fiber tray, the recycled wastepaper went through a pulping process, followed by pulp formation into the tray and drying. Specifics regarding the molded fiber production process were not given, but due to the relative simplicity and not-strict requirements for material thickness or coarseness, it is assumed a plain molding process was used [46]. The molded fiber eggcup was found to be preferable to the thermoformed PS alternative in most of the reported impact categories. Only in the carcinogenic substances and heavy metals categories was the molded pulp found to be more impactful but following normalization the difference was found to be small. The authors make note that the accuracy of the reported results is dependent upon the robustness of the utilized data. Based on the geographic scope of the study, they stated that finding accurate data for the molded fiber and PS production phase was difficult. Due to the uncertainty associated with the utilized data, the authors concluded the results of the study do not indicate a more environmentally friendly option of the two packages studied.

Madival et al. conducted a comparative life cycle assessment of PET, PS, and PLA thermoformed clamshells used to package strawberries, finding the PET container to have the largest impact in most studied categories, which the authors attribute to the higher weight of material require to produce the tray [49]. The study included global warming, acidification, ozone layer depletion, aquatic eutrophication, respiratory organics, respiratory inorganics, land occupation, non-renewable energy, and aquatic ecotoxicity for indicator categories. Specifically, the PS tray was found to have lower impacts in all categories compared to the PET tray and use less energy during its life cycle. Similar work on thermoformed PET, PS, and PLA boxes by Leejarkpai, Mungcharoen, and Suwanmanee found the PET container to have a larger global warming potential impact compared to the PS equivalent, again attributing the difference in impact to the higher weight of the PET container [50].

PE Americas, the maker of the GaBi LCA software, conducted a life cycle assessment of PET, PP, and PLA to support decision making on the most environmentally friendly material to use for a cold drink cup with a flat lid [51]. The PET cup/lid combination was found to have a larger primary energy demand and be more impactful in the GWP, acidification potential, and eutrophication potential categories compared to both low and high weight PP cup/lid combinations. For both the PET and PP cup/lid combinations, the resin production phase was shown to use the majority of the life cycle energy and produce the majority of the life cycle global warming potential in kg-CO_2eq. The end of life impact for both PET and PP in landfill has found to be essentially negligible due to both materials being inert. Additional studies of drinking cups made from different materials for use at European events by Vercalsteren, Spirinckx, and Saelee [52] and Pladerer at al. [53] have focused on polycarbonate (PC), PP, PE-coated cardboard, and PLA and PET, PS, coated cardboard, PLA, and a disposable styrene-acylate polymer, respectively. Bertolini et al. conducted a comparative life cycle assessment of packaging for extended shelf life milk, including a PET bottle, a HDPE bottle, and carton including an internal and external coating of LDPE [54].

Three additional life cycle inventory studies were identified that focused on materials similar to those used to produce frozen meal trays. Franklin Associates conducted two life cycle inventories, the first focused on foodservice products made from PS, PLA, and paper-based materials and a second, earlier study focused on packages from PS, PET, PP, and PLA [55], [56]. Both of the studies included the development of inventory information such as energy use, solid waste generation, greenhouse gas emissions, and water use. For the foodservice products, inventory information was generated for heavy duty plates produced from LDPE-coated paperboard, molded fiber and PS foam, considering the material production, plate forming, and end of life phases. The molded fiber plate was found to be more energy intensive based on the included life cycle phases and produced more greenhouse gas emissions than the LDPE-coated paperboard at comparable levels of decomposition at end of life. The PS foam was found to use less energy and produce less greenhouse gases depending on the decomposition level assumed for the LDPE-coated paperboard. The earlier study generated inventory data for 16 oz drink cups made from PET and PP [56]. Focused on raw material extraction through package fabrication and end of life, that study found the PET cup to use more total energy and produce over double the greenhouse gas emissions in CO_2-eq compared to the PP cup. Additionally, the study indicated that the bulk of the energy for both materials was used from cradle to material production; the remaining fabrication and end of life phases used a much smaller amount of energy. Finally, Singh and Krasowski conducted a life cycle inventory comparison of paper and plastic based packaging systems for use in strawberry distribution [57]. The study focused on the energy use and greenhouse gas emissions of corrugated, paperboard, molded fiber, and PET produced from both virgin and recycled resin from cradle to grave. Compared to the PET alternative, the molded fiber used approximately 4-6% less energy, but emitted approximately 67% less greenhouse gas emissions during its life cycle. The paperboard package was found to emit more greenhouse gas emissions during its life cycle than the molded fiber tray, but less than the PET alternative.

Systematic reviews and meta-analyses of life cycle assessment studies were also identified during the preliminary literature search. Zumsteg, Cooper, and Noon provide the following definition of systematic review and meta-analysis, which is often preformed as a section of a systematic review [47].

> "Systematic review is a structured evaluation of the literature with the goal of answering a specific research or application question with a synthesis of the best available evidence. Meta-analysis is the melding of data from multiple studies, usually involving additional mathematical analyses, with the goal of utilizing this synergy of information and data size to answer questions that cannot be answered by existing individual studies or to improve the certainty or impact of known findings by increasing the sample size"

Systematic review can include both qualitative methods, such as summarizing expert opinion, and quantitative methods, such as adjusting impacts based on a common functional unit between studies [47]. Use of both methods can provide information on how materials may compare to each other and give a better idea of what could be expected from an LCA focused on the comparative analysis of fiber-based and plastic frozen meal trays.

Systematic reviews and meta-analyses were identified focused both on specific package forms as well as broad material categories such a fiber and plastics. Van der Harst and Potting compared ten disposable cup life cycle assessments, some of which were discussed earlier, to evaluate the robustness of the individual study results [58]. The authors analyzed each study based on the choices made for each life cycle phase, but only quantitatively compared global warming potentials by recalculating the functional unit used within each respective study to a consistent unit of measurement. Comparison using the updated functional unit showed paperboard cup systems with incineration or a combination of landfill/incineration to have the lowest global warming potential compared to PLA and traditional plastics, but the authors note that assumptions regarding decomposition in landfill, methane generation, and landfill management can have a large impact on those results. Sun et al. conducted systematic review and meta-analysis of the energy use, carbon emissions, and environmental burdens associated with the pulp and paper industry, finding that the pulp making process uses a majority of life cycle energy and causes a large portion of life cycle impact in other indicator categories [59]. Further, the authors also make note of inconsistencies across life cycle studies related to methodological choices such as system boundaries and assumptions regarding biogenic carbon. Rajendra et al. conducted a review of life cycle assessments focused on polyethylenes and polypropylene alternatives produced from recycled plastics and renewable resources in comparison to traditional polyolefins and polyolefin composites [60].

Weiss et al. conducted the only identified review focused on comparing the impact of traditional materials to biobased alternatives, including materials used for packaging and other applications [61]. The research included a review and meta-analysis of nearly 60 biobased materials, aiming to identify patterns in the environmental impacts associated with a wide range of biobased materials. The authors make note that essentially all studies differ from one another in terms of assumptions and methodological choices, but corrections for these differences were not made based on the scope of the review.

Based on the reviewed studies, the authors found that, on average, biobased materials reduced nonrenewable energy use and produced less greenhouse gas emissions, expressed in CO_2-eq, compared to materials traditionally used within their respective categories. The biobased alternatives were also found to have a higher eutrophication potential and increased impact on stratospheric ozone depletion, which is attributed to agricultural activities such as fertilizer application [61].

3.3 – Conclusions

As noted by Pladerer et al. [53], “with all LCAs, the results only apply to the examined systems or products. Any conclusions regarding other applications can only be permissible with restrictions even if the applications have similar situation parameters.” On that basis alone, none of the identified studies can be used to draw definite conclusions on the comparative impact of frozen meal trays. Additional exists as to why the included studies should not be used as proxies for a comparing the environmental impact of the frozen meal trays. First, the identified literature focuses on packages likely formed using different conversion processes than those used for the frozen meal trays, which is relevant due to differences in resource and energy demands. For example, Didone et al. states that the precision molding drying process used to form the frozen meal trays requires a larger amount of energy input compared to a plain molding drying process used for items such as egg cartons [46]. Further, methodological differences between studies, including geographic scope, inventory data, and life cycle impact assessment methodologies make comparisons across studies likely inaccurate due to a large number of required assumptions. Finally, the limited inclusion of molded fiber within life cycle assessment and inventory studies coupled with the package forms studied in the few that do exist makes it difficult to draw comparative conclusions versus the other materials. This lack of environmental literature focused on molded fiber is noted in recent work by Didone et al. [46]. Instead, the literature above can be viewed as a means to identify general trends. For example, multiple identified studies showed PET packages as having the largest impact in many indicator categories, producing more life cycle greenhouse gas emissions, and use more energy compared to the studied alternatives [49]–[51], [56].

CHAPTER 4 – ACCESS TO END OF LIFE OPTIONS

Although there is a large body of literature focused on the environmental benefits of recycling, composting, and incineration compared to final disposal in landfill, there is a lack of detailed, consolidated discussion of the availability of the different types of waste management infrastructure. This likely due to the high geographic and temporal specificity in terms of waste management make-up [62]. Nonetheless, understanding the availability of waste management options provides context for pragmatic discussion of end of life impacts based on the prevalence of waste management systems and the opportunity of a package to be handled by a waste management option other than final disposal. With that in mind, this section aims to better understand the opportunity for each tray to be handled by a preferential form of waste management in the United States from which environmental benefits can be realized.

Reports generated by governmental groups, related bodies, and nonprofit organizations were found to contain much of the municipal solid waste management information relevant to this portion of the research. Fortunately, each of these groups produce information with a focus on different scales or on specific methods of solid waste management. For example, World Bank reporting focuses on the solid waste management at the global scale [62], work done by the United States Environmental Protection Agency includes information on solid waste management on the national level [17], and research conducted by groups such as the Sustainable Packaging Coalition provides insight into specific waste management infrastructure [63]. Consolidated analysis of these studies provide a picture of waste management infrastructure within the United States and access to its various forms. Consumer access and residential access will be used interchangeably throughout this section. Both will refer to access to programs accepting materials defined as municipal solid waste.

4.1 – Access to Landfill and Incineration

According to the World Bank [62], waste collection coverage in North America is essentially ubiquitous, sitting at around 99%. For all intents and purposes, waste collection coverage is complete within the United States. Due to the high income standing of the North America countries, waste collection coverage is generally advanced, operating in a relatively environmentally safe manner and providing a high capacity that can serve practically all residents [62]. Disposal of solid waste in modern, sanitary landfills is the most common waste management practice in the United States, with 1,738 MSW landfills operating in the U.S. in 2015 [19], [64]. Sanitary landfills are designed with environmental controls, monitored to ensure limits to impacts, and include some form of gas capture system [62], [64]. The Resource and Recovery Act codifies proper collection and disposal of MSW in landfills in the United States, ensuring access to all residents [65].

Approximately 7.2 million tons of containers and packaging was incinerated in the U.S. in 2015, accounting for 9.3% of total container and packaging waste generation. Currently, 86 incinerators operate in 25 different states, mainly located in the Northeast portion of the country [66]. Consumer access to incineration is best discussed alongside landfill because it acts as a piece of the complete landfill coverage. Unlike other forms of waste management considered more environmentally favorable within the EPA’s Waste Management Hierarchy [20], the use of incineration is not dependent on a choice by the consumer. Rather, it depends on utilization of the waste management practice by municipalities or companies providing waste collection services. Like landfill, disposal of MSW through incineration is without material prejudice. If frozen food trays are not collected to be recycled or composted, both will end up in the same, disposal-bound stream. A portion of that stream may be diverted to incineration, but diversion to incineration is not impacted by the type of material the tray is made of. There are extremely limited instances of voluntary waste collection programs utilizing waste-to-energy operations for select portions of the municipal solid waste stream. An example is Dow Chemical's Energy Bag program, currently operating pilots in California and Nebraska [67]. The program only accepts plastics and access is limited to the point that it can be considered inconsequential, totaling roughly 555,000 residents or 216,000 households in the two cities in which the pilot operates, Omaha, NE and Citrus Heights, CA [68], [69].

4.2 – Access to Recycling Programs

The Sustainable Packaging Coalition (SPC) conducted a study from late 2015 to early 2016 investigating consumer access to recycling programs [63]. Instead of quantifying materials being recycled, work that has been done as part of the EPA's Advancing Sustainable Materials Management report, the study instead aimed to determine the percentage of U.S. residents that have access to some form of recycling program. For the purposes of the study, program accessibility is defined as a resident having access to one or more of the following services: curbside recycling provided automatically to their home by the public or private sector, curbside recycling provided on an opt-in or subscription basis at their home by the public or private sector, publicly or privately operated drop-off centers within the municipality where the resident lives, or instruction from the resident's municipality, county, or other local government directing them to a drop-off location as the appropriate recycling center [63].

According to the SPC, the vast majority of U.S. consumers have access to recycling in some form, coverage sitting at a nearly universal 94%. Approximately 73% of the U.S. population has access to curbside recycling programs, with 53% of the U.S. population having access to curbside programs that are automatic or universal. 64% of the U.S. population has access to curbside and drop-off programs, and 21% of the U.S. population has access only to drop-off facilities. Figure 5 shows the percentage breakdown of access to curbside and drop-off collection programs.

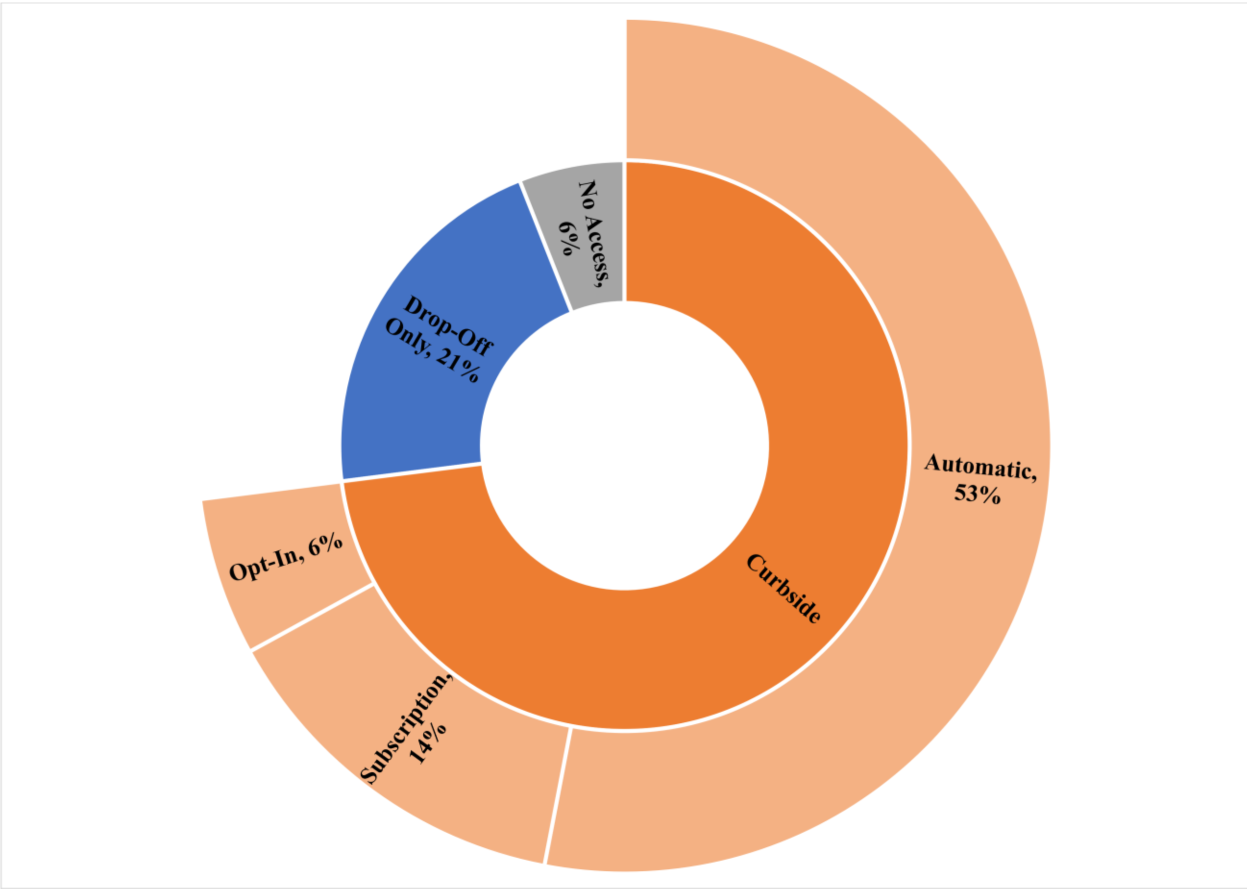

Figure 5: Access to recycling programs as percentages of the total US population (data from the Sustainable Packaging Coalition [63])

The SPC also reports regional access, which shows a relatively high level of consistency. Among the four regions reported (Northeast, South, Midwest, and West), percentages of total regional access were 96%, 93%, 92%, and 89%, respectively. Broken down by collection scheme percentage, the consistency remains. Access to curbside collection ranges from 68% - 84%, access to drop off programs only ranges from 12% - 23%, and residents with no access peaks at

11% in the West. Access to recycling programs in some form does not appear to be region-specific, but rather remains consistent across the U.S.

The SPC reports 6% of the population has access to opt-in curbside recycling programs and 14% of the population has access to subscription curbside programs. Though the types of programs are similar, there is a slight variation in how they operate. Opt-in programs indicate programs where “signing up” in some form has to occur, but the resident does not have to identify a waste hauler themselves [63]. In the subscription format, the resident has to identify one or more hauler and decide to pay the designated fee [63].

The SPC identified four different types of material sorting schemes used for single-family curbside collection programs: single-stream, dual-stream, source separated, and mixed waste. Source separated refers to a system where materials to be recycled are sorted into three or more streams prior to collection, while mixed waste refers to a system where recyclables are sorted from collected trash at a specialized facility [63]. Collection programs utilizing source separated and mixed waste formats were shown to be extremely limited (<1% of all programs used either), leaving single-stream and dual-stream as the two main types of sorting methods [63]. Single stream refers to a system where all accepted materials are collected together for recycling in a single bin, after which the materials are sorted at a material recovery facility (MRF) [63], [70]. Dual stream refers to a system where some limited sorting occurs at the source of the waste generation, generally into container and fiber material streams, which are then collected separately and further sorted at a MRF [63], [70], [71]. For the 2015 – 2016 timeframe of the study, single-stream programs accounted for 89% of curbside collection programs, while dual stream accounted for 10% [63]. 44% of single-family curbside programs used carts as the collection container [63].

4.2.1 – Material Acceptance in Recycling Programs

The SPC also provides a review of material acceptance within recycling programs categorized by different materials and respective package forms. The distinction is important, due to reasons related to recyclability that will be discussed in a later section. Table 2 shows material categories in which the frozen meal trays could be placed.

Table 2: Percentage of US population with recycling programs for materials similar to the frozen food trays (data from Sustainable Packaging Coalition [63])

Material	Less than 20%	20% - 60%	60% or greater
PET containers/trays			X
PP tubs/containers (<5 gal buckets)			X
PP clamshells			X
Molded fiber (service wear/containers/carriers/egg cartons)		X	
Coated non-foodservice paper containers		X	
Paper take-out clamshells/containers/trays	X		
Paper ice-cream tubs	X		

Seven material and package form categories from the SPC's study were identified as relevant based on the following: similarities between categories, the placement of each tray into a respective category, and tray categorization can impact the understanding of tray acceptance by recycling programs. Specifically, the PP and the coated paperboard come into question. The placement of trays made from PET and molded fiber is straightforward as two categories explicitly include the materials, PET containers/trays and molded fiber, respectively. For the PP tray, category placement is inconsequential. Whether the tray is more appropriately placed in the PP tubs/containers (<5 gal buckets) category or the PP clamshells category, the number of consumers with access to recycling programs that accept the trays still sits at 60% or greater. For the coated-paperboard, categorization is not insignificant. Two material categories reported within the SPC's study exist within which the coated paperboard tray could potentially be categorized, coated non-foodservice paperboard containers and paper take-out clamshells/containers/trays; the former accepted by more recycling programs than the latter.

The Foodservice Packaging Institute (FPI), a trade association for the foodservice packaging industry in North America, provides the following definition for what the group considers foodservice packaging [72]:

> "Foodservice packaging primarily includes single-use products such as cups (beverages and portion), plates, platters, bowls, trays, beverage carriers, bags (single-use and carry-out), containers, lids and domes, wraps, straws, cutlery and utensils for the service and/or packaging of prepared foods and beverages in foodservice establishments. Other related products such as placemats, doilies and tray covers; trays used in packaging raw meat, poultry, seafood, produce, and other food products; and egg packaging are also included."

Notably, the group considers trays used for packaging other food products as foodservice packaging. Although the definition is vague, the coated paperboard tray would technically fall under that category. This ambiguity is the reason for the inclusion of the paper ice-cream tub category. Although containing different products, a coated paperboard frozen food tray and a paper ice-cream tub serve quite similar functions during much of the "use" phase of their life cycle, maintaining frozen food products largely through the retention of moisture. This is achieved by applying a plastic coating to the side of the paperboard in contact with the food. Between this similarity and the FPI foodservice packaging definition, it is relatively safe to assume that less than 20% of US residents have access to recycling programs in which coated paperboard trays used for frozen foods would be accepted.

From the SPC's review of material acceptance, it appears that, although acceptance rates differ, all frozen food trays are accepted at some level within recycling programs. Based on the reported percentages of programs accepting each material, both the PET and PP trays are the most widely accepted trays for recycling with 60% or more of reviewed programs accepting the material. The next most accepted is the molded fiber tray with 20% - 40% of programs accepting the material nationally. However, it is important to note that the 20% - 40% acceptance is likely referring to uncoated molded fiber packaging. Finally, the coated paperboard tray is the least accepted with less than 20% of recycling programs in the U.S. accepting the material.

4.3 – Access to Composting Programs

For this study, the molded fiber tray is the only package considered compostable due to plastic contamination in compost being associated with negative environmental impacts, considered detrimental to product quality and causing issues with continued program viability [33], [73], [74]. In theory, the current molded fiber tray could be composted under the cooler, at-home conditions, but the application of any additional coating to the material would more than likely render the tray suitable only for composting in an industrial setting. For the purposes of this review, the assumption will be made that the molded fiber tray can only be composted in large scale operations.

BioCycle Magazine and the Institute for Local Self-Reliance (ILSR) published a survey of residential food waste collection programs, an update to prior research the two organizations conducted in 2014 [75], [76]. The study, titled "Residential Food Waste Collection Access in the U.S.", reviewed programs offered through local governments and municipalities that collect food waste and ancillary materials from residential customers. In their work, Streeter and Platt define access as, "the number of households able to participate in a given program, regardless of actual participation," meaning the number of households with access is not necessarily reflective of participation rates [75]. Additionally, the study intentionally avoids using the word composting as the purpose of the review was not to determine access to strictly compost programs. Rather, the work is aimed at identifying programs that accept residential food waste, which may include other forms of organic waste management such as anaerobic digestion. Acceptance of other organic materials ancillary to food waste, including molded fiber and coated paper used for food products, was also reviewed within the study.

Two types of residential collection schemes are identified by Streeter & Platt [75]: curbside, where material is collected directly from the place of residence, and drop-off, where residents travel to the collection point and drop off their organic waste. In total, 148 curbside programs and 67 drop-off programs were identified. Table 3 outlines the number of communities, defined as incorporated cities and towns, and the number of households with access to each type of collection scheme in the 25 states with residential food waste collection programs. In some cases, collection programs will provide services to multiple communities, causing the discrepancy between the number of communities and programs.

Table 3: Communities and households with access to curbside and drop-off food waste collections programs (data from Streeter and Platt [75])

	Curbside Collection		Drop-Off Collection	
	Communities	**Households**	**Communities**	**Households**
Alaska	-	-	1	500
California	97	1,740,212	1	41,730
Colorado	14	293,325	17	601,295
Connecticut	-	-	5	28,364
D.C.	-	-	1	255,000
Idaho	1	73,738	-	-
Illinois	24	148,448	53	207,000
Iowa	4	83,601	-	-
Maine	2	926	1	23,012
Maryland	4	18,425	-	-
Massachusetts	10	45,319	22	412,103
Michigan	2	47,419	-	-
Minnesota	52	188,015	118	1,087,016
New Hampshire	-	-	1	5,244
New Jersey	3	21,521	-	-
New York	3	790,090	13	3,159,035
North Carolina	-	-	20	509,000
Ohio	1	443	-	-
Oregon	10	188,441	-	-
Pennsylvania	1	3,600	-	-
Texas	2	403,000	-	-
Vermont	24	19,767	44	93,840
Virginia	1	3,025	2	25,166
Washington	69	980,578	15	253,622
Wisconsin	3	23,176	-	-
Total	**326**	**5,073,069**	**318**	**6,701,927**

Ideally, the number of households with access to curbside collection and the number of households with access to drop-off collection could be added together to get a total count of households with access to residential food waste collection in general for each state. Due to the existence of communities with access to both curbside and drop-off programs, this cannot be done. For example, households located in Minneapolis, Minnesota have access to both curbside and drop-off collection programs, 106,000 households and 168,385 households, respectively. According to the U.S. Census Bureau [77], Minneapolis included 172,082 households as of

2017, confirming that the number of households with access to each collection program cannot be combined to get a total count of households with access. Taking the larger of the two household access figures as the total number of households with access is also problematic since the amount of program access overlap is not provided. Issues with a total count are further complicated by the fact that some counties and waste districts offer both curbside and drop-off programs to multiple communities, as is the case for Spokane County, Washington, which contains 13 communities. Based on data presentation, it is impossible to distinguish which of those communities have access to which programs and how that impacts percentages of the households with access to each.

Of the 25 states where curbside, drop-off, or both types of programs are offered, there is a noticeable concentration of community and household access within a small number of states, as shown in Table 4. In terms of community access, 92% of curbside programs and 90% of drop-off programs could be found in 11 states. Further, 67% of communities with curbside access and 68% of communities with drop-off access are located in 5 states, Minnesota falling into the top three for both types of collection schemes. A similar concentration of programs can be seen in terms of household access, where 93% of households with access to curbside programs and 97% of households with access to drop-off programs are located in 10 states and the District of Columbia. Further, 69% of households with curbside program access and 72% of households with drop-off are located in 5 states; New York is in the top 3 in terms of household access for both curbside and drop-off programs. Notably, all 3,159,035 households located in New York City, considered a single community, are considered to have access to drop-off collection programs. New York City alone accounts for just under 50% of total household access to drop-off programs in the U.S.

Table 4: Percentages of total community and household access based on top 3, top 5, and top 8 states for curbside and drop-off food waste collection programs (data from Streeter and Platt [75])

Curbside Programs (327 communities, 5,073,069 households)					
States	**Communities w/ Access**	**% of Total Communities' w/ Access**	**States**	**Households w/ access**	**% of Total Households' w/ access**
CA, MN, WA	218	67%	CA, WA, NY	3,510,880	69%
CA, MN, WA, VT, IL	266	81%	CA, WA, NY, TX, CO	4,207,205	83%
CA, MN, WA, VT, IL, CO, MA, OR	300	92%	CA, WA, NY, TX, CO, OR, MN, IL	4,732,109	93%
Drop-Off Programs (318 communities, 6,701,927 households)					
States	**Communities w/ Access**	**% of Total Communities' w/ Access**	**States**	**Households w/ access**	**% of Total Households' w/ Access**
MN, IL, VT	215	68%	NY, MN, CO	4,847,346	72%
MN, IL, VT, ME, NC	240	75%	NY, MN, CO, NC, MA	5,768,449	86%
MN, IL, VT, ME, NC, CO, WA, NY	285	90%	NY, MN, CO, NC, MA, WA, DC, IL	6,484,071	97%

Table 5 shows household access to collection programs compared to 2017 state and national household totals. Percentage of households with access within each state can be seen in Table 3. Here, limited access is apparent. Even in states with relatively high numbers of household access to either type of program, compared to the state household totals, the resulting percentage of households with access surpasses 50% only once (if Washington D.C. is not considered) and is generally much lower. On average, 7.0% of households in states with curbside collection programs have access to said programs while 20.0% of households in states with drop-off programs have access to said programs (15.0% if Washington D.C. is not considered). In terms of total U.S. households, household access to curbside and drop-off programs sits at 4.0% and 5.3%, respectively.

Table 5: Percentage of households with access to curbside and drop-off food waste programs based on 2017 state and national household totals (data from Streeter and Platt and U.S. Census Bureau [75], [78], [79])

	State Households	Households w/ Curbside	% of State Households	Households w/ Drop-Off	% of State Households
Alaska	250,000	-	-	500	0.2%
California	13,010,000	1,740,212	13.4%	41,730	0.3%
Colorado	2,140,000	293,325	13.7%	601,295	28.1%
Connecticut	1,360,000	-	-	28,364	2.1%
D.C.	280,000	-	-	255,000	91.1%
Idaho	630,000	73,738	11.7%	-	-
Illinois	4,810,000	148,448	3.1%	207,000	4.3%
Iowa	1,260,000	83,601	6.6%	-	-
Maine	540,000	926	0.2%	23,012	4.3%
Maryland	2,210,000	18,425	0.8%	-	-
Massachusetts	2,600,000	45,319	1.7%	412,103	15.9%
Michigan	3,930,000	47,419	1.2%	-	-
Minnesota	2,160,000	188,015	8.7%	1,087,016	50.3%
New Hampshire	530,000	-	-	5,244	1.0%
New Jersey	3,220,000	21,521	0.7%	-	-
New York	7,300,000	790,090	10.8%	3,159,035	43.3%
North Carolina	3,690,000	-	-	509,000	13.8%
Ohio	4,670,000	443	0.01%	-	-
Oregon	1,600,000	188,441	11.8%	-	-
Pennsylvania	5,010,000	3,600	0.1%	-	-
Texas	9,620,000	403,000	4.2%	-	-
Vermont	260,000	19,767	7.6%	93,840	36.1%
Virginia	3,120,000	3,025	0.1%	25,166	0.8%
Washington	2,840,000	980,578	34.5%	253,622	8.9%
Wisconsin	2,350,000	23,176	1.0%	-	-
Total	**126,220,000**	**5,073,069**	**4.0%**	**6,701,927**	**5.3%**

4.3.1 – Material Acceptance in Composting Programs

Streeter and Platt reviewed acceptance of 10 categories of food waste and ancillary organic waste materials in both curbside and drop-off food waste programs. Other than yard trimmings, food soiled paper, and compostable plastic bags, difference in acceptance rate of materials between curbside and drop-off programs is small, within 10 percentage points. All curbside and drop-off programs accept fruit and vegetable scraps, while meat, fish, and dairy were slightly less accepted, 91% and 88% for curbside and drop-off programs, respectively.

Table 6: Material acceptance rates for curbside and drop-off food waste collection programs (data from Streeter and Platt [75])

	Curbside (148 Programs)		Drop-Off (67 Programs)	
	# of Programs Accepting Material	Acceptance Rate	# of Programs Accepting Material	Acceptance Rate
Fruit & Vegetable Scraps	148	100%	67	100%
Meat, Fish & Dairy	135	91%	59	88%
Yard Trimmings	105	71%	30	45%
Paper Bags	101	68%	38	57%
FSP – Uncoated	105	71%	54	81%
FSP – Coated w/ Conventional Plastic	10	7%	4	6%
FSP – Coated w/ Compostable Plastic	51	34%	24	36%
Molded Fiber Containers	33	22%	18	27%
Compostable Plastic Foodservice Items & Packaging	63	43%	26	39%
Compostable Plastic Bags	60	41%	36	54%

FSP = Food Soiled Paper

Acceptance rates for non-food materials was lower, especially for fiber materials used to produce the frozen food trays. Behind food materials, uncoated food soiled paper (FSP) had the highest material acceptance rate, 71% for curbside programs and 81% for drop-off programs. The application of a plastic coating to the food soiled paper, be it conventional or compostable plastic, lowered the acceptance rate of the material substantially, especially if the paper was coated with conventional plastic. Often considered non-compostable, the study showed that FSP coated with conventional plastic is also not a material desired by programs processing food waste and related materials, accepted by less than 10% of either program type. Molded fiber containers were the next least accepted material, accepted by 22% of curbside programs and 27% of drop-off programs. The limited acceptance of FSP coated with compostable plastic is also important to note, approximately 35% of each type of collection program accepting the material. If a coating were applied to a molded fiber tray to ensure product integrity, it may impact acceptance of the molded fiber tray, even if the coating is deemed compostable. With that said, only 5 of the 33 programs that currently accept molded fiber containers do not accept FSP coated with compostable plastic, but the application of a coating to the molded fiber tray could have the effect of limiting acceptance of the tray by additional programs.

4.4 – Definition of Drop-Off Access

Although both the SPC and BioCycle studies provide a definition of access, strictly defining access to drop-off recycling or compost locations is difficult, making it difficult to say with certainty that the numbers reported by each study are truly reflective of access to these programs. In the SPC's study, drop-off recycling locations were considered available if they were located in the municipality where the resident resides or the resident's municipality, county, or local government instructs them to a drop-off as the appropriate recycling outlet, likely meaning outside of the municipality [63]. The definition used within the BioCycle study is broad, stated as the number of households able to participate in a given program [75].

Both definitions understandably fail to take into account the open-use nature of drop-off locations as it would make estimates of drop-off collection access difficult. An example of Michigan State University's (MSU) drop-off recycling location illustrates this point well; the facility is open to public use with no restrictions. A hypothetical scenario of a staff member at

MSU will be used. The staff member lives in a municipality where neither curbside nor drop-off recycling programs are offered. Further, the municipality does not direct its residents to the use of an appropriate recycling center. By definition, this resident would not have access to recycling programs. At the same time, the staff member travels to MSU for work and may utilize the recycling drop-off facility on campus for their means of recycling. In this case, the MSU staff member would not have access to recycling by the strict definition used with the SPC's study, but they are able to use a recycling location all the same.

The widespread nature and relatively consistent geographic distribution of recycling programs around the country may provide a self-correction for this difficulty in defining drop-off access, but the same argument can be used for drop-off access to limited food waste programs, The best example here is the drop-off food waste program in New York City, which all households within the city are considered to have access to [75]. Information provided on New York City's Department of Sanitation Compost webpage does not indicate that food waste drop-off program use is restricted to only city residents, meaning that anyone commuting into the city for work, for example, could potentially use the program to dispose of their food waste and ancillary materials [80]. Further, food waste drop-off locations appear to be well distributed around the city, but considerations such as transportation restrictions in major cities make the expectation of every New York City household having access to a drop-off food waste location likely unrealistically high.

Both of the provided examples show that estimations of drop-off access may be inaccurate. Whether the numbers are lower or higher than reality is difficult to say. It should also be noted that work has been done to better understand the drivers for recycling behavior, specifically use of drop-off locations. Saphores et al. found that closer proximity to a drop-off center increased recycling e-waste [81]. This finding was echoed by Sidique, Lupi, and Joshi, who reported that the expected number of visits to a recycling drop-off facility decreases as mileage from the drop-off location increases, indicating that proximity places an important role in drop-off recycling participation [82]. Convenience has also been reported as a common driver of recycling participation [82], [83].

4.5 – Recyclability of Frozen Meal Trays Following Collection

Though consumer access to recycling programs that accept the frozen meal trays appears to be higher than other preferred waste management systems, collection is only the first step in the recycling process. As noted earlier, for a product to be fully recycled it must also be sorted, reprocessed, and ultimately reused in the manufacturing of new products [21]. To better understand the ability of the trays to go through the full recycling process, this section will provide real world examples of how the trays may be handled should they be collected for recycling. It will start with an overview of recycling options for the trays based on the practices and experience of a recycling brokerage company located in Southeast Michigan, Metro Recycling Solutions. Examples from material recovery facilities (MRFs) located in the United States and Canada will be used to further illustrate sorting practices once the trays have entered a recycling facility. Throughout this section, the words "stream" and "bale" will be used to describe a unspecified quantity of diverted material moving through steps of the recycled process, "stream" generally referring to the material during the sorting process and "bale" referring to material after it has been sorted and prepared for shipment to be reprocessed.

The prior discussion of consumer access to waste management infrastructure and collection of materials raises an important point for a continued discussion of recycling, the difference between recycling and diversion. According the Federal Trade Commission's Green

Guides, a package or product should not be considered recyclable if it cannot be collected, sorted, reprocessed, and ultimately reused in manufacturing or to create another item. Further, there needs to be a substantial likelihood that the package can meet all of the above criteria in the majority of the communities where the package is sold [84]. On the other hand, waste diversion is broadly encompassing, focusing solely on the diversion of waste from the landfill, which can be achieved through methods such as source reduction, recycling, or composting [85]. Diverting a package does not mean it automatically meets all of the criteria to be recycled. Further, diverting a package following use does not automatically imply that the package will not end up in final disposal at a later time.

4.5.1 – Metro Recycling Solutions

Jill Brown of Metro Recycling Solutions, based in Sylvan Lake, MI, was contacted for an initial discussion about the recyclability of the frozen food trays [86]. Metro Recycling Solutions is, by volume, the largest pure recycling brokerage company in Michigan, providing services to businesses, manufacturers, and municipalities for a wide range of recycled materials, including paper, metals, plastics, and other specialty item [87]. As a brokerage service, the company itself does not operate any MRFs. Rather, Metro Recycling purchases materials from recyclers and markets them to be further sorted or used in reprocessing operations. The company acts as the brokerage service for materials collected to be recycled on Michigan State University’s campus. Although not sorting material firsthand, the company provides a broad perspective as to how the trays may potentially be handled by a range of recyclers the company partners with.

For Metro Recycling, both the PET and PP frozen food trays are considered undesirable materials, making identification of markets for each to be further recycled difficult. According to

Brown, both trays would likely be sorted into a mixed #1-#7 or #3-#7 stream if they are included within materials purchased by Metro from a recycler.

In contrast to this, Brown noted the recycling of the fiber trays to be more straightforward. Whereas difficulties in recycling plastics together due to molecular immiscibility and processing requirements exist, a stream of mixed fiber still has utility in reprocessing operations. Of course, there are sources of fibers that are preferential to others based on the quality and length of fiber they provide. Additionally, streams including only a single, specific source of fiber exist, but Brown stated that there is a far greater level of ease when mixing these materials together to create a stream of material that can be used for further reprocessing.

Based on that flexibility, Brown stated that there are two different streams that the fiber-based trays, specifically the molded fiber if uncoated, could be sorted into: mixed paper and old corrugated containers (OCC). This is especially relevant to the uncoated molded fiber, which does not include any additional materials as part of the package that would act as contamination within a fiber stream (the potential for other sources of contamination, including food waste, will be ignored for now). The PET-laminated paperboard, on the other hand, proves to be more of a problem when it comes to recycling within a fiber stream due to the resin layer. According to Brown, the laminated paperboard contains too much resin to be considered a pure fiber source, while the fiber does not allow the material to be recycled within a plastic stream. A similar issue would likely arise if a coating layer was applied to the molded fiber tray. With that said, the quantity of laminated paperboard would likely be small enough that it could be treated as a contaminant and still be sorted into either of the aforementioned fiber streams. Which of the two streams the fiber trays are sorted into is dependent upon the market value of either stream at any given time [86]. At the time of the conversation with Metro Recycling, mixed paper streams were at a negative while OCC streams could be sold at a positive value. If the flexibility in sorting holds true, it would be preferable to sort either of the trays into an OCC stream.

Additional factors that impact how the trays may be sorted once they enter a MRF were provided by Brown. These included sorting capabilities in the MRF, capacity of the MRF in terms of materials storage, and ability of the MRF to market its materials.

4.5.2 – Material Recovery Facility Sorting Practices and Capabilities

Material recovery facilities (MRFs) located in the United States and Canada were contacted as a means to validate Metro Recycling's experiences with tray recyclability and to provide a better picture of sorting operations. Resource Recycling, an industry magazine for recycling news and analysis, includes a section within each monthly edition titled "MRF of the Month". According to Resource Recycling's Associate Editor Jared Paben, the goal of these articles is to represent MRFs located in a variety of geographies and utilizing a variety of equipment makers, which includes both old and new facilities [88]. Paben also noted that when information is available, an additional goal of the article is to highlight MRFs that are taking active steps to deal with market challenges currently being faced by the recycling industry [88]. The use of MRFs featured in the articles as industry examples allows for some level of comparison as each article includes consistent technical information, including number of processing lines, throughput, and residual rate. Additionally, the articles provide information on a variety of MRFs in terms of geographic location and processing capabilities. Since providing a complete overview of MRF sorting practice as it pertains to the trays is outside the scope of this work (let alone being extremely difficult to accomplish), the articles provided an accepted industry source that could be used to identify MRFs from which additional sorting insight could be gained.

A total of 24 MRF of the Month articles from 2017 and 2018 were reviewed. Contact information for each MRF was identified using publicly accessible internet resources. Contact information found included direct employee email addresses, company-specific email addresses, and contact forms included on company websites. If no contact information was found on the company website or contact forms/email addresses were not included for general questions, MRFs were not contacted. For example, some company websites included contact forms for customers to use related to service-specific questions and areas of concern, such as the option to request a service quote or pay a bill online [89]. Additionally, MRFs operated by national service providers Republic Services and Waste Management were featured in 3 of the 24 articles [90]–[92]. Both company websites provided generic customer service questions forms, but specific contact information for the MRFs included in the articles could not be identified [93], [94]. Finally, one article focused on the recycling program of a Marine Corps base [95]. Contact information for the on-base recycling program could not be identified. In total, 15 of the 24 MRFs included in the articles were contacted. Table 7 includes the names and locations of contacted MRFs.

Table 7: Contacted MRFs

Facility Name	Location
Emerald Coast Unities Authority Material Recovery Facility	Pensacola, Florida
EBI Environnement Ice.	Joliette, Quebec
Northumberland Country Material Recovery Facility	Grafton, Ontario
Sims Municipal Recycling Sunset Park Material Recovery Facility	Jersey City, New Jersey
Eureka Recycling	Minneapolis, Minnesota
Boulder County Recycling Center	Boulder, Colorado
Kent County Recycling and Education Center	Grand Rapids, Michigan
Mid Valley Disposal Elm Avenue Material Recovery Facility	Fresno, California
City of London Regional Material Recovery Facility	London, Ontario
City of High Point Material Recovery Facility	Jamestown, North Carolina
Monterey Regional Waste Management District Materials Recovery Facility	Monterey County, California
Penn Waste Recycle Facility	York, Pennsylvania
Firstar Fiber	Omaha, Nebraska
The Regional Municipality of Durham Material Recovery Facility	Whitby, Ontario
GreenWaste Recovery Mixed Waste Material Recovery Facility	San Jose, California

Each MRF was contacted via email, in which a brief project description and the following three questions were included. If required, additional follow up questions were asked to ensure sufficient understanding of sorting practices for each responding MRF.

1. Are any of the following packages collected by programs from which your MRF accepts materials?
    a. Black, thermoformed PET trays
    b. Black, thermoformed PP trays
    c. Molded fiber trays
    d. PET-laminated paperboard trays
2. If any of the above materials are collected and processed by your MRF, what material streams would they likely be sorted into on your line?

3. If received by your MRF, would any of the trays not be sorted or left in a residual waste stream?

Of the 15 MRFs contacted, a total of 6 responded to the email inquiry. Table 2 gives information on each MRF, including information provided by the Resource Recycling articles (number of processing lines, throughput, and residue rate) and information gathered through email and phone conversations. To account for differences in throughput reporting within the article (tons/hour, tons/day, annual tonnage), all throughputs were converted to tons/day. All articles reported some information on the number of facility employees, number and length of shifts, and number of days the facility operates per week, the latter two being used in the calculation. If neither the number of shifts, length of shifts, or number of days operating per week were reported, it was assumed the facility operated on a standard 8-hour shift, 5 days a week, resulting in 260 operational days per year [96]. Additionally, some facility throughputs were reported as a range. To ensure accuracy of information, the upper and lower limits of the throughput range were converted to tons/day and reported. Table 8 includes information provided by the Resource Recycling articles, as well as responses to the questions provided in the email inquiry.

Table 8: Information from Eureka Recycling (ER), The Regional Municipality of Durham Material Recovery Facility (RMoD), Monterey Regional Waste Management District Materials Recovery Facility (Mont), GreenWaste Recovery Mixed Waste Material Recovery Facility (GW), Sims Municipal Recycling (Sims), Boulder County Recycling Center (BC) (number of processing lines, facility square footage, throughput, and residue rate from Paben and Leif [91], [97]–[101])

MRF	ER	RMoD	Mont	GW	Sims	BC
Number of Processing Lines	1	3	1	2	2	1
Facility Square Footage	120,000	70,000	120,000	52,000	*	50,600
Throughput (tons/day)	350	180	127 - 151	720	1000	204
Residual Rate (%)	6.5	6.7	15	25	15	8
PET Accepted?		X		X	X	X
PET Stream	R	C: MP B: R	R	PET	C: MP B: R	C: PET B: MP
PP Accepted		X		X	X	X
PP Stream	R	C: MP B: R	R	C = MP B = R	C = MP B = R	C = PP B = MP
Laminated PB Accepted?		X		X	-	
Laminated PB Stream	R	MPap	R	*	-	R
Molded Fiber Accepted?		X		X	-	X
Molded Fiber Stream	R	MPap	R	*	-	MPap
Residual Material	I	*	L	*	L	L

X = Accepted
B = Black, C = Clear
PET = PET, PP = PP, MP = Mixed Plastic, MPap = Mixed Paper, R = Residual
L = Landfill, I = Incinerator,
*Not reported

Two of the MRFs, Eureka Recycling, located in Minneapolis, Minnesota and Monterey Regional Waste Management District Materials Recovery Facility, located in Monterey County, California would not sort any of the materials into a stream to be further recycled. None of the four trays were accepted by residential recycling programs from which those MRFs accept material. If any of the trays were to enter the sorting operations of the facilities, they would remain in a residual waste stream that would leave the MRF to be sent for final disposal.

Both of the fiber-based trays were sorted into mixed paper streams based on responses of two MRFs [102], [103]. If the mixed paper streams are truly at a negative and OCC streams at a positive, this would indicate that none of the responding MRFs sorted the material into a value-positive material stream. Instead, all sorted material into a mixed paper stream, a stream that allows a higher level of contamination than that associated with an OCC stream. This will be discussed in a later section. The key takeaway here is that it appears MRFs are unwilling to jeopardize the value of a stream like OCC, which can be sold at a positive, in order to mix in materials more commonly associated with contamination, regardless if they would actually cause issues when mixed into an OCC stream. More specifically, 3 of the MRFs sort the molded fiber and 2 of the MRFs sort the laminated paperboard. A response was not provided by GreenWaste Mixed Waste Material Recovery Facility, located in San Jose, California, as to which stream the facility sorts the fiber-based trays, both of which are accepted in its facility and sorted out of residual material. Additionally, Sim Municipal Recycling, located in Jersey City, New Jersey, only accepts plastics in the facility featured in its respective “MRF of the Month article”, meaning the question of how the facility would handle fiber-based trays is not relevant since those materials were not included in streams of materials destined for that facility. It should also be noted that if additional coating material were added to the molded fiber tray, it may end up being handled in a similar manner to the plastic-lined paperboard tray

Compared to the fiber-based trays, handling of the plastic trays was less straight-forward. Overall, more facilities sorted the plastic trays into recycled streams compared to the fiber-based trays, 4 of the 6 responding facilities sorting the trays into some form of recycled stream. Only the two MRFs mentioned above that did not sort any of the materials did not sort the plastic trays. Here, importantly, a specific characteristic of some frozen food trays, their black color played a role in what stream the trays were sorted into. Difficulty associated sorting black plastics will be discussed in the next section.

For the PET tray, three different potential material streams were reported, PET-specific and mixed plastic streams if the trays were sorted correctly, and a residual stream if they were not sorted correctly. In only one case was the PET able to be sorted into a PET-specific stream, regardless of color. In all other instances, the stream PET was sorted into depended on its color. Three responding MRFs reported that clear PET would be sorted differently than black PET. One MRF reported sorting clear PET trays into a PET-specific stream of material, while the other two sorting clear and black PET differently reported sorting clear PET into a mixed plastics stream. For those MRFs, black PET was only sorted into a material stream once, specifically mixed plastic. For the other two responding MRFs, the material remained in the residual waste stream.

A similar trend in sorting was observed with the PP tray as well, with the trays being sorted into three different streams based on responding MRFs. Unlike PET, all MRFs sorted clear and black PP differently. The clear trays were sorted into a PP-specific stream of material by one MRF, while that same MRF sorted the black PP trays into a mixed plastic stream [102]. Interestingly, that MRF treated different colored PET trays in a similar manner, the clear going into a PET-specific stream of material and the black going into a mixed plastic stream. All three of the other responding MRFs sorted clear PP trays into a mixed plastic stream while black PP trays reminded in an unsorted residual stream destined for final disposal.

As Brown noted in the initial discussion with Metro Recycling, additional MRF-specific factors can impact how a MRF decides to sort incoming materials [86]. These include the sorting capabilities of the MRF, which refers to how each MRF is able to sort materials into streams to be recycled, the capacity of the MRF to store materials following sorting, and the ability of the MRFs to identify ways to get their material to markets in which it can be reprocessed and ultimately reused to make new products. Each Resource Recycling article includes information related to the sorting capabilities or capacity of a MRF, such as information on specific equipment and total facility square footage, but it is difficult to draw any conclusions from those details due to the interplay between capabilities and capacities. For example, a MRF may include the capabilities to sort materials into highly specific streams, but limited ability to store materials following sorting may mean the MRF will not target as many materials in favor of sorting more valuable materials with higher specificity. This example also illustrates that the ability to find markets for materials also adds into the complexity of MRF-specific factors impacting sorting operations. The ability to market materials was only discussed with one responding MRF, GreenWaste Solutions, located in San Jose, CA. Kevin Martinez, who serves in a community relations role for the facility, made note that the facility's ability to sort and market material at the speed it does is a result of connections the company's MRF manager has in the industry [104]. This response illustrates the difficulty in quantifying the ability of a MRF to market material. As such, no real trends could be identified regarding the MRF-specific factors that can impact sorting noted by Brown. Further, Cimpan et al. have found literature focused on topics such as process efficiency in MRFs to be scare [70].

4.5.3 – Discussion of Tray Recyclability Based on Real World Examples

Based on the responding MRFs, it appears that if the trays are sorted into a stream of materials to be further recycled, it is most commonly into a mixed material stream. For the plastic trays specifically, in two cases the PET tray was sorted into a PET-specific stream, in one case the PP tray was sorted into a PP-specific stream. If the trays are colored black, there was only 1 case of a tray being sorted into a material-specific stream, specifically PET, 1 case where both the PET and PP trays were sorted into a mixed plastic streams, with the remainder of the MRFs reporting they would remain in a residual material stream. This response appears to validate Brown's statement of the difficulty of sorting black plastics, which will be discussed in a later section.

Taking that into consideration, the initial discussion with Metro Recycling can give insight into what happens to the mixed material streams after they leave the MRF. Here, the assumption will be made that trays sorted into material-specific streams, in the case of the responding MRFs only PET and PP, have a higher likelihood of being reprocessed. Further, Metro Recycling does not currently purchase mixed material streams due to the low bale value [86]. As such, the discussion with Metro Recycling can give some indication as to what happens to a mixed plastic stream after it is purchased by the company.

As mentioned earlier, Metro Recycling does not operate its own MRF as a brokerage service. Instead the company purchases materials from MRFs and markets them to be reprocessed or further sorted, the latter in the case of a mixed plastic bale. Mixed plastic streams can include either mixed #1 - #7 plastics or mixed #3 - #7 plastics, dependent on prior sorting at the MRF [105]. Metro Recycling sells bales of these materials to a Canadian company where higher value plastics, such as cloudy high-density polyethylene (HDPE), are sorted out. Due to the undesirability of the plastic trays, Brown gave no indication that they would be further sorted in a manner similar to cloudy HDPE packaging. Further, Brown was unsure of what happens to the residual plastics following sorting at the Canadian company. The materials may be stored until a time they can be marketed for a higher value, but the Canadian company had gone through bankruptcy in the past, causing it to liquidate stored material and send it to final disposal. As the Canadian company, ReVital Polymers, was not contacted, this is not to say that other plastics are being sorted and potentially used in reprocessing operations. Rather, discussion with both Metro and responding MRFs illustrates the difficulty in determining the likelihood of the frozen meal trays being fully recycled.

4.6 – Issues related to Recyclability and Compostability of Frozen Meal Trays

Reasons exists for why the frozen food trays are not or cannot be targeted for more specific material sorting in MRFs or why a molded fiber tray is not included in material accepted by composting programs. This section will focus on a more detailed discussion of issues related to tray recyclability. The bulk of the discussion will focus on the recyclability of plastics trays. Specifically, why issues related to resin specifications and colorants cause the trays to be sorted into less valuable mixed plastic streams, even though they are accepted by the majority of recycling programs. Recyclability of the fiber trays will also be discussed, but the lower acceptance within recycling programs reported by the SPC indicates a lower potential for the fiber trays to end up in MRF sorting operations in the first place. Further, the lower acceptance of the PET-coated paperboard indicates that the application of an additional barrier coating to the molded fiber tray could cause acceptance within recycling programs to decrease. Finally, reasoning for the limited acceptance of molded fiber and similar materials in composting programs will be discussed.

Outside of material-specific issues, the post-consumer nature of the frozen meal trays also limits their recyclability, largely due to the increased chance for residual food waste contamination, which reduces the desirability of both materials due to the additional washing and purifying steps required to make material usable for recycling [106].

4.6.1 – Plastic Tray Recycling: Resin Specifications and Intrinsic Viscosity

Diverted resin feedstocks must be able to meet the material property specifications required by different applications, as is the case with virgin plastics [107]. Resins produced with application-specific material properties are referred to as different “grades” of plastic [21]. For plastics produced from virgin material, meeting application-specific criteria simply entails producing resin with the required properties. This is not the case for diverted plastics though, especially those collected within mixed material streams, largely due to two main reasons. First, the majority of plastics used to produce packaging materials are immiscible at a molecular level and require different processing conditions at a macro scale, limiting the utility of mixed-polymer feedstocks and creating the need for sortation at MRFs based on plastic types [21], [108]. Second, degradation of polymers during the recycling process can also limit the usefulness of the recycled material [21]. Based on the required material properties of resin used to produce a package and the degradative processes that occur during recycling, some grades of resin are better suited for reprocessing into new products following recycling than others.

To further illustrate the potential impact resin grades can have on recyclability, it is beneficial to look at examples of how different grades of plastic are handled within the recycling industry. Based on the responses of Brown and other recyclers, if packages produced from PP are sorted at a MRF, it is often into mixed plastics streams (either a mix of #3-7 or #1-7 plastics), as opposed to PP-specific streams [86], [103], [105], [109]. Even if packages produced from PP are sorted into a PP-specific stream at a MRF, there is no indication that PP frozen food trays could not be sorted into either a small rigid or an all rigid PP stream based on model bale specifications created by the Institute of Scrap Recycling Industries, Inc. (ISRI) [105] or The Association of Plastic Recyclers (APR) [110], which reflect the reprocessing requirements of the plastics industry. The small rigid specification refers to small PP containers and packaging while the all rigids specification allows for the inclusion of large, bulky items such as 5-gallon buckets or crates. In fact, microwavable trays are listed as an example of a package that can be sorted into PP small rigid plastics steams in model bale specifications produced by both groups [105], [110].

The case for PET is not quite as straightforward. According to Scheirs [111], bottle-grade PET generally has one of the highest scrap values of any recycled plastic, current sorting practices of multiple recyclers reflecting the continued validity of that statement [86], [104], [112]. ISRI and APR model bale specifications both include standards for bottle-grade PET bales specifically, including criteria for different grades of PET bales based on levels of contamination, allowing bales with a higher total weight of PET (and subsequently lower levels of contamination) to be marketed for a higher scrap value [105], [113]. Unlike bottles, PET frozen food trays are made from a sheet-grade PET resin, produced using cast sheet extrusion followed by a thermoforming process [49], [50]. ISRI and APR both include PET thermoform-specific bale criteria within their model bale specifications, but similar to PP-specific bales, conversations with recyclers indicate that sorting based on that bale criteria is very limited. Material quantity and market limitations are the likely reason for the lack of thermoform-specific PET streams, but unlike the PP trays, the PET thermoforms are specifically listed as a contaminant in the PET bottle bale specifications [105], [114]. The question is what barriers related to resin characteristics exist that limit the recyclability of thermoformed, PET trays along with bottle-grade materials?

In a study conducted by the National Association of PET Container Resources (NAPCOR) [115], resin intrinsic viscosity was identified as a commonly considered barrier to recycling PET thermoforms within PET bottle streams. Intrinsic viscosity is one of the most common measures of a polymer’s average molecular weight [108], [111]. Of the relevant material properties, it is often discussed due to its importance in determining the rheological and mechanical characteristics of the polymer [106]. Outside of polymer characteristics, it is also important due to the dramatic impact degradative processes can have on polymer molecular weight. Depending on the molecular structure, residual contamination, and processing conditions, polymers will commonly experience some form of degradation during the recycling process. The most common is thermal-mechanical degradation caused by the heat and shear a polymer experiences during reprocessing [106]. Residual contamination also has the potential to cause degradation, such as degradation catalyzed by the presence of acids from closures and adhesives or hydrolytic oxidation due to residual water, the latter being of particular importance for condensation polymers such as PET [107]. Regardless of the cause, polymer degradation, specifically mechanisms such as chain scission and depolymerization that directly impact bonds within the polymer’s backbone chain, has the potential to cause a significant decrease in average molecular weight and, subsequently, impact resin utility during reprocessing [106]–[108], [111]. This decrease in molecular weight is confirmed in the literature, where Kang, Auras, Vorst, & Singh [116] found that, in general, the higher the percentage of recycled PET in extruded sheets, the lower the corresponding intrinsic viscosity and viscosity average molecular weight. It has also been found that major decreases in molecular weight generally occur within the first three extrusion cycles, which is of particular importance considering food contact packaging is commonly produced from virgin resin [117]–[119].

Although the United Kingdom’s Waste and Resources Action Programme (WRAP) [120] notes that the sheet-grade PET resin used to produce thermoformed trays has a lower intrinsic viscosity than bottle-grade PET resin, the difference may not be as large as commonly believed, assuming both grades are produced from virgin material. According to Awaja & Pavel [107], bottle-grade PET generally has an intrinsic viscosity range of 0.73 – 0.8 dl g^{-1}, while Kang, Auras, Vorst, & Singh [116] report virgin sheet-grade PET to have an intrinsic viscosity of 0.722 ± 0.029 dl g^{-1}.

This could indicate that ISRI and APR model bale specifications are not fully reflective of materials that could be included within a valuable bale of diverted PET. This would be consistent with the aforementioned NAPCOR study [115], which reported that most reclaimers who handle curbside materials were recycling PET thermoforms within their PET bottle bales. That study also reported that other perceived barriers to recycling PET thermoforms along with PET bottles, including the potential for acid-catalyzed degradation due to the presence of adhesives and the effectiveness of common PET sorting methods to identify and sort the thermoformed container, were not as significant as generally believed [115].

The findings of similar intrinsic viscosities could also indicate that other issues cause the continued status of thermoforms as a contaminant within PET bottle bales. In a study focused on thermoformed PET pots, tubs, and trays, WRAP [121] found that the drying process used during PET bottle-grade recycling resulted in high yield loss when applied to less biaxially oriented sheet grade PET, causing the material to come apart during washing. That same study also found that recycled thermoformed containers produced flakes with a large diameter to thickness ratio, creating long, thin flakes with a different geometry than those produced from bottle-grade resin [121]. This could potentially be problematic based on reprocessing constraints for flake diameter of greater than 0.4 mm and less than 0.8 mm reported elsewhere in the literature [107]. Earlier work by WRAP [120] also found that a stream of sorted thermoformed containers still was charged a fee at a plastics recovery facility, except when PET bottles were present within the bale, indicating the sheet-grade resin was a less desirable material.

As much of the discussion thus far has focused on PET thermoforms in general, additional issues may also exist related to the CPET commonly used for frozen food trays. Outside of an issue related to differences in the reflected near infrared (NIR) spectrums of different grades of PET, which will be covered in the next section, CPET-specific recyclability problems were difficult to identify in the literature.

Taking that all into consideration, it would appear that in the case of both the PP and CPET microwave trays, resin specific properties may not have a dramatic impact on the recyclability of the materials. In the case of PET thermoforms, a more desirable material in the form of bottle-grade PET resin exists, but it is difficult to confirm whether the perceived barriers to recycling the different resin grades together are as large as commonly believed. Instead, other aspects related to the resin or inherent to the role of the trays in packaging food may have larger impacts on the recyclability of the trays.

4.6.2 – Plastic Tray Recycling: Black Colorant

Black colorant used within the frozen food tray can also have a negative impact on recyclability due to potentially limited applications of the black colored recycled resin. Additionally, issues related to the inability of equipment commonly used to sort plastics to detect and accurately sort black colored plastics have been recognized.

Black plastics used for food packaging are commonly colored using a pigment called carbon black due to its low cost, high tint strength and opacity, and its ability to provide a contrasting background that allows food colors to stand out [7]. Pigments make up one of the two major categories in plastic colorants, the other being dyes. Carbon black, as one of the most stable pigments available, is used for a huge variety of applications in packaging [122].

According to Charvat [122], a pigment can be defined as a distinct particulate material that remains unchanged during both the processing and life cycle of the plastic it is coloring. The goal of a pigment is to achieve a target color for the plastic within which it is used. To do this, the pigment is dispersed within the resin during the resin's production [122]. During dispersion, carbon black agglomerates formed during production of the pigment are broken up to primary aggregates that can be uniformly spread throughout the resin. In an ideal dispersion, all of the carbon black would be deagglomerated into primary aggregates, after which each aggregate would be separated from every other aggregate and completely covered by the resin [123]. Realistically, ideal dispersions are often not achieved, but the description provides an excellent example of how the pigment is incorporated within the resin.

This understanding of the dispersion of carbon black provides insights into the difficulties of recycling plastics it has been incorporated into. Processes do exist to remove pigments such as carbon black, but issues related to residual pigment impurities and thermal degradation can occur [124], [125]. Additionally, the process of removing pigment is likely prohibitively expensive considering the collection, sorting, and reprocessing costs of recycling plastic compared to those associated with production of virgin resin [126]. Due to the processing requirements of colored resins following collection and sorting, it is instead much more efficient to use a recycled resin close to the target color of the new resin being created [124]. To achieve the target color for a recycled resin, additional corrective colorant is added to overcome the colorant present within the recycled material. This process is also expensive, but it can help to cut down on the amount of corrective coloring required during reprocessing of the polymer. As noted by Blakeman [124], “recycled resins that are farther off color will require much more pigment to overpower the colorants in the recycled resin.”

The prior discussion illustrates the difficulty in recycling black colored plastics into anything other than new dark plastics. Considering carbon black’s small particle size, the pigment features an incredibly high color strength [123]. Due to this, it would be both difficult and likely expensive to overcome the pigment through corrective coloring, making the idea infeasible. As mentioned earlier, processes also exist that can remove carbon black from the recycled resin, but these too would likely be cost prohibitive.

An additional issue exists related to sorting equipment commonly used by material recovery facilities. Fourier-transform near-infrared spectroscopy (FT-NIR) is a well-developed and extremely common sorting technique utilized in even basic MRFs to positively sort plastics out of incoming mixed materials [21], [127]–[130]. Further, optical sorters are used to differentiate between colored packages made from the same resin [21]. FT-NIR identifies and sorts plastics based on their chemical structure and associated infrared spectrum; once the reflected spectra of the desired material is detected by the equipment, an air jet ejects of the material off the line, positively sorting the desired material from the rest of the recycled stream [127]. FT-NIR sorting equipment can be set to detect a wide range of plastics, specific sorting practices being largely dependent on the capabilities and capacity of the MRF utilizing the equipment [128]–[130].

Carbon black creates an issue for FT-NIR and optical sorting equipment due to the colorants limited reflection of visible light and strong absorption of the infrared (IR) spectrums [130]. Work has been done to identify black colorants that can be detected by current FT-NIR technology, but increased cost of the colorants compared to the widely utilized carbon black likely would limit adoption of the detectable colorants [130]. Different technologies, including Mid Infrared (MIR) and NIR equipment with the ability to detect black plastic have been proposed, but issues associated with commercialization of the technology (specifically, MIR) and limited implementation by the industry have reduced the usefulness of these solutions [130], [131]. The use of hand-sorting could also negate equipment-related sorting issues, but the usefulness of this practice is likely related to the quality of material a MRF is processing and line speeds. Further, the ability to hand-sort black plastics does not impact the desirability of the material or its utility as a feedstock.

This raises the question of whether the availability of markets justifies the efforts aimed at making it easier to sort the frozen food trays. WRAP [7] found that CPET using detectable black colorant could be reused at a 15 – 20% rate in flexible textiles and amorphous polyethylene terephthalate (APET) sheets without diminishing product quality. Interestingly, it was also found that different grades of PET resin reflect different NIR spectrum, a large difference in the case of CPET, which could pose additional challenges even if the trays were clear [7], [121]. While the use of diverted black CPET may still be valid, it remains uncertain whether a similar market exists for these materials in the U.S. or whether MRFs and brokers within the U.S. would be willing to dedicate resources and space to the collection of black plastics instead of materials with more robust markets such as PET bottles.

4.6.3 – Fiber Tray Recycling

Unlike the plastic trays, specific issues related to sorting of the fiber trays in the MRF could not be identified. Sorting of fiber packaging in MRF is mainly done through the use of a series of disk screens, during which lighter fiber materials flow over the top of the rotating disks while heavier materials fall through [132]. This type of sorting operation allows for flexibility in fiber sorting based on MRF equipment setup, fiber can be sorted into material-specific streams such as OCC or bulk sorted into mixed paper streams [70], [133]. Bajpai also notes that optical sorters are increasingly being utilized to sort fiber materials based on surface characteristics, but sensor application is expensive and each piece of equipment is limited in the number of different materials it can sort [134]. Pulping of recycled fibers is also not as material specific as plastics reprocessing, allowing for an increased level of fiber mixing during reprocessing. The limited acceptance and sorting of the fiber trays appears to be related to undesirable contamination by the plastic coating and, more importantly, the high availability of recycled fiber in the form of corrugated containers, which is the most recycled of any packaging materials based on the most recent EPA data [19].

As with the plastic trays, it is helpful to look at ISRI bale specifications for insight on how the recycling industry may view the fiber trays in comparison to other fiber materials. Brown was the only one to indicate that either of the trays could potentially go into the highest value stream, either OCC or mixed paper, with other recyclers indicating either tray would be sorted into a mixed paper stream, if accepted at all [86]. Based on ISRI bale specifications, it appears that an OCC bale, which includes corrugated containers using test or kraft liners, would be a higher utility bale compared to a MP bale, in which no limitations are set on paper quality or fiber content. OCC bales are allowed a higher percentage of “outthrows” materials, defined as all papers whose presence within a specified paper grade would render it unsuitable for consumption, but the higher percentage of allowed contaminants is a product of a higher level of material specificity required by the bale [105]. MP bales only allow 3% of the included material to be outthrows, but the lack of paper grade restrictions within the bale allows for the inclusion of a wide range of paper products, the frozen food trays included. Even if the trays were considered outthrows in the bale due to the coating or residual food, Brown stated that they are collected in such small quantities compared to other paper materials, they could be included within the 3% contamination limit [86]. Additionally, responses from MRFs indicate that most facilities are generating a sorted MP stream, negating the need to include the fiber trays within a OCC bale. Uses of a mixed paper stream of material were not identified.

4.6.4 – Molded Fiber Tray Composting

Multiple reasons may exist for the limited acceptance of biobased materials commonly associated with food waste. Low acceptance could be related to the materials themselves and their ability to processed by organic waste facilities that exists within the U.S. Although intentionally avoiding the use of the phrase composting, Streeter and Platt note that the majority of programs reviewed in their residential access study in fact use composting to process organic waste [63]. To achieve a high-quality finished product, specific conditions must be met during the composting process, including specific temperatures, moisture content, and ratio of carbon to nitrogen (C:N). To reach those conditions, feedstocks must be of a high enough quality and purity [74]. Many different forms of compost infrastructure exist and how they function largely determines the types of materials they are suitable to process, some formats less effectively degrading some materials than others [33], [135]. This may indicate that not all of these programs classified as food waste are suitable to process ancillary materials as part of a complete, residential food waste collection program. With that said, large scale composting operations, which presumably make up the of bulk programs reviewed in the study, are associated with temperatures reaching the thermophilic range, high enough to meet the conditions needed to degrade any of the included materials, including biopolymers [36]. Recent work has also shown that blends of organic materials containing large amounts of compostable foodservice packaging, including molded wood pulp and PLA-coated paperboard, did not have a positive or negative effect on quality of finished compost [136]. Full decomposition of the foodservice packaging did require an additional 3 weeks of in-pile processing, including specific pile management strategies to adjust moisture and pile temperature to ensure increased degradation [136]. Packaging marketed as “eco-friendly” has also been a noted source of non-compostable packaging contamination in compost facilities in recent years, which may cause composters to stop accepting similar, compostable materials in an attempt to limit contamination [137]. Skepticism about the processability of materials such as bioplastics also exists, even though literature confirming their biodegradability is available [138]. Wariness to accept organic materials other than food may also apply to other organic foodservice packages, including molded pulp and coated paperboard.

The current organic waste infrastructure in the U.S. is likely also insufficient to process residential food waste and similar materials [33], [139]. In 2015, 39.7 million tons of food waste and 34.7 million tons of yard trimmings were generated, including residential, commercial, and industrial sources, totaling approximately 75 million tons of potentially compostable material [19]. That year, 23.4 million tons of organic material was composted, 91.0% of which was yard trimmings, organic material that is legislatively banned from landfill disposal in many states [33], [139], [140]. That means roughly 2.1 million tons of food waste and other, undefined organic MSW was composted in 2015 [19]. Presentation of the EPA’s data makes it impossible to distinguish what quantity of that material was other organic waste or what portion of the material came from residential sources. Survey results published by Platt, Goldstein and Coker in 2014 found that only 9% of the reported 4,914 compost facilities were classified as food scrap or mixed organics facilities (433), compared to 70% that were classified as yard trimming facilities at that time [33]. Compared to the 215 programs reported by Street and Platt [75], it would appear that there is room for residential collection to grow, but facilities permitted to process food waste are more likely to accept that material from commercial and institutional sources that generate less contaminated and more consistent streams of material. Permitting processes in some states also make it difficult to compost large volumes of organic wastes other than the yard trimmings they are already permitted for [139]. The potential of increased process time required to degrade foodservice packaging may cause facilities to only focus on food to ensure effective use of limited capacity.

4.7 – Conclusions

Understanding the opportunity of a tray to be handled by preferred waste management systems such as recycling, composting, and incineration is beneficial because it provides a context for continued discussion of environmental impact associated with the end of life section of a package's life cycle. Based on the identified literature and further analysis, conclusions regarding access to the different forms of waste management infrastructure and how that impacts the opportunity of a tray to be handled by a waste management scheme other than final disposal can be drawn. First, the opportunity for the molded fiber tray to be handled by a compost program appears to be extremely low, considering both the limited availability of residential food waste programs and the limited acceptance of molded fiber within the programs that exist. Next, determining the specific likelihood of a tray entering a stream destined for incineration is difficult, but based on the most recent EPA number it appears the likelihood of the trays being handled by incineration is also low. Finally, consumer access to programs in which the frozen meal trays can be recycled differs based on the material. This ranges from above 60% of the plastic trays to 20% or less for the coated paperboard tray, but issues related to the recyclability of all trays indicates that a high level of acceptance within recycling programs does not automatically mean the tray will go through the entire recycling process.

Consumer access to different options for waste management is dynamic and this section should be read as such. The presented information on access to waste management infrastructure is based on literature sources that are as up to date as could be identified, aiming to provide an accurate reflection of the current waste management infrastructure landscape. With that said, it is a picture of the current landscape, one different from that of 5, 10, and 20 years ago, with notable trends visible in the literature that illustrate this point. The example of curbside collection growth in the United States is show in Table 9.

Table 9: U.S. curbside residential food waste collection programs in 2013/14 vs. 2016/17 (data from Streeter and Platt [75])

	2013/14	2016/17	Change
Number of Programs	79	148	+69 (87% increase)
Number of Communities	198	326	+128 (65% increase)
Number of States	19	20	+1 (5% increase)
Number of Households	2,740,000	5,073,069	+2,333,069 (85% increase)

Although small compared to total U.S. households, Streeter and Platt report nearly a 50% increase in the number of households with access to residential food waste collection programs since their previous study in 2014 [75]. Since 1990, the percentage of MSW disposed of in U.S. landfills has decreased almost 14.9% while the percentage of MSW going into recycling increased 11.9% [64]. The number of incinerators operating in the U.S. has also fallen, from 115 facilities in 2010 to the current 86 [141]. Based on the evolution of waste handling, it is safe to assume that the waste management infrastructure landscape will be different 5 – 10 years from now. As the waste management within the U.S. continues to change and grow, so too will consumer access to its various forms.

CHAPTER 5 – CONCLUSIONS AND RECOMMENDATIONS

A preliminary review of published life cycle assessment and inventory literature resulted in the identification of no studies focused specifically on trays used for frozen meals. Further, no studies were identified that included a comparative analysis of all four of the materials in focus for the purposes of this research. Life cycle assessment and inventory work that included similar package forms or the comparison of some materials in focus were identified, but differences in production processes and methodological choices means the use of these studies as a proxy for the environmental impacts associated with the frozen meal trays would likely be inaccurate. The review aided in illustrating general trends associated with the comparison of fiber-based materials to plastics, but inconsistent results between studies do not allow any meaningful, comparative conclusions between the materials used for the frozen meal trays to be drawn. Fiber-based trays may provide an environmental benefit compared to plastic trays, but a full life cycle assessment that includes details specific to the trays themselves, including materials and converting processes, is required.

Compared to final disposal in landfill, environmental benefits associated with other forms of waste management have been widely identified in the literature. Based on the information presented, determining the opportunity for a frozen meal tray to be fully recycled is difficult to say with certainty due to issues related to the materials themselves, their use as frozen meal packaging, and the recycling system operations. On the other hand, it can be said with relative certainty that the opportunity of the molded fiber tray to achieve the environmental benefits associated with being industrially composted is low due to limited acceptance of molded fiber packaging within the relative few residential food waste programs that exist.

Analysis of consumer access to waste management indicates that the ability of a frozen meal tray to be handled by waste management systems deemed preferential to final disposal does not automatically imply that the package will achieve the associated environmental benefits. With a specific focus on recycling, an assumption that high levels of acceptance within recycling programs automatically implies a high likelihood of a material moving through the entire recycling process also appears to be invalid.

Package handling at end of life is an incredibly complex, nuanced system, which makes it difficult to say with any level of certainty how the frozen meal trays rank in terms of comparative impact at end of life. On one hand, the research provides justification for a deeper understanding of waste management systems and material flow at end of life during package design. This would include focusing on package designs that pragmatically work within the systems available to achieve environmental benefits associated with preferred waste management options. Most importantly, the difficulty in articulating concrete results for comparative impact of the trays at end of life further illustrates the need for full life cycle analysis to provide a complete picture of comparative environmental impact between the frozen food trays.

Based on the results of this research, recommendations for continued research on the comparative impact of the frozen meal trays includes the following:

- Life cycle assessment of the frozen meal package forms and materials to elucidate and compare the life cycle impacts of the trays. This should focus on the processes and materials used specifically for the frozen meal trays.
- Any life cycle work should also include considerations of the coating applied to the molded fiber tray, which was largely ignored in this work.

- An expansion of scope to include the opportunity of the frozen meal trays to be handled by waste management options in counties or regions as waste management program make up can have high levels of geographic specificity.

APPENDIX

Table 10: Weights and serving sizes of identified frozen meal trays. Weight and serving size ranges given for PP and coated paperboard due to the identification of multiple trays

Material	Weight (g)	Serving Size (g)
CPET	18.28	241
PP	15.23 – 17.62	280 – 340
Coated Paperboard	14.42 – 15.81	266 – 326
Molded Fiber	23.91	262

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