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# Separation and processing of plastic films

David W. Reed, Jeffrey A. Lacey and Vicki S. Thompson

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# SUMMARY

A successful flexible plastic packaging (FPP) recycling process will require the best of technological development, conscientious industry strategy, an environmentally aware community and likely, governmental support and legislation. FPP is used in almost every industry and can have a wide range of physical and chemical characteristics that lead to the series of challenges encountered at current recycling facilities. FPP is typically a one-time use product, and makes up about 30% of municipal waste plastics (Davis, 2016). Due to its versatility and light weight nature, plastics are the second most commonly used packaging material next to corrugated board (WPO, 2008). Furthermore, FPP and glass are the most detrimental of recyclables to the success of recycling processes. While glass is known to jam conveyors and melt in some separations at recovery facilities, FPP is far more burdensome and challenges the separation processes at recycling facilities. In the U.S. over 250 M tons of solid trash is generated each year, about 32 M tons consisting of plastic (Sandford, 2016; EPA, 2015b). 8.7 M tons of FPP was produced in 2013 in the U.S. (Sandford, 2016) with only 7.5% of FPP being recycled currently (EPA, 2015a). Of the material that is being recycled, 83% originated from commercial sources with 51% of it being clear polyethylene (PE) stretch wrap and poly bags, 20% consisting of mixed color PE stretch wrap films and 12% PE agricultural films (Moore Recycling Associates, 2017). Of the remaining recycled films, 16% originated from consumer sources as PE retail bags, sacks and wraps collected at store and consumer drop off centers. Only 1% of recycled PE films were obtained from curbside recycling programs and processed through material recovery facilities (MRFs). Other types of films such as polyvinyl chloride (PVC) and polypropylene (PP) are essentially not recycled. Only 43% of the recycled FPP is truly recycled back into films/sheets, 44% is down-gauged into plastic composite lumber and the remaining material goes to uses such as marine and agricultural products, crates, buckets and pallets (Moore Recycling associations, 2017).

There are several reasons that FFP is difficult to manage at the recycling facility. Flexible plastic packaging comes in many shapes, sizes, and forms, and not all film behaves similarly. Some may be light and very flexible and others maybe more rigid and heavy. The technologies developed for sorting materials are often not sufficiently sophisticated in design to separate the multitude of films that are present. These materials are often difficult to distinguish from other materials due to the very thin and uneven weight of the material. For example, a single layer flat FPP may resemble paper and be sorted with the fiber stream. Alternatively the FPP may be multilayer and separate with 3-dimensional plastic types. Often the thin plastic film is too small or too large to be accurately detected. Furthermore, most types of sorting equipment are unable to adequately distinguish material types when they have highly glossy, dark colored surfaces, paints and coatings. When they are sorted with other waste materials, they are considered contamination, thereby devaluing those waste streams or forcing them to be landfilled due to their poor quality. Moving the FPP throughout the processing facility also poses challenges as they often wrap or tangle around axles, gears, wheels, and conveyers, thereby clogging, disrupting or stopping the recycling process. Taken together, plastic has the lowest recycle recovery rate of any waste stream even though it is progressively becoming a larger portion of the total waste stream.

A major challenge antagonizing improved separation technology development is the lack of industry engagement and resources for innovation. About 80% of recyclers are small companies servicing small areas with limited resources for research and/or purchase of high-end technology (Davis, 2016; IBIS,

2016). There is very little incentive to companies to develop an improved separation process to remove and collect FPP when the cost to benefit ratio may be unfavorable, even if it is environmentally green.

This report includes a current state of the scientific and trade literature and entertains topics about the challenges of FPP separation including variables such as chemical composition, amounts, types, waste streams, contamination, fate, and current and emerging detection technologies. Additionally, equipment manufacturers and MRFs have been contacted to identify and evaluate their methods or approaches for plastic film separation and recovery. Some of their solutions that have been implemented are discussed and potential strategies are suggested to reduce the growing FPP waste problems of the future.

# ACKNOWLEDGEMENTS

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# ACRONYMS

EPA – Environmental Protection Agency

FPP – Flexible plastic packaging

FT-IR – fourier transform infrared

HDPE - High-density polyethylene

HIS – Hyperspectral imaging

LDPE - Low-density polyethylene

LLDPE - Linear low-density polyethylene

MRF – Material recovery facility

OCC – Old corrugated cardboard

PE – Polyethylene

PET – Polyethylene terephthalate

PP – Polypropylene

PS – Polystyrene

PS – Polystyrene

PU – Polyurethane

PVC - Polyvinyl chloride

QC – Quality control

RDF – Refuse derived fuel

UPC – Universal product code

# Separation and processing of plastic films

## Introduction

A successful flexible plastic packaging (FPP) recycling process will require the best of technological development, conscientious industry strategy, an environmentally aware community and likely, governmental support and legislation. FPP is used in almost every industry and can have a wide range of physical and chemical characteristics that lead to the series of challenges encountered at current recycling facilities. FPP is typically a one-time use product, and makes up about 30% of municipal waste plastics (Davis, 2016). Due to its versatility and light weight nature, plastics are the second most commonly used packaging material next to corrugated board (WPO, 2008). Furthermore, FPP and glass are the most detrimental of recyclables to the success of recycling processes. While glass is known to jam conveyors and melt in some separations at recovery facilities, FPP is far more burdensome and challenges the separation processes at recycling facilities. In the U.S. over 250 M tons of solid trash is generated each year, about 32 M tons consisting of plastic (Sandford, 2016; EPA, 2015b). 8.7 M tons of FPP was produced in 2013 in the U.S. (Sandford, 2016) with only 7.5% of FPP being recycled currently (EPA, 2015a). Of the material that is being recycled, 83% originated from commercial sources with 51% of it being clear polyethylene (PE) stretch wrap and poly bags, 20% consisting of mixed color PE stretch wrap films and 12% PE agricultural films (Moore Recycling Associates, 2017). Of the remaining recycled films, 16% originated from consumer sources as PE retail bags, sacks and wraps collected at store and consumer drop off centers. Only 1% of recycled PE films were obtained from curbside recycling programs and processed through material recovery facilities (MRFs). Other types of films such as polyvinyl chloride (PVC) and polypropylene (PP) are essentially not recycled. Only 43% of the recycled FPP is truly recycled back into films/sheets, 44% is down-gauged into plastic composite lumber and the remaining material goes to uses such as marine and agricultural products, crates, buckets and pallets (Moore Recycling associations, 2017).

There are several reasons that FFP is difficult to manage at the recycling facility. Flexible plastic packaging comes in many shapes, sizes, and forms, and not all film behaves similarly. Some may be light and very flexible and others maybe more rigid and heavy. The technologies developed for sorting materials are often not sufficiently sophisticated in design to separate the multitude of films that are present. These materials are often difficult to distinguish from other materials due to the very thin and uneven weight of the material. For example, a single layer flat FPP may resemble paper and be sorted with the fiber stream. Alternatively the FPP may be multilayer and separate with 3-dimensional plastic types. Often the thin plastic film is too small or too large to be accurately detected. Furthermore, most types of sorting equipment are unable to adequately distinguish material types when they have highly glossy, dark colored surfaces, paints and coatings. When they are sorted with other waste materials, they are considered contamination, thereby devaluing those waste streams or forcing them to be landfilled due to their poor quality. Moving the FPP throughout the processing facility also poses challenges as they often wrap or tangle around axles, gears, wheels, and conveyers, thereby clogging, disrupting or stopping the recycling process. Taken together, plastic has the lowest recycle recovery rate of any waste stream even though it is progressively becoming a larger portion of the total waste stream.

For the past two decades China has processed about half of the world's export of waste plastic. As imports of waste plastic increased, the quality of imported material began to decrease, and increasing amounts of the waste plastic were unusable. In 2013, China first enacted a "Green Fence" policy that intended to curtail contaminated recyclables by enforcing previous enacted legislation. The intent of this policy was to improve the quality of material being imported to China in part to improve recycler profits, to facilitate development of their own recycling collection and sorting infrastructure, and possibly more importantly to improve the quality of the environment for the health of the people of the nation. By

2018 the transport of materials had slowed significantly due to crackdowns on illegal imports, limited import permits, additional restrictions on contamination allowance, and a backlog material buildup. Additionally, early in 2018 China began to limit or exclude the import of certain recyclable waste materials including almost all polyethylene terephthalate (PET), which is used extensively in FPP. As a result, MRFs in the US and around the world are receiving an internal deluge of plastics waste without adequate outflow. In some cases this has improved the quality of the shipments to China, but has also led to increased landfilling of plastics in the U.S. It is anticipated that U.S. consumer use of plastics will continue to increase in quantity, therefore to circumvent added pressure on landfill operations and to improve recycling economics, it is imperative that technologies be developed and implemented in the U.S. to better generate homogenous plastic waste streams, including that of FPP.

A major challenge antagonizing improved separation technology development is the lack of industry engagement and resources for innovation. About 80% of recyclers are small companies servicing small areas with limited resources for research and/or purchase of high-end technology (Davis, 2016; IBIS, 2016). There is very little incentive to companies to develop an improved separation process to remove and collect FPP when the cost to benefit ratio may be unfavorable, even if it is environmentally green. This report includes a current state of the scientific and trade literature and entertains topics about the challenges of FPP separation including variables such as chemical composition, amounts, types, waste streams, contamination, fate, and current and emerging detection technologies. Additionally, equipment manufacturers and MRFs have been contacted to identify and evaluate their methods or approaches for plastic film separation and recovery. Some of their solutions that have been implemented are discussed and potential strategies are suggested to reduce the growing FPP waste problems of the future.

## Waste Flexible Plastic Packaging

FPP serves multiple functions including prevention of product contamination, extension of shelf life, protection from abrasion, transportation, storage as well as other functions such as providing product information, attractiveness and product advertising (PlasticsEurope, 2012). As manufacturers design packaging material to meet these functions, very little consideration is given to ease the waste recovery processes and challenges facing MRFs. FPP comes in a multitude of shapes, sizes and forms ranging from film grocery bags, pillow pouches, food bags, stand-up pouches and wraps. Only 7.5% of FPP was recycled in 2015 (EPA, 2015a) primarily into either films/sheets or downgraded into plastic composite lumber. This FPP originated from either commercial sources (83%) or as clean bags from drop-off centers (16%), and never actually entered MRFs for sorting (Moore Recycling Associates, 2017); therefore, this fraction represents the most easily recovered and recyclable materials available.

A recent characterization study conducted during a FPP separation trial in a MRF demonstrated that commonly used food packaging types and quantities of each were highly diverse. While this diversity improves the breadth of packaging types available for food, it increases the packaging types encountered in municipal solid waste as well as their relative percentages of FPP (Table 1).

**Table 1.** Relative amounts of various types of packaging found in flexible packaging waste. Percentages were calculated by the amount of each type of flexible packaging divided by the total amount of flexible packaging in the characterization sample times 100.

| Packaging Type[a] | % | Packaging Type | % | Packaging type | % |
|---|---|---|---|---|---|
| Bread bags | 16.2 | Blue chip bags | 2.6 | Pet treat pouches | 1.2 |
| Diaper wrap | 2.0 | Duckling bags | 0.7 | Detergent pouches | 2.3 |
| Air pillows | 2.0 | Roaster chicken bags | 0.9 | Case wrap | 3.0 |
| Bubble wrap | 2.0 | Large jerky pouches | 0.4 | Shrink film | 1.0 |
| Dog food bags | 2.8 | Small jerky pouches | 1.1 | Grocery bags | 18.0 |
| Cereal bags | 16.0 | Salad bags | 2.6 | Retail bags | 7.0 |
| Paper Towel wrap | 4.0 | Wipes pouches | 2.6 | Storage bags | 5.0 |
| Yellow chip bags | 2.5 | Candy pouches | 1.2 | | |
| Black chip bags | 0.5 | Baby food pouches | 1.2 | | |

[a]https://www.materialsrecoveryforthefuture.com/wp-content/uploads/2018/01/MRFF-Equipment-Testing-Findings.pdf

To further complicate the FPP waste stream, a specific type of package can be made from more than one type of plastic depending upon the functions required for the package. Typical plastics used for FPP may include PET, polystyrene (PS), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC) among others or mixtures and variation of these components (Kaiser et al., 2018). While single types of plastics are used for many packaging applications, often they do not have all the required properties needed for packaged product protection, for example PET does not provide a sufficient oxygen barrier needed for some applications. Multilayer structures allow packages to perform a number of functions that single layer plastics cannot and usually with less material. However, these multilayer materials represent a new challenge for recycling as the layers of material must be separated.

The simplest multilayer is the two-layer package where the inner layer faces and is compatible with the product and may provide product specific needs such as temperature sealability; the outer layer provides external protection such as resistance against abrasion, structural integrity, a print surface and/or some type of barrier such as resistance to liquids or gases. Common sealant layers consist of additional polymers types such as ethylene-vinyl acetate, polyethylene plastomers or ionomers. Additional layers may add a moisture barrier, grease/oil resistance and/or an oxygen barrier using other material such as ethylene vinyl alcohol and metals such as aluminum (Kaiser, 2018). Multilayer materials complicate complete recycling because once the layered components are separated, the plastics will have to be sorted by resin grade for reuse or recycling and separated from non-plastic components such as aluminum and paper. These different grades can be almost impossible to separate visually with the human eye yet their separation is crucial because even a little contamination can spoil a resin. As an example of how sensitive this process can be, even 50 ppm of PVC can ruin a load of polyethylene terephthalate (PET) (Dubanowitz, 2000). Plasticized PVC, which is commonly manufactured into building components, is also used in packaging films, wrapping materials, shopping and garbage bags (Singh, 2016). Currently, MRFs are challenged due to the lack of infrastructure for sorting, cost-effective sorting of resins, organic contaminated material, and the costs associated to ship material elsewhere (Reclay, 2014). While landfilling is an option with multilayer packaging materials, these materials may take hundreds of years to degrade in the landfill and some of these plastics contain toxic trace elements that are released upon decay.

## Waste Stream Contamination

Contamination is a major concern for FPP. Bags used for trash, medical (biological contamination) and hazardous material (chemical contamination), and food may preclude reuse or recycling due to contamination (Reclay, 2014). Residual product left in packaging is problematic due to the broad range of products being sold (Table 1) as well as physical and chemical properties of those products (acidic, basic, greasy/oily, viscous, solid/liquids, detergents, etc). If FPP is recovered from municipal solid waste or single or dual stream recycling, the chances of external contamination from residual products are also much higher than FPP recovered from store or consumer drop off centers that only collect retail shopping bags. Some MRF designs incorporate washing steps to remove contamination and have improved in efficiency such that only 2-3 $m^3$ of water is required per ton of material treated while other technologies are being developed to remove organics through friction rather than water (Hopewell et al., 2009). Variables that affect washing effectiveness include residence time, temperature, agitation and the chemical environment (Biddle et al., 1999). However, washing technologies add cost and require that the plastic material be sized reduced to ensure good contact between the plastic and water for effective contaminant removal. If washing is done prior to polymer separation, the challenge of optically sorting smaller particles would likely overwhelm those systems, thus decrease throughput. If done after separation, then each polymer type would require its own wash step, increasing costs.

Multilayer packaging also results in contamination with different polymer types used as the barrier, sealant and so forth as well as non-plastic contamination with metal, paper and adhesives. Contamination with other polymer types due to incomplete separation is also a cost concern for companies who recycle and down-gauge because they often have stringent requirements for material they utilize, which depend upon application (Table 2). The HDPE bales are often used for wood/plastic composites and need to meet these requirements since polymer contaminants such as PET, PP and PVC have higher melting temperatures than polyethylene. The presence of these contaminants results in incomplete melts that cause a disruption to the composite structure. Other contaminants such as moisture, colored plastics, paper and wood can also interfere with the extrusion process or produce off specification materials (Najafi, 2013; and Turku et al, 2017).

**Table 2**. Quality requirements for two types of recycled plastic bales

| Bale Type | Content or Contaminants[a] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HDPE | LDPE | LLDPE | PE[b] | PET | PP | PVC | Paper | Moisture | color | Wood | PS/PU[c] |
| HDPE | 70% | <30% | n/a | >95% | 0 | 0 | 0 | <2% | 0 | <5% | 0 | 0 |
| LLDPE | <2% | ok | >96% | n/a | 0 | 0 | 0 | <2% | 0 | <2% | 0 | 0 |

[a]https://www.plasticfilmrecycling.org/recycling-commercial-film/businesses-post-consumer-bag-film-recycling/set-up-a-collection-program/design-collection-strategy-educate/bale-specs/
[b] Polyethylene
[c] Polystyrene/polyurethane foams

Sorting errors at the MRF account for another type of contamination in the recycling process where one material is sorted with a different type of material. For example it has been reported that the FPP separates mostly with paper fiber streams (Sandford, 2016). Indeed ~88% of the thin flexible film flows to the fiber lines mostly because it resembles and behaves like paper during the sorting process. Unfortunately it is anticipated that this will impact the cost and availability of quality recyclable fiber and lead to unacceptable grades of fiber products such as paper, boxes, tissue, etc. (Weber, 2007). To separate plastics from paper after initial fiber separation, technologies have been developed to assist indirectly and the extraction of these materials is state-of-the-art for most MRFs (Reclay, 2014). The most common and widely sold sorter for large enterprises is that of optical sorting, a unit that uses NIR and visible light to detect plastics. With this separation method, the spectrum of light is reflected off of the plastic surface to identify resin type and color and then the components are sorted, often by plastic grade. NIR spectroscopy is very useful for sorting polymers found in large quantities in most plastic packaging waste mixtures as these can be sold for a profit as long as the sorted products qualifies for the appropriate specification (Jansen, 2015). Unfortunately some materials with a similar resin such as polyethylene are not well sorted by grade since they all appear the same to the optical sorter. Preferably all light weight FPP (films), the very challenge in a sorting facility, should be removed prior to separation to improve the capacity of the NIR sorters. Generally optical sorters extract a clean stream of FPP but they are often overwhelmed with excess FPP and unable to remove all of it from the paper in an MRF process. Field testing showed that 71% of seeded FPP was removed with an optical sorter, however some paper was ejected with the plastic, resulting in two contaminated streams (Sandford, 2016).

A final issue that results in contamination occurs because the public is generally uninformed about the proper way to recycle plastics, especially when it comes to recyclable FPP. Curbside recycling is an attractive strategy to improve recycling among residential households and businesses. The most attractive current approach is single-stream collection or process of collecting mixed materials in the same container, as it lowers costs and challenges for the consumer and municipalities collecting the material. While the total volume of recyclables has increased in recent years from the single-stream recyclable collection process, this increase has come at the expense of an increased rate of contamination among the recyclable streams. (Rogoff, 2016; Weber, 2007). Some of the increased contamination present in single-stream recycling may be more due to the increased variety of container types and packaging plastics that have entered the market over the past few decades (Marshall, 2016; Rogoff, 2016).

## Standard Unit Operations in MRFs

To substantially increase the amount of FPP recycling, it will be necessary for curbside recycling programs to accept FPP and process this material through MRFs. However, this poses a number of challenges as most current MRFs were not designed to handle and separate FPP. There are two main approaches to separations in MRFs: the first method separates large materials such as furniture and appliances and proceeds to separate the remaining material; the second approach also separates out large materials, but then shreds the remaining materials and proceeds with a series of screens to classify materials into different size ranges followed by optical, magnetic and eddy current sorting. A description of the first method is given based on a design from Machinex Industries, while the second method is based on a design by Vecoplan, LLC.

***Machinex Industries Inc.***

A brief description is included of each step and the incoming and outgoing fractions are described and a flow diagram is provided in Figure 1. Steps that involve FPP separation that may be sensitive to FPP fouling or contamination are noted and solutions (underlined) are offered to mitigate FPP that may show up in these process streams.

1. Tipping floor. Bulk unsorted material offloaded from trucks and loaded into the processing line with a front end loader. The composition of the material on the tipping floor will depend upon the source of the material. Residential vs. industrial, single stream vs. multi stream recycling. The source of the material can also change the types and number of unit operations that are involved in the sorting systems.
2. Metering bins, drum feeders. Metering bins and drum feeders serve to limit the flow of biomass into the MRF such that processing stations do not become overwhelmed. This station also serves to break open garbage bags. No FPP is removed from the material at this stage.
3. Manual pre-sort stations. Nearly all MRFs require at least one manual sorting station. In this initial manual inspection, laborers remove FPP, very large items, or other materials that are not compatible with the downstream sorting systems. As much FPP as possible should be removed from the process line in this step in order to avoid its interference later on in the sorting process. The FPP hand-picked from this station is typically put into a vacuum collection system and sent to one of the balers.
4. OCC Screen. The OCC (old corrugated containers) screen removes large flat corrugated fiberboard. It typically consists of a star-screen or other type of rotary screen with large gaps between the rotating disks or stars. The large, flat, rigid cardboard rides on top of the OCC screen and is moved into a collection bin, while everything else falls through the openings for more processing. This is the first station that is prone to fouling with FPP as the FPP can easily become wrapped around the axles of the star screen. Excessive fouling of this screen will begin to close the gaps between the stars, eventually contaminating the higher value fiberboard screen with materials that no longer fall between the gaps between the stars. At this point, the processing line is shut down while laborers cut away the FPP that has become entangled around the stars and axles of the screen. <u>Potential solutions for this problem include the use of star screens with larger diameter axles and switching to machines with no rotating parts, such as ballistic separators.</u>
5. Scalping screens. The scalping screen serves two purposes. First, it breaks glass into smaller pieces. Second, it separates the material into 5”+ and 5”- for further processing. This is another step that is prone to contamination from FPP due to the rotating parts of the screen.
6. Fines screens. The 5”- fraction from the scalping screen is further separated into 2”+ and 2”- by the fines screen. This is another step that is prone to contamination from FPP due to the rotating parts of the screen.
7. News screens. The 5”+ fraction from the scalping screen is processed on a news screen to remove the newspaper. The process is another sort of star screen where the flat paper travels up the screen and into a collection bin and containers fall through the screen. All previous fractions may be redirected to a news screen to maximize the amount of fiber collected in the process. This star screen is prone to contamination from FPP due to its rotating parts.

8. Optical sorting for cleaning fiber fraction. Optical sorters are used to clean the fiber fractions, removing contaminants such as brown cardboard, containers, and metals that may have traveled up the collection screen with the newspaper. <u>This step can be combined with an air separator to remove FPP that still remains in the process.</u>
9. Manual sorting of fiber fraction for QC. The isolated newspaper/fiber fraction is sent to a manual sorting station where laborers remove any remaining contamination. This process insures a high quality fiber product for maximum value.
10. 3D finishing screens. Two 3D finishing screens produce three fractions from the 2-5" fraction separated at the scalping screens and the small fraction from the news screen. This is another sort of star screen but it is sloped up and to one side. Particles less than 2" fall between the rubber rotating disks and are sent to the glass cleaning system. 3D containers roll down the side slope and are collected. A mixed paper fraction sticks to the rubber disks and is moved up the slope where it is collected. Due to the rotating parts of this separator, this is another location that is susceptible to contamination from FPP.
11. Ballistic separator. A ballistic separator is an alternative to the 3D finishing screens or star screens, and it has no rotating parts. It can perform the same basic functions as the 3D finishing screens, yielding a fines fraction that can be sent to the glass cleaning system, a hollow containers fraction, and a mixed fiber or flat item fraction. <u>This type of separator is less affected by contamination from FPP as there are no axles for the FPP to become wrapped around.</u>
12. Optical sorting for cleaning mixed paper. The stream of mixed paper from the 3D finishing screens is cleaned using optical sorters to remove all contaminants. This cleaned paper fraction is sent to the fiber quality control line to be manually sorted.
13. Ferrous magnet. The 3D containers fraction collected from the 3D finishing screen is first manually sorted to remove any large 3D fiber products such as books, cartons, or boxes. The stream is then processed through the ferrous magnet to remove any steel cans.
14. Optical sorting for #2 plastics, HDPE. The remaining 3D containers are sent through an optical sorter where HDPE plastics are removed from the stream.
15. Plastic perforator. A plastic perforator is used to flatten the 3D plastic containers and aluminum cans to facilitate their separation in optical sorters and Eddy Current separators.
16. Eddy current magnet. The flattened 3D containers from the plastic perforator are conveyed over an eddy current magnet to remove aluminum cans from the stream. The aluminum can stream is manually sorted to ensure a high purity fraction for maximum value.
17. Optical sorting for #1 plastics, PET. The stream of flattened containers is then sent through another optical sorter where PET is removed. This is a positive sort, where the PET is targeted for removal from the stream.
18. Additional optical sorting for #1 plastics, PET. This optical sorting process is divided into two parts. The first part is a negative sort of the PET stream from the previous step, where the PET remains in the stream and any contaminants are rejected. The cleaned PET is sent to a mixed plastics bin. The second part of this system receives the remainder of the flattened containers after the PET removal from the previous step. This stream is sorted into Tetrapak type containers, mixed plastics, and rejects. All of this material receives a manual quality control sorting step at the end of the process.
19. Storage bunkers. All of the cleaned and sorted material is sent to individual storage bunkers.

20. Balers. Balers are used to compact cleaned and sorted materials, making them better suited for transportation.
21. Glass cleaning system. The 2”- fraction from the fines screen and the fine fraction from the 3D finishing screen are sent to the glass cleaning system. An air separator removes light particles. The heavy fraction that contains the glass passes through a trommel screen to remove oversized particles and an Eddy Current magnet to remove any remaining aluminum. The remaining material after these separations is a high quality glass fraction. The light fraction from the air separator and the oversize fraction from the trommel screen are sent to the landfill.
22. Rejects compactor. The rejects from each processing line are compacted and sent to the landfill.

As would be expected with this type of design, FPP can fractionate into both flat and 3-D streams depending upon the type of packaging. A recent study by Resource Recycling Systems examined the efficiency of FPP seeded into a waste stream for a typical mid-life MRF serving San Diego and found that the system was able to correctly sort 43% of the FPP and that 88% of the FPP fractionated into the flat fiber streams (Sandford, 2016). In subsequent testing in newer MRF systems with optical sorting added into the flat fiber stream, 71% of the FPP could be correctly sorted and up to 89% if the material was passed through the sorter three times. While these results are promising, the improved efficiencies come at the expense of throughput because the optical sorters are overwhelmed when processing at the designed throughputs (for the 71% efficiency, the throughput was reduced by 50% and for the 89% efficiency, the throughput was reduced by 80%). In addition, the more efficient designs also require placement of optical sorters in the fiber lines which adds costs and may not be practical in older facilities.

***Vecoplan, LLC***

Previous work at INL developed a simulated process flow diagram for the MSW sorting process based upon Vecoplan, LLC design as shown in Figure 2. Unit operations for this process include shredding, magnets for ferrous separation, screening, air classification, eddy current for non-ferrous separation, and near-infrared detection for plastic recovery. The feedstock is first size reduced in a shredder to ≤ 10” -. Magnetic separation is then used to separate ferrous material. Experience gathered in the MSW sorting industry demonstrates that most contaminants such as soil and dust are normally less than a nominal size of 2”. In addition, other waste types such as leaves or glass are generally reduced to less than 2“ after size reduction in the shredder; and, therefore, such materials are removed by a 2” screen. This results in a small particle waste stream that is removed and discarded to a landfill. This accounts for about 26.5% of the total MSW entering the MRF.

The remaining stream consists of the fraction with particle sizes larger than 2” which then passes an air classifier to remove heavy material which primarily consists of food waste with high water content. About 6.7% of the heavy waste is discarded. Next, the light fraction continuously passes through a second magnetic separator to remove residual ferrous material, an eddy current separator to remove non-ferrous material, and near-infrared optical separator to remove plastics. The final stream represents a residual organic waste stream with a mass efficiency of 48%. This organic waste stream which would ordinarily be landfilled. Material recovery efficiencies for each type of material received into the MRF are given in Table 3.

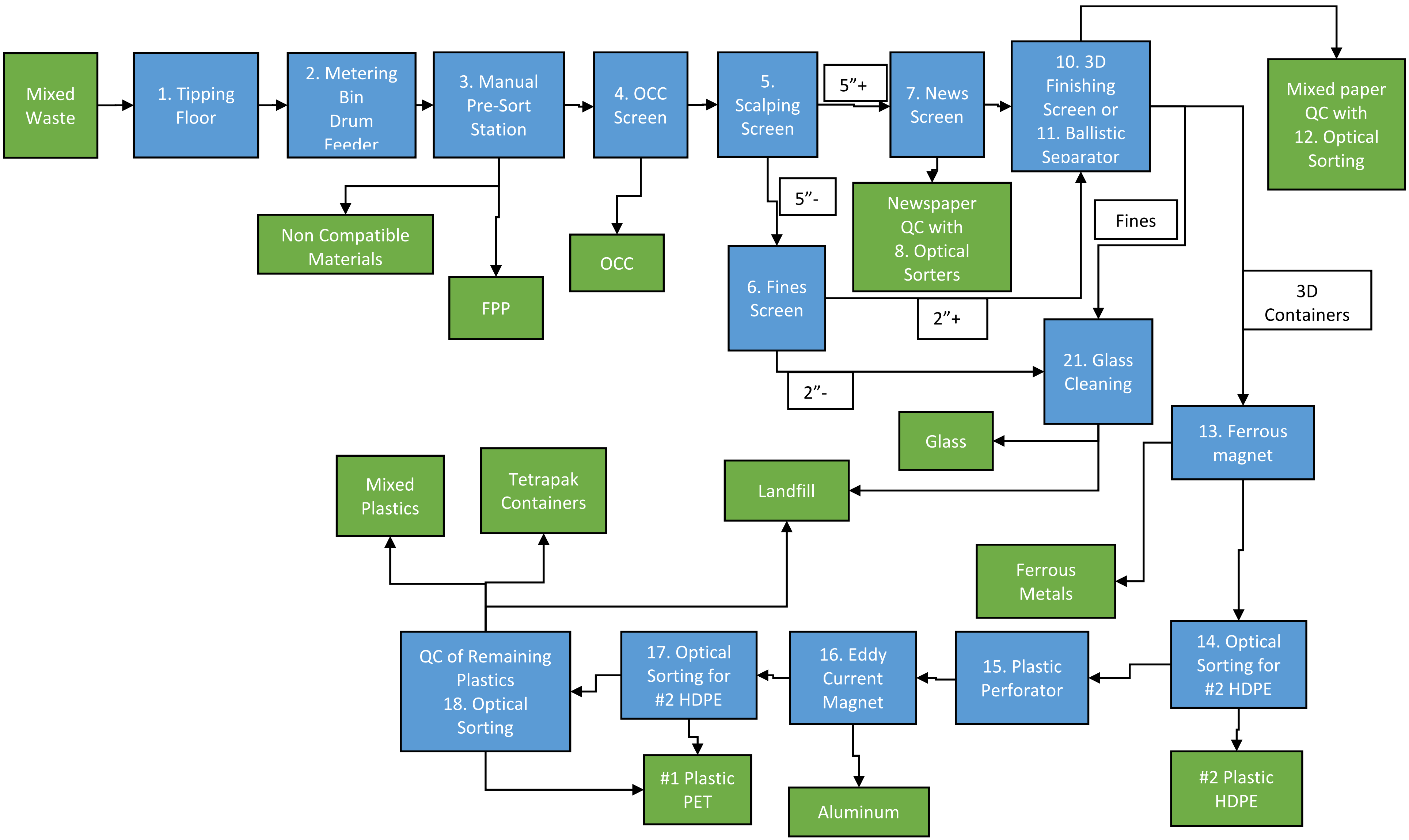


**Figure 1**. Process flow diagram for Machinex, Inc. MRF design

**Figure 2**. Process flow diagram for Vecoplan, LLC MSW sorting process

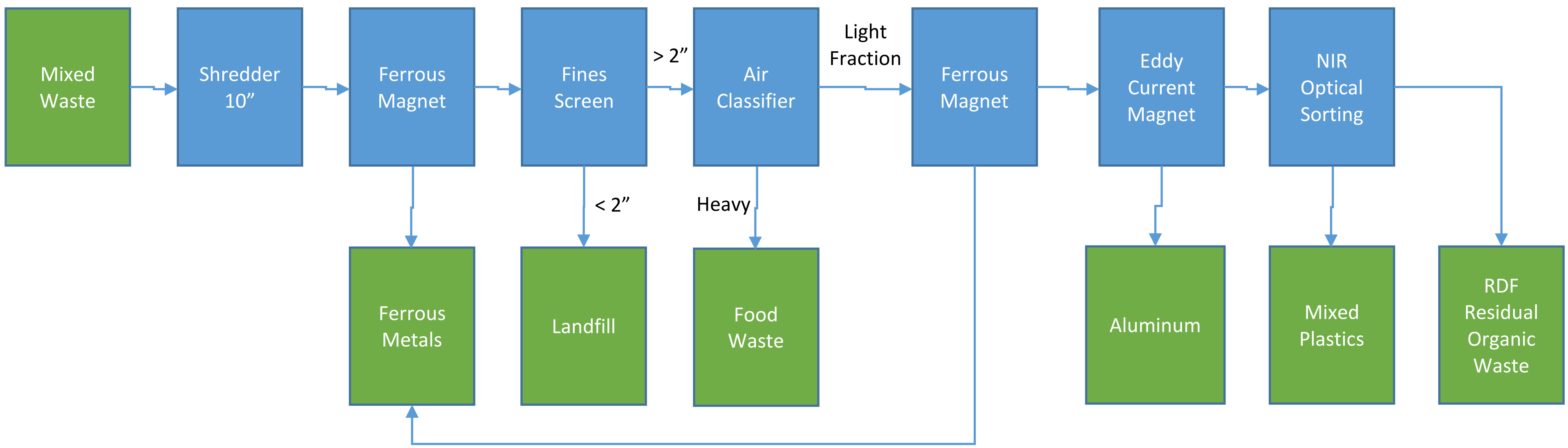

**Table 3.** Overall material recovery for a MSW stream containing the 2015 EPA national average waste composition.

| Category | Paper | Plastic | Biomass | Organic wastes | Ferrous | Non-ferrous | Glass |
|---|---|---|---|---|---|---|---|
| Recovery (%) | 84.5 | 85 | 65 | 45 | 91 | 90 | - |

## Emerging Technologies

Although a number of solutions and technologies have been identified and applied with the testament among some manufactures that "the (FPP) problem has been solved", MRFs seem to have a different view, contamination is still occurring and eating into profits. This section describes technologies that have been proposed in the literature and by companies as well as existing technologies adapted to help solve these issues.

The film grabber developed by Bollegraaf is designed to pick film from a recyclable stream. It has a drum with protruding fingers that rotates over a mix of recyclables passing over a belt conveyer. Flexible film is hooked and lifted out. As the drum rotates, the fingers retract at the top and the film is blown off into a container. The fingers must be very close to the belt to hook films which is problematic for 3-D packaging which must be removed prior to this step. This process seems to works well for thin flexible bags with claims of 70% collection by the developer, although its performance in a dual stream MRF in Canada ranged from 30-60% (ReclayStewartEdge, 2014). This technology also does not work well for small sized material and thicker and multiplex bags like cereal box liners and may also pick up other non-plastic items such as paper. Technologies that have been adapted for FPP are air classification which passes the recycle stream over a fan and light film materials are blown up to a collection container or air separators that apply suction to pull light flexible mixed plastic and paper materials off the conveyor. Unfortunately when using the air separators with an optical sorter, it was noted that the film plastics do not stick well to the fast conveyor belts and the jets of air used for separation have a difficult time controlling the exit direction of the ejected flexible plastic. However, given the large range of size and shapes of FPP, several parallel processing lines and methods will likely be needed.

Mastellone *et al.* (Mastellone, 2017) evaluated the performance of an MRF fed with a mixed package waste and identified several areas of improvement for existing MRF systems: (1) optimal waste mixture distribution to be fed to the facility, (2) operating variables that maximize the performance indicators relative to operability and yields, (3) inserting a NIR detector downstream the LDPE sorting from the 2D material in order to intercept the flattened liquid containers present, (4) NIR detector upstream the aluminum sorting in order to intercept the containers (PET, HDPE and PP) not sorted by the 3D line, (5) Minimization of unplanned stops for maintenance.

An approach being developed in Europe is to have "plastics only" MRFs. This is similar to dual stream recycling in the U.S. where plastics are collected in separate bins from residential customers. Given the chemical similarity of plastics compared to paper, metals and other recyclables, this type of MRF will likely need more and better methods to identify different polymer types. (Singh, 2017) recently described a number indirect methods to target compositional differences: Laser introduced break-down spectroscopy (LIBS) for analysis of the major constituent's carbon and hydrogen present in polymer matrices; fourier transformed infrared (FT-IR) technique for comparison of the spectra of waste samples to that of different model polymers; a tribo-electric based separation device can differentiate materials on the basis of a surface charge transfer phenomenon (Hearn, 2005); X-ray fluorescence spectroscopy

(XRF) identifies different flame-retardants materials embedded in plastics. Fourier Transform Raman Spectroscopy has been shown to accommodate shape, color, surface state in discriminating polymers (Florestan, 1994). Furthermore thermal imaging (a type of IR) could be used as an inexpensive dirty environment, robust method to separate single wastes streams into broad categories of dry recyclables (Gundupalli, 2017b). Finally, NIR hyper spectral imaging (HSI) technology digitally captures and analyzes plastic spectra by physical and chemical characteristics (Zheng, 2018). Another technology being explored is to tag materials with dyes or metals, such as rare earth elements, as unique tracers to a plastic type to identify with XRF and lend help with separation (Bezati, 2009; Langhals, 2017). Another potential type of tag is to use a universal code of UPC symbols on all products (Thomas, 2009).

The Vecoplan, LLC shredding approach solves the issues caused by FPP such as wrapping around axles and shafts and blocking screening equipment as well as the complications of sorting different size and shape FPP into different fractions. However, shredding materials increases the complexity of separation as the number of pieces of material to be separated greatly increases. There are, however, a number of separation technologies that are amenable to smaller particle sized materials and work well with plastic materials. Gundupalli et al., 2017a, recently reviewed a number of these methods. In magnetic density separation (an optical sensing technology), waste is introduced into water that flows past large magnets and creates a magnetic field gradient that acts as a pseudo density gradient. This system is very efficient at separating plastic polymers of varying densities (Biddle, 1999). A hydrocyclone uses centrifugal force to separate polymers based on density differences. Triboelectrostatic separation works by imparting charge to plastic pieces and allowing them to separate in an electric field. Jigging concentrates plastics by pulsing a solid-water mixture of plastics which induces a current that lifts particles based on density, size and shape (Gundupalli, 2017a). Froth flotation is based on the hydrophobicity of plastic where plastic particles are mixed with water and fine bubbles are passed through the water (Shent, 1999). More hydrophobic plastics attach to the bubbles and get lifted to the top of the fluid. To the best of our knowledge, no study has yet been published assessing the efficiency of this type of sorting technology on separating FPP from waste streams. It is also unclear how efficient shredders would be in size reducing flexible films versus harder materials such as rigid plastic containers and cardboard.

Another emerging technology that seems promising is that of artificial intelligence coupled with optical/visual capabilities and robotics to analyze a waste stream and robotically sort it. Bulk Handling Systems recently introduced Max-AI, a learning system that uses 3D vision capabilities to identify specific types of waste, make decisions on how they should be sorted, and robotically pick these items from the material stream. Machinex also debuted its AI system, SamurAI, with similar capabilities. While the robotic picking arm is capable of sorting faster than humans, it is not fast enough to handle a full scale stream of materials. As such, the functions of current installations of this system are limited to QC steps to remove contaminants from an already separated stream of materials. Advancements in robotics and machine learning could improve this technology to take on a larger and more complex role within the MRF.

A non-recycling option has been evaluated to use only biodegradable material for single use primary packaging material such as that in FPP (Davis, 2006). Food packaging is one of the most noted sources of environmental litter and MRF contamination. Biodegradable FPP could be used for foods, personal and health care, consumer goods, and disposable bags. Such materials could be composted and incinerated, however not likely landfilled or recycled and may exasperate the plastic recovery process (Davis, 2006).

## Potential End-Use for FPP

Unfortunately, flexible polymers in FPP are not generally of interest to recyclers even if they are comprised of the same polymer type; rather they are more interested in rigid plastics. However, one option that has already developed a robust market is to recycle polyethylene FPP into wood polymer composites. The FPP currently being utilized is recycled films from commercial sources and consumer drop-off centers. These materials are relatively clean and can meet the stringent specifications required by the manufacturers including PE content greater than 95%; no trash, food or loose paper; no PVC, PS, PP or PET and no hazardous materials (plasticfilmrecycling.org). However to increase recycling of FPP beyond this clean FPP stream will require overcoming barriers such as difficult and costly separation of FPP from single/dual stream recycling and mixed waste, contamination of FPP during collection and separation, unknown effects of plastic mixes on material properties and the lack of techno-economic (TEA) and life cycle (LCA) analysis impacts on the recovery and recycling process.

Sometimes recycling of FPP is not possible or economically feasible for some waste streams, therefore options preferable to landfill are the conversion of wastes to energy and chemicals. Conversion options may include pyrolysis, gasification, engineered fuel, industrial use and waste-to-energy (Reclay, 2014).

***Pyrolysis***

One developing technology is pyrolysis or the use of high temperatures (350-800°C) under low oxygen conditions for melting hydrocarbons into small molecular weight carbon chains. Most efforts have focused on plastic conversions although pyrolysis can be applied to rubber, organics and mixed waste materials. The gaseous fractions produced can be utilized to power the gasification process. Roughly 80-90% of the chemical recovered is a crude-like oil that can be refined and blended with traditional crude oil refinery products. This process is being actively utilized in the U.S. at the commercial scale with 40 tons/day at facilities. Advantages of the process include the ability to accept FPP contaminated mixed plastic materials, although chlorinated (e.g., PVC and PVDC) plastics are not as energetic favorable and require follow on treatment to remove the chlorine. The most energy favorable polymers are polyolefin and engineering grade resins. Metals can be extracted from the process waste for additional profits. For successful economics of pyrolysis, a process should be collocated near a waste collection facility.

***Gasification***

Similar to pyrolysis gasification melts a wide variety of plastics and mixed municipal solid wastes at temperature 800-1200°C sometimes with more oxygen for full decomposition into hydrogen synthesis gas (hydrogen, carbon monoxide, ash, slag). FPP can remain with the solid waste material. This process may contribute as a renewable for natural gas for heat and energy. Furthermore syngas can be collected for conversions into chemicals such as ethanol and methanol. Currently, demonstration scale facilities are operating in the U.S. Gasification is an appropriate process to follow where recyclables have been removed although the economics likely require tipping fee payments for profitability.

***Engineered Fuel***

Mixed plastics, organics, paper, etc are processed to remove unsuited material (e.g., PVC and metallic films such as potato chip bags), size-reduced and pressed into pellets or cubes to be sold as fuel for industrial boilers, cement kilns, and power plants. These materials can replace coal, wood, and petroleum coke. Generally recyclable materials are removed prior to processing at commercial plants. Tipping fees charged improves the process profitability.

### *Industrial uses*

FPP can be used a supplemental fuel sources to burning tire and coal for industries. Examples include fueling kilns to produce Portland cement and lime, pulp and paper mills and steel mills. Cement kilns require shredded material of plastics and metallized film and may pay or charge small tipping fees. Steel mills require carbon for processing iron ore to steel. PE plastics at 86% carbon is an excellent option to replace coal and natural gas. PVC must be removed from the FPP.

### *Waste-to-Energy*

Mixed municipal solid wastes are combusted to produce electricity at some facilities and non-recycled FPP can be easily added. Tipping fees are charged to help with profitability.

## Conclusions

There does not seem to be a silver bullet solution to the FPP contamination challenges. It is likely that several factors will be required to produce an economical process for recycling separation of FPP, such as: (1) legislation (local, regional, or national) to encourage recycling and provide financial backing to manufacturers, recycling enterprises and end-product buyers, (2) education to encourage the public to recycle and help them understand better how to separate wastes at the curb or forefront of the process, and (3) better application of old technologies and/or development of new technologies to circumvent some of the challenges associated MRF separations.

A MRF requires significant capital investment for high technology plastic reclaiming equipment. Currently only six high-technology facilities exist in U.S.; each can process 13,000-55,000 tons per year but require sourcing material regionally to operate most economically (Reclay, 2014). Future work is needed in high technology, including sorters with controlled air flow to separate fiber from plastic, end market assessment for large scale use of mixed multi-layer multi-polymer resin, TEA for municipalities, installation of new equipment to sort flexible packaging, TEA and LCA for secondary markets including additional cleaning and sorting, and community curbside demonstration pilots. Additional needs may include larger screening areas and a better solution to the small 3D flexible packaging. (Sandford, 2016). However, as mentioned in the introduction, 80% of recycling facilities are small companies serving limited areas.  These facilities are not going to have the resources to invest in state of the art technology nor to keep with up technological advances. Options for these facilities to include FPP as part of their recyclables include shipping/selling their materials to regional facilities described above or to incorporate manual sorting strategies to their existing systems to remove FPP.

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