Cleaning Agricultural Plastic Film for Recycling

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Abstract

This project’s goal was to increase agricultural plastics recycling by developing systems to reduce used film contamination. Recycling can occur when recycling center managers are satisfied with the plastics’ cleanliness. Recycling is a cost effective and environmentally friendly substitute to burying or burning. This eliminates the need for landfill space, reduces pollution and preserves resources. This project developed a machine for contamination removal. Contaminants are any material other than low density polyethylene.

A test machine utilizing brushes and scrapers was built. This machine had the capability to vary the speed ratio between the feeding rolls and cleaning brushes. The speed ratio controls how much brushing occurs per length of plastic. The brushes effectively removed dry soil and crop, but had difficulties with moist material. Rubber scrapers removed some wet substances, but failed to remove enough wet material to reach the less than 4% contamination goal. The machine removed substantial amounts of typical contamination.

We believe waste plastic left on the ground for extended periods or located in muddy areas contributes to the soil build up. Less contaminated plastic was more likely to reach the cleaning goal. Clean plastic is more appealing for recycling, because it is less expensive to reuse.
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1.0 Introduction

1.1 Project Justification

Agricultural plastics offer a cost efficient alternative to high capital cost silos. Tower silos last for years, but bunker silo covers and silage bags must be disposed after they are used. The most popular disposal methods are burning, burying on site, or transporting to a landfill (Garthe, C10). The most environmentally friendly solution for the used plastic disposal problem is recycling. The plastic does not need to be burned or buried; it can become other useful products.

This project’s goal was to increase recycling of agricultural plastics through contamination removal. Silage bags and bunker covers are the main focus, since they are the predominant plastic film used on Wisconsin farms. The move towards plastics has caused predicaments. Plastics comprises one-fifth of the agricultural waste stream by volume (figure 1) (Garthe, C10). Agricultural plastic films create a mess which is unpleasant. Low density film piles are easily scattered by the wind. Cleaning up these plastic piles can be painstaking, because plastic sheets are arduous to handle. This is a nuisance to using plastic films, but picking it up has to happen.

Figure 1 The percentage distribution of the agricultural waste stream (Garthe, C10).

The move toward silage bags is spurred by increased productivity compared to vertical silos or bunkers. Agricultural applications are utilizing more plastics, because of lower investment and annual cost. Silage bags could save nearly 10,000 dollars yearly on a typical 220 cow dairy farm (Josefsson, 2000).

Figure 2 Annual costs of different silage storage selections (Josefsson, 2000).
Agriculture can become more productive and efficient by appropriately applying plastics (Garthe, C10). Silage bags also offer flexibility in storage capacity that is attractive if future needs are uncertain. Yearly storage needs are satisfied by adjusting bag diameter, length and number. Silage bags are commonly 8 to 12 feet in diameter and 100 to 250 feet in length, and cost between 100 and 500 dollars. They can offer better feed quality with less spoilage than the alternatives. Smaller farms find them appealing, since they are less likely to have the resources to make the capital investment of a vertical silo (Levitan and Barros, 2003). Agricultural plastic bags are not reusable, unlike silo structures. Silage bags are cut apart while feeding out of them.

Current plastic film disposal methods are estimated to cost each user less the 100 dollars annually. Little willingness exists to pay more or travel more than 25 miles to recycle the plastic. People will do some small extra steps to help make plastic more recyclable, such as shaking off the plastic and keeping it as clean as possible (Negra and Rogers, 1997). Any recycling scheme needs to be economical and brief so people will practice it. Disposal costs at landfills are increasing because of a reduction in available landfill space. This will propel people to find cheaper choices, likely burning. Burning is the most common practice, because of the low cost and inherent handling difficulties (Garthe, C10). Burning accounts for 60 percent of plastic disposal (Levitan and Barros, 2003). Low density polyethylene (LDPE) will burn with little visible smoke, which makes it easy to hide. Foreign materials within the burning pile might not burn cleanly. Adoption of an inexpensive alternative will reduce burning.

A dumpster can easily be filled with plastic film, but the mass inside is not significant. Silage bags and bunker covers are light weight and tend to occupy a large volume, which makes them difficult to handle. It is difficult to justify high landfill tipping fees for an insubstantial weight. This is why many people tend to pile the plastic and ignite it. Some people might be tempted to use an agricultural baler to reduce plastic volume. No agricultural baler design includes compacting plastic as a designed use, and it is dangerous. Shipping the plastic to the landfill is not cost effective.

Recycling can be an economically and environmentally friendly solution. However, agricultural debris and concerns about ultra-violet (UV) degradation has caused recycling of these plastics to lag behind others. It is also difficult to cheaply collect enough volume to make recycling viable. Selling the plastic to manufactures can offset some recycling costs. Silage bags and bunker covers use a high quality plastic to ensure the product will endure weathering and physical damage. Clean plastic has some value, but this is not a lucrative venture, and conceivably needs some government assistance to be successful. An aspiration to recycle exists, but a desirable method does not.
1.2 Tips for Recycling

Plastic users can do important things to make collecting plastic more attractive for recycling centers. The first is to keep different plastic recycling numbers separated (figure 3). Plastics are recycled in seven categories.

![Figure 3 Plastic recycling symbols and their meaning.](image)

<table>
<thead>
<tr>
<th>Recycling Number</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PETE  Poly(ethylene terephthalate)</td>
</tr>
<tr>
<td>2</td>
<td>HDPE  High Density Polyethylene</td>
</tr>
<tr>
<td>3</td>
<td>UPVC  Unplasticised Polyvinylchloride</td>
</tr>
<tr>
<td>4</td>
<td>LDPE  Low Density Polyethylene</td>
</tr>
<tr>
<td>5</td>
<td>PP    Polypropylene</td>
</tr>
<tr>
<td>6</td>
<td>PS    Polystyrene</td>
</tr>
<tr>
<td>7</td>
<td>Other</td>
</tr>
</tbody>
</table>

Recycling centers are more willing to accept plastics if they are not required to sort the plastic. Different plastic types have different properties and uses, mixing types is undesirable for recycling centers. Recycling requires the different types of plastics are identifiable. Most rigid containers have the recycling triangle symbol with the plastic type, indicated by a number (figure 3), embossed on the bottom. Silage bags, bunker covers, greenhouse film, and bale wrap are all recyclable under the number 4 category.

The second thing users can do to make plastics more recyclable is to keep the plastic as clean as possible. Silage bags stay relatively clean if not left on soil. Most soil adhesion occurs from driving over the plastic or dragging it through muddy soil. Placing the silage bags on an area that stays dry helps prevent soil build up. A gravel or concrete pad helps to keep the bag bottom clean and also eliminates cover (weeds) that rodents use to get close to the bag. Rodents will eat the silage, and the access hole allows air to spoil the silage. Bunker silo covers rarely contact the soil in normal use conditions, besides the small portion that might be covered to seal the edge. Proper management will eliminate a large amount of the contaminants that could accumulate.

Another suggestion is to locate a collector to accept the plastic. This varies depending on location, but recycling centers are usually willing to accept clean separated plastic. Usually there is no drop-off fee, but they require the plastic compacted in some form. Area recycling centers are in the phone book’s yellow pages.

Many of the recycling centers contacted about this research expressed an interest in accepting agricultural plastics. A concern is the plastic be clean enough, meaning that it is free of all hard objects and had a relatively small amount of dirt. A second concern is that a large enough quantity is available for collection, but ordinarily they accept drop-offs. Small steps to keep the plastic clean early makes a big difference later.
1.3 Film Blown Extrusion

The process to make both silage bags and bunker covers is film blown extrusion (figure 4). A cut along the tube’s length changes a silage bag into a bunker cover. Bunker covers, typically 5 thousands of an inch, are thinner than silage bags, normally 7.5 to 9 thousands of an inch (Levitan et al, 2005). Recently, farmers have recognized the benefits of thicker bunker covers, and are increasing their use. The manufacturing process involves an extruder that melts granular polymer pellets and then builds pressure to push the melt through an annular die attached to the end of the barrel. The annular die produces a molten plastic ring. A molten ring stretches to form a tube. Nip rolls pull the plastic tube upward, while air pressure inside the tube expands it to the desired size. This process imparts a biaxial stretching to produce a stronger tube by aligning polymer chains (Osswald and Menges, 2003). Biaxial stretching means the plastic expands in the circumferential and axial directions.

![Diagram of film blown extrusion process](image)

Figure 4 Film blown extrusion process shows the annular die and a depiction of the tower. (Osswald and Menges, 2003)

Film blown extrusion is vertical to prevent the tube from sagging, which would cause a deformity. Cooling fans reduce the size of the film blowing tower by solidifying the polymer quickly. Beyond the frost line, where the polymer freezes, the tube does not change size. The air pressure inside the tube, the extruder’s throughput and the nip speed change the tube’s size and thickness (Osswald and Menges, 2003). Film blowing is a continuous process once started. This is because startup is an expensive and problematic procedure.
1.4 Dioxins

Dioxins are a problem with uncontrolled burning of agricultural plastics. Burning the plastic in a controlled environment, such as a waste to energy power plant, decreases the dioxins released due to the greatly elevated temperature compared to open air burning. Dioxins have been suspected to be a carcinogen since 1981, but it was not until January 2001 that enough information was gathered to support the claim (U.S. Department of Health and Human Services, 2005).

Dioxins have a bioaccumulation effect, which means small trace amounts present in small animals, such as fish, accumulate in larger animals which eat the smaller ones. Inhaling smoke is not the only way for a person to feel the negative effects of dioxins. Fish, meat and dairy products cause nearly all of a person’s exposure to dioxins. Bioaccumulation is a large problem because dioxins’ half life is over 11 years in humans, meaning it takes that long for half the mass to break down. This can cause many health problems.

2, 3, 7, 8-tetrachloro-dibenzo-p-dioxin (TCDD) and dioxin-like compounds have been linked to the development of endometriosis. Endometriosis is associated with more than a hundred thousand hysterectomies each year, which has a health care cost of over one billion dollars in the United States (Rier and Foster, 2002). Studies have shown even trace amounts of dioxins can cause cognitive and motor disabilities in small children (Vreugdenhil et al., 2002). Many people who burn the plastic are unaware of the detrimental effects it can have (Weisensel, 2004). This is why it is important to provide an economical alternative to open air burning.
1.5 Plastics Summary

Thermoplastic consist of long chain molecules having properties arising from the interaction between these long chains. Longer chains typically have more desirable properties, because they are able to interact with more chains. Degradation causes the chains to break, which reduces desirable properties. Degradation can occur by ultraviolet light when plastics are exposed to the sun. Processing plastic also causes chains to break down.

If too much chain scission has occurred then it could be used as filler. Linear low density polyethylene (LLDPE), used as bale wrap, is compatible with low density polyethylene (LDPE) for recycling purposes. However, some recycling centers might not like the two mixed, because of the property differences. The difference is chiefly the crystallinity, or the amount of lamellas formed (figure 6). Lamellas are higher density crystal structures. The folding pattern increases density, but also allows for large deformations before ultimate failure by unfolding.

Linear polyethylene (LPE) or low pressure polyethylene is a more brittle type of polyethylene. Instead of having long branches, there are only short whiskers branching from a single long chain (figure 7). Linear polyethylene’s whiskers restrain the formation of lamella. This reduces the amount of deformation that occurs before failure. The short whiskers are also less likely to entangle with other chains which helps in yielding. This plastic can be used to manufacture less stringent products, such as toys. European manufactures use 85 percent LPE in many products. This is because it is much easier, cheaper and more compact to produce LPE (Giacomin, 2004).
The final obstacle to recycling is the dispersion of plastic within a region. Agricultural plastics are currently being recycled on larger sites in Colorado, New Mexico and California. Ag-Bag International Ltd., formerly of Warrenton, Oregon, started this program in 1993 to recycle plastic resin. The collection costs are justified by the large concentration of film in a single location (American Plastics Council, 1996). Wisconsin farms are smaller, and create less plastic waste per site. It might be more feasible to have a collection point where multiple users could drop their plastic. The only requirement would be a shelter to keep the plastic dry and out of the dirt. Transportation arrangements could be made once enough plastic is collected.

Agricultural plastics are acceptable to recycling centers as long as they are clean. Recycling is an environmentally friendly and cost effective option to burning or burying. Less plastic film in landfills is beneficial for all. Recycling preserves more resources for the future.
2.0 Design Process

The concept of this project was to develop a machine which would clean agricultural plastic films and compact them on the farm. This would make the films more convenient for the producer to accumulate and transport to a local collection center. The clean compacted film would be more attractive to recyclers, thus encouraging them to accept the plastic films for recycling.

The goal of this project was to develop a machine to clean the plastic. Three objectives were used to break down the overall goal, which were:

- Cleaning plastic
- Ease of use
- Cost

Cleaning plastic was the most important objective, because it was closely linked to the desired result of recycling. Ease of use and cost were objectives that dealt with the implementation of the machine.

The design process, used in this study, helped to develop solutions for reducing contamination on waste plastic. Brainstorming generated many different ways of separating the contaminants from the plastic. Critical thinking reduced the plethora of ideas to something manageable. This process required machine experience, because predicting how each works determined the best method. This can be a long process, but if done correctly it saves future time.

2.1 Objective Tree

An objective tree, figure 8, is the first design step. The construction process helps to identify the goals and their relative importance. A machine that makes agricultural plastic acceptable for recycling was the overall goal. The three objectives contributing to the goal were to clean plastic, ease of use and cost. Contamination removal and robustness were the clean plastic sub-categories. Ease of use was sub-categorized into ergonomics, aesthetics, interface and safety. Cost’s three sub-categories were initial investment, operating and maintenance. The sub-categories contributed to accomplishing the larger goal. Each objective and sub-category had a weighted percentage based on its importance. Weighting each established how important it was to accomplish the goal. Higher weight means it was more essential to the project. The weighted objectives table used these percentages to determine the best design.

![Figure 8 The objective tree used for this project.](image-url)
2.2 Function Analysis Flowchart

The function analysis flowchart (figure 9) maps out the sequence of events. A well constructed function analysis flowchart accounts for all major machine functions. The inputs to the machine were plastic, contaminants and energy. The link between the plastic and contaminants must be broken for separation to occur. The functions were to convey the plastic into the cleaning system, separate the debris from the plastic, and transport each to different locations. It was important to not specify any particular method so as to not limit the possibilities. The concept generation stage developed as many ideas for each function as achievable.

![Function Analysis Flowchart](image)

Figure 9 Functional analysis flowchart shows how material and energy are required.

2.3 Concept Generation

The function analysis flowchart showed the design needed a means to feed the plastic into the separation system. The design needed a means to convey contaminants and plastic to different locations after the separation system. Brainstorming schemes generated numerous concepts for both functions. Reviewing each idea eliminated unworkable, duplicate and incompatible designs. Robust feeding and separation ideas formed viable concepts. The final product needed to be the best concept. The separation method received more development effort, because it was the most important function.

Separating the debris from the plastic is the largest barrier for recycling. Contamination is any foreign material, such as soil, the bag contents and water collected with the plastic. A major reason for not accepting dirty plastic at the recycling center is the additional cost of the cleaning process. Any hard object, metallic or stone, poses a very large risk for plastic particle reduction processing machines. Transporting contaminants adds cost to an operation. Additional cost dissuades many recyclers from accepting agricultural plastics.

Many different methods and combinations were considered to remove as much contamination as possible. These included high velocity air and water, different brushing styles, and rigid scrapers. The final design should remove as much debris as achievable.
with a simple compact machine. An objective was to keep the machine cost as minimal as possible. This would help keep the overall operation costs low.

2.4 Cleaning Method Determination

The plastic sheet’s strength limits cleaning. A very aggressive cleaning system is difficult to make function because even if the pull through force is available the plastic will tend to tear. Each plastic piece had a different strength depending on variation in environmental conditions, its thickness as well as holes in the sheet. The aim was to optimize the amount of cleaning done to the sheet while limiting the time it takes to clean it. The cleaning process needed to be effective and timely.

It was obvious that some cleaning process must occur. The dilemma was determining the best way. Cleaning ideas were categorized into four different groups: blowing, washing, scrapping, or brushing. Each category was analyzed to determine the benefits and shortcomings. The most promising category warranted further development.

The first category was using air to blow contaminants off. High velocity air did not appear to have enough inertia to remove the foreign material. The soil is usually baked onto the plastic, requiring a more abrasive cleaning action. Power requirements to generate a continuous compressed air supply would have been large. The dirtiest plastic is usually the bag ends and the bottom, which are wrinkled. An air stream is not able to clean under a fold, unless it is pointed into the air stream. This system is quite noisy with an air compressor running, plus high speed air flowing over the plastic tends to produce a high pitched whistle. Air jets require little equipment cleaning since they do not foul.

The second alternative was washing the plastic with water. Water was undesirable due to freezing in the winter and disposal of waste water is problematic. This method also required access to an adequate supply of water. Washing required there be less water and contamination mass on the plastic after the cleaning than before. Removing the water is a difficult endeavor and it was unlikely much water will evaporate if the plastic is compacted immediately after the cleaning.

The next category used a scapping action to remove contaminants. Rigid scrapers tend to get stuck on holes in the plastic and tear it. To thoroughly clean the plastic, a small gap between the scraper and the plastic needed to be maintained. A small gap tends to fill with foreign material quickly, and then is difficult to pass the next plastic sheet through. This made scrapers a poor choice for removing thin layers of contaminants. Large clumps are removed well by this method.

The final cleaning category used brushes. Dry brushing was the most appealing method. This method required no additional inputs besides power. It was the quietest way to remove as much foreign material as possible. The problem with cleaning under a fold remained, but that is present in all methods. Concerns whether the brushes would puncture the plastic existed. This method demanded fewer expensive components requiring maintenance.

Stationary brushes needed to have a large contact area. The amount of brushing was a test variable that might be investigated. To change the amount of brushing per pass would likely require large machine modifications. Stationary brushes require frequent cleaning, because there is no mechanism for dirt to escape from the bristles.

Moving brushes were able to greatly decrease the space allocated for brushing. This was because the brushes could move in the opposite direction of the plastic, thereby
creating a longer theoretical brushing length. This helped to keep the machine compact. Two cylindrical brushes were simple and moved the dirt counter to the plastic flow. This created a stripping action while brushing the dirt off. The rotating motion also helped to clean the brush. The next step was to generate designs when using this cleaning method.

2.5 Concepts

The best ideas were modeled in SolidWorks 2004, a three dimensional modeling software package. This gave a much better feel of the equipment scale and motion. Potential problems were easier to detect with a computer model, because it was possible to rotate, move and manipulate the objects. Three dimensional modeling ensured components did not interfere with one another. Building a three dimensional model was similar to how a physical model is built. Computer modeling difficulties foreshadowed manufacturing concerns. This helped narrow the field to three concepts.

The first idea (figures 10 and 11) used two feed roll sets and a set of cleaning brushes. The plastic sheet started through the machine, in its feed position, and then stopped. Then the top brush and front rolls were swung downward with a ninety degree rotation. From this position, the remaining sheet was fed through and cleaned. This design had two side plates with a complex curved slot to guide the front assembly. The size, complexity and weight were major disadvantages. The switch between the feeding stage and the start of the cleaning stage required either a user input or some intricate electronics. A complex belt drive system would have driven the brushes inward in the feeding position, and in the opposite direction in the cleaning position.

![Figure 10 The swing design in the initial or feeding position.](image-url)
The lever design, figure 12, is the second idea, which used levers to create separation between the brushes and rolls. The plastic sheet was fed through the gap by the user and then the levers were returned to their starting position. The design is very simple, but requires multiple awkward inputs from the operator. Clumsy operations were this design’s downfall. Spring loaded rolls and brushes add the risk of pinching one’s hand while putting plastic through. This is especially a worry at the hard intake rolls since a large force was required to pull the plastic through.
The third concept (figures 13 and 14) is the hinge design. It worked much like the lever design, but allowed the bottom brush and top roll to hinge open together. Gas springs held the arm up, which freed the user from having to hold it. The front assembly was box tube to reduce the weight. This made it easier and safer since it was directly operator controlled. A box tube frame was a relatively simple structure and required no complex curves. The functioning was reasonably simple and required fewer awkward operations. The machine could still pinch a hand, but the danger was less than the lever design.

Figure 13 Method of starting a plastic sheet in the hinge design.

Figure 14 Plastic’s path during cleaning.
2.6 Weighted Objectives Table

The weighted objectives table (table 1) compared these three designs. This process yielded an impartial design ranking. Each design was graded individually, and the final scores were compared. A weighted objectives table guided the final design choice. The objectives, from the objective tree, were the deciding factors. Each design received a score based on how well it performed each objective. The highest overall score determined the best design. If the scores were closer it might have been necessary to re-evaluate them, but in this case the hinge design was the clear winner. Each objective’s weight came from the objective tree, figure 6.

Table 1

<table>
<thead>
<tr>
<th>Sub Themes (objectives)</th>
<th>Parameter</th>
<th>Weight</th>
<th>Swing Design</th>
<th>Lever Design</th>
<th>Hinge Design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Score Value</td>
<td>Score Value</td>
<td>Score Value</td>
</tr>
<tr>
<td>Contamination Removal</td>
<td>Weight of remaining contaminants</td>
<td>0.35</td>
<td>65</td>
<td>29.8</td>
<td>55</td>
</tr>
<tr>
<td>Robustness</td>
<td>Number of failed sheets</td>
<td>0.15</td>
<td>80</td>
<td>12.0</td>
<td>50</td>
</tr>
<tr>
<td>Ergonomics</td>
<td>Number of awkward motions</td>
<td>0.01</td>
<td>90</td>
<td>0.0</td>
<td>50</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>Appearance</td>
<td>0.02</td>
<td>65</td>
<td>1.3</td>
<td>50</td>
</tr>
<tr>
<td>Interface</td>
<td>Number of controls</td>
<td>0.03</td>
<td>70</td>
<td>2.1</td>
<td>45</td>
</tr>
<tr>
<td>Safety</td>
<td>Machine controlled motions</td>
<td>0.14</td>
<td>45</td>
<td>6.3</td>
<td>30</td>
</tr>
<tr>
<td>Initial Investment</td>
<td>Amount of materials</td>
<td>0.09</td>
<td>35</td>
<td>3.2</td>
<td>70</td>
</tr>
<tr>
<td>Operating</td>
<td>Energy input required</td>
<td>0.12</td>
<td>80</td>
<td>9.6</td>
<td>50</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Components that require maintenance</td>
<td>0.09</td>
<td>55</td>
<td>3.0</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>70.1</td>
<td>70.2</td>
<td>70.4</td>
</tr>
</tbody>
</table>

Scores were assigned based on how well the design was predicted to meet the objective. This was when experience with machinery was invaluable. The value was the product of the weight and score. The design with the highest summation of all values was predicted to be the best performing.

2.7 Machine Design

The hinge design clearly scored the highest in the weighted objectives table. Now the concept must be developed into a functioning model, so decisions about powering, mounting and functioning needed to be made. These concepts were subject to change during construction. Attaching the machine to a tractor’s three point hitch made it more mobile instead of having to move the machine by truck or on wheels. A tractor had ample power to operate the machine.

Hydraulic fluid power was readily available on the tractor, so it was used to power the motors to rotate the brushes and rolls. A chain drive transferred the power from the hydraulic motors to the brushes and rolls. Hydraulic motors also allowed for the speed ratio between the brushes and rolls to be adjustable. This led to a theoretically infinitely variable speed ratio between the two. This was valuable to the research, because it allowed testing another variable. However, the design does not require individual motors for brush and rolls. The second motor was added to the test design so different speed ratios could be tested.

A John Deere 7820 tractor was used to test the machine, because it offered adjustable hydraulic flow rate through individual ports. This allowed independent changes in speeds of either the rolls or brushes. An alternative solution would have used electric motors and control operations through a computer program. This would have been a more costly method, because less equipment was already available.
Another variable investigated was the difference between bristle types. The two brushes tested were manufactured to the dimensional specifications, but do not have the same bristles. Replicate tests were conducted to determine if one brush cleans better.

2.8 Machine Function

The primary function of the machine (figure 15) was to separate the dirt from the plastic. A nip point between two hard rubber rolls pulled a plastic sheet through a brushing system. Two cylindrical brushes rotated to create a continual sweeping motion. The overall brush width was four feet, but a typical sheet tested was three feet wide, which provided allowance for some misalignment.

![Figure 15 Machine's right side while in the closed position.](image)

The first step in the operation was to open the machine’s arm by lifting the top brush assembly (figure 16). Gas springs, mounted on either side, assisted in lifting the front arm, and held it in the open position. This prevented the operator from having to perform two tasks at once. Next, the plastic sheet’s leading edge was set on top of the bottom rubber roll (figure 16). The next step was to carefully close the arm, making sure the gears meshed fully and the plastic sheet remained between the rubber rolls. The plastic was ready for the cleaning stage.

The cleaning stage was accomplished when the two hydraulic control levers on the tractor were pulled, which activated the brushes and rolls. This pulled the sheet through, while the brushes swept off contaminants. A final version would either have a single control lever, or possibly use some other power source. This was a test fixture and a final design necessitates more safety devices.
Figure 16 Plastic initially placed into the machine.

Figure 17 Plastic’s path through the machine.
2.9 Machine Modifications

The original design had difficulties handling very muddy plastic sheets. When the hard rubber rolls got muddy they would lose their pulling power. This typically required the rolls be cleaned before subsequent sheets could be cleaned with any consistency.

Muddy samples required more aggressive rolls. The new rolls utilized a rubber frictional tape (figure 18) to generate more friction. The tape was wrapped around a steel pipe which provided a cylindrical structure. The frictional tape had rows of rubber peaks running across the width, which gripped the plastic sheets better. Crushing the peaks into the valleys crimped the plastic between the rolls.

![Figure 18 Frictional tape’s physical structure.](image)

The new intake rolls (figure 19) prevented the plastic from slipping, which produced better cleaning. However, if too much force was used to remove contaminants, the plastic ripped. This was a larger problem with thinner bunker cover plastic, because it was not as strong as the thicker silage bag plastic. Holes in the plastic can reduce the sheet’s strength causing the sheet to rip when pulled through the machine. Even though more pull through force was available, only so much resistance can be applied to the plastic before it failed.

![Figure 19 The new friction rolls in the machine.](image)

The new rolls were slightly larger than the hard rubber rolls, but the new ones were softer. This allowed for the surfaces to deform when pressed together. No gears were required to drive the top roll, because the top roll was driven by friction off the bottom roll. With these rolls, there was only one gear set between the brushes to mesh when the arm was closed. The fit between the friction rolls occasionally stopped the arm
from remaining closed completely. A small latch (figure 20) was added to keep the arm closed while the machine was running.

![Figure 20 Latch to keep the arm closed.](image)

Rubber scrapers (figure 21) were added to remove contaminant clumps before they entered the brushes. Large muddy clumps tended to accumulate in the bristles and hinder cleaning. The friction tape rolls made the rubber scrapers plausible. The hard rubber rolls would not pull plastic through the rubber scrapers. The machine’s form was not changed by the scrapers, but they helped remove contaminants. A reasonable gap must was left between the scrapers to prevent the plastic from tearing. The rubber scrapers stripped clumps from the plastic, and the brushes swept small dry materials off. These small modifications have decreased the number of sheets the machine cannot handle. They also helped remove debris.

Other options were considered for pulling plastic sheets through, such as spur gears, steel banded rolls and others. Ultimately these ideas were not used because they were not functionally sound. A procedure similar to choosing the machine design, described in section 2.4 was repeated to reach this decision.

![Figure 21 The scrapers’ location on the machine.](image)

The brushes came from a single manufacturer, Tanis Incorporated (www.tanisinc.com), and both were standard brushes. The larger brush had bristles that were .030 inches in diameter and were 3 inches long. The smaller brush’s bristles were .006 inches in diameter and 1.25 inches long. Polypropylene bristles were good for this application, because they were relatively stiff to scrub debris off, but not too stiff to tear the plastic. The larger diameter bristles were approximately 45 times stiffer then the smaller. The smaller brush had a greater bristle density on its face, because of the smaller overall diameter (figure 19).
3.0 Testing

The important variable investigated was the relative speed between the intake rolls and brushes. The amount of debris removed was believed to be related to the relative speed between the rolls and brushes. We hypothesized that a higher brush: roll speed ratio would result in more cleaning and therefore cleaner plastic. Testing was conducted with contaminations of corn silage, hay silage, water and different soil types. The goal was to optimize the machine’s performance over the spectrum of different conditions.

The largest difficulty with the testing was obtaining uniformity in obtaining sample sheets of plastic. Used plastic was typically torn, or at least stretched and piled. It was also hard to handle the plastic in even a light breeze, because it blew around and twisted. The loose contamination chunks were shaken off before the initial weight measurement. This was considered a handling loss. Many small particles fell off during handling, and it was challenging to account for them all. It is likely most of these losses occur during typical handling.

It was too difficult and time consuming to collect extremely muddy samples. A different procedure was implemented. Precut samples were soiled as desired and then tested. This gauged how the machine performed with plastic contaminated more than normally occurs in practice.

3.1 Procedure A

In procedure A, plastic samples were collected from waste piles on commercial dairy farms and at UW agricultural research stations. This cleaning procedure was an attempt to simulate what occurs with plastic exposed to normal conditions. This was a very difficult process, because of infinite degrees of contamination. Plastic was selected because it was dirty; this was not a random process. If a particular section looked exceptionally dirty, it was cut out in a rectangular sample and tested. The bag bottom tended to have the greatest amount of contaminants. The bag’s sides and top had small amounts of contaminants and required little cleaning. For this reason most plastic tested was from the bag bottoms or ends that were buried.

The first step in determining the machine’s performance was to collect dirty plastic samples. This was difficult because there was no standard size or contamination type. However, it was not necessary to obtain standard contamination, because the machine needed to work well over an entire range of contamination. Typical sample size was three feet wide and five feet long, but there was a generous variance. Samples were normally collected from used silage bags. A scale (600 gram, accurate to 0.1 gram) was used to measure the initial weight.

The machine was first attached to the tractor’s three point hitch. The hydraulic hoses for each motor were connected to remote ports. Adjusting the motor’s speed required that the machine was running. A tachometer (figure 22) established the speed, which was a cheaper alternative to a flow rate meter. The flow rate was adjusted until the desired speed was reached.
Once the machine was properly setup, testing the collected plastic began. The machine’s arm was lifted (figure 13), and a sheet was laid on top of the bottom roll. Then the arm was carefully closed to make sure the gears mesh and the plastic does not shift. The machine was operated to clean the plastic. Observations were recorded at this time. After cleaning, the sheets were reweighed to determine post treatment weight.

The final step was to wash, dry and weigh the plastic for a clean or zero foreign (washed) material weight. Hand washing each sheet removed the debris left by the machine. The sheets are hung to air dry over a period of roughly eight hours. Once the sheets were completely dried they were reweighed and cleaning efficiency determined.

### 3.2 Procedure B

The extremely contaminated cases were manufactured. This was done to examine the repeatability of the machine. The first step was to get clean bunker cover plastic, and cut it into rectangular samples, roughly 2 feet wide and 6 feet long. Bunker covers are thinner and weaker than silage bags. If bunker cover plastic did not rip in the machine, then thicker plastic should not rip either. The sheet’s strength was the limiting factor for cleaning. The sheet ripped if too much resistance, caused by the cleaning systems, was applied to the sheet.

Mud was the contaminant of choice, because it appeared in previous tests to be the most difficult to remove. Water was mixed with top soil in a wheelbarrow until the desired moisture content was reached. The mixture was stirred until it was homogenous. Next the mud was spread over the white side of the plastic (figure 23). The soil thickness varied from 0 to 3/8 of an inch. The plastic sheet was then folded, with the mud on the inside, to prevent the soil from drying.

Testing begins once all the samples were soiled. A sheet was unfolded, shaken to remove loose clumps, weighed and finally cleaned in the machine. Typically two to four pounds of soil were on the sheet when it was cleaned. After cleaning, sheets were
reweighed. Soil samples were collected to determine the moisture content in accordance with the American Society of Agronomy (Gardner, 1986). This contamination was in the upper extreme of anything experienced when sheets were collected from different sites. However, this might be typical of plastic being rejected at recycling centers.

3.3 Procedure C

This procedure was designed to simulate what happens when the plastic is dragged through mud. A wheelbarrow of soil was prepared the same way as “Procedure B”. However, instead of spreading the soil on plastic, the plastic is patted down while it was dragged across the mud (figure 24). The sheets collected a similar amount of foreign material as experienced in procedure B. Only one side of the sheet was soiled. Soil thickness was approximately the same as procedure B.

![Sheet patted into mud and Contaminated sheet](image)

Figure 24 Procedure C and its resulting plastic sheet

All the sheets were air dried to determine how the machine performed at low soil moisture content. The plastic was left with the mud exposed for roughly twenty minutes. Weather conditions were favorable (72° Fahrenheit and there was a slight breeze) for this experiment. The soil became very flakey and was easily shaken from the plastic. A fraction remained on the sheet for cleaning. Shaking dirt from the plastic was a simple process that somebody could do when cleaning up plastic films if the film got this filthy. The sheets were weighed, cleaned through the machine and reweighed. Soil, shaken from the plastic, was collected to determine moisture content.

3.4 Testing Observations

The importance of roll alignment was very noticeable; proper alignment ensured the plastic pulled straight through. Spacers and an adjustable stop adjust each side’s alignment independently. The traveling roll should stop inline with the stationary roll and the hinge point. This was not something that required attention each time cleaning occurred. It was very noticeable when the plastic was not feeding properly. A properly closed position was established once the correct spacers were in place and the stop was set correctly.

When enough wet soil built up on the rolls, they would lose their pulling properties. The brushes pulled the sheet out, because the mud was shearing between the rolls and plastic. This required a quick cleaning of the rolls.

A third observation was that the machine occasionally had some problems with tracking a sheet. This was likely due to the inconsistencies with the brushing forces. If
the brushes pulled harder on one side of the sheet, it tended to turn the sheet slightly. Multiple folds in the same location caused the sheet to pull through the rolls faster at the fold location. Tracking problems could also be from the rolls being slightly misaligned.

The machine had a problem pulling a particularly muddy sheet through. It was believed the excessive mud allowed the brushes to pull more forcefully on the sheet. This was definitely a severe case and was not the norm. It would likely have gone through with more aggressive rolls or if some type of tread pattern were cut into the rolls to allow for mud and water to move away from the nipping point. More aggressive rolls might alleviate this problem.
4.0 Results

The project’s goal was to make agricultural plastic recyclable through contamination removal. The best way to do this was to remove enough foreign material so recycling centers accepted it. A cleaning aim was set at 4 percent contamination, because many recycling centers set contamination level requirements between 1 and 10 percent. If an estimated 3/4th of a silage bag was clean and the remaining 1/4th had been cleaned to 4 percent contamination, then the entire bag would have 1 percent contamination. All percentages were calculated by dividing the contaminants’ weight by the total weight and multiplying by one hundred. This should easily meet recycling center’s requirements.

The results from testing showed the machine performed better when the plastic’s contaminants were relatively dry. Moisture likely increases the adhesion of dirt and silage particles to the plastic. The mud covered sheets did not clean nearly as well as others. The tests performed on dry sheets showed very good improvement in cleanliness. The machine was unable to remove dirt stain. To remove this remainder required assertive scrubbing with a granular cleaning product. This is not a large concern, because this is small (less then 1/2 %), but it made the white side of the plastic look dirty. Removing the bulk of the contaminants was the major concern.

Wet soil made up a significant part of the foreign materials on the plastic. Plastic dragged over muddy soil can collect a significant amount of soil. Mud built up in the brushes and on the rolls was a challenging problem. This made it harder to clean subsequent sheets. The following sheets did see a significant decrease in contamination, but it was not as much as desired. Rubber scrapers helped keep mud from the brushes by removing some before it entered, but it did not eliminate it. This is less of a problem with sandy soil, because it fell out of the brushes freely. The vast majority of mud tended to build up in front of the nip point and did not go around the intake rolls. Paper towels were used to clean the rolls with the machine stopped, but offered little help to the started sheet. It was important to remove the mud before it reached the intake rolls. Once the mud reached the intake rolls, it had already past the brushes and no further cleaning could be expected.

An upper speed ratio limit for the hard rubber rolls occurred when the brushes rotated 7.5 times faster than the intake rolls. More problems with feeding and alignment occurred, at speed ratios greater then 7.5:1. Switching to more aggressive intake rolls (friction tape rolls) changed this. The friction rolls allowed for higher brush: roll speed ratios. It would not be advantageous to use less aggressive brushes, because this would reduce the cleaning. More aggressive brushes might also cause more problems with puncturing the plastic. Puncturing of the plastic was a concern with the stiffer brush. This did not appear to be a problem with either of these brushes.

Initial testing suggests the smaller brush is better at removing debris. The discrepancy might be from the rubber scrapers. The sheet’s bottom side was pulled over the bottom rubber scraper, unlike the top side that only came close to scraper. It was also possible that the bristle packing density, number of bristles per face area, could be the difference. The smaller brush has a much higher bristle density. The cause is being investigated further.
Graph 1 shows results from hay silage, corn silage and unknown bag contents for bags stored on soil. The unknown origin plastic came from a plastic pile and had very little silage material. It had a lower initial contamination percentage, because rain had cleaned it slightly. However, the dirt stains made this plastic harder to clean. A speed ratio of roughly 7.5 brushes to rolls was used in this test. The only sheet that failed to feed was an extremely muddy sheet, from the unknown group.

No correlation between the initial and final contamination percent is visible. Only one sheet failed the four percent final contamination percent objective. This does not include the sheet that did no pass through the machine and is not shown on the graph. However, the initial contamination is primarily under 25 percent, which is not particularly high.
Graph 2 shows cleaning results from a silage bag of stover that was located on soil. The speed ratio was roughly 7.5. Cleaning up the plastic right away and the low moisture content of the stover both helped to keep the initial contamination percentage low. This made it much easier to clean, and would not need to be run through the machine at all to meet the 4 percent goal. The soil beneath the silage bag was dry enough that it cleaned off easily.
Graph 3 shows the plastic cleaning test results from a hay silage bag located on soil. A 10 to 1 brush to roll speed ratio was used in this test. The specimens were wetter than the first test (graph 1), causing the increase in initial contamination. The wetter conditions did not seem to have contributed to soil staying on the plastic. The ground conditions were moist, but not muddy, which kept the machine from fouling. The machine performed favorably. A majority of the sheets cleaned are within the 4 percent objective, and three exceed the objective. The data appears to follow a third order polynomial well. Further investigation is needed to determine if this polynomial is repeatable. The polynomial’s equation was not consistent through experiments, and it likely had a multitude of factors.
Graph 4 is the results of two speed ratios. Corn silage and soil was the contamination on the plastic. The high speed ratio operated the intake rolls are 20 rpm and the brushes at roughly 150 rpm (7.5:1). The low speed ratio (3.75:1) keeps the intake rolls the same but reduced the brushes to 75 rpm. It does not appear the speed ratio has a large effect on the amount of contaminants removed. Theoretically, more brushing removes more debris. It is difficult to conclude that from this data.

The two highly contaminated sheets, the top right two points, initially exceeded the capacity of the scale, so weights were estimated. These were muddy sheets, and it seemed to be a fine soil type. The cleaning of these samples is disappointing, but they were much wetter than anything tested previously. A polynomial pattern is visible in this graph, but determining a relationship require more testing.
Graph 5: Cleaning Test Results with High Moisture Soil Contamination

Graph 5 shows the results of cleaning for fabricated high moisture sheets. These samples were created following procedure B. The objective in this test is to determine how well high moisture contaminated sheets were cleaned. Friction rolls were used in place of the hard rubber rolls, and the rubber scrapers were added. The high speed ratio in this was 10:1 brushes to rolls and the low was 5:1. The soil moisture content, on a dry basis, was roughly 53%, which is nearly saturation. These conditions were comparable to soil exposed to a heavy rain. The scrapers did most of the cleaning in this test, which is their designed purpose. However, some of the samples were torn during cleaning. The scrapers likely resisted too much and the plastic was unable to pull through. The variance in the results was due partially to the brushes fouling. Another source might be the soil’s distribution, because large clumps were removed more easily. Though the samples did not reach the 4% goal, a significant amount of soil was removed. The machine removed over 50% of the soil.
Graph 6 is the results of cleaning tests using Procedure C. These data sets show a significant improvement in the final contamination percentage for the higher moisture samples in procedure B. The speed ratios were 10:1 brushes to rolls and 5:1 for the high and low speed ratios respectively. Initially they were of equal contamination as the high moisture (procedure B), but after they were allowed to dry much of the soil was easily shaken loose. This helps to reduce the initial contamination percentage. The soil’s moisture content was roughly 22% on a dry basis. This test averaged 85% soil removal from the sheet.
Graph 7 depicts the combination of graphs 5 and 6 with information about which brush did the cleaning. The smaller brush was more efficient at removing contamination. The majority of the high moisture soil was removed by the scrapers. The plastic was pulled over the bottom scraper and only came near the top. This is believed to have accounted for some of the discrepancy between the high moisture tests.

The soil had less adhesion to the plastic in the low moisture test. This made the soil come off the plastic easier. The smaller brush’s greater bristle density was better for removing this type of contaminant.

The lack of strong correlations is from the data scatter from one test to the next. More tests could make trends more visible. Both the soil and bag contents varied in type and conditions from one plastic source to the next. The ideal relationship would be asymptotic, where no matter how high the initial contamination the final contamination level would be under 4 percent. This is not the case at all. When the plastic’s contaminants were dry, a fair amount of foreign material was removed.

The test data does not account for the un-brushed portion, started in the intake rolls. This is something that will happen on every sheet. Cleaning this would remove more debris, but there would have to be some part of each sheet to start the process. The machine’s design keeps this length short. Each sheet’s length determines what fraction does not get brushed. Longer sheets would reduce this fraction. Accurate weight measurements prevented extremely long sheets from being used in this study.
4.1 Conclusions

Testing generated many questions. Why is one piece of plastic dirtier than another, when the conditions are similar? Why are cleaning results better with certain contamination types? Key differences between situations help to answer these questions.

Users will have to make some practice changes to make bags contaminated with very muddy soil acceptable for recycling centers. Picking up plastic scraps as they are generated improves their cleanliness. The tractor deposits dirt by forcing the plastic into the soil. Since, most grass under the bag is dead; there is nothing to hold the soil together. This makes the ground muddy on wet days. Even dragging the plastic across muddy areas can deposit large amounts of soil. If the bag is trimmed and collected as it is used, there is less opportunity for it being driven over. Soil makes up a vast majority of the unwanted matter. The wet soil is the hardest to remove, and it does not take many dirty pieces to discourage recycling.

4.2 Summary

What can be done with the plastic if it is recycled? Some plastic is extremely dirty, but a majority is not too badly contaminated. Recycling centers seem misinformed about the amount of contaminants on silage plastic. Most plastic, when managed properly, retains few contaminants. Some centers were willing to accept the plastic, but would not offer any payment. The used plastic has little value, but if a market develops some money might be available to those delivering (Ludwig, 2004). Used colored low density polyethylene currently sells for pennies or less per pound. The virgin plastics’ costs are increasing and this will help the demand for more recycled materials.

Recycling is an option, but it is unlikely this plastic could be returned to silage bags because of the fear of lost properties. It is important to ensure the bag does not fall apart due to poor quality resin. The plastic could be used in other markets. This “downcycling” means the plastic cannot be reused for the same purpose, but can only be used for something of less quality (Garthe, 2004). Today many plastic products have fillers, which are cheap low quality materials. The Budd Company developed a sheet molding compound that is 46.1% (by weight) filler (soybean/corn) (Maas, 2003). The filler’s main purpose is to occupy volume without adverse effects on the material properties. The degradation of a high quality resin to a lesser quality is due to a change in the molecular structure.

Recycling centers’ contaminants concern must be alleviated before the plastic is acceptable. Further research is necessary to determine how much degradation has occurred. This project’s focus is developing a machine for contamination removal. Contamination is any matter other then low density polyethylene. Brushing the plastic appeared to be the best method for removing undesirable solid substances. The brushing amount needed for cleaning was the testing variable. Controls allowed for variability in the speed ratio between the feeding rolls and cleaning brushes. Changing this ratio determined how much brushing was done by changing the residence time in the machine. The objective was to determine how much was required to clean the plastic. It was favorable to optimize the throughput to make cleaning this plastic as quick as possible.

The machine has difficulties with moist material, but removed dry soil and crop particles easily. Wet matter tended to build up in the brushes and rolls, which then need cleaning. Picking up the plastic up in a timely manner keeps the wet soil from
accumulating. Plastic with lower initial contamination will be closer to the objective of less then four percent contamination after cleaning.

Some small modifications help deal with muddy plastic. The best way of dealing with muddy plastic is to avoid it. This can be done by collecting it in a timely manner or by letting it dry slightly before cleaning.

**5.0 Future Research**

More testing with the machine will help to establish an optimal design. It is unlikely the best possible combination of roll speed, brush speed and brush type has been discovered. Additional features might help clean the plastic. Mechanisms that make the design more robust would be helpful in assuring cleanliness. The best way to discover these mechanisms is through trial, because little data and research currently exist.

To make a complete machine design, a compaction unit must be added. Various compaction unit concepts have been considered, but nothing has been designed or built yet. It would be helpful to keep the compaction unit small and inexpensive to keep the entire project inexpensive.

Another important key in getting agricultural plastic recycled is better quantifying the properties. Recycling centers have concerns that too much ultraviolet (UV) degradation has occurred in the plastic. A study looking at the properties of virgin plastic and “used” plastic could help to determine the amount of degradation. A quick and easy way of doing this would be to conduct a Melt Flow Index (MFI) test. A melt flow indexer is a standard instrument in the plastic industry. The test is a single measurement which is compared to a control. A larger melt flow index would suggest a shorter average molecular weight. The shorter the average molecular weight the more chain scission has occurred. The procedure is described by ASTM D1238 test (ASTM, 2004). If the difference in the melt flow index between the virgin and “used” plastic is small it would suggest that little UV degradation has occurred.
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