An Analysis of Recycling High Density Polyethylene with Limited Resources

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Abstract – Since polyethylene makes up the largest percentage of plastic produced globally, and has the potential to be recycled indefinitely, it makes an excellent starting point for mitigating the severe impacts plastic waste has on the global environment. The community of Arroyo Norte in Santo Domingo, Dominican Republic is a prime example of a community in need of jobs that is heavily impacted by the constant stream of plastic waste due to the lack of end-use management. After three years of research and trial and error by the Practivistas Dominicana group from Humboldt State University, this manuscript provides an analysis of three of the most suitable plastic recycling methods using high-density polyethylene (#2 plastic) that can be performed with limited resources. Methods include: melting in a toaster oven with c-clamps for compression, melting in vegetable oil with c-clamps for compression, and melting in a modified convection oven which uses a car jack for compression. These methods were developed using a variety of online "do it yourself" tutorials and were tested in both Arroyo Norte and further developed in Arcata, California, USA. Each method was analyzed using a weighted decision matrix, regarding criteria dictated by Arroyo Norte community members. Results show that each method has the potential to create high quality recycled plastic materials for various production scales and resource availability, given further improvements on each process. This research intends to share lessons learned by Practivistas to promote and encourage further work in plastic recycling with limited resources.

Index Terms – appropriate technology, compression molding, high density polyethylene, plastic recycling, plastic waste, recycling HDPE

INTRODUCTION

Plastic waste is a widely-known global environmental issue that is plaguing the planet due to the lack of end-use management. Humans have produced 8,300 million metric tons (Mt) of virgin plastics since their introduction in the 1950s. As of 2015, only 9% of that plastic has been recycled globally¹.

Large volumes of plastic waste can be found all over the planet; even the most remote environments such as the Mariana Trench cannot escape the plague of plastic waste. This manuscript aims to contribute to this world-wide mitigation effort by exploring the feasibility of

plastic recycling production in Arroyo Norte—a small, informal community in Santo Domingo, Dominican Republic. Humboldt State University (HSU) students were introduced to the Arroyo Norte community through the Practivistas Dominicana Appropriate Technology program at HSU, which uses project-based, service-learning with international and local university students to work with communities that are addressing local issues. Through community meetings, Arroyo Norte's City Council, *Junto de Vecinos*, found jobs to be the top need and waste materials from the adjacent landfill to be the top available resource.

Arroyo Norte is located adjacent to the nation's largest landfill, and the repurposing of waste found in the dump is already an established economy in the area. High-Density Polyethylene (HDPE, #2 Plastic) is a waste material that is readily available in the "Duquesa" or landfill area. Bringing this material out of the waste stream and reintroducing HDPE into the community as a new product is what makes this an "Appropriate Technology" project. One aspect of Appropriate Technology is the practice of utilizing locally abundant waste materials and turning them into a useful resource by other means. Because communities like Arroyo Norte exist all over the world, the success of this project can be widely applicable and has the potential to benefit many more communities.

This manuscript will consider the melting and compression processes explored by Practivistas Dominicana program in 2014 and 2015 and then by returned US students in 2017 and 2018. This manuscript will compare the quality of the plastic product produced by each method as well as discuss and analyze each method using a weighted criteria matrix. These associated analyses will help determine the costs and benefits of implementing a plastic recycling program in Arroyo Norte, Dominican Republic and can be used as a feasibility study for other similar communities around the world.

PRACTIVISTAS DOMINICANA PROGRAM

The Practivistas Program unites local and international students to work together usually with communities of limited financial resources. Practivistas focus on building projects together that address real current needs through collaborative and iterative design. In the Practivistas Dominicana Program, students from Humboldt State University (HSU) and Universidad Iberoamericana (UNIBE) studied design, appropriate technology, social innovation, and environmental science at UNIBE while working directly with community members of three financially poor barrios: La Yuca del Naco, Las Malvinas II, and Arroyo Norte.

Since 2005, students and staff in Practivistas do not come with answers, and in fact do not know what projects they will be working on until after the community meetings occur. Projects are selected through open community-based processes including resource and need assessment and prioritization. Community members take on students into teams dedicated to a specific need and/or resource. Together the team leverages their available resources and knowhow (e.g. community electrical work with student research and university testing equipment) to adapt existing technologies to meet their prioritized needs².

Practivistas usually works with a local community liaison group. In Santo Domingo, that group is Colectivo Revark. Practivistas Dominicana is co-directed by Arq. Wilfredo Mena who is also a founding member Colectivo Revark. Practivistas is directed by Lonny Grafman. It is worth noting that in the Practivistas Dominicana program, US students each live with a local family. This

type of immersion living helps students adjust to their new environment and provides a support system for the six-week program.

This manuscript focuses on one community (Arroyo Norte) and one project (upcycling plastic) spread out over multiple years and teams.

LITERATURE REVIEW – WHY IS THIS IMPORTANT TO INVESTIGATE?

The literature review section is intended to support and validate the attempts to implement a recycling start-up business in Arroyo Norte and expand on the need of these types of projects around the world. Project potential and associated impacts will be discussed, as well as scientific knowledge regarding the material properties and the design process for creating recycled plastic products with limited resources.

The section will explore the creation of post-consumer HDPE tiles and blocks for non-structural applications. The focus on non-structural, plastic products is important because pure HDPE will exhibit creep and breakage when put under long-term stress. To strengthen the material, manufacturers commonly mix the polymer with another tensile material, creating composite materials that are unable to be incorporated in the recycling stream. There is a wealth of information on the internet regarding locally sourced and sustainable composite HDPE materials, but not a lot of information is shared with the public regarding the recycling of pure HDPE products. Therefore, this manuscript will discuss technical information including instructions on how to create recycled HDPE products using compression molding techniques and other factors necessary for developing pure HDPE recycled products, primarily used to create household items.

Project Potential and Impact

This project focuses its application and experience in the small community of Arroyo Norte in Santo Domingo, Dominican Republic, but similarly sheds light on a common condition of many regions throughout the world that lack access to recycling resources. Arroyo Norte is an informal settlement that exists adjacent to the nation's largest waste dump, Vertadero Duquesa. The management of the Duquesa waste site has not only been an environmental and health concern of the citizens of Santo Domingo, but also a political one. *Diario Libre*, a newspaper in Santo Domingo, has a series of reports, news updates, and editorials that portray the concerns of local Dominicans and their demands for better waste management³. This project offers an alternative to sending plastic through that waste stream, and avoids the burning of plastic waste, which is a hazardous common practice in the area.

A large amount of families in the area rummage through the local landfill searching for sellable items; for many this is their main source of income. Arroyo Norte's *Junto de Vecinos*, or City Council, voiced great interest in the repurposing and recycling of plastic as building materials and as sellable products to Practivistas in 2014 and 2015. This project aims to provide trial-tested, researched and trustworthy methods of recycling HDPE plastic via compression molding. The results will produce high quality, strong, and aesthetically pleasing plastic products, that have potential to mitigate the waste-related concerns as well as provide business opportunities for the community.

A trial-and-error process was required when exploring melting methods for HDPE due to a lack of public information available on the process. Motivation to provide a review of open-source, legitimate melting processes stems from the difficulty experienced by Practivistas when

searching for compression molding literature or instructions on the internet. Most information found in the local library and online detail injection molding or molding in general, but not compression molding of HDPE specifically. Most of the resources available for original projects are home-made YouTube videos or blog posts by hobbyists. Plastic molding guide books were utilized but were not easy to access, are outdated and primarily only regard industrial and manufacturing settings. This project aims to provide a recycling method that is easily accessible, and does not require sophisticated industrial machinery, but still produces high quality materials.

Why HDPE?

High density polyethylene is a commonly used and recycled thermoplastic, that is currently found in a variety of applications such as household chemical bottles, food containers, children's toys and many types of rigid containers. In Practivistas' experience, HDPE is readily available in the Duquesa area. Community Members can charge approximately 200 Dominican pesos to collect a large garbage bag's worth of HDPE from the Duquesa.

The unique properties of HDPE result from the strong and rigid linear molecular structures that make up the material. HDPE is resistant to degradation by fungus, bacteria, and rodent and animal attacks, making it a great material for a wide variety of applications⁴. Recycled HDPE is an incredible material for the entrepreneur, as it can be recycled indefinitely, using common household tools and appliances.

Why Compression Molding?

In 2014, Practivistas and Arroyo Norte members created a block of HDPE through compression which resulted in very positive feedback from the community. Compression molding is traditionally used to form products such as slabs, tiles, and blocks, or other simply shaped products. Figure 1 shows products made by online users, who either used a plastic tile or slab to carve a product or melted the plastic directly into the product mold.

FIGURE 1
EXAMPLES OF PRODUCTS MADE WITH COMPRESSION MOLDING. THE PULLEY WHEEL
(LEFT) WAS WORKED USING A RECYCLED HDPE TILE⁵. THE BOWL (RIGHT) WAS MADE
USING A MOLD WITH MELTED HDPE BOTTLE CAPS⁶

The most important aspects of the compression molding process are melting temperature, pressure, and mold design. The plastic is heated to its melting point while in the mold, then pressed to form the material. Because it is a thermoplastic, the material may be heated and reheated repeatedly, making it an excellent material for recycling, when done properly.

Health and Safety Considerations

When melting thermoplastics, such as HDPE, there are a range of hazards that call for proper precautions to protect workers against short-term and long-term health effects:

- The work area should be free of toxic gases, vapors and fluids that would be harmful to humans, as HDPE will off-gas various volatile organic compounds (VOCs) at different temperatures during the melt. For optimal safety, there should be a chimney or enclosure with a fan to vent the combustion vapors and smoke to the outside⁷.
- Workers will be exposed to high heat during the compression molding process and will need to protect themselves accordingly. High-temperature gloves should be used when transferring the heated plastics, up to at least one hour after the melting process has completed, and tools should be used to transfer plastics whenever possible to minimize the risk of thermal burns.
- Impact-resistant eye protection should be worn, preferably with eye shields during any operation where plastic is being sawed, ground, machined or melted to protect against eye injuries⁸.
- After the melt has been completed and the product has been cooled, there will likely be a need for “finishing”, which will turn the molded piece of plastic into a marketable product. During this process, hand files or small sharp knives will be the most common tool for small-scale applications, which will have minimal harm to workers.
- When dealing with larger-scale mechanical finishing, static electricity is a major hazard because plastics are usually dielectric, meaning static charges can accumulate on lateral surfaces of the plastic. For this reason, all plastics processing equipment should be grounded for static and current charges. Buffing and grinding machines create the greatest charges due to the nonconductivity of the wheels that are used, therefore, the operator should be provided with a conductive floor plate and adequate ventilation for maximum safety⁹.

PROJECT CRITERIA

There are multiple aspects contributing to the feasibility of this project. Successful product criteria can be seen in Table I. These criteria and their descriptions are derived from criteria outlined by Arroyo Norte *Junto de Vecinos* and Practivistas Dominicana program in the summer of 2014¹⁰. This list was further developed and revised from the original criteria, based on what has been learned about the melting process since 2014 when project goals were established.

TABLE I
CRITERIA CONSIDERED WHEN EVALUATING THE QUALITY OF THE PLASTIC PRODUCT. EACH
CRITERION IS ACCOMPANIED BY A DESCRIPTION AND A WEIGHT VALUE DENOTING ITS
IMPORTANCE

	Criteria	Description	Importance Weight
1	Resource appropriateness and accessibility	Resources appropriateness for a method favors low the environmental impact of obtaining necessary resources. Necessary resources should be easily accessible.	10
2	Material quality	The final repurposed HDPE product should be at least a complete melt all the way through the block, without surface or interior imperfections.	10
3	Low cost	Startup costs should be as low as possible from initial capital costs to the running costs.	10
4	Safety	The process of manufacturing post-consumer HDPE into new products should at least cause long-term health issues, and at best create no volatile organic compounds (VOCs) in the manufacturing facility.	10
5	Aesthetics	The final products must at least be visually appealing, and at best look clean, comparable to pre-consumer manufactured products.	9
6	Reproducibility	The process should be reproducible at least on a small-scale, and at best for larger-scale production.	9
7	Scalability	The process should be cost-effective and energy efficient to improve the scalability of a recycled HDPE business.	8
8	Low net energy	The energy source must at least be efficient and at best have low environmental impact.	7

Each criterion is weighed by its importance, or impact on the feasibility of a project. Each criterion has a different impact and importance.

Resource appropriateness and accessibility

The process is appropriate for the setting if the materials suggested are locally abundant, have low environmental impact and are easily accessible to community members. The project should be encouraged by the community and should be beneficial to all.

Material quality

Good quality materials are stronger, longer lasting, more trustworthy, and more sellable. Material quality can be analyzed by observation according to manuals from the 1970's, which reference the following imperfections to analyze the quality of a molded plastic product¹¹.

1. Blistering, pimples, pits, or fissures.
2. Flash.
3. Plastic adheres to the mold and/or is flexible on discharge.
4. Surface of piece is dull, clouded, and/or colors are segregated.
5. Pieces are warped.
6. Pieces crack at once or when in storage.
7. Weak, mechanically.

Each of these imperfections can be traced to a flaw in the molding process. Plastic Molding Technique provides a table for each of the listed imperfections¹². This table was used to improve on the melting process after each iteration.

Low cost

Arroyo Norte is very low-income neighborhood. A large motivation behind this project is the potential profit that can come to the community from the recycled products. Ideally, this project is scalable, and the materials are readily available for free from the waste stream. Thus, profit from a small-scale melting process can be used to purchase more sophisticated materials later, e.g. a toaster oven process can eventually be profitable enough to purchase a convection oven or plastic grinder. This would increase production rates and consequently increase profits, and the business may be improved further.

Safety

When thermoplastics are heated at high temperatures, they off-gas harmful chemicals that can be hazardous to human health and are considered a carcinogen. For this reason, all workers involved in the recycling and melting process must be protected from these harmful toxins. Adequate ventilation is a necessity to keep workers safe, and heat protection should be worn always during the melting process.

Aesthetics

The plastic products should be clean-looking, without impurities or irregularities, and attractive, for marketability. Lids and detergent bottles are usually dyed with various colors during initial manufacturing. Incorporating these colored elements into the clear HDPE plastics can add customizable attractive designs to the finished product. Without colored pieces, the plastic might appear dirty or obviously recycled.

Reproducibility

The optimal process should be reproducible and adaptable for various settings and communities. A method requiring less expensive capital costs and less sophisticated machinery should be easily reproducible, e.g., electric ovens are a common appliance and thus easily reproducible.

Scalability

The project should be scalable as a business, allowing for growth. For example, human power can be used to shred plastic, or for a larger scale, a shredding machine can be utilized, depending on product demand, available funds and availability of high-voltage electricity sources.

Low net energy

Because Arroyo Norte is an informal community, access to electricity from power lines is extremely limited. In Arroyo Norte specifically, less reliance on power lines would make the project easier to implement. Other methods of energy generation are worth considering, e.g., propane is used widely in the area, but will result in a different cost than the energy sources considered here.

PREPARING TO MELT

It is crucial to carefully prepare all equipment and materials before melting to avoid imperfections. The following section describes important considerations to follow before beginning the melting process. Mold design and well-prepared HDPE material will result in the best quality product.

Creating a Mold

In researching compression molding techniques, mold design was frequently considered one of the most important aspects of any type of plastic molding. The following section summarizes important considerations when creating a mold for compression molding.

Creating a standard mold that is long-lasting, affordable and easy to use is the primary goal for this project, and depending on the application, wood or steel molds prove to meet these criteria the best. When the plastic is not being melted inside the mold, wood may be the best material, paired with parchment paper to ensure the plastic does not stick to the wood. Wood is ideal for these applications because it can be screwed together and apart easily, can hold its' shape with the pressure from c-clamps, and is an easy product to assemble using standard household tools and materials.

In applications where the plastic is being melted inside the mold, ¼" steel or slightly thinner gauge steel is preferred, paired with a lubricant to act as a release agent for the final product. Steel is ideal for these applications because it can hold its' shape with large amounts of pressure, can safely withstand various sources of heat, and can be re-used indefinitely. The molds used for this process were made of ¼" steel and worked well under various amounts of pressure. Steel plates should be easily accessible at scrap yards and can be relatively easy to cut and weld into a standard mold shape with the proper equipment.

The best mold is one that has a smooth interior surface with no impurities, and one that has a slightly wider mouth opening than the base. This slight angle increase will allow the final product to slide out of the mold easily without the need for additional processes.

Mold shapes that have been successfully developed in these trials are those that could create *HDPE* rectangular cubes, flat sheets, and a bowl shape for further development. The shape of the mold depends on the product to be created. The best thing about recycling HDPE at home is the that there is virtually no limit on what kind of product that can be made.

Trial and error on behalf of the Practivistas Dominicana program have resulted in knowledge of the materials and the process by which it is recycled through compression molding techniques. Large rectangular blocks of re-melted HDPE can be sliced into tiles with a bandsaw, much like a solid block of wood. This method could produce roughly 18 tiles from one melt, depending on the thickness of the tiles and size of the initial mold.

Other mold shapes that prove to be successful are creating a recycled sheet material that could be cut into multiple shapes. This mold could create clipboards, interior shelves, exterior building siding material, hobby parts, etc.

Before use, the steel mold should be clean and wiped with a lubricant, e. g. a high temperature cooking oil, and the wooden mold should be lined with parchment paper, so the final product can easily release from the mold.

Cleaning the Material

The first step in the process is to collect recycled HDPE #2 plastic from around the home, trash and recycling bins, or local trash dumps and recycling centers. The most common HDPE products include milk jugs, home cleaning product containers, shampoo and conditioner bottles and soap containers; look on the bottom of the container and look for the #2 logo. After collecting the pure HDPE recyclables, wash and scrub with a soap and water solution to remove dirt and debris. Cut off all labels to keep the melt as pure as possible, otherwise paper and glue will be included in the melt material, which will decrease the integrity of the final product.

Cutting the Material

The final step in preparing the recycled HDPE plastic is to cut the prepared plastic into small pieces that will easily melt in the mold. The rule of thumb here for prepped plastic is the smaller the better. There are many methods for cutting plastic, either by using human power or electric power.

If using human power, the most efficient method is to cut plastic, using sharp scissors or pruning shears, into long strips. Then, multiple strips can be cut at a time into small ($\frac{1}{2}$ square inch) pieces. This method works best with a team of people helping, as it takes about 2 hours for one person to cut enough plastic necessary to fill one rectangular mold (producing a product roughly 4" wide x 6" long x 2" tall). Volunteers were crucial at this stage of the project. Volunteers were willing to help without pay in Arroyo Norte, as they had incentive that the project would benefit their community. In Arcata, CA, friends and colleagues were willing to help with the incentive of helping friends and enjoying food.

For larger applications, electrical power could be used to cut plastic by using a simple household blender that could be found for a very reasonable price, if not free. For even larger applications, plastic could be fed into an industrial-sized shredding machine that could produce barrels of plastic within a couple of hours. Table II shows example images of each of these preparation techniques (Cleaning and cutting).

TABLE II
 IMAGES DEMONSTRATING CUTTING AND CLEANING TECHNIQUES USED IN ARROYO NORTE,
 SANTO DOMINGO IN 2014.

STEP 1	STEP 2	(OPTIONAL STEP)
<p>First, wash plastic with soap and water to remove debris and oils.</p>	<p>Second, cut plastic into 1" x 1" pieces, remove all labels. Use sturdy scissors like pruning shears for thicker pieces.</p>	<p>OR Cut plastic strips with a meat grinder or blender for finer plastic.</p>

Cooling the Plastic

After melting is complete, the plastic should continue to be compressed while being cooled. Cooling can have a significant effect on the material structure of the final recycled HDPE product. When slowly cooled from the melt, HDPE results in a crystalline structure that is more elastic than one produced from a faster cool, therefore it is beneficial to cool the material as slow as possible to allow for greater elasticity in the final product¹³.

MELTING METHODS

This section describes and summarizes the most successful melting methods used by Practivistas to melt HDPE. Each method and process were explored separately. These methods were created referencing a variety of resources including videos, blog posts, and compression molding literature explored by Practivistas from 2014 – 2017 and were tried multiple times in the urban and rural areas of both the United States and the Dominican Republic. The methods described here represent the techniques that met the specific project criteria and seemed to work the best from a qualitative viewpoint. This section aims to provide a thorough explanation of each method, that can be an easily-accessible resource for melting HDPE plastic with limited resources.

Three methods of melting plastic were explored in this project: 1. Melting with a toaster oven, a steel mold, and C-clamps. 2. Melting in vegetable oil on a stovetop, a wooden mold and C-clamps. 3. Melting and compressing in an electric oven with a steel mold and a two-ton car jack. These methods seemed to be the most feasible, reproducible, and effective methods explored by Practivistas. Table III shows a step by step tutorial of each method, aligned for easy comparison. Table III should serve as easily-accessible and understandable instructions for recycling HDPE with limited resources.

TABLE III
STEP-BY-STEP PROCESSES OF MELTING HDPE PLASTIC. IMAGES SHOW PRACTIVISTAS IN SANTO DOMINGO, DOMINICAN REPUBLIC IN 2014 AND ARCATA, CALIFORNIA, USA IN 2017.

METHOD 1	METHOD 2	METHOD 3
<p>Step 1-1. Lubricate steel mold with high-heat oil (Canola oil).</p>	<p>Step 2-1. Pour 1 quart of high-heat oil (Canola oil) into large pot on the stovetop and add plastic.</p>	<p>Step 3-1. This oven used a 2.5-ton car jack for compression. Download instructions from www.preciousplastic.com to build a compression molding machine¹⁴. Acquire oven either from scrap yard, craigslist, etc. Make sure oven functions when plugged in, and that there is a compatible outlet nearby. Electric ovens often require high voltage outlets (240V).</p>
<p>Step 1-2. Fill mold with plastic, add lid, and bake in pre-heated toaster oven (325 °F) for 60 minutes or until melted.</p>	<p>Step 2-2. Turn stovetop to med-high heat and track the oil temperature until it reaches 325 °F. Maintain temperature until all plastic has melted. Line the wooden mold with parchment paper, if applicable.</p>	<p>Step 3-2. Pre-heat oven to 325 °F. Place plastic in mold. Once the oven reaches temperature, place mold and plastic in oven and start a timer for 60 minutes. After 45 minutes, begin to compress with the car jack.</p>

Step 1-3. Use high heat gloves to remove steel mold from the oven. In 1 minute or less, add 3 6" C-Clamps (4500 lb. capacity each). Tighten C-Clamps until plastic begins to flash (seep through cracks). Wait 5 minutes and continue to tighten C-Clamps every 10 minutes until the plastic is cool.

Step 2-3. Quickly transport melted plastic to a wooden mold and add 2 12" C-Clamps (9300 lb. capacity each) for a large mold. Tighten C-Clamps until plastic begins to flash (seep through cracks). Wait 5 minutes and continue to tighten C-Clamps every 10 minutes until the plastic is cool.

Step 3-3. Compress plastic until flash occurs. Flash is when the plastic seeps through cracks in the mold. This is an example of too much flash and can result in poor material quality and makes the final product difficult to remove from the mold. Compress slightly every 10 minutes (watching for flash) until the timer goes off. Turn off oven and wait 1 hour to cool. Be sure to perform this outdoors or in a ventilated area with masks. Toxic fumes may be produced during the process.

Step 1-4. Once cooled, remove plastic from mold.

Step 2-4. Once cooled, remove plastic from mold.

Step 3-4. Once cooled, remove plastic from mold.

Prior to the melt, the heating source and/or mold should be preheated anywhere from 180 °F to 225 °F (82-107 °C) for 20 minutes to one hour, and the material should be loaded hot whenever possible to create the most consistently melted final product. It is important to watch the material as it is melting. It is important to keep the melting time to a minimum as to avoid over heating the plastic and producing toxic gases. Be sure to perform these methods in a well-ventilated area, or preferably outside. Pressure should be applied to the plastic until the point of flash, where the plastic begins to seep out of the cracks in the mold. The exact pressures vary for each trial as they depend on the size and orientation of the mold, but in this case, the pressures applied were in the range of 500-700 psi.

Lastly, it should be emphasized that these methods were developed over several melting trials, where not every block or tile produced was of good material quality. Appendix B shows results from other melting trials, and what Practivistas think went wrong during those processes.

METHOD ANALYSIS

The results of these trials include each method's associated energy and cost per plastic block produced along with a weighted criteria matrix which scores each method on various criteria. These results are intended to guide the reader in choosing an appropriate method to melt their own plastic. The results of these analyses will be used to score each method for each of the criteria that has been outlined in Table I.

Energy and Cost Analyses

The purpose of the cost analysis is to consider the difficulty in starting a plastic molding industry in Arroyo Norte. The cost is analyzed using American dollars, and products were chosen based on the most available and affordable resources in Arroyo Norte. This analysis considers both capital costs and operating costs.

TABLE IV
SUMMARY OF COST ANALYSIS FOR EACH METHOD

METHOD 1. Toaster Oven		
Cost Calculations		
Item	Location/Source	Cost (\$)
Toaster oven	Craigslist	\$10.00
Steel for mold	Scrap yard	\$4.00
C-clamps	Loan – HSU Engineering Dept.	\$0.00
Plastic	Humboldt Sanitation and Recycling	\$0.00
Soap	Grocery Store	\$3.00
Energy	Electricity @ 0.13/kWh, 1051kW, run time 1.5 hours	\$0.20
	Total Cost to produce 1st unit	\$17.20
	Total Cost to produce each additional unit	\$0.20

METHOD 2. Natural gas stovetop in cooking oil		
Cost Calculations		
Item	Location/Source	Cost (\$)
Natural gas stovetop	Loan- Home appliance	\$0.00
Steel for mold	Scrap yard	\$4.00
C-clamps	Loan – HSU Engineering Dept.	\$0.00
Plastic	Humboldt Sanitation and Recycling	\$0.00
Soap	Grocery Store	\$3.00
Vegetable Oil	Grocery Store	\$10.00
Energy source	Natural gas @ \$1.59/therm, 0.17 therms, run time 1.7 hours	\$0.27
	Total Cost to produce 1st unit	\$17.27
	Total Cost to produce each additional unit	\$0.27
METHOD 3. Electric compression oven		
Cost Calculations		
Item	Location/Source	Cost (\$)
Electric oven	Craigslist	\$0.00
Steel for mold	Scrap yard	\$5.00
Cut steel	Fabrication shop	\$14.00
C-clamps	Loan – HSU Engineering Dept.	\$0.00
Plastic	Humboldt Sanitation and Recycling	\$0.00
Soap	Grocery Store	\$3.00
Energy source	Electric rates \$0.16/kWh, 10.6 kW, run time 1.25 hours	\$1.00
	Total Cost to produce 1st unit	\$23.00
	Total Cost to produce each additional unit	\$1.00

As illustrated in Table IV, Method 1 exhibits the lowest capital costs, and then Method 2 and Method 3 show an increase in costs, respectively. Similarly, energy costs (or operating costs) are more expensive in the same order. This was expected, as Method 3 is much more sophisticated to prepare and will likely produce higher quality plastics than Method 1 and Method 2.

Various energy sources may be used to create products out of recycled HDPE plastic. Natural gas, and electricity were explored in the methods. Method 1 requires electricity, as toaster ovens are only electric appliances, whereas Method 2 and Method 3 can use other fuel sources. For this energy analysis, only the fuel types used by Practivistas were considered. Table V shows the energy use for each method normalized into kilowatt-hours (kWh).

TABLE V
SUMMARY OF ENERGY CONSUMPTION FOR EACH METHOD

METHOD 1. TOASTER OVEN			
Energy Calculations			
Fuel Source	Run time (hours)	Power (kW)	Total Energy Consumption per melt (kWh)
Electricity	1.50	1.05	1.58
METHOD 2. STOVETOP			
Energy Calculations			
Fuel Source	Run time (hours)	Total Energy Consumption per melt (therms)	Total Energy Consumption per melt (kWh)
Natural gas	1.70	0.17	4.98
METHOD 3. ELECTRIC COMPRESSION OVEN			
Energy Calculations			
Fuel Source	Run time (hours)	Power (kW)	Total Energy Consumption per melt (kWh)
Electricity	1.25	5.00	6.25

As illustrated in Table V, Method 1 exhibits the lowest energy consumption, and then Method 2 and Method 3 show an increase in consumption, respectively. This is expected as Method 2 and Method 3 can be used on much larger scales and require more sophisticated equipment.

Criteria scores

These scores are intended to evaluate and demonstrate the advantages and disadvantages of using each method. Each method is scored out of 10 points and then is multiplied by its weight. The scores in each criterion are then summed for total criteria score for each method. Furthermore, the methods are scored based on the results from Practivistas' experience (Empirical), then scored in general conditions (General). The general conditions consider how each method will perform once each method is further improved in a general scenario or location. For example, in Practivistas experience, the toaster oven worked well, but it is not believed to work as well in other scenarios, so it will score lower "in general." Table VI shows each score, Table VII (Appendix A) expresses each score with added commentary for clarification.

TABLE VI
SCORES FOR EACH METHOD FOR EACH CRITERIA OF INTEREST. EACH METHOD IS SCORED BASED ON PRACTIVISTA'S EXPERIENCE AS WELL AS HOW THE METHOD IS PREDICTED TO PERFORM IN OTHER SCENARIOS, OR IN GENERAL.

METHOD 1				METHOD 2				METHOD 3			
Criteria	Weight	Our Results	General Conditions	Our Results	General Conditions	Our Results	General Conditions	Our Results	General Conditions	Our Results	General Conditions
Resource Appropriateness	10	7	7	9	9	8	8	8	8	8	8
Material Quality	10	7	8	8	8	9	10	9	10	9	10
Low Net Cost	10	7	6	10	10	5	6	5	6	5	6
Safety	10	10	10	10	9	6	9	6	9	6	9
Aesthetics	9	9	10	7	10	9	10	9	10	9	10
Reproducibility	9	7	7	10	10	6	7	6	7	6	7
Scalability	8	5	5	7	7	10	10	10	10	10	10
Low Net Energy	7	8	8	10	10	8	8	8	8	8	8
Weighted Score		550	559	649	666	551	619	551	619	551	619

Table VI shows Method 1 with a score of 550 for Practivistas and 559 in general. Method 2 has a score of 649 for Practivistas and a higher score of 666 in general. Method 3 shows a score of 551 for Practivistas and 619 in general. Table VI shows that the oil + stovetop method scored the highest based on criteria weights. The oil + stovetop method is not Practivistas personal preferred method. Commentary in Table VII (Appendix A) should be carefully considered as the scores in Table V were difficult to decide.

DISCUSSION AND RECOMMENDATIONS

The criteria matrix serves to demonstrate how each method performs in various aspects or criteria. Though the scores differ, each method is feasible, and the appropriate method should be chosen and improved for the given scenario. The following section provides a discussion for each method and how they may be improved or adapted.

Method 1 – Toaster Oven

Method 1 utilizes a toaster oven, a mold, and c-clamps for compression. This method scored highest in safety, aesthetics, and low net energy. This method scored the lowest in scalability, reproducibility, and low net costs.

FIGURE 2

FINAL PLASTIC BLOCK CREATED USING A TOASTER OVEN AND C-CLAMPS

The following is a list of the most significant benefits and complications that might arise when using the toaster oven method, which should be considered when choosing the appropriate method.

- Melting time – Because of heat loss in the toaster oven, safety settings, and an automatic shut-off timer, this process required lower temperatures and longer melting time. This had both positive and negative effects:
 - Lower temperature and longer melt time resulted in less off-gassing of the plastic, which is a great safety concern.
 - Long melt time requires a consistent electric power source, which may not always be accessible and thus this method is most appropriate when electricity is readily available.
 - The low temperature of the oven significantly increased melting time, and the plastic was not melted completely through. This can be improved with an even

longer melt time, a thinner steel plate for the mold, or a shallow mold that has greater surface area for more even melting.

- Energy use – This method scored high for its lower energy usage, relative to the other methods. This lower energy use has a few major effects on the feasibility of this method:
 - A lower energy rating could be more beneficial when there is limited access to higher voltage outlets. An appliance with a low energy rating may be powered by a small generator or solar panel, rather than having to rely on grid-provided power.
 - A lower energy rating would also result in lower energy costs, given consistent power. This is attractive when electricity costs are being paid to an electric utility company.
- Scalability – Lastly, the toaster oven method is greatly constricted by scale:
 - The size of the toaster oven does not fit the 12” C-clamps required for optimal pressure, and thus the plastic cannot be compressed while heating. For the best results, the plastic should be compressed when it is hot. This was probably one of the causes of uneven melting through the block seen by Practivistas.
 - The energy use benefits of this method are directly related to the size of the toaster oven, which can only produce one piece of plastic product at a time. Therefore, this method is ideal for producing smaller plastic blocks and for start-up projects where the process will be scaled up later.

Ultimately, this method is ideal for small scale, or beginner projects. If a toaster oven is available at a low cost, and there is enough reliable power available, this method should be adopted to produce small tiles and blocks of plastic.

Method 2 – Oil and stove top

Method 2 utilizes vegetable oil as heating medium, a natural gas stove top for a heat source, and 12” c-clamps for compression. This method scored the highest in resource accessibility, low energy usage, low cost, and reproducibility, some of the highest weighted criteria. This method scored the lowest in material quality, aesthetics, and scalability. This method also scored the highest out of each method, regarding empirical results and in general.

FIGURE 3

FINAL BLOCK OF PLASTIC MADE USING OIL AS A HEATING MEDIUM AND C-CLAMPS FOR COMPRESSION

The following list discusses the potential behind the method and how it may be improved. Though this method is accessible, and is low in energy and cost, there are complications that should be discussed.

- **Material Quality and Aesthetics** – These criteria are weighted heavily alongside energy and cost, but they scored low. The reasons why this method scored low in these aspects have great potential to be improved:
 - The material quality in this method was greatly affected by oil impurities. When the plastic is melted in the oil, and then transferred to the mold, oil remains in between the melted plastic. When pressed, the oil then creates boils, bubbles, and holes which interferes with the strength and aesthetic of the result. This could potentially be avoided by separating the plastic from the oil, either in a sealed mold or a heat resistant bag.
 - It is optimal to compress the plastic as it is being melted. This method can be set up so that pressured is applied inside of the melting pot. This would require the mold to be inside of the melting pot as well, which would solve the problem of oil impurities that Practivistas experienced but may be difficult to implement.
- **Scalability** - The biggest problem with this method is the ability to scale.
 - Vegetable oil may not be accessible in large quantities everywhere, and thus will likely be limited to small scales.
 - If more vegetable oil is used, it must eventually be disposed of. This is not a sustainable practice in terms of reducing waste, low environmental harm or keeping costs low. In theory, this can be improved by re-using the oil for future melts or for other purposes such as Bio-Diesel fuel.

This method has great potential. In Practivistas' experience, the results were flawed, but with more iterations and improvement of the process, this method can be executed well.

Method 3 – Compression Oven

Method 3 was developed based on preliminary designs by Dave Hakkens of Precious Plastics, a non-profit, educational website intended to share resources and promote small-scale recycled plastic production¹⁵. This method utilizes a crafted compression oven made with a recycled electric oven paired with a 2.5-ton car jack for compression. This method scored the highest in material quality, scalability, and aesthetics. This method scored the lowest in reproducibility, cost and energy, and safety. This method scored much higher in the general sense. This implies that with investment and available resources, this method has great potential.

FIGURE 4
FINAL BLOCK OF PLASTIC MADE USING THE COMPRESSION OVEN

The following list is a discussion of the mentioned criteria and how they will impact the result. This method has potential to create high quality products efficiently, but the method must first be improved to yield acceptable results.

- **Reproducibility** – The capabilities of reproducing this method are limited. Firstly, an electric oven might be difficult to find for some scenarios, as some cannot afford one even for personal use. More so, creating the oven required a lot of materials and advanced welding skills, which may or may not be accessible in a small community. Therefore, this method should be used when an oven and a local welder is available to help at an affordable price.
- **Energy and Cost** – A problem with this method is the large energy load that an electrical oven will require, especially an older oven which will likely be the case in communities like Arroyo Norte. A large energy load from an electrical oven will require a reliable 240-volt power source and will likely be costly if this source is from an electric utility. Extreme caution should be used when working with high voltages.

- **Material Quality** – This method will likely provide the best quality materials. The oven has its own thermostat, which provides control over the system so that the plastic will not burn. More importantly, being able to compress the plastic while it melts makes this method as close to an industrial process as possible. With further work, this method can create very high-quality products with minimal human effort.
- **Scalability** – This method has the greatest potential to scale-up the melting process. The oven is physically larger than the previous methods, and thus can make a variety of products. Furthermore, if a larger industrial oven is desired, one can be built using brick or other traditional oven types.

This method was inspired by the Precious Plastics compression molding project. The compression oven provides high control over the quality of the product and can be used in a large-scale setting. This method requires capital investment, and thus should only be considered when appropriate and resources are easily available.

Improvements on the Mold

After numerous trials using wood and ¼” steel for the mold materials, we see potential in using both methods, depending on the application.

For wooden molds, parchment paper is a tried and true method for easily releasing the final product from the mold. Further improvements for wooden molds would be to construct them in a way that they could be easily taken apart and put back together multiple times. This could mean attaching braces to the outside 90-degree L-shaped corners and connecting the 90-degree L-shaped edges to each other with hinges, then once the product is cooled, the mold can be taken apart, leaving a clean final product with minimal effort.

For steel molds, the oil did not work very well as a release agent. Issues that were encountered during trial and error include flash, or melted plastic seeping up and over the lid. In extreme cases, heavy flashing, when cooled, creates a lock around the mold, making the lid and final product extremely difficult to remove (this can be seen in Step 3-3 in Table III). A steel mold that is welded in 90-degree L-shaped corners and attached with hinges would greatly improve the ease of use and product removal for these methods. This mold would be further improved by adding a high-heat, flexible silicone mold to the interior of the steel mold, which would self-contain the plastic in the steel mold, and the final product would easily pop out of the cooled steel mold once the hinge is released.

SUMMARY AND CONCLUSION

The time has come to start mitigating the worldwide plastic epidemic that is plaguing the planet. After working in a community like Arroyo Norte, it is clear to see the potential that projects like this can provide in communities that are impacted by too much unmanaged waste, with no opportunities for recycling. After 3 years of research and trial and error, this manuscript provides an analysis of three of the most suitable plastic recycling methods that can be utilized with minimal resources, among other crucial criteria.

The results of this research show that each method has potential to create high quality recycled plastic material, given that further improvements are made. Each method should be

investigated and utilized according to the available resources and appropriateness of the method to the scenario. This research and trial and error process resulted in a wealth of information on what not to do when recycling plastic with limited resources. Hopefully communities like Arroyo Norte can use this manuscript to learn from previous mistakes, and use this knowledge to create jobs, gain financial security, and create new products out of an overlooked resource such as waste high-density polyethylene, that would otherwise be wasted in the landfill.

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The authors would like to thank the various Youtube users who make instructional videos for melting HDPE. The authors encourage readers to utilize these videos in addition to the information provided in this paper. To achieve our waste reduction goals, we must all work together.

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APPENDIX A

The following is a version of the criteria score table which includes comments on the scoring logic. These comments should be carefully considered, as each score requires context.

TABLE VI
CRITERIA SCORES WITH COMMENTARY

Criteria	Method 1			Method 2			Method 3		
	Our Results	General Conditions	Notes	Our Results	General Conditions	Notes	Our Results	General Conditions	Notes
Resource Accessibility/ Appropriateness	7	7	Toaster oven was easy to find in the US, but may be more difficult to find in other locations around the world.	9	9	Most people in the US and the Dominican Republic have stovetops; more-so than an oven and a toaster oven. Not all communities have accessibility to large amounts of oil, and the waste oil is less appropriate.	8	8	Ovens are expensive to purchase, and might be hard to find for free in a low-income area. A consistent electricity source may be difficult to find in many areas to draw a large load.
Material Quality and Strength	7	8	Even the best result from our trials did not produce a consistently melted block. Final product had smooth faces, but was not fully melted inside. The thickness of the steel mold requires additional pre-heating time in the oven.	8	8	Product was fully melted plastic, but was difficult to press into the mold as a hot taffy-like material. It cooled while transporting to the mold, which often left “chunks”, where the plastic broke later. A separate container while melting in the oil would avoid this problem because it would already be in a mold.	9	10	Our trial failed due to over-compressing, but with practice and more trials this method has the best potential, as it allows for compression during the melting process.

Low Net Cost	7	6	We paid a low price for the toaster oven, but it might be more expensive or harder to find elsewhere.	10	10	Gas and oil are generally cheap and easily accessible.	5	6	Had to hire a welder and purchase more materials to make it work. High in electricity costs. Elsewhere, might not pay for electricity and might have local welders.
Safety	10	10	Did not off-gas because of the slow melting process.	10	9	Did not off-gas because of the slow melting process, but you are exposed to fumes and hazards from the cooking fuel.	6	9	Heating for too long as well as holes in the oven walls resulted in a lot of off-gassing. Oven should be used at lower temperature for a slower melt, which would reduce off-gassing significantly.
Aesthetics	9	10	Looked good, but the consistency will look better after method is perfected.	7	10	Our trials produced a solid, fully melted block when the melted material was pressed into a mold in one single mass. Higher pressure in the mold will result in a smoother face.	9	10	If compressed correctly will leave product clean and fully melted
Reproducibility	7	7	Toaster oven is a luxury item and will have to be found at a flea market or home appliance store, which may be costly	10	10	Required the least amount of materials with the most accessible energy source, and should be easy for most to reproduce.	6	7	Required a lot of materials and skill for welding. Would take more time and planning to reproduce. Ideally have access to scrap materials, workshop and a local Maker to help build.
Scalability	5	5	Can only melt one block at a time, and is limited to a small product due to the internal	7	7	Can be used in larger batches, but larger batches would require more oil. Although oil could be re-used many times, it would still create a lot of waste oil.	10	10	Oven has larger internal dimensions and can fit a variety of molds. Ovens can be built larger or designed using a brick oven, etc.

			dimensions of the toaster oven.						
Low net energy	8	8	Requires a consistent energy source to draw the high electric load. Considering the amount of time it would take to perform multiple melts, the energy consumption makes more sense in a larger oven.	10	10	Only requires a small stovetop. Camping stove works fine and only uses a small amount of fuel.	8	8	Older ovens (which are likely used) are less energy efficient. Requires a 220-V electric outlet, and a consistent energy source to draw the high electric load.
Weighted Score	550	559		649	666		551	619	