Achieving Cost-Effectiveness in the Production of High-Quality Plastic Tiles through Chemical Recycling

Emmanuel Ophel Gilbert
University of Northern Iowa

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Emmanuel Ophel Gilbert

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Approved by:

______________________________ 4/3/2024
Advisor-Rukmini Srikant Revuru Date

______________________________ 4/3/2024
Second Reviewer- Julie Zhe Zhang Date

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Introduction

Plastic has found several applications for daily usage such as drinking bottles, grocery bags, cigarette butts, and 3-D printing (Geyer et al., 2017). The usage of plastic gained popularity due to its cost-effectiveness, application flexibility, and multifaceted nature (North & Halden, 2013). However, the growing issue with the disposal of used plastics has led to the implementation of many rules and regulations across the globe. The world generates 381 million tons of plastic waste annually, and with the amount of plastic waste set to double by 2034, recycling plastic is vital (ISM Waste & Recycling, 2013). There are approximately 50 various groups of plastics, with hundreds of different types (ISM Waste & Recycling, 2013). It is believed that plastics can take over 500 years to decompose. According to Malavika (2018), every minute, one million plastic bottles are purchased globally, but only 7% of them are recycled; the remaining bottles end up in landfills or water bodies, posing a significant threat to the environment. It is reported that as per a prediction, by the year 2050, the amount of plastic waste in the ocean will exceed the total weight of fish. “If we keep burning fossil fuels at our current rate, it is generally estimated that all our fossil fuels will be depleted by 2060” (Zhang, 2023). More so, Zhang continues saying “with the world’s population snowballing, there might be less than 60 years of farming left if soil degradation continues.”

Recycling of plastic waste is seen as a sustainable way of disposal of the plastic waste. Recycling plastic waste materials (synthetic byproducts from fuel fossils- crude oil) would enhance the sustainability of fossil fuels, improving the environmental conditions of aquatic and terrestrial life (Malavika, 2018; Zhang, 2023). Recycling is one of the modern technologies used to mitigate the capital intensiveness in the production of non-biodegradable products especially, plastics. Recycled plastic is used in several applications including plastic bags, bottles, PVC pipes, plastic tiles, etc. Recycled plastic tiles have the potential to significantly reduce the amount of plastic waste that ends up in landfills or in the environment (Atieh et. al, 2022). This sustainable alternative can also help conserve natural resources, such as clay, sand, or water, typically used in traditional tile production. In addition, recycled plastic tiles can offer other benefits, including lower production costs, higher durability, and improved resistance to water, fire, and insects (Arn et. al, 2017). Moreover, they can be customized to cater to different aesthetic and functional preferences. Most plastic materials can be recycled, which makes recycling a crucial step in reducing the amount of waste sent to landfills and ultimately, to oceans, thus preventing the environmental damage caused by plastic waste (ISM Waste & Recycling, 2013).

Plastic recycling and tile manufacturing can be combined to create high-quality plastic tiles that are durable, cost-effective, and environmentally friendly. The inconsistency in plastic waste segregation at many waste-transfer stations presents a barrier to achieving high-quality plastic tiles through chemical recycling (O'Brien, 2023). Different heterogeneous plastic waste materials (difficulty in segregation) have different transient temperatures at which they undergo chemical recycling. Hence the segregation of different plastic waste materials is important for proper processing and recycling.

Lately, different automated techniques are being used in this process. AlexNet emerges as one of the most efficient pre-trained models on the ImageNet database, having secured victory in the ImageNet Large Scale Visual Recognition Challenge (ILSVRC) in 2012 (Sai Susanth et al., 2021). It has a highly competent architecture and can efficiently segregate plastic waste using image processing. Different images of the waste are processed and the model divides the waste into different categories. Although it is commonly used for waste segregation, its efficiency is not as high as some other pre-trained models. Many other models could be used in plastic waste segregation which many authors adopted and cited. Osiany, et al (2014) designed and created a rotor robot model (Automatic Garbage Collector- AGATOR) that effectively collects and removes garbage from rivers to prevent accumulation and promote efficient flow. The robot can handle a full load of up to 5 kg of garbage at the collection point. Its average speed during garbage collection is 0.26 m/s. Hulyalkar, et. al (2018) envisaged a system that automatically segregates waste at the source, reducing physical effort. The program is based on machine learning principles, image recognition, and the Internet of Things (IoT). The project aims to capture images of individual waste materials and effectively segregate them into four categories: metal, glass, paper, and plastic. Thung & Ynag (2016) gathered images to create a dataset, and then utilized machine learning and neural networks to segregate plastic waste materials. They used a Support Vector Machine (SVM) to categorize waste into six distinct groups, as well as an 11-layer Convolutional Neural Network (CNN). The SVM proved to be more effective, with a 63% accuracy rate, while the CNN only achieved 23% accuracy.

Another issue in plastic tile production is the low quality of produced tiles. Due to the manufacturing of plastic tiles without regard for quality considerations in recycling, manufacturers face threats in the competitive market. The primary challenge in adopting recycling for plastic tile production lies in the subpar quality it often entails. The use of recycled plastic tiles can face various challenges related to the technical, financial, and social aspects (Mohan & Gayathri, 2019). Several challenges persist, such as the absence of defined value benchmarks, regulations, and certifications, alongside restricted plastic waste availability and accessibility. Additionally, high initial investment and maintenance expenses for equipment, coupled with low consumer awareness and acceptance, pose hurdles, alongside potential health and environmental risks from additives, pollutants, or emissions in plastic materials.

On the contrary, plastic tiles manufactured while accounting for material costs and aligning with the purchasing power of end-users for desired quality have a large demand in the market. An exhibit at the Swachhta Abhiyaan in New Delhi, India, featured a demonstration of innovative technology utilizing chemical recycling to convert discarded plastic bottles and bags into colorful tiles (Malavika, 2018).

With a density of around 2400 kg/mm^3, these tiles closely match the density of conventional tiles, rendering them suitable for a wide range of applications where reducing weight is crucial (Blaifi et al., 2023). According to ISO 15622:2006 standards, a minimal breaking force of 1500 N would be necessary to pass a compression test if conducted experimentally, indicating that the plastic tiles are suitable for use in applications with no high weight-bearing requirements (Haridkar et al., 2019). Additionally, the burning rate of the plastic tiles produced would not exceed 100 mm/min to meet the criteria of the vertical flammability test if conducted in the laboratory, ensuring their suitability for normal daily applications and minimizing the risk of slippage. Moreover, considering the coefficient of friction of the produced plastic tiles, they are designed to seamlessly integrate with commercially available household flooring in terms of design and specification. This finding opens avenues for further research and improvement of the coefficient of friction to develop anti-skid tiles.

Another significant challenge in maintaining the quality of the tiles is the presence of traces of contaminants in recycled plastics. Importantly, these traces have a proportional impact on the properties of plastics, directly influencing the quality of plastic tiles produced through recycling. Traces of contaminants found in recycled waste plastics (such as food residue, oils, dirt, or non-recyclable materials) diminish the quality and value of recycled products. This situation leads to environmental pollution and greenhouse gas emissions, causes damage to recycling equipment, and increases downtime during recycling processes, rendering the recycled materials less desirable for manufacturers. An existing material-flow analysis model of the Dutch recycling chain for post-consumer plastic packaging waste in 2014 and 2017 was used to track the source of impurities in recycled Polyethylene (PE) - (HDPE- High-Density PE and LDPE- Low-Density PE) and polypropylene (PP) samples (Brouwer et al., 2018; Brouwer et al., 2019). When impurities are added, significant changes in (mechanical properties) tensile strength, temperature (triple point), elasticity, plasticity, etc. can be observed in comparison to the 100% recycled polypropylene (rPP) (Alvarado et al., 2020).

To mitigate the adverse effects of impurities on plastic recycling, it is essential to correctly sort, clean, and preprocess plastic waste. Bakker et al. (2009) provided a concise examination of various techniques such as selective dissolution/precipitation, electrostatic separation, near-infrared spectroscopy-based commercial technology, sink-float process, and inverse magnetic density separator (IMDS) to manage the quality of PP and PE. According to Bakker and Rem, the electrostatic separation technique demonstrates the potential for yielding high-quality PP and PE. Results from Daiku et al. (2001) show that the electrostatic separator achieved 99.9% and 99.5% high-quality outcomes for PE and PP, respectively.

For effective separation and recovery, it is crucial to employ suitable mechanical actions and sorting strategies, necessitating rapid, accurate, and reliable identification of plastic waste properties, including PE, PP, and contaminants (Serranti & Gargiulo, 2011). Compostable bioplastics like non-toxic Polylactic Acid (PLA) present a viable and sustainable alternative to conventional plastics (Papong et al., 2014). Researchers focus on synthesizing bio-based plastics to mitigate the adverse environmental, economic, and social impacts associated with conventional plastics (Ohja & Kapoor, 2019).

Educating the public on recycling methods, enhancing recycling infrastructure, and implementing stricter quality control measures in recycling facilities can help mitigate the effects of contaminants. Bakker et al. (2009) suggest that the grade of PE (PETE, HDPE, and LDPE) and PP should be at least 97% to be reused in the production of high-quality products. Treatment of traces would promote the development of environmentally friendly packaging designs.

For proper recycling, an estimate of the recyclable quantities is critical. A typical city waste would comprise several components, including food waste, durable goods, plastics, etc. Plastics constituted approximately 12% of Municipal Solid Waste (MSW) by weight in 1996 (table 1), leading to an upsurge in the solid waste stream (Franklin Associates Ltd, 1998).

Table 1

Sample Table Showing the Plastic Solid Wastes and its Weights (Franklin Associates Ltd, 1998)

Plastic Solid Wastes	**Weight (tons of 1000)**
Durable goods	6260
Non-durable goods	5350
Bags, sacks and wraps	3220
Soft drinks, milk etc. containers	1350
Other containers	1280

Polyethylene forms the largest fraction, which is followed by PET in the plastic waste stream (Subramanian, 2000). Table 2 for the study would only consider parameters of PETE, HDPE, and LDPE. Hence, an equal proportion of 60% of each recycling resin could be used as the study may be found to show in a small-scale production.

Table 2

Sample Table Showing Recycling Resin and its Weight (Franklin Associates Ltd, 1998)

Recycling Resin and Codes	**Weight (tons of 1000)**
Polyethylene terephthalate (PETE)	1700
High-density polyethylene (HDPE)	4120
Low-density polyethylene (LDPE/HDPE)	5010
Polypropylene (PP)	2580
Polystyrene (PS)	1990
Other	3130

There are three different methods and technologies for manufacturing plastic tiles from recycled materials namely, chemical recycling, mechanical recycling, and biological recycling.

Referencing the Swachhta Abhivaan exhibition (Malavika, 2018), the study focuses on utilizing chemical recycling for PETE, HDPE, and LDPE (plastic bottles and bags) to achieve cost-effectiveness in producing high-quality plastic tiles. These specific types of PETE, HDPE, and LDPE wastes are chosen due to their widespread availability and ease of recycling. Given their economic ubiquity and recyclability, the resulting product, high-quality plastic tiles, would offer cost-effectiveness for both manufacturers and consumers. Chemical recycling is exclusively considered because it yields high-quality and value-added products of plastic tiles. This technique involves breaking down plastic waste into its molecular components, enabling the creation of top-quality raw materials. Such an approach surpasses traditional methods like mechanical recycling, aiming to enhance material quality and reduce waste.

Purpose of Study

The majority of recycled plastic tiles suffer from low quality attributed to deficiencies in the raw materials, resulting in deformation. Ensuring that recycled plastic tiles are produced with high quality would alleviate deformation issues, leading to increased durability against extreme weather and climate changes—an aspect of particular interest in the study.

To improve cost-effectiveness in the production of high-quality plastic tiles through chemical recycling, it is essential to consider potential capital-intensive costs associated with achieving high quality. These costs are proportionate to the selling price and could potentially reduce market demand, posing a threat to manufacturers.

Method of Study

The current research utilized a combination of literature review, interview, and direct observation to optimize the cost-effectiveness of producing high-quality plastic tiles through the chemical recycling of plastic bottles and bags.

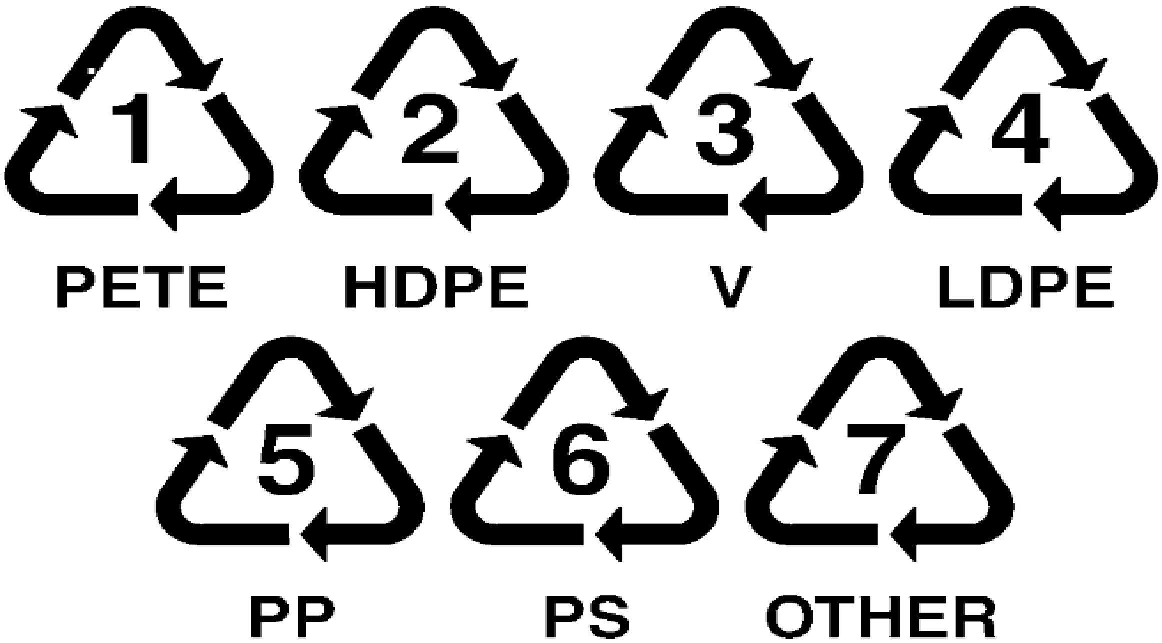
Mr. Eric O'Brien, University Sustainability Director at University of Northern Iowa, was consulted for obtaining the information on the manufacturing of plastic tiles. He referred to Mr. Doyle Smith at the City of Cedar Falls Public Works/Parks Department - Refuse Section for observing the process. Mr. Smith was interviewed to obtain information on the process. Since the interview involved only one subject, clearance from the university IRB was not required as per the guidelines. The interview questions and responses are given in the appendix. The process was observed from start to finish i.e., collection and segregation of waste plastic materials, removal of impurities, shredding of waste plastic materials, addition of mixers, heating of pellets, and finally, packaging of the plastic tiles. The details are provided in the subsequent sections.

Collection and Segregation of Waste Plastic Materials

At the outset, waste materials including plastic bottles and bags were gathered from landfill sites and sorted into high-density and low-density plastics, respectively. These specific plastic waste materials were chosen for their prevalence, high tensile strength, ease of melting, and non-toxic nature, which contribute to environmental cleanup efforts. The selected waste plastic bottles and bags correspond to recycling numbers (resin codes) 1, 2, and 4, as depicted in Figure 1 below, aligning with the desired properties outlined above.

Figure 1

Standard Plastic Recycling Codes with Numbers



Removal of Impurities

Crucially, the plastic bottles and bags underwent thorough purification to eliminate traces of impurities and solvents before utilization. This process aimed to prevent any deviations in melting points that could lead to excessive smoke emission. Pure plastic bottles and bags (as illustrated in Figure 2 below) were employed to address the adhesion issues of the heated materials.

Figure 2

Pure Plastic Bottles and Bags in the Standard Codes

Shredding of Waste Plastic Materials

The plastic bottles are then shredded into tiny pieces, some of which are smooth and some of which are boisterous. The shredding of the waste plastic materials into small fragments encouraged the melting process easier and aided with being able to get all the plastic into the right shape before melting.

Figure 3

Shredded Plastic Bottles and Bags (diagram adopted from *https://skill-lync.com/student-projects/injection-molding-and-injection-mold-nomenclature-challenge-1*)

Addition of Mixers

Different additives such as stabilizers, phthalates (ester compound for fragrance), chalks, blowing agents, accompanying agents, and colorants were then added to the shredded plastics to generate pellets (figure 4 below).

Figure 4

Colored Pellets Ready for Plastic Tiles Production

Heating of Pellets

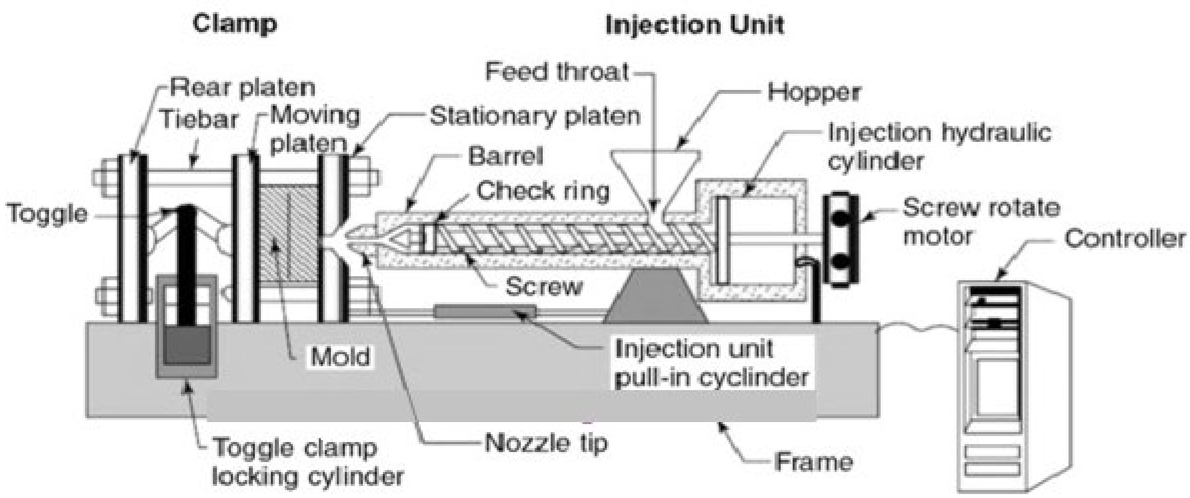
Before initiating the heating process, the plastic injection was positioned in a well-ventilated area to prevent operator suffocation when activating the molding machine. To maintain stability in temperature, the heating procedure was conducted during the evening, benefiting from cooler atmospheric conditions, thus averting any abnormal temperature fluctuations caused by the machine that could potentially compromise the production of high-quality plastic tiles. After accounting for these environmental factors, the pellets were fed into the plastic injection molding machine and subjected to heating, reaching the optimal temperature of 250°C with a pressure of 80 MPa, under findings by Alvarado et al. (2020), Gregory (2011), and Guo et al. (2021). As depicted in Figure 5, which illustrates the molding machine, the resulting molten paste was poured into molds, yielding plastic tiles. Subsequently, the plastic tiles were left to cool at an ambient temperature of 25°C.

Figure 5

Embedded Plastic Injection Molding Machine Produced Freshly High-Quality Plastic Tiles (adopted from *https://skill-lync.com/student-projects/injection-molding-and-injection-mold-nomenclature-challenge-1*)

Figure 6

Schematic Diagram of Plastic Injection Molding Machine (adopted from *https://skill-lync.com/student-projects/injection-molding-and-injection-mold-nomenclature-challenge-1*)



Packaging of the Plastic Tiles

Lastly, the cooled plastic tiles (figure 7) were trimmed in a snipping machine according to the customers' requirements (figure 8) and packed in layers to avoid any damage.

Figure 7

Produced High-Quality Plastic Tiles

Figure 8

Trimmed Plastic Tile

Summary and Conclusion

By employing the chemical recycling method, high-quality plastic tiles can be produced by recycling plastic bottles and bags, including PETE, HDPE, and LDPE. These tiles have a similar density value and strength as the conventional tiles, making them suitable for various applications where weight reduction is essential.

This approach is both environmentally friendly and economical. These tiles can be used to construct lightweight structures that are resistant to corrosion and chemicals. They have a significantly low cost of production and a long service life. Crucially, they contribute to tackling the problem of plastic waste by utilizing recycling methods and promoting sustainability.

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Appendix (Interview questions and responses)

Question 1:

Does the University of Northern Iowa dump their plastic waste at City of Cedar Falls Public Works/Parks Department- Refuse Section?

Response

Yes, the University of Northern Iowa dump their plastic waste at City of Cedar Falls Public Works/Parks Department- Refuse Section.

Question 2:

How does the segregation of plastic waste materials take place?

Response

It is the most tedious task in the recycling of plastic materials because different composite materials are made up of different resins. It takes a lot of days to separate the plastic bags because of their capacity (pounds).

Question 3:

After segregation, do you take it to the shredder?

Response

No, the plastic wastes have to be built up and will be taken to a public services location in Waterloo and it will be shipped to Iowa City.

Question 4:

How about Resin 2?

Response

It is not separated here, it is only built up here. They only make the bills here and send the wastes to Iowa City where they are segregated for processing.

Question 5:

Is there any specific day for the disposal of plastic wastes at the City of Cedar Falls Public Works/Parks Department- Refuse Section?

Response

No, there is no specific day for the disposal of plastic wastes at the City of Cedar Falls Public Works/Parks Department- Refuse Section.

Question 6:

How long does it take to transfer the bills to the waste station in Iowa City?

Response

There is no specific time for the transfer of the bills to the waste station in Iowa City.