

RECOVERY OF POLYOLEFINS FROM NON-RECYCLABLE WASTE FOR PROPERTY EVALUATION AND VARIABILITY ASSESSMENT

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Abstract

In this work, solid waste streams were randomly collected from construction & demolition and commercial waste sites in the US Northeast in Spring and Fall and processed to recover plastic- and fiber-rich subfractions. The collected materials underwent ballistic screening, removing unwanted debris and separating waste into three subfractions: 2D, 3D, and fines. The 2D and 3D subfractions were then passed through rock traps, an air classifier, hand sorting, and robotic sorting to remove contaminants, metals, rocks, and magnetic particles. The 2D and 3D plastics were ground to ~3 mm, and polyolefin samples were recovered using a water float/sink method. The separation results showed that at least 70% of the recovered plastic streams consisted of polyolefins, largely independent of Season (Spring vs Fall), Dimension (2D vs 3D), or Batch (A vs B). Polyolefin samples were then melted, homogenized by batch mixing, and compression molded into tensile bars for mechanical testing. Statistical analysis of the tensile data revealed that Dimension (2D vs 3D) has a substantially stronger effect on mechanical performance than either Season or Batch. The mean tensile strength, yield strength, and tensile modulus of the 3D-derived samples were 14.14 MPa, 9.10 MPa, and 755.24 MPa, respectively, corresponding to increases of approximately 49%, 142%, and 143% relative to the 2D-derived counterparts. In contrast, Season and Batch did not exhibit statistically significant effects on the tensile properties within the ranges studied. Overall, the recovery protocol and variability analysis presented here provides a steppingstone toward scalable, low-energy recovery of polyolefins from landfill waste streams, supporting more robust polyolefin recycling and contributing to the circular economy.

Keywords: Recovery, Non-Recyclable Waste, 2D and 3D Plastics, Polyolefins, Season

Introduction

Municipal solid waste (MSW) is a significant environmental issue, representing the waste generated from households, businesses, and institutions within urban areas. Human activities have made municipal solid waste (MSW) generation unavoidable and a global discussion. Over 292.4 million tons of municipal solid waste (MSW) were generated in 2018 [1]. According to the U.S. Environmental Protection Agency (EPA), in 2018, over 27 million metric tons of plastics ended up in landfills, which is 18.5% of MSW [2]. Similarly, the organic materials that make up the largest MSW are natural fibers from wastepaper, corrugated boxes, and paperboard [3]. By volume, plastics and paper make up over 50% of municipal solid waste in landfills from post-consumer, post-industrial, and packaging items [4]. Landfilling remains the predominant method for NR-MSW disposal, despite its drawbacks. Landfills contribute to greenhouse gas emissions, leachate contamination of soil and water resources, and consume valuable land space [5].

Therefore, research and development activities tackling end-of-life issues for plastics have increased significantly in the last few years. Recycling is preferred as it contributes to the circular economy and preserves the material and its embodied energy from exiting the cycle [6]. Several recycling approaches include thermomechanical, biological, chemical, and combinations. While chemical approaches can typically produce higher-quality recycled materials [7] they are more energy intensive, produce more CO₂ emissions, and may use toxic acids and solvents; moreover, there are no industrial-scale chemical recycling plants yet to produce material. On the other hand, mechanical recycling is an established industrial practice for some plastic waste, such as rigid HDPE and PET packaging [8, 9]. Regarding NR-MSW, the major challenges with mechanical recycling include the low separation, fractionation, purification, and remanufacturing efficiency, ultimately making recycling an expensive practice.

Polyolefins, such as polyethylene (PE) and polypropylene (PP), are widely used in packaging and consumer products due to their desirable properties, durability, and low cost [10, 11]. While high density PE is recycled to some extent, low density PE and PP currently end up in landfill. Given the amount and environmental impact of polyolefin waste, it is crucial to recover it from MSW streams [12]. The goal of this study is to develop a simple, replicable recovery process of polyolefins from currently non-recyclable waste streams. This determination not only aids effective waste management practices but also informs recycling efforts, helping to divert plastics from landfills and reduce the ecological footprint. A lot has been done on the chemical recycling of polyolefins from MSW [13-15]; fewer studies have considered mechanical recycling [16, 17].

The focus of this effort is to assess the recoverability of post-consumer plastic waste from currently non-recyclable waste streams, measure the yield of polyolefin sub-stream therefrom and evaluate their mechanical performance and variability. First, the step-by-step processing of MSW stream to recover polyolefins using dry and wet separation techniques is discussed. The process includes ballistic screening, air classification, manual sorting, Autonomous Manipulation and Perception (AMP) robotic sorting, milling, water sink/float separation, and melt mixing. The percentage recovery of plastic-rich samples and polyolefins therefrom were measured and discussed. Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy analysis was used to verify that the stream was mainly composed of polyolefins. The mechanical properties of recycled polyolefin samples were evaluated in detail to analyze the variability with reference to Season (Spring and Fall), Dimension (2D and 3D), and Batch, using a full factorial design of experiment.

Materials and Methods

Non-Recyclable waste samples were collected from Debris to Green (DTG) Recycle Group's Material Recovery Facilities (MRF) at the US Northwest Region (Figure 1).



Figure 1 Examples of collected non-recyclable waste samples: a) Spring and b) Fall samples from DTG MRFs.

The samples were collected in Spring 2024 and Fall 2024, each batch totaling about 1,000 kg. Figure 2 gives an overview of the process flow for the recovery of plastic-rich and fiber-rich streams. The process began with the material being fed from a drop bucket elevated 10 feet above a ballistic screen. Dropping the material from this height onto cross-sectional diverging screens helped to break the glass and distribute the material evenly across the screens. These screens function like rigid walking sandpaper, creating friction to aid in separating materials into three fractions: 2D (e.g., films and thin sheets), 3D (e.g., rigid plastic objects), and pre-screened fines (less than 2 inches). This initial step removed a significant portion of unwanted debris. From this stage onward, the 2D and 3D fractions were processed separately. The next step involved hand-sorting to remove large items that could obstruct subsequent mechanical sorting stages. The material then passed through an air classifier that separated dirt, dust, sheetrock, and other contaminants. The cleaned material streams were sent to an AMP robotic sorter, which used a neural network-based visual identification system to sort the materials by polymer type. A suction gripper collected the desired fractions, while any remaining non-processable dirt and debris were removed and discarded.

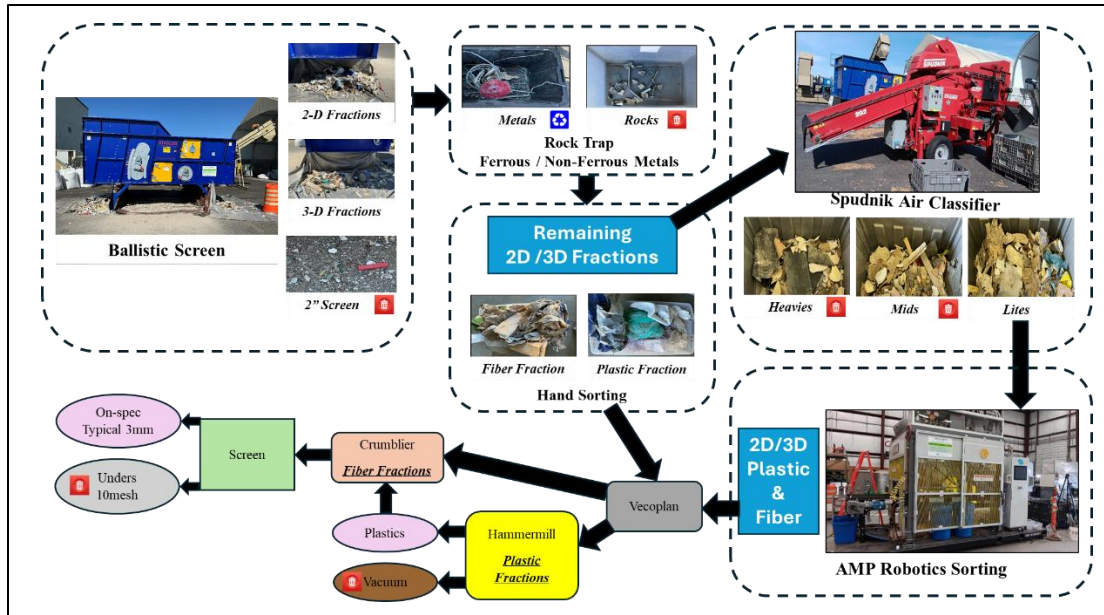


Figure 2 An overview of the process flow for the recovery of plastic-rich and fiber-rich streams.

The sorted material streams were then subjected to mechanical size reduction. This step involved grinding the material to approximately 3 mm particle size as shown in Figure 3. The visual inspection of recycled plastic waste from Spring 2D and 3D starting materials shows that 2D is primarily film and flexible sheet type packaging plastic, while 3D is more rigid products such as buckets, pails, containers, and bottles. The ground 2D is relatively fluffier than the ground 3D. Moreover, seasonal differences in the ground and homogenized samples can be observed in color. Spring samples are decorated with blue plastic spots (Figure 3c and d), while fall samples have black and red plastic spots (Figure 3e and f). These characteristics are a factor of the starting material present in the waste at the time of collection.

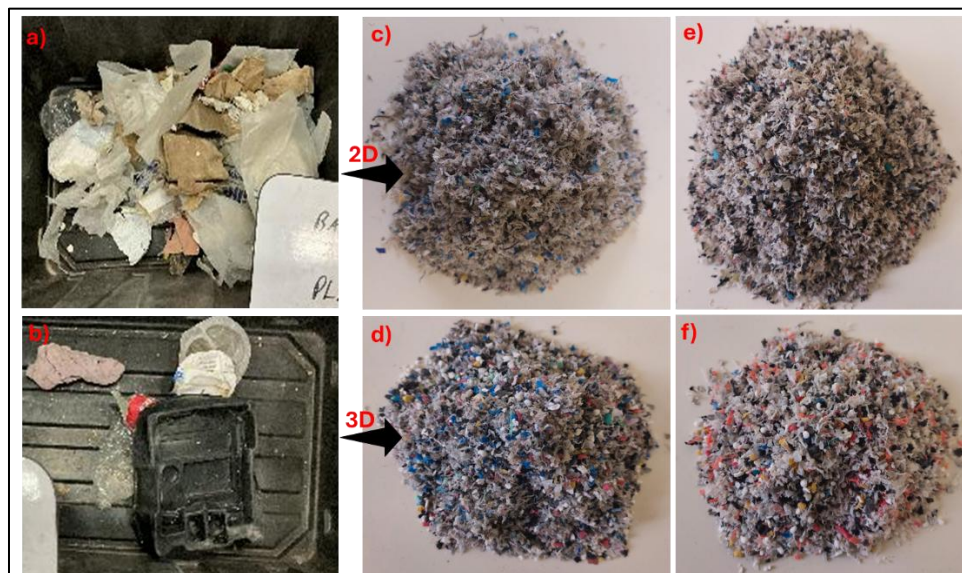


Figure 3 Recycled plastic waste from Spring collection: a) 2D starting material, b) 3D starting material, c) 2D sample after grinding (2DS), and d) 3D sample after grinding (3DS). Recycled samples from Fall collection: e) 2D sample after grinding (2DF) and f) 3D sample after grinding (3DF).

The ultimate goal is to valorize both plastic and fiber streams. Therefore, the recovery process was developed such that both sub-streams can be recycled. The Spring samples were labeled as 2D Spring (2DS) and 3D Spring (3DS), while the Fall samples were labeled as 2D Fall (2DF) and 3D Fall (3DF). For each sample, two batches were considered, called A and B. Table 1 shows the utilized design of experiment with a total of 8 runs. Water density separation technique was then used to obtain polyolefin fractions. The samples were soaked in water for 1 h until samples were fully wet and the float fraction was separated from sunk. Lighter plastics (density < 1 g/cm³) float, while denser ones sink, allowing for easy separation. The percentage of float and sink fractions was calculated after drying the samples for 24 h at 60 °C.

Table 1 Factor level combinations and experimental runs for 2³ full factorial design.

| Parameter | Level 1 | Level 2 |
|-----------|---------|---------|
| Dimension | 2D | 3D |
| Season | Spring | Fall |
| Batch | A | B |

| Run Order | Replication # | Season | Dimension | Batch | Sample code |
|-----------|---------------|--------|-----------|-------|-------------|
| 1 | 4 | Spring | 2D | A | 2DS-A |
| 2 | 4 | Fall | 2D | B | 2DS-B |
| 3 | 4 | Spring | 3D | A | 3DS-A |
| 4 | 4 | Fall | 3D | B | 3DS-B |
| 5 | 4 | Spring | 2D | A | 2DF-A |
| 6 | 4 | Fall | 2D | B | 2DF-B |
| 7 | 4 | Spring | 3D | A | 3DF-A |
| 8 | 4 | Fall | 3D | B | 3DF-B |

The float samples were compounded using a CW Brabender Model DDRV (Hackensack, NJ, USA), at a rotor speed of 200 rpm and a temperature of 180 °C. Before compounding, the samples were dried at 105 °C for 4 h to remove any moisture. Approximately 50 g of material was added into the batch mixer and masticated until constant torque (after about 5 min) was achieved. The batch mixed samples were compression molded into flat sheets with a thickness of 0.62 mm, a length of 126.38 mm, and a width of 111.14 mm. The molding process used a temperature of 180 °C and a pressure of 103 MPa within a CARVER Inc. model 4394.4PL3003 (Wabash, IN, USA) compression molder. After an 8-min compression cycle, the molded sheets were cooled to 20 °C in 5 min.

The recyclates were evaluated using a Thermo Scientific NICOLETiS50 ATR-FTIR (Waltham, MA, USA) in the wavenumber range 4000 to 600 cm⁻¹. Spectra were recorded by averaging 64 scans at room temperature. Tensile samples were die cut following ASTM D638 Type V size and tested using an Instron 5966 (Norwood, MA, USA) with a 10 kN load cell at a displacement rate of 10 mm. Each sample was evaluated on four replicates, and the results are presented for the tensile strength, yield strength, Young's modulus, and elongation at break. The ANOVA analysis was conducted to examine the differences in Season (Spring and Fall), Dimension (2D and 3D), and Batch (A and B).

Results and Discussion

Material recovery and density separation results

Figure 4 shows the waste recovery yields across Season and Dimension. The plastic recovered for Spring is 3.20% and 3.24% for 2D and 3D plastics, while those for Fall are 6.90% and 2.10%, respectively. When examining the total amount of plastic yield relative to the overall shipment, Spring plastics accounted for 6.44% of the total weight, while Fall plastics accounted for 9.00%. The Fall shipment contained a higher percentage of 2D plastics, up 3.70% from the Spring shipment, while the 3D plastics for Fall were short by 1.14% compared to Spring. The total recovered plastic in Fall is 2.56% higher than that in Spring, and the total recovered plastic for 2D and 3D is 5.05% and 2.67%, respectively. Overall, the total recovered plastic (2D + 3D) is 7.72% which is lower than the average NR-MSW of 18% plastic content provided by the United States Environmental Protection Agency (EPA) 2018 report [1]. This is because the source of waste in this study is construction and demolition and commercial streams as opposed to household waste. However, according to the Global Waste Recycling and Circular Economy Market Outlook report 2020, the plastic content in construction and demolition waste is 5.1%, slightly lower than the value reported in our

study [18]. It was noted that during the Fall sampling, the materials exhibited higher moisture content, resulting in increased debris sticking to the recovered plastic, which could adversely affect the recovery rates. Nevertheless, the overall plastic recovery rate was higher in Fall. This seasonal difference may be attributed to consumer behavior, though additional data collection and statistical analysis are required to further verify it.

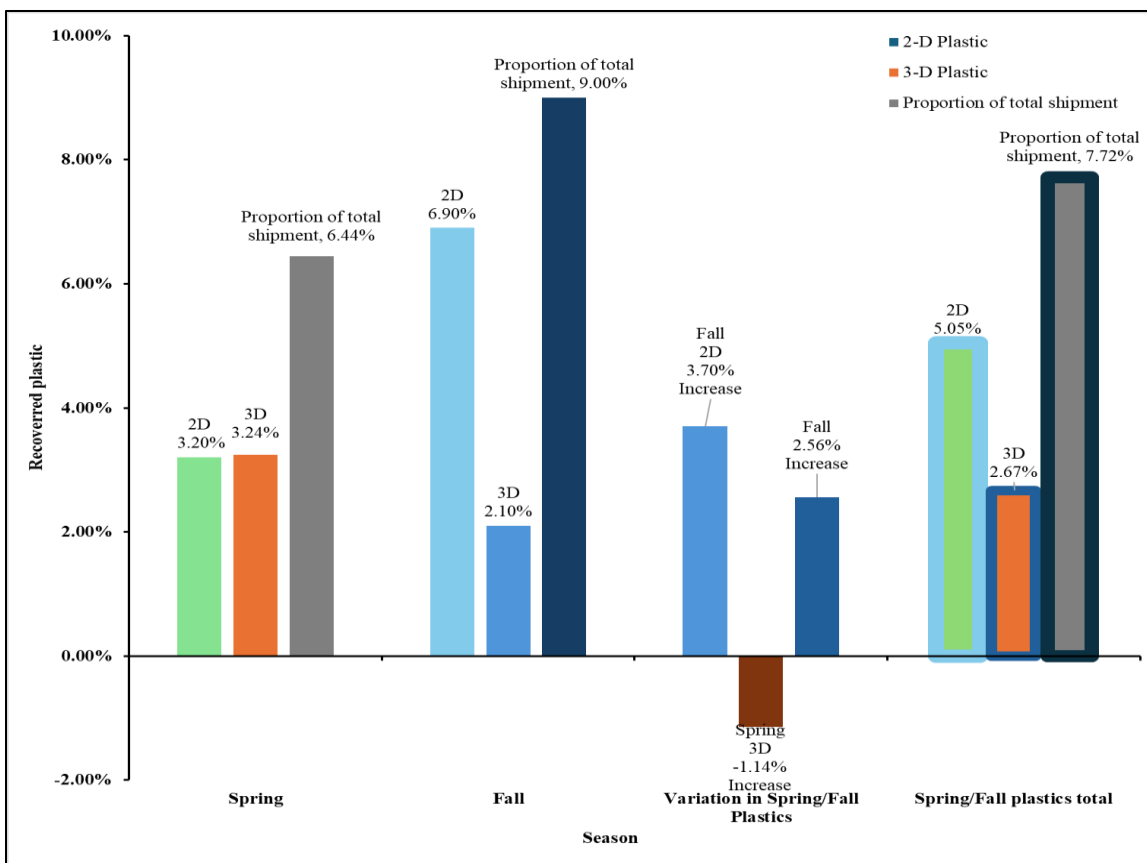


Figure 4 Recovery rate of various plastic streams from Fall and Spring collections relative to the mass of overall collected waste.

The mean recoveries of polyolefin samples are plotted in Figure 5. The results show that the average yield of all samples fell between 74% and 87% in float plastic (polyolefins). Relatively low standard deviation values of yield were observed in the density-separated samples (Figure 5) which indicate that the variability within each batch is relatively low, which could be related to the thorough mixing after grinding (evidence in Figure 3c-f). ANOVA revealed that Dimension (2D vs 3D) had a very significant effect on the float fraction (with a p -value of 0.0006) while Season effect (Fall vs Spring) appeared less significant (with a p -value of 0.0131). 3D samples showed lower polyolefin yield likely due to having more content of high-density plastics. Seasonal variations could also be plausibly attributed to consumer behavior and environmental condition differences. For instance, an increased use of plastic tarps was noted in Fall samples. There has been no report on the variability classification of density-separated samples based on Season or Dimension. A report by Lipp et al [19] obtained a polypropylene recovery yield of 50-70%, depending on the purity level of the initial sorting done on the MSW stream. Their study corroborated the high content of polyolefins in plastic waste obtained in this study.

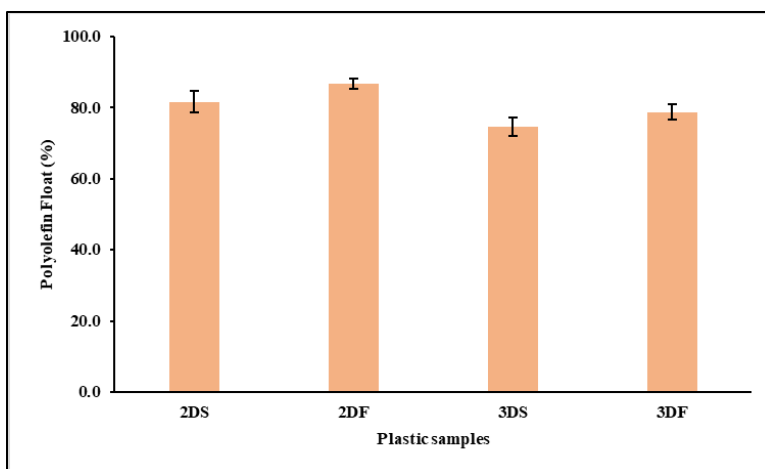


Figure 5 Polyolefin (float) yield percentage obtained from water float/sink separation for various samples (error bars show the standard deviation of three replicates).

FT-IR result

The result of the FT-IR is shown in Figure 6. The samples show major peaks belonging to polyolefins. The first peak at 720 cm^{-1} is a polyethylene CH_2 vibration, and next to it at 1377 cm^{-1} is the methyl (CH_3) asymmetric peak typical of polypropylene. After that is another PE-specific peak at 1470 cm^{-1} , which represents CH_2 scissoring, and the last major peak common to both PP and PE between 2700 and 3000 cm^{-1} , which is a C-H chain stretching region. The previous report confirms these distinguishing peaks between PP/PE. The peaks at 720 and 1470 cm^{-1} confirm the presence of polyethylene, while the peak at 1377 cm^{-1} confirms the presence of PP. However, since we have both peaks at higher intensity, this result confirms that these are the major components of the float samples. The FT-IR analysis indicates the float fraction of water density separation is primarily polyolefins. Other absorbance peaks are methyl peaks, not specific to a certain class of polymers. ATR-FTIR has been used to confirm the presence of specific polymers in recycled plastics [20]. In a study, ATR-FTIR was used to confirm the presence of polypropylene and polyethylene at unique peaks of 1377 and 1471 cm^{-1} , respectively, in simulated waste plastics [21]. A similar study of mixed plastic waste from bags and drums has similar peaks as reported in this study [22].

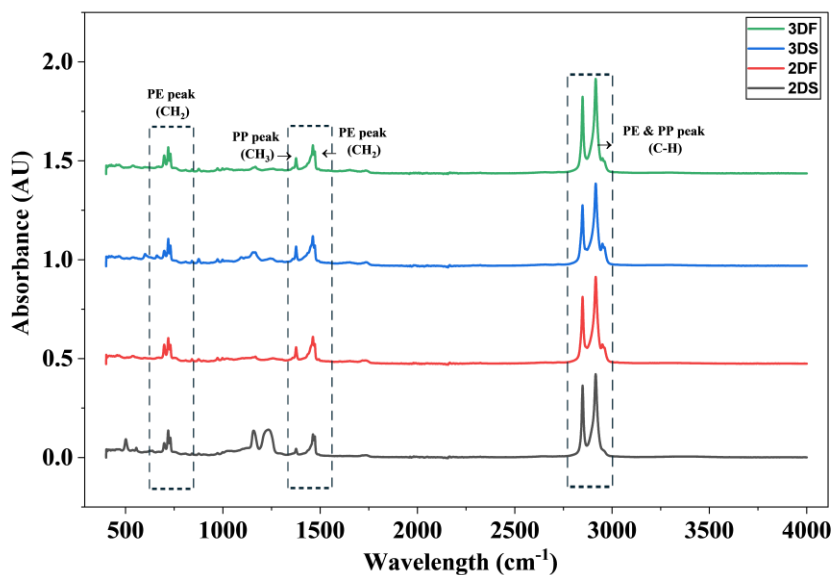


Figure 6 FT-IR of recycled plastic float fractions for various samples (2D/3D and Spring/Fall).

Tensile properties

The tensile strength, yield strength, tensile modulus, and elongation at break for all eight conditions are shown in Figure 7. The main-effects plots for the influence of Season (Spring vs Fall), Dimension (2D vs 3D), and Batch (A vs B) on the tensile properties are also summarized in Figure 8. Overall, the 3D samples produced markedly stiffer and stronger materials with lower ductility than the 2D samples (thin flake like). The 3D samples exhibited tensile strengths of 14.12–14.17 MPa, yield strengths of 8.87–9.44 MPa, and moduli of 746.55–763.80 MPa. The largest relative differences between 2D and 3D samples were 48.63% for tensile strength, 142% for yield strength, and 143% for tensile modulus. ANOVA (Table 2) gives extremely small p-values (on the order of 10^{-9}) for Dimension, confirming highly significant differences between the 2D and 3D samples. The greater strength and stiffness of the 3D fraction are likely related to the presence of higher contents of PP or HDPE and likely filled plastic, which are in line with the materials used in starting waste products.

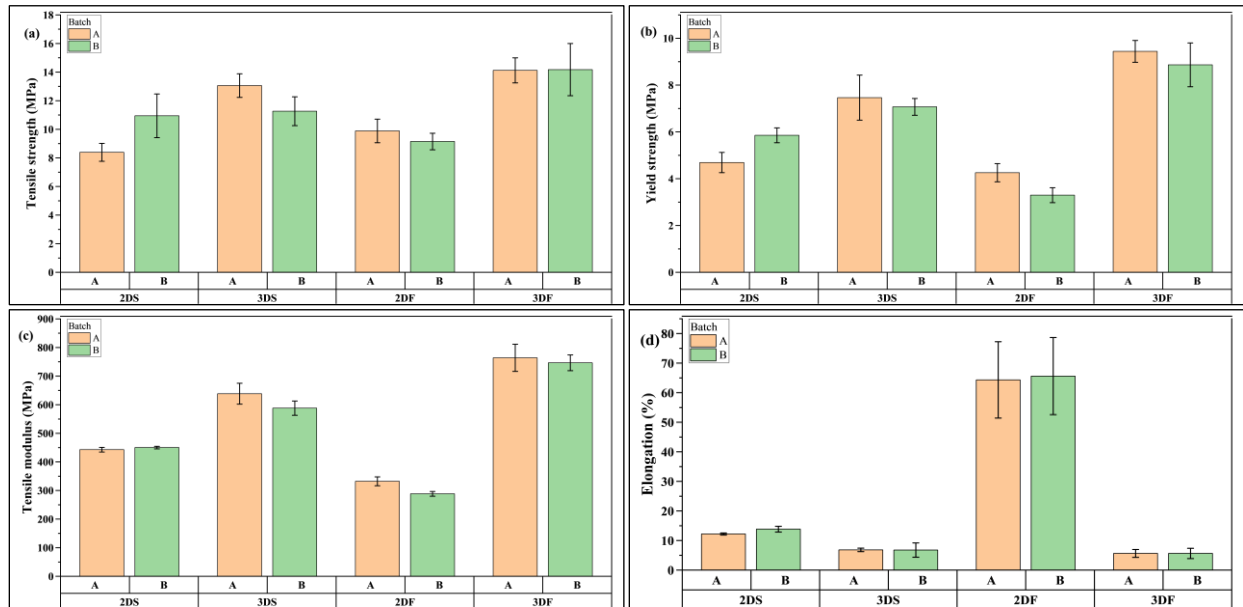
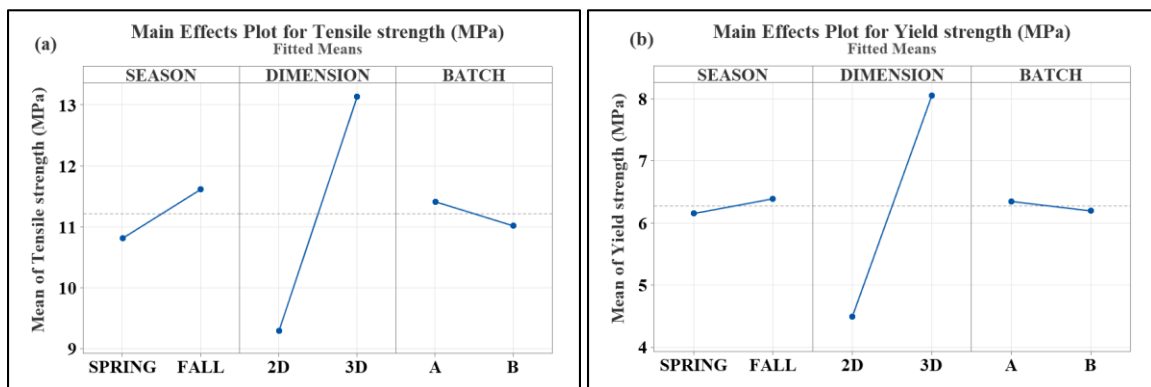


Figure 7 Tensile properties of recycled polyolefins: a) Tensile strength, b) Yield strength, c) Modulus, and d) Elongation at break.

Compared to Dimension, Season effect on strength and stiffness are modest (changes in the mean values below ~10%), some statistically insignificant and some marginally significant. Season however appears to strongly affect the ductility, with elongation at break in Fall samples being more than twice of those in Spring samples. Batch effects are the smallest for all properties, with changes in mean values typically below 4%, indicating that the two batches are broadly representative of the same recycled plastic stream.



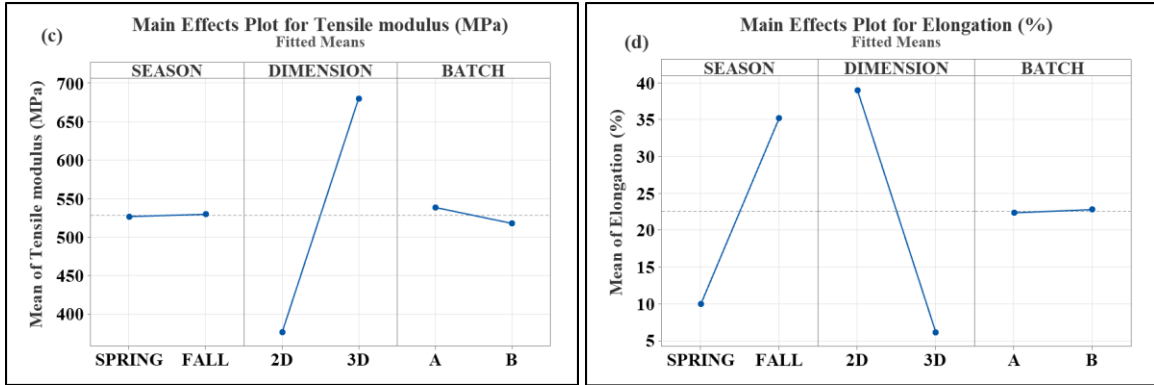


Figure 8 Main effect plots of Season, Dimension, and Size of a) Tensile strength, b) Yield strength, c) Modulus, and d) Elongation at break of recycled plastic.

These trends are consistent with the ANOVA results in Table 3 and the standardized effects including interactions in Figure 9. Across all properties, Dimension has the highest F-values and $p < 0.001$, confirming it as the critical factor controlling mechanical performance. Season is statistically significant for tensile strength and elongation but not for modulus. The seasonal differences in mechanical properties could be attributed to changes in the composition of recovered materials driven by the specific types of plastics being discarded because of consumer behavior. Batch is either not significant or only weakly significant, as expected for samples intended to be representative of the same feedstock. Figure 9 also shows that the interaction terms (e.g., Season \times Dimension, Season \times Dimension \times Batch) are smaller than the main effect of Dimension. Some interactions reach statistical significance for specific properties, but their magnitudes remain low compared to the Dimension effect and do not alter the overall factor ranking.

Overall, the results demonstrate that separation into 2D and 3D fractions has a far greater impact on tensile properties than seasonal variation or batch-to-batch differences, and that the role of interactions is secondary to this dominant Dimension effect.

Table 2 ANOVA results and percentage contributions of Season, Dimension, and Batch to the tensile properties of recovered polyolefins.

| Properties | Parameters | Adj SS | Adj SS Contribution (%) | F-value | P-value |
|------------------------|------------|-----------|-------------------------|---------|---------|
| Tensile strength (MPa) | Season | 5.15 | 4.14 | 7.47 | 0.0116 |
| | Dimension | 117.91 | 94.84 | 170.91 | 0.0000 |
| | Batch | 1.26 | 1.01 | 1.83 | 0.1890 |
| Yield strength (MPa) | Season | 0.45 | 0.44 | 2.13 | 0.1575 |
| | Dimension | 101.42 | 99.37 | 476.08 | 0.0000 |
| | Batch | 0.19 | 0.19 | 0.88 | 0.3574 |
| Tensile modulus (MPa) | Season | 67.00 | 0.01 | 0.09 | 0.7625 |
| | Dimension | 735045.00 | 99.52 | 1018.60 | 0.0000 |
| | Batch | 3452.00 | 0.47 | 4.78 | 0.0387 |
| Elongation (%) | Season | 5096.21 | 37.15 | 117.47 | 0.0000 |
| | Dimension | 8621.50 | 62.84 | 198.72 | 0.0000 |
| | Batch | 1.50 | 0.01 | 0.03 | 0.8536 |

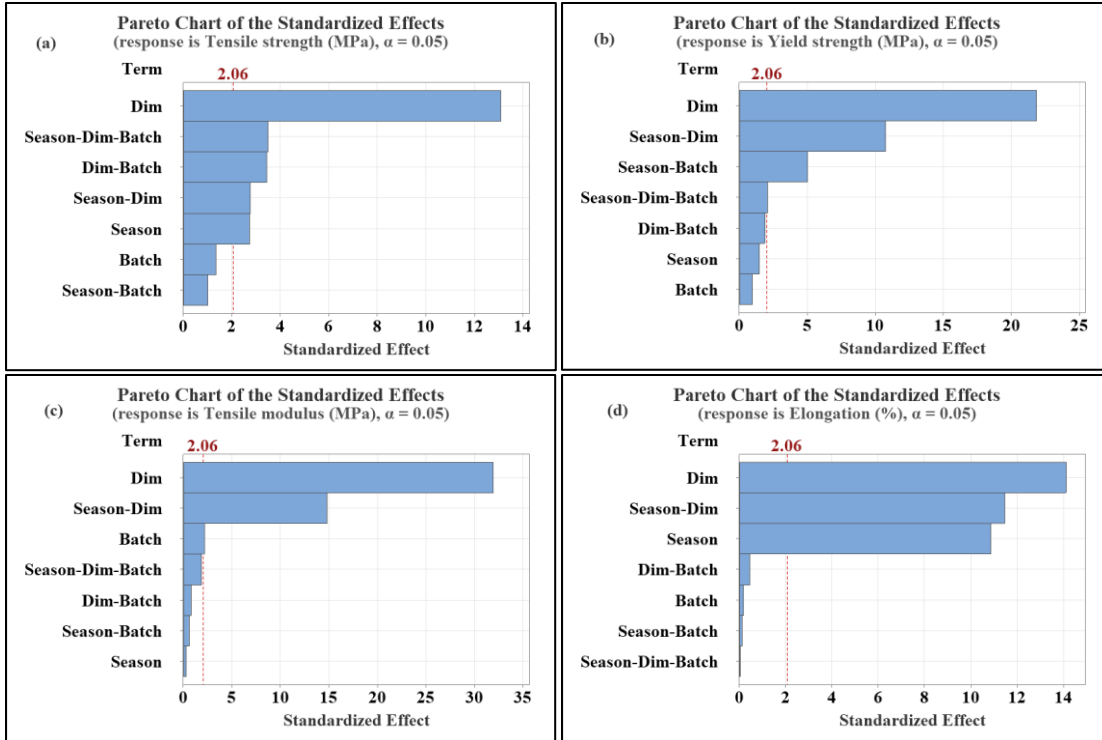


Figure 9 Pareto chart of the standardized effects for a) tensile strength, b) yield strength, c) modulus, and d) Elongation at break, showing the relative importance of Season, Dimension, Batch, and their interactions; the vertical dashed line indicates the significance threshold at $\alpha = 0.05$.

The percentage contribution of each factor was also calculated using the Adjusted Sum of Squares (Adj SS) for each tensile property. The average percentage contribution of each signal for tensile strength, modulus, and elongation was used to plot the pie chart given in Figure 10. Similar to the ranking from the ANOVA analysis, the highest effect on the properties of the recycled polyolefins was Dimension (89.1%), followed by Season (10.4%) and then Batch (0.4%). Based on this analysis, the percentage contribution of Season and Batches combined is less than 11%, showing that properly separating the plastic waste into 2D and 3D may allow us to obtain reasonably uniform performance independent of Season and Batch.

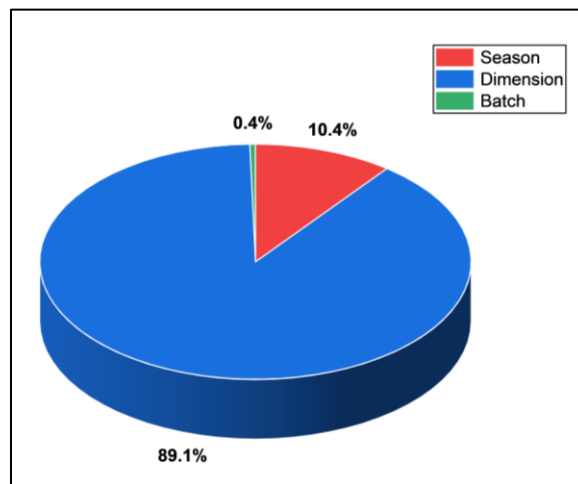


Figure 10 Overall contribution of Dimension, Season, and Batch factors to the mechanical properties.

This study focused on recovering polyolefins from non-recyclable waste and assessing their performance and variability. It is part of a greater effort that aims at recovery of fiber and plastic (three sub-streams of low-, medium-, and high-density) waste streams from non-recyclable waste. The next steps are a) assessing the sink/float separation and melt compounding in pilot scale and how the lab-scale data is transferrable to pilot scale separation and extrusion processes, b) assessment of yield, processability, and performance of fiber subfractions and plastics' high density subfractions, and c) utilization of recovered fiber streams to reinforce the recovered plastics or other plastics types, e.g., virgin polyolefins.

Conclusion

This study demonstrated the recovery of polyolefins from non-recyclable waste samples for property evaluation and variability assessment. The multi-step dry separation, sink/float wet separation, and melt mixing provide an excellent polyolefin recovery path where the contaminants can be effectively removed and a homogenous polyolefin feedstock can be obtained. The findings also demonstrate that seasonal changes could marginally affect the mechanical performance of recovered plastics, driven by variability in waste composition plausibly resulting from consumer behavior.

A total of 7.72% plastic was recovered from the non-recyclable waste samples collected from construction and demolition and commercial streams, where 2D subfraction was greater than 3D ones. A relatively noticeable difference was observed in the recovery rate between Spring and Fall which could be attributed to consumer behavior. Density separation experiments showed that the majority (74 - 87%) of recovered plastics has a density of less than 1 g/cm³ and they are primarily polyolefins as ATR-FTIR analysis suggested.

Overall, the tensile results showed that modulus, strength, and elongation at break did not change significantly as a function of Batch and were only partially affected by Season. In contrast, Dimension (2D vs 3D) exhibited a pronounced effect on mechanical performance, where 3D samples significantly outperformed the 2D ones (roughly twofold on average strength, and modulus). This was attributed to having higher amounts of PP or high-density PE or filled resins. ANOVA F-values and adjusted sums of squares indicated that Dimension accounts for about 89% of the variation in mechanical properties, far exceeding the contributions of Season and Batch.

Overall, this low-energy density-separation approach offers a practical route for selectively recovering polyolefins from landfill-derived waste streams, supporting more sustainable recycling strategies and contributing to the circular economy.

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