Upcycling of Waste Biomass and Ocean-Recycled Plastics through Fused Deposition Modeling

Valorization of Waste Plastic and Waste Biomass

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BIOPRODUCTS DISCOVERY & DEVELOPMENT CENTRE

FDM Vs Injection Molding (IM)

AM

- Uses computer-aided design (CAD) files to build 3D parts layer by layer

Advantages

- Low Unit Cost
- Product Quality
- Speed

Disadvantages

- Speed
- Product Quality

IM

- Fast production process
- Injects a molten plastic or other build material into a pre-made mold
- Every mold typically lasts for thousands or tens of thousands of production cycles

Advantages

- Low Initial Cost
- Flexibility

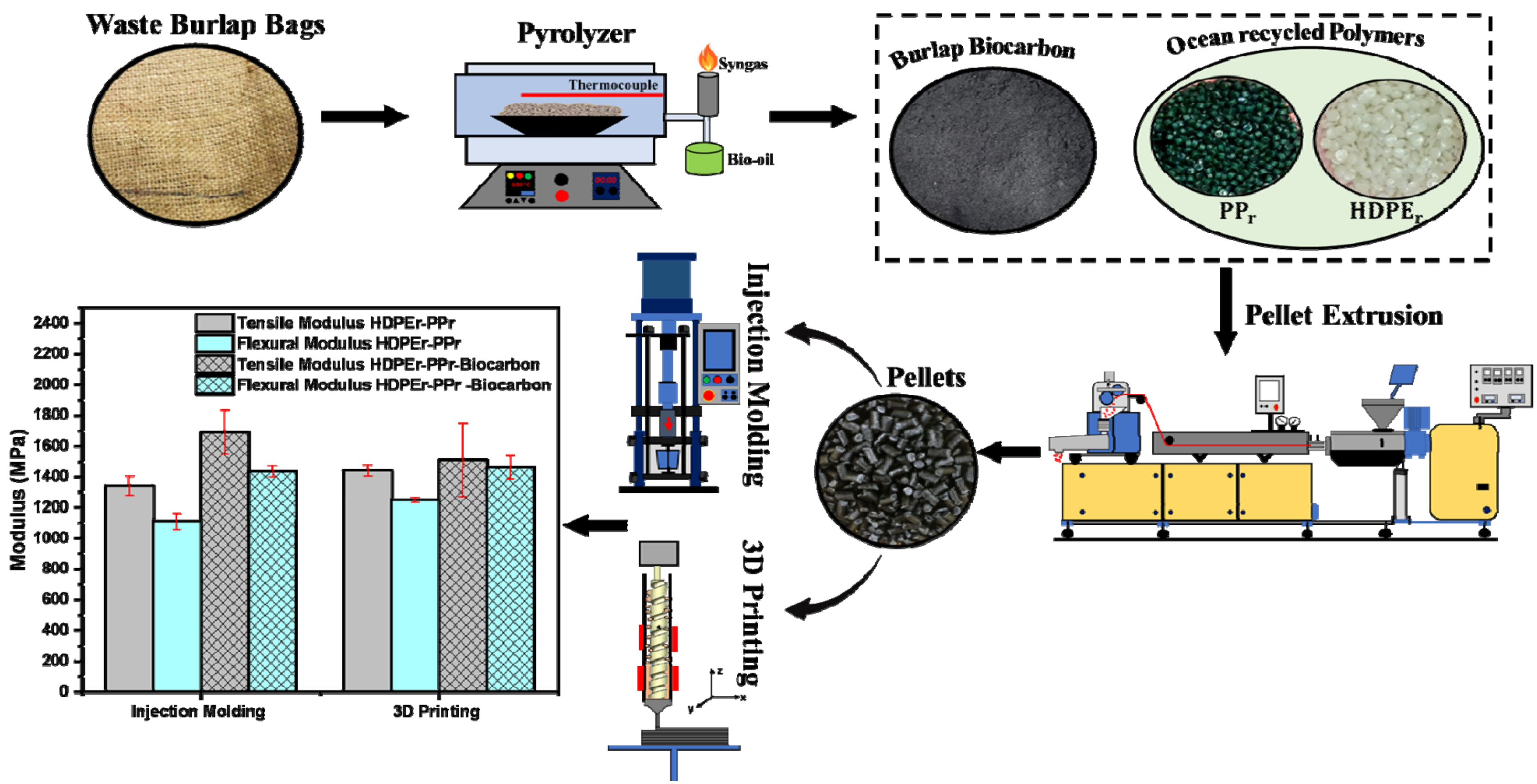
Disadvantages

- Upfront Investment in the Mold
- Modification Limits

Objectives

Upcycling of waste ocean plastics and post-consumer waste through FDM

Optimization of 3D Printing parameters using Taguchi and Grey relation analysis (GRA)



Research Design

Pyrolysis
↓
Fabrication of Pellets
↓
Taguchi Orthogonal Array Design
↓
3D Printing
↓
Mechanical Testing
↓
Signal to Noise Ratio Calculation using Taguchi
→
Normalization of Data
↓
Determining the deviation sequence → $$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}$$
↓
Determining the Grey Relational Coefficient → $$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{oi}(k) + \zeta\Delta_{max}}$$
↓
Determining the Grey Relational Grade → $$\gamma_i = \frac{1}{n}\sum_{i=1}^{n} \xi_i(k)$$
↓
Prediction of optimum values through Taguchi

$y_i(k)$ represents the corresponding S/N ratio of data points
n represents the number of response variables
$\zeta_i(k)$ symbolizes GRC of individual response
Δ_{min} **and** Δ_{max} represent lowest and highest deviations of individual mechanical data.

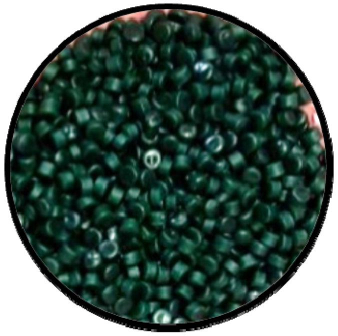
Material

- Ocean recycled **high-density polyethylene** (rHDPE) provided by Oceanworks®
- Ocean recycled **polypropylene** provided by Oceanworks®
- The **burlap** bags as a post-industrial waste from Club Coffee, Ontario, Canada

Properties of rHDPE and rPP

	rHDPE	rPP
Grade	190121	190252
Colour	Light grey	Green
Melt flow index	0.6263 ± 0.012 g/10 min at 190°C	3.6463±0.07 g/10 min at 230°C
Melting Point	130-135 °C	150-160 °C
Density	0.962 ± 0.007	0.966 ± 0.003

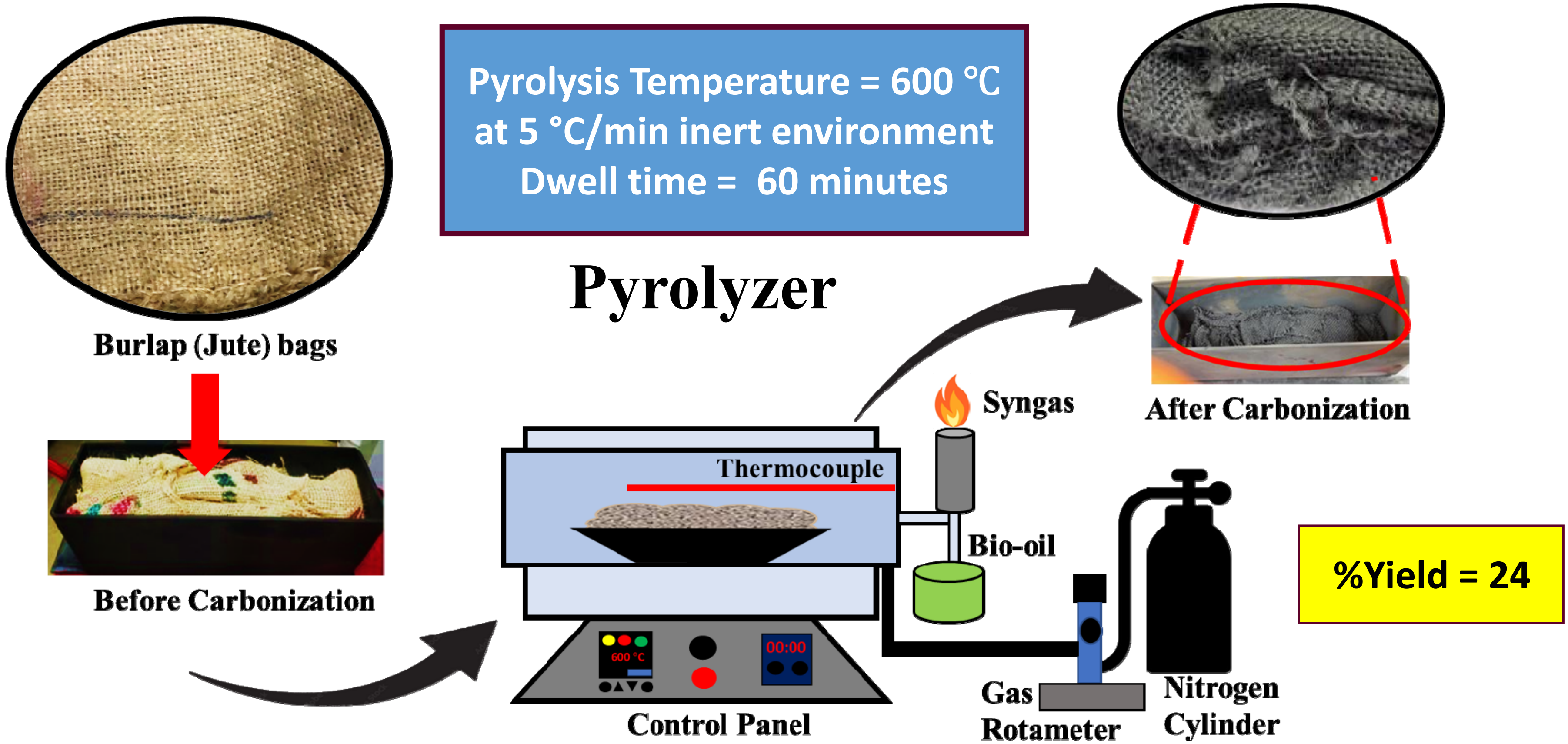
rHDPE



rPP

Waste Burlap bag

Pyrolysis of Waste Burlap Bags

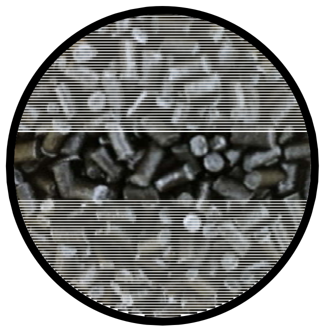


- Retsch ball mill machine
- Ball milled for 1 hour at 200 rpm in a 500 mL stainless steel ball mill container
- 100 zirconium oxide balls with diameters of 10 mm and weights of 3.34 g each

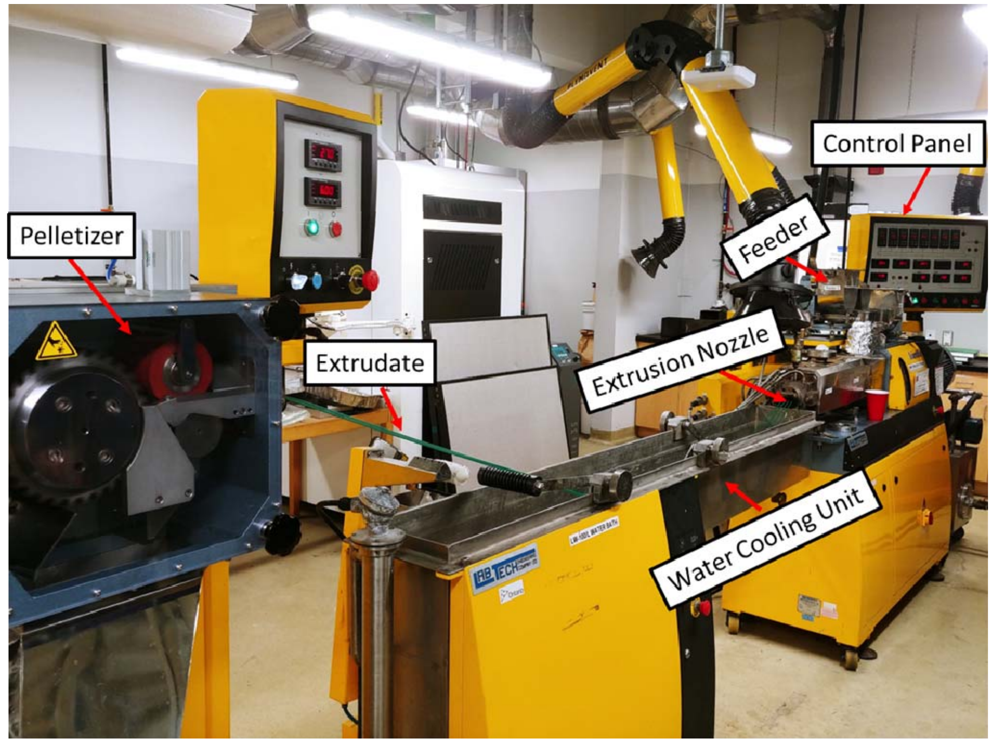
$$\%\,Yield = \left[\frac{Weight\ of\ Burlap\ Biocarbon}{Weight\ of\ dried\ burlap\ bags}\right] \times 100$$

Preparation of pellets

rHDPE/rPP Pellets



rHDPE/rPP/biocarbon Pellets

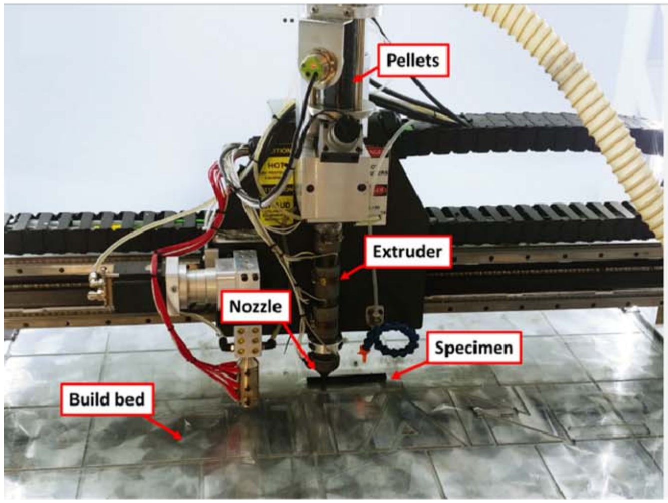


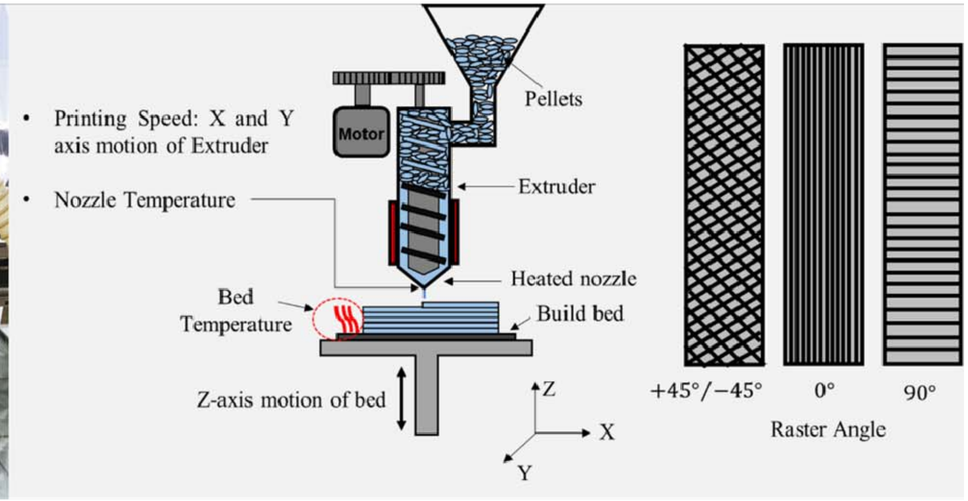
Experimental setup for pellet fabrication (LabTech Extruder)

Acronyms and Weight Percentages for Blend and Composites

Sample Name	Acronym	Weight Percentage (%)		
		rHDPE	rPP	Biocarbon
(rHDPE/rPP)(70%/30%)	rHDPE/rPP	70	30	--
(80%)[(rHDPE/rPP)(70%/30%)]/Biocarbon (20%)	rHDPE/rPP/biocarbon	56	24	20

3D Printing of Sustainable Composites





Fixed parameters to perform 3D printing experiments

Nozzle Diameter	0.8 mm
Extrusion Width (mm)	0.6
Layer Height (mm)	0.5
Infill Percentage	100 %
Infill Pattern	Rectilinear
Bed Temperature	92 ℃
Enclosure Temperature	55 ℃

Orthogonal array L9 of the experimental runs

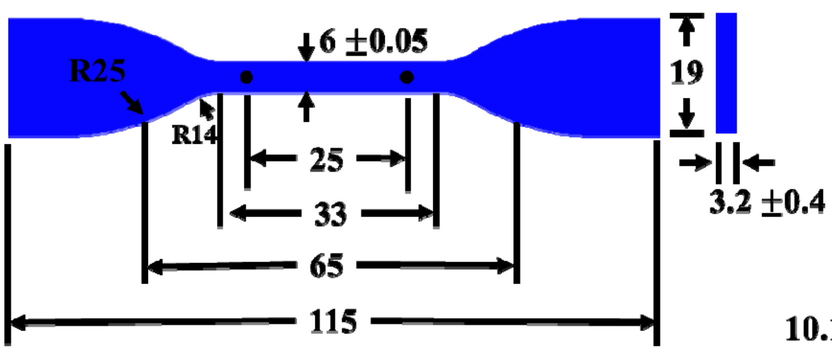
Experiment No.	Printing Speed (mm/min)	Nozzle Temperature (℃)	Raster Angle (°)
1	900	215	0
2	900	235	+45/-45
3	900	255	90
4	1200	215	+45/-45
5	1200	235	90
6	1200	255	0
7	1500	215	90
8	1500	235	0
9	1500	255	+45/-45

Characterization of Blends and Composites

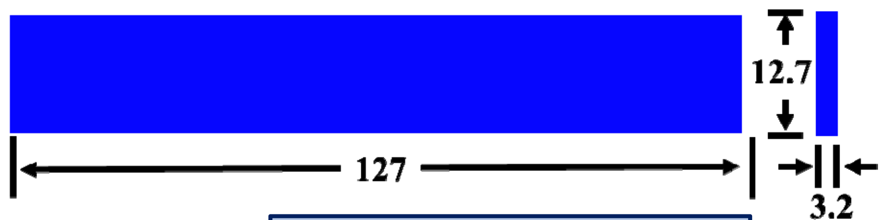
• Rheological behavior

- ➢ Anton Paar rheometer (MCR 302, Germany).
- ➢ The tests were conducted in a nitrogen environment using a parallel plate setup having a gap of 1 mm and diameter of 25 mm.
- ➢ The frequency range was set from 0.1 to 100 rad/s, with a 0.1% strain.
- ➢ The rheological measurements were performed in dynamic oscillatory mode at three different temperatures: 215 °C, 235 °C, and 255 °C.

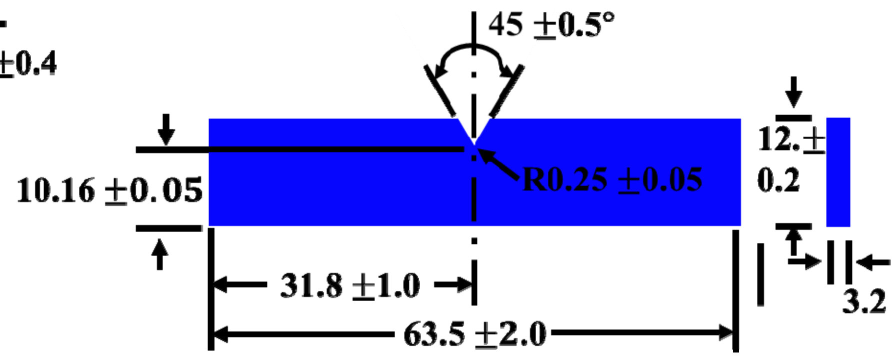
• Mechanical Testing



Tensile: ASTM D-638 (type IV)

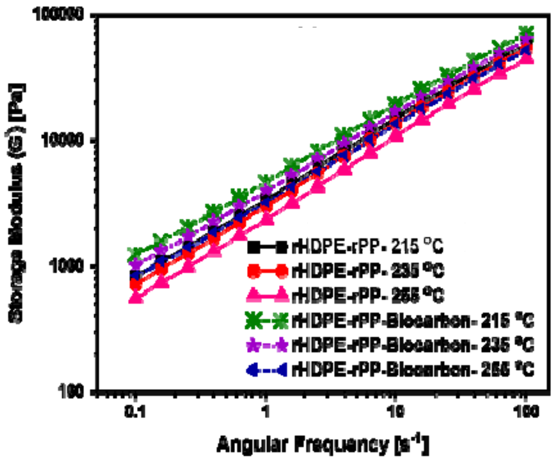


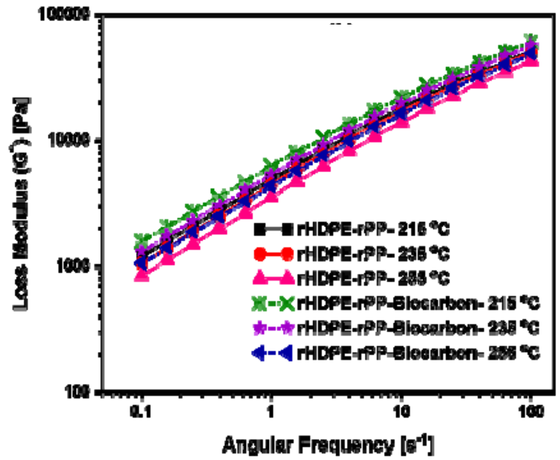
Flexural: ASTM D-790



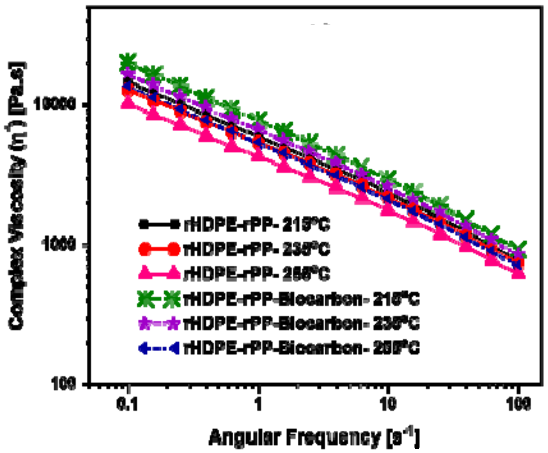
Impact: ASTM D-256

Rheological Behavior





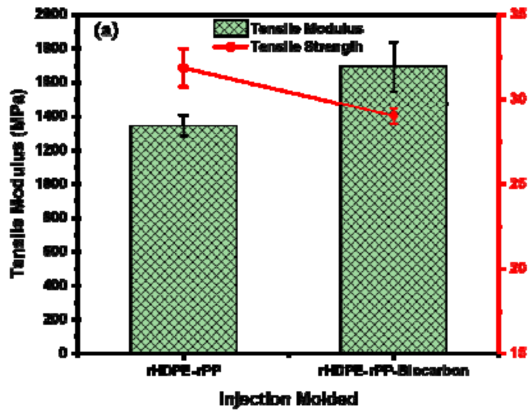
The complex viscosity decreased with increasing angular frequency, indicating the **shear thinning**

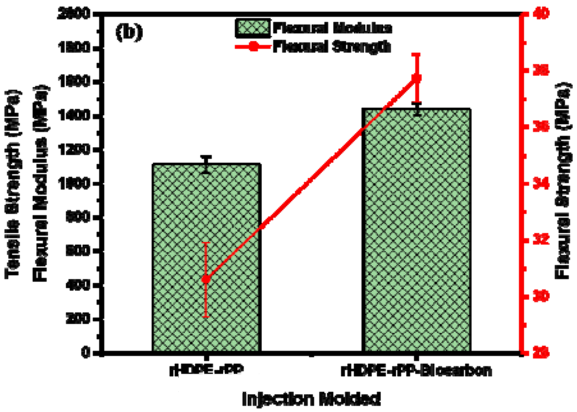


Rheology analysis of $HDPE_r$-PP_r blend and $HDPE_r$-PP_r -Biocarbon composite

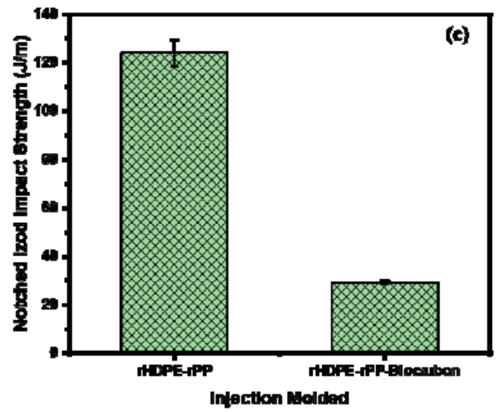
- As the angular frequency increased, both the storage and loss modulus of blend and composite increased, indicating that they adhere to the **linear viscoelastic theory**
- Decrease in storage modulus due to increase in temperature for the blend: transformation of a rigid mass into a more flowable substance
- For composite, stiff filler in the matrix resulted in higher storage modulus of the composite due to the **mobility restriction** of polymer chains
- High complex viscosity of the rHDPE-rPP-biocarbon composite than that of the rHDPE-rPP blend indicating the filler requires more **relaxation time to flow**, and **high shear stresses**

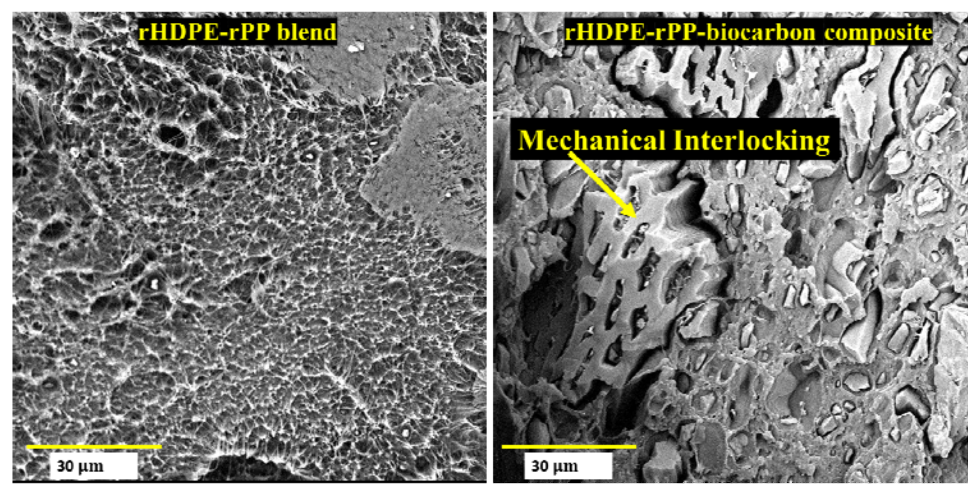
Mechanical Properties (IM)



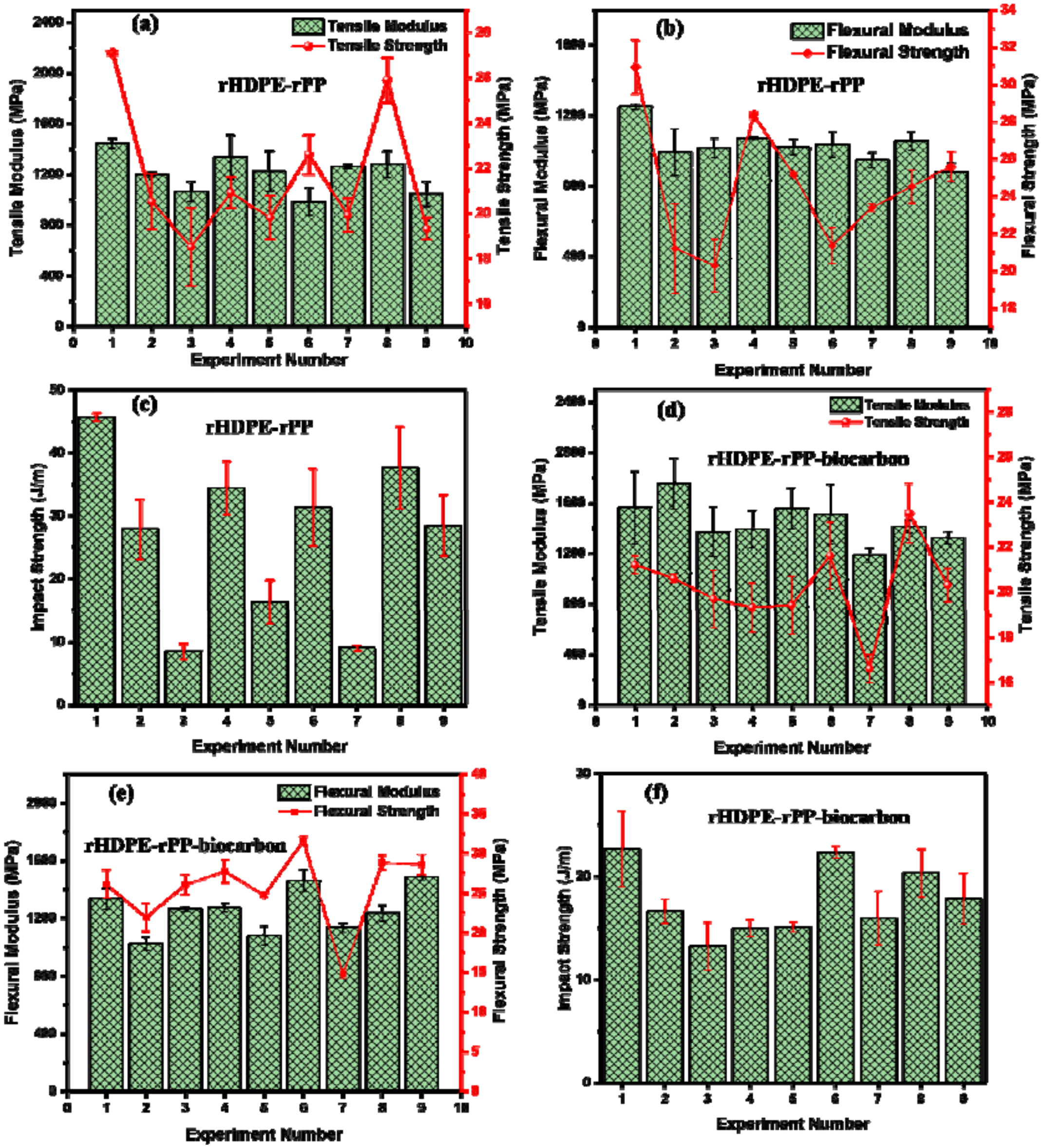


- Tensile strength decreased by 9% with biocarbon addition ; weak interaction of biocarbon to the matrix, stress concentration zones
- Flexural modulus increased by 29%, strength by 23% with biocarbon addition due to:
  - Mechanical interlocking and Biocarbon hardness
- Impact strength decreased significantly with biocarbon addition because:
  - Porous nature of biocarbon limited matrix energy dissipation.
  - Stress concentration zones due to biocarbon presence facilitated fracture initiation.





Mechanical Properties (3D Printed)



Experiment No.	Printing Speed	Nozzle Temperature	Raster Angle
1	900	215	0
2	900	235	+45/-45
3	900	255	90
4	1200	215	+45/-45
5	1200	235	90
6	1200	255	0
7	1500	215	90
8	1500	235	0
9	1500	255	+45/-45

rHDPE-rPP Blend:

- **Experiment 1** conditions exhibited optimal mechanical properties.
- Lower tensile and flexural and impact strengths were observed for samples printed according to **experiment 3**

rHDPE-rPP-biocarbon Composite:

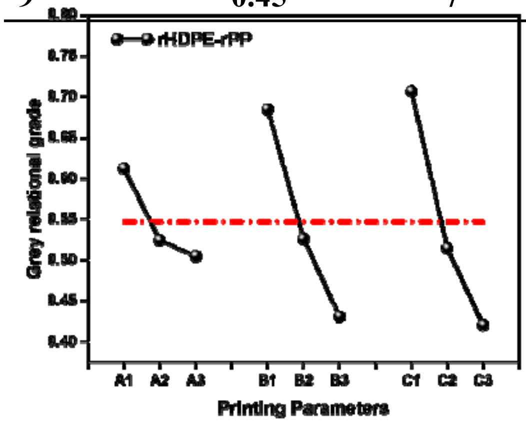
- 0° raster angle resulted in maximum tensile strength, flexural strength, and impact strength.
- Maximum tensile and flexural modulus were seen with ±45° raster angle.
- Printing speed, nozzle temperature, and raster angle influenced stiffness, interlocking, and bonding between layers.

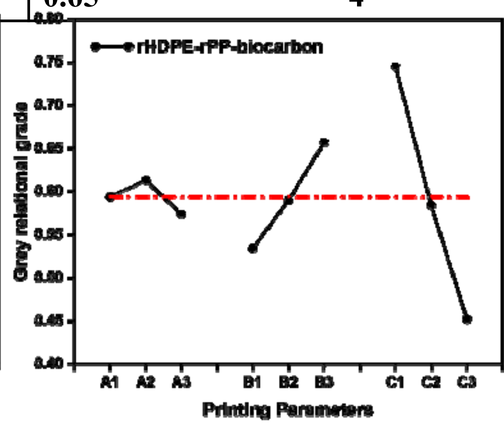
Grey Relation Analysis

Rank based on Grey relational grade.

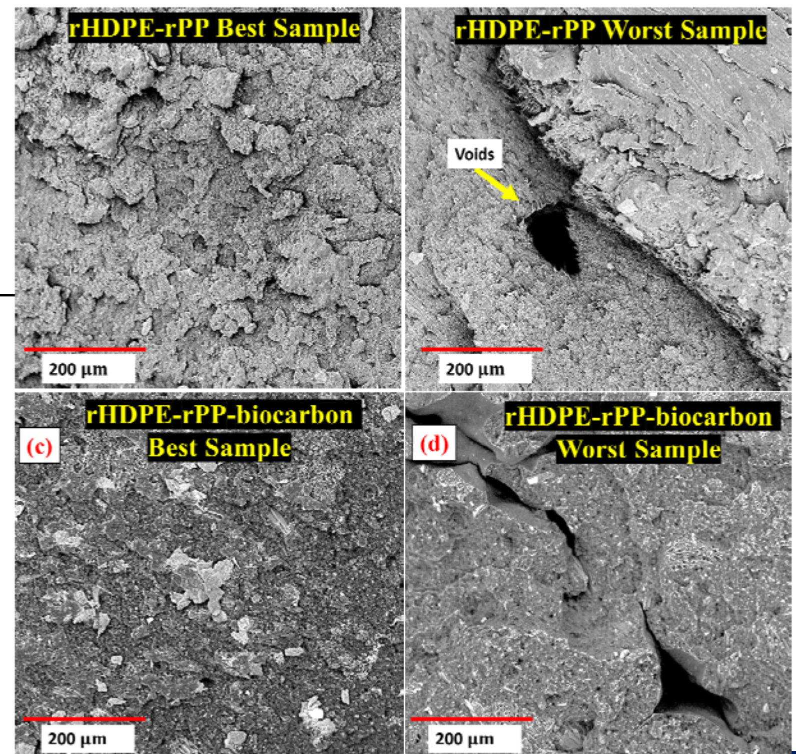
Experiment No.	$HDPE_r$-PP_r Grade	$HDPE_r$-PP_r Rank	$HDPE_r$-PP_r-Biocarbon Grade	$HDPE_r$-PP_r-Biocarbon Rank
1	1	1	0.71	2
2	0.47	6	0.58	5
3	0.37	9	0.49	8
4	0.63	3	0.52	6
5	0.47	5	0.49	7
6	0.48	4	0.82	1
7	0.42	8	0.37	9
8	0.64	2	0.70	3
9	0.45	7	0.65	4

Experiment No.	Printing Speed (mm/min)	Nozzle Temperature (°C)	Raster Angle (°)
1	900	215	0
2	900	235	45
3	900	255	90
4	1200	215	45
5	1200	235	90
6	1200	255	0
7	1500	215	90
8	1500	235	0
9	1500	255	45





Mean grey relational grade for each level of the printing parameters.



Comparison Between IM and 3D Printing

	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Impact Strength (MPa)
Injection Molding					
rHDPE-rPP	31.8±1.1	1344±64.6	30.6 ± 1.3	1111±52.5	123.8±5.7
rHDPE-rPP-biocarbon	29 ± 0.4	1691 ± 148.3	37.74 ± 0.8	1438±39.1	29.17±0.8
3D Printing at optimized conditions (Experiment 1 for blend and 6 for composite)					
rHDPE-rPP	27.1±0.07	1443±38.7	30.94 ± 1.4	1250±17.1	45.67±0.6
rHDPE-rPP-biocarbon	21.6±1.4	1510±238.13	31.62 ± 0.5	1462±76.3	22.34±0.5

- By comparing the 3D printed and IM HDPEr-PPr blend results, a decrease in impact and tensile strength was observed for 3D printing. However, the 3D printed samples demonstrated higher tensile and flexural modulus. No considerable difference was noticed in flexural strength. The 3D printed HDPEr-PPr-Biocarbon composite sample has less tensile and flexural strength, tensile modulus, and impact strength. However, no considerable difference was observed for flexural modulus.

Conclusions

- The optimal printing parameters for the improved mechanical performance of the rHDPE-rPP blend were at a printing speed of 900 mm/min, nozzle temperature of 215 ℃, and raster angle of 0°
- The rHDPE-rPP-biocarbon composite has optimal printing parameters as a printing speed of 1200 mm/min, nozzle temperature of 255 ℃, and raster angle of 0°
- With the addition of biocarbon, it was found that the tensile and flexural modulus of 3D printed specimens at optimized conditions increased by ~17% and 5%, respectively
- The tensile and impact strength of the 3D printed rHDPE-rPP blend was found to be lower than the IM counterpart. However, the 3D printed samples showed higher tensile (percent increase ~7 %) and flexural modulus (percent increase ~12 %) with no significant difference in flexural strength observed
- The 3D printed rHDPE-rPP-biocarbon composite exhibited no significant difference in tensile and flexural modulus compared to IM samples.

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Many Thanks for Listening!

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