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MECHANICAL AND THERMAL PROPERTIES OF POLYPROPYLENE (PP)/ WASTE CELLULOSE (WC) COMPOSITE FOR INDUSTRIAL APPLICATIONS

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Abstract: This study investigated the mechanical and thermal properties of recycled polypropylene (rPP) composites reinforced with waste cardboard cellulose (WC) and modified with aluminum hydroxide $Al(OH)_3$ and potassium alum ($KAl(SO_4)_2 \cdot 12H_2O$) additives. The composites were fabricated using a twin-screw extruder and characterized before and after UV exposure .Waste cellulose was dispersed as a homogeneous suspension rather than a solution, as cellulose is insoluble in water.
Results showed that tensile strength increased by 15–30% with cellulose addition (10–30 wt.%), while elastic modulus improved by 20–40% depending on filler content and additive type. Composites containing $Al(OH)_3$ exhibited higher tensile performance compared to alum-modified ones. Impact strength showed a moderate enhancement with cellulose addition but slightly decreased with inorganic additives. DSC analysis revealed an increase in melting temperature (Tm) by 2–5°C and crystallinity (Xc) by 5–10% for cellulose-reinforced composites. Although no conventional compatibilizer such as maleic anhydride-grafted polypropylene (MAPP) was employed, the observed mechanical improvement is attributed to physical interlocking, hydrogen bonding interactions, and the stabilizing effect of inorganic additives .Alum-modified composites exhibited enhanced thermal stability, while cellulose-containing composites retained 85–90% of their initial mechanical properties after UV exposure, compared to 70–75% for neat rPP .
Keywords: Polypropylene PP, Cellulose waste CW, Alum, Al(OH)3, DSC, Mechanical properties.

1. INTRODUCTION

In response to escalating environmental concerns and the rapid depletion of non-renewable resources, the global polymer industry has experienced a significant shift toward the development sustainable, environmentally friendly, and circular materials (Ali et al., 2022; Maiti et al., 2022). Conventional petroleum-based plastics, despite their widespread use due to low cost and versatility, present major challenges related to carbon emissions, waste accumulation, and end-of-life management. Polypropylene (PP) is one of the most widely used polymers belonging to thermoplastics because of its low weight,

high process ability, mechanical stability, and the possibility to recycle it, which is almost irreplaceable in the packaging, automotive, construction, and consumer goods industries (Abel and Coates, 2025; Luo et al., 2025). Therefore, the increased environmental awareness has increased the interest in research on the integration of renewable and waste-based reinforcements to make PP-based materials less ecologically foot printed.

The recent research findings have paid more and more attention to sustainable PP composite development, including bio-based fillers like natural fibers and cellulose derivatives. The cellulose reinforcements are of interest, especially because they are renewable, biodegradable, stiff to weight compared to high, and require fewer densities (Kargarzadeh et al., 2017). It has been stated by several researchers that cellulose micro- and nanofillers serve as efficient reinforcing and nucleating agents in PP matrices, resulting in the strengthening of tensile strength, elastic modulus, crystallinity, and thermal stability (Dufresne, 2013; Jiang et al, 2023). The benefits are better mechanical performance and aiding in the shift to more sustainable composite materials.

But the hydrophilic properties of cellulose and the hydrophobic and nonpolar properties of PP tend to cause poor interfacial adhesion and result in low efficiencies in transferring stress and further agglomeration of fillers and loss of ductility. In order to solve this dilemma, various compatibilization and surface modification methods have been suggested. Kabir et al. (2012) also proved that chemical modification, such as alkali and silane modification, could help greatly improve fiber-matrix interfacial bonding, and Tejaswini et al. (2022) proved that maleic anhydride-grafted polypropylene (PP-g-MA) could also help to improve mechanical and thermal performance due to its ability to promote covalent bonding between the chains of cellulose and PP. Also, it has been demonstrated that optimized processing paths, especially extrusion-based methods, enhance filler dispersion and performance of the composite in general (Oksman et al., 2016; Phiri et al., 2023). In addition to traditional cellulose reinforcement, recent studies have tried to use hybrid and multicomponent composite systems to enhance functional characteristics further. According to Iskakov et al., (2025), eco-friendly PP composites that were reinforced with cellulose fibers showed good stiffness and dimensional stability, though overloading of the filler can have adverse effects on ductility. On the same note, Caramitu et al. (2025) revealed that PP composites with hybrid natural fillers had better mechanical and thermal properties that could be applied in industries and automobiles. As another potentially successful strategy towards the valorization of cellulosic waste streams, the use of waste-derived cellulose has also been cited, both in support of the circular economy goals and without significant compromise to the performance of the composite (Marquardt et al., 2017; Mohanty et al., 2018).

Besides mechanical improvement, the property of PP/cellulose composites to withstand environmental aging conditions has also gained more and more attention. The use of cellulose fillers has been shown to affect the crystallization of PP, which leads to greater levels of crystallinity and better thermal stability, both of which are strongly associated with mechanical performance (Yi et al., 2020). However, most of the published works are on the virgin PP systems, whereas research on the recycled polypropylene (rPP) reinforced with waste-derived cellulose, especially under ultraviolet (UV) conditions, is limited. Furthermore, the mutually reinforcing impact of waste cellulose and inorganic additives on the mechanical, thermal, and UV resistance attributes of rPP composite has not been adequately assessed.

To address these gaps, the current research intends to produce and describe recycled polypropylene (rPP)-based composites that are reinforced with waste cellulose (WC) material extracted from used cardboard packaging. The composites were made at different loadings of WC and modified with alum additives and aluminum hydroxide to make them stable in temperature and UV-resistant. Although no conventional compatibilizer like MAPP was used, tensile strength and stiffness were improved. The behavior can be explained by the development of physical interlocking between cellulose fibers and the rPP matrix, the existence of hydrogen bonding demands with the hydroxyl group, and the inclusion of inorganic additives that limited the mobility of the polymer chains and helped to transfer stress more effectively.

2. MATERIAL AND METHODS

2.1. The Materials Used in this Study

Recycled Polypropylene (rPP): It is a bio-plastic derived from post-consumer and post-industrial polypropylene waste feed stocks. It ranks as a sustainable alternative to virgin polypropylene due to its lower environmental impact, higher stiffness (particularly when filled), and better flexibility (when unfilled). It is commonly used in various applications, including packaging, automotive parts, and construction materials, as shown in the Table 1 physical and chemical properties of rPP.

Table 1
Physical and mechanical properties of recycled polypropylene (rPP).

Property	Test method	Data	Unit
Tensile Strength	ASTMD-638	20-30	MPa
Elastic Modulus	ASTMD-638	0.12-0.13	GPa
Density	ASTMD-1505	0.87	kg/m3
MFR	ASTMD-1238	25	g/10 min

All properties were measured according to the corresponding ASTM standards. Values represent average ranges provided by the supplier

Waste Cellulose from Cardboards (WC): Waste cellulose from egg cardboards was used in this study. The cardboards were cut into small pieces and soaked in water for 24 h. The soaked material was mechanically mixed to form a homogeneous cellulose suspension, as cellulose does not dissolve in water but disperses as fibrous particles. The suspension was transferred to plastic plates, where it was left to dry at room temperature. What remained was dried and ground into a fine powder using an electric blender.

Fig. 1. Waste cellulose (WC) obtained from discarded cardboard

Table 2
Waste Cellulose.

Property	**Description / Typical Value**
Appearance	Brown or greyish-brown, fibrous material.
Moisture Content	Hygroscopic (typically 5-12%).
Chemical Composition	40-60% Cellulose, 20-30% Hemicellulose, 10-20% Lignin, 5-15% Ash (fillers, contaminants).
Functional Groups	Hydroxyl groups (-OH), making it hydrophilic.
Solubility	Insoluble in water and common solvents (swells).
Ash Content	High (due to coatings, fillers, and impurities).

The reported values represent typical ranges for waste cardboard cellulose and may vary depending on source and processing conditions

Aluminum Hydroxide ($Al(OH)_3$): It is an inorganic substance that has several distinguishing characteristics. It is an amorphous, white, insoluble powder in water but soluble in acidic and alkaline solutions. It is also famous for its applications as an antacid, flame retardant, and water purifier.

Table 3
Aluminum Hydroxide

Property	**Value / Description**
Appearance	White, crystalline powder
Density	2.42 g/cm³
Melting Point	Decomposes at ~180°C →Al_2O_3 (Alumina) and water

Based on thermolysis at about 180°C, it liberates water and forms alumina (Al_2O_3).

Alum: is a mineral salt that is often referred to as potassium alum, the chemical formula of which is $KAl(SO_4)_2 12H_2O$, and it can be used to reduce inflammation, tighten the skin, and prevent an infection. Alum can also dissolve in water; it is frequently a crystalline octahedron and has a sweetish astringent flavor. Also, it is acidic to litmus and may occur in different varieties, such as potash alum, soda alum, ammonium alum, and chrome alum.

Table 4
Physical and chemical properties of potassium alum [$KAl(SO_4)_2 \cdot 12H_2O$]

Property	**Value / Description**
Common Name	Potash Alum
Appearance	Colorless, transparent crystals
Density	1.76 g/cm³
Melting Point	92.5°C (it dehydrates before liquefying)
Solubility in Water	Highly soluble (14.0 g/100 mL at 20°C)

Potassium alum undergoes dehydration above ~92°C prior to melting.

UV resistant material: are developed to alleviate the adverse impact of ultraviolet (UV) radiation, such as discoloration, surface cracking, and degradation of polymer chains. These materials are used as they can absorb or reflect UV radiation and so do not penetrate into the polymer matrix. The addition of UV-resistant agents assists in preserving the color, mechanical properties, and long-term stability of polymer composites.

Table 1
Physical & Mechanical Properties of UV-Resistant Materials

Property	Description / Characteristic
Primary Function	Resist degradation (embrittlement, fading, cracking) caused by ultraviolet (UV) light.
Common Materials	ABS, Polycarbonate, ASA, PVDF, HDPE (with stabilizers), PTFE, Glass.
Key Additives	UV Stabilizers (e.g., HALS), Carbon Black, UV-absorbing pigments.
Surface Integrity	Maintains color (minimal fading) and surface texture (no chalking or cracking).
Impact Strength	Retains toughness and does not become brittle after prolonged sun exposure.
Flexural Strength	Maintains stiffness and load-bearing capacity over time outdoors.
Durability	Significantly extended service life in outdoor applications compared to non-resistant versions.

2.2. Preparation of Polymer Composites

rPP, cellulose [$Al(OH)_3$]and alum accurately weighed according to predetermined formulations and dry-mixed at room temperature using a mechanical stirrer. The extrusion process was carried out using a twin-screw extruder (SLJ-30A) at the College of Materials Engineering, University of Babylon. The mixture was fed through a hopper, heated by barrel heaters and shear forces, then compacted as the screw channel depth decreased. The molten material exited through a die as a sheet. Screw speed started at 25 rpm and increased to 50 rpm, with temperatures ranging from 165–155°C for rPP/cellulose blends. The extrude passed through two co-rotating rollers to enhance molecular orientation and remove voids, then was cut into required shapes using a CNC laser cutting machine.

Table 6
Composition of rPP/WC composites with inorganic additives (wt.%)..

rPP	WC	Al (OH3)	Alum	UV-stabilizer
100	0	-	-	-
90	10	-	-	-
80	20	-	-	-
70	30	-	-	-
90	10	10	-	5
80	20	10	-	5
70	30	10	-	5
90	10	-	5	5
80	20	-	5	5
70	30	-	5	5

Alum refers to potassium alum ($KAl(SO_4)_2 \cdot 12H_2O$). $Al(OH)_3$ indicates aluminum hydroxide

Fig. 2. Shapes of prepared composite specimens.

2.3. Characterization

Mechanical properties before and after UV

Tensile strength: can be used to evaluate the mechanical properties of materials before and after exposure to UV radiation, focusing on tensile strength. This is used to assess the resistance of the material to tension failure as well as the capability of the material to stretch or lengthen before failure. This is a test of tensile strength, yield strength, and ductility that is accomplished by applying a known controlled force on a specimen in the form of stretching until a breakage occurs.

Impact strength refers to the capacity of a material to absorb energy under a sudden impact or shock before breaking. It is a sensitive characteristic of the materials that are used in areas where there are high chances of sudden impacts. It is a gauge of the toughness of a material, which is its resistance to fracture when stressed.

Hardness test: a test of the ability of a material to resist deformation, in this case, plastic deformation, under the influence of a force. It is a useful instrument for measuring material characteristics such as strength and wear resistance, and is often applied in materials science and engineering in order to regulate quality and select materials.

Differential Scanning Calorimetry (DSC): This is a thermal analysis method that is utilized to measure the temperature and the heat flow related to the phase transitions and chemical reactions of a material in relation to temperature and time. The principle of its operation is that the heat flowing into a sample is compared with that of a reference material when the two are exposed to a controlled temperature program. This can detect thermal events such as melting, crystallization, and glass transitions, which can give a lot of information about the thermal behavior and stability of a material.

3. RESULT AND DISCUSSION

3.1. Tensile Properties

Figures (3 – 5) demonstrate the tensile characteristics, such as tensile strength, elastic modulus, and elongation percentage at break of neat recycled polypropylene (rPP) and composite recycled polypropylene (rPP/waste cellulose) before exposure to UV. Figure 3(a) indicates that neat rPP had a tensile strength of about 21 MPa. The tensile strength increased gradually with the content of WC added (10, 20, and 30 wt%), and this is explained by the reinforcing property of the cellulose fibers and the stress transfer efficiency in the composite material. Moreover, tensile strength was improved further by the introduction of alum and aluminum hydroxide [Al(OH) 3] into the product. Interestingly, the strengthening effect of Al(OH) 3 was more pronounced compared to alum, and this could have been attributed to the fact that the material disperses better and has a higher interaction with the polymer matrix.

Figure 4(a) shows the elastic modulus of rPP/WC and rPP composites. Neat rPP exhibited a modulus of elasticity of about 0.51 GPa. There was a steady rise in elastic modulus with the addition of WC content that is indicative of the stiffening influence of the rigid cellulose fibers. Moreover, the addition of alum and $Al(OH)_3$ also improved the elastic modulus of the rPP/WC composites at all the loads of filler relative to the respective WC-filled systems, which have not been pretreated with any additives.

Figure 5(a) was used to test the elongation at break of the rPP and rPP/WC composites before exposure to UV. The elongation at break of neat rPP was about 30%. Nonetheless, incorporating WC at the rising proportions of weight led to a considerable decrease in elongation at break, that is, the shift in polymer behavior to a more brittle one as the

mobility of the polymer chains is limited. The presence of Al(OH) 3 and alum also reduced the elongation at break more than the rPP/WC composite, which can be explained by higher stiffness and lower ductility caused by the inorganic additives.

Figures 3(b), 4(b), and 5(b) show the tensile performance of rPP and rPP/WC composites in the case of 144 h of UV exposure. As can be seen in Figure 3(b), the tensile strength of neat rPP was reduced to about 20.3 MPa after UV irradiation, which means that there was photo-deterioration of polymer chains. Conversely, the tensile strength of rPP/WC composites was considerably constant with only slight variation to the pre-UV tensile strength. Equally, the elastic modulus and the elongation at break of neat rPP were significantly influenced by the exposure of the material to UV, but the rPP/WC composites had slight or no significant changes, as depicted in Figures 4(b) and 5(b). This behavior suggests that the presence of WC and inorganic additives provides a protective effect against UV-induced degradation, likely by limiting chain scission and enhancing structural stability.

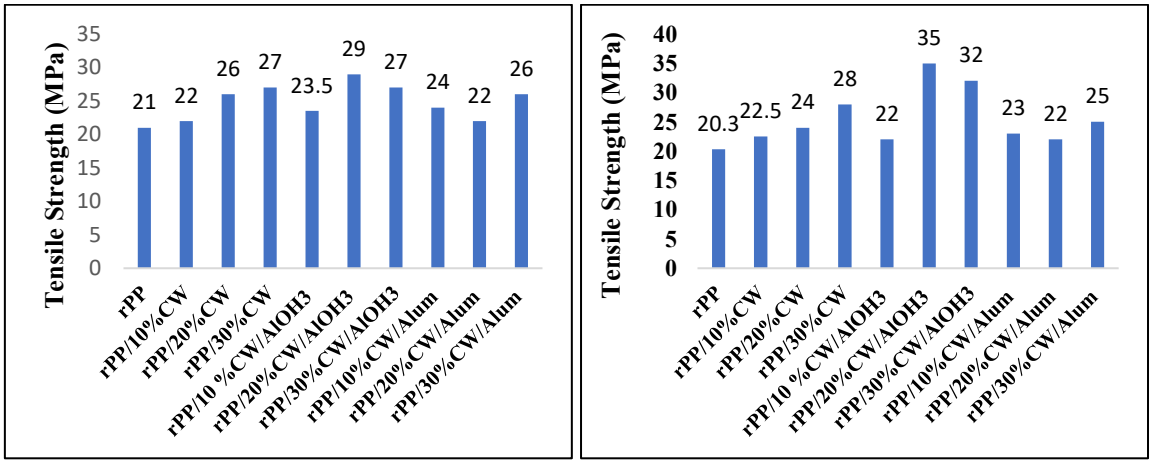

Fig. 3. Tensile strength of recycled polypropylene (rPP) and rPP/WC composites with different WC contents (10, 20, and 30 wt%) (a) before UV exposure and (b) after UV exposure for 144 h

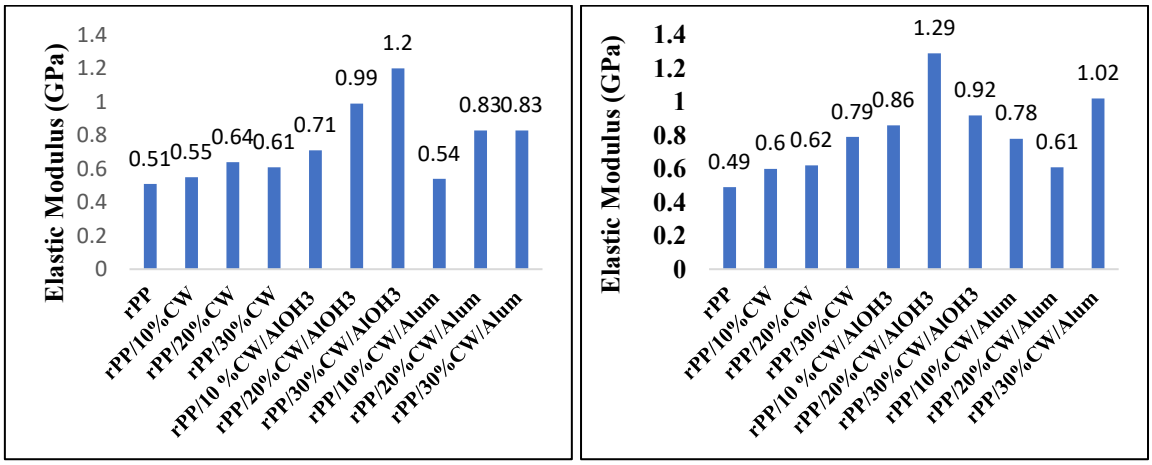

Fig. 4. Elastic modulus of rPP and rPP/WC composites as a function of WC content (a) before UV exposure and (b) after UV exposure for 144 h.

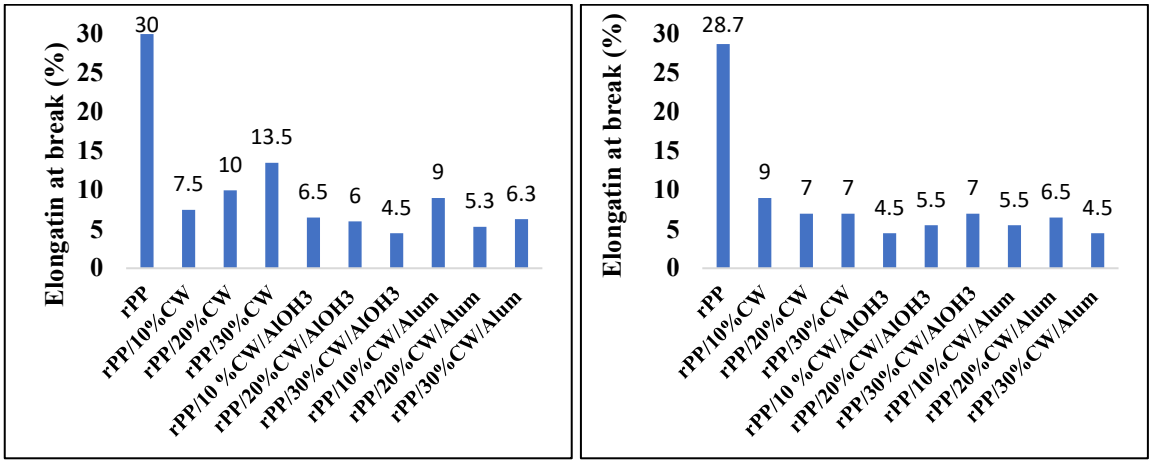

Fig. 5. Elongation at break of rPP and rPP/WC composites with varying WC contents (a) before UV exposure and (b) after UV exposure for 144 h.

3.2. Impact Strength Results

The impact strength of rPP and rPP/CW composites are shown in Figure 6(a and b). From Figure 6(a) for rPP and rPP/CW before exposing to UV, it is found that rPP has impact strength of 9.4 J/m2 and it is found that the impact strength of rPP/CW was improved to higher value than that of rPP as the amount CW increased. When AlOH3 and Alum were added to rPP/CW composites it is found that the impact strength was higher than that of rPP but lower than that of rPP/CW composite.

When the sample were exposed to UV as in Figure 6b, it is found that the value of impact strength for rPP dropped to 8.9 J/m2 while the other values for rPP/CW were remained approximately unchanged or changed slightly.

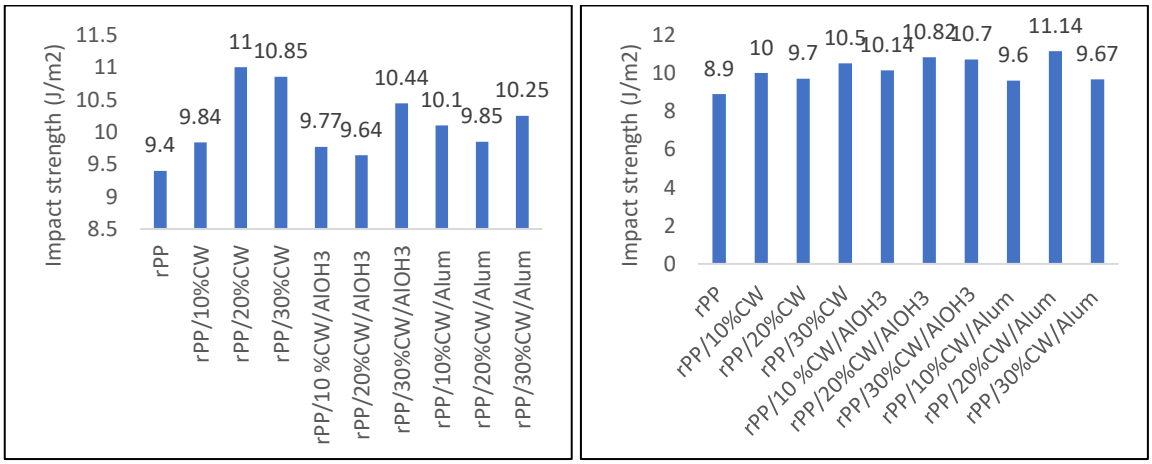

Fig. 6. Impact strength of rPP and rPP/WC composites (a) before UV exposure and (b) after UV exposure for 144 h

3.3. Hardness Test Results

Figure 7(a-b) show the hardness (Shore D) of rPP and rPP/CW composites. From Figure 7a of samples before exposing to UV, it is found that rPP has a hardness of 60.1 Shore D and by the addition of CW with different weight percentages it is found that rPP/CW composite hardness were improved. Also, the addition of AlOH3 and Alum to rPP/CW composites increased the hardness.

When the rPP and rPP/CW composites exposed to UV, it is found that the rPP hardness was increased to 63 Shore D and the hardness of rPP/CW were slightly changed or approximately remain unchanged as shown in Figure 7b.

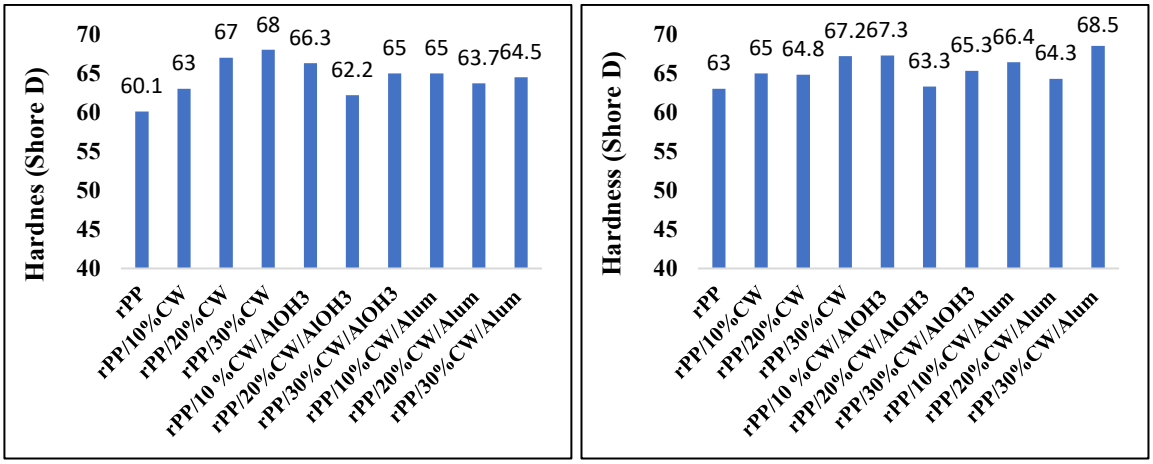

Fig. 7. Shore D hardness of rPP and rPP/WC composites (a) before UV exposure and (b) after UV exposure.

3.4. DSC Analysis Results

Figure 8 presents the DSC thermograms of neat recycled polypropylene (rPP) and rPP/waste cellulose (WC) composites. The thermal parameters, including the melting temperature (Tm), melting enthalpy (ΔHm), and degree of crystallinity (Xc), were determined for all samples and compared with those of neat rPP. As indicated in Figure 8, neat rPP exhibited a melting temperature of approximately 163.29°C, a melting enthalpy of 28.72 J/g, and a degree of crystallinity of 13.87With the incorporation of WC at different weight fractions, a noticeable increase in Tm, ΔHm, and Xc was observed for the rPP/WC composites, as summarized in Table 7. This is due to the nucleating effect of cellulose fibers, which caused more organized crystalline regions in the rPP structure, which in turn had an enhanced thermal property characterized by improved melting enthalpy and level of crystallinity. In addition, the presence of alum in the rPP/WC composites and the presence of aluminum hydroxide [$Al(OH)_3$] resulted in an even greater increase in thermal properties, as indicated by greater melting enthalpy and degree of crystallinity. This pattern is connected with the thermal stability and inorganic properties of these additives, which limit the mobility of polymer chains and promote crystalline development. It is important to note that the composites with alum showed slightly better thermal parameters than the composites with $Al(OH)_3$, which suggests a more powerful stabilizing and nucleating effect of the crystallinity degree (Xc). The thermal values are in good agreement with the mechanical performance of the composites, as shown by the correlation between the degree of crystallinity (Xc) and increased tensile strength, stiffness, and hardness. Overall, the amount of crystallinity increases the mechanical properties of materials because of the increased packing density and load-bearing capacity of crystalline regions due to their role (summarized in Table 7). The DSC results The DSC results are valuable information on how the composition of the materials and the additives affect the thermal stability and phase transitions of polymer-based films and composites. (Sabr et al., 2024).

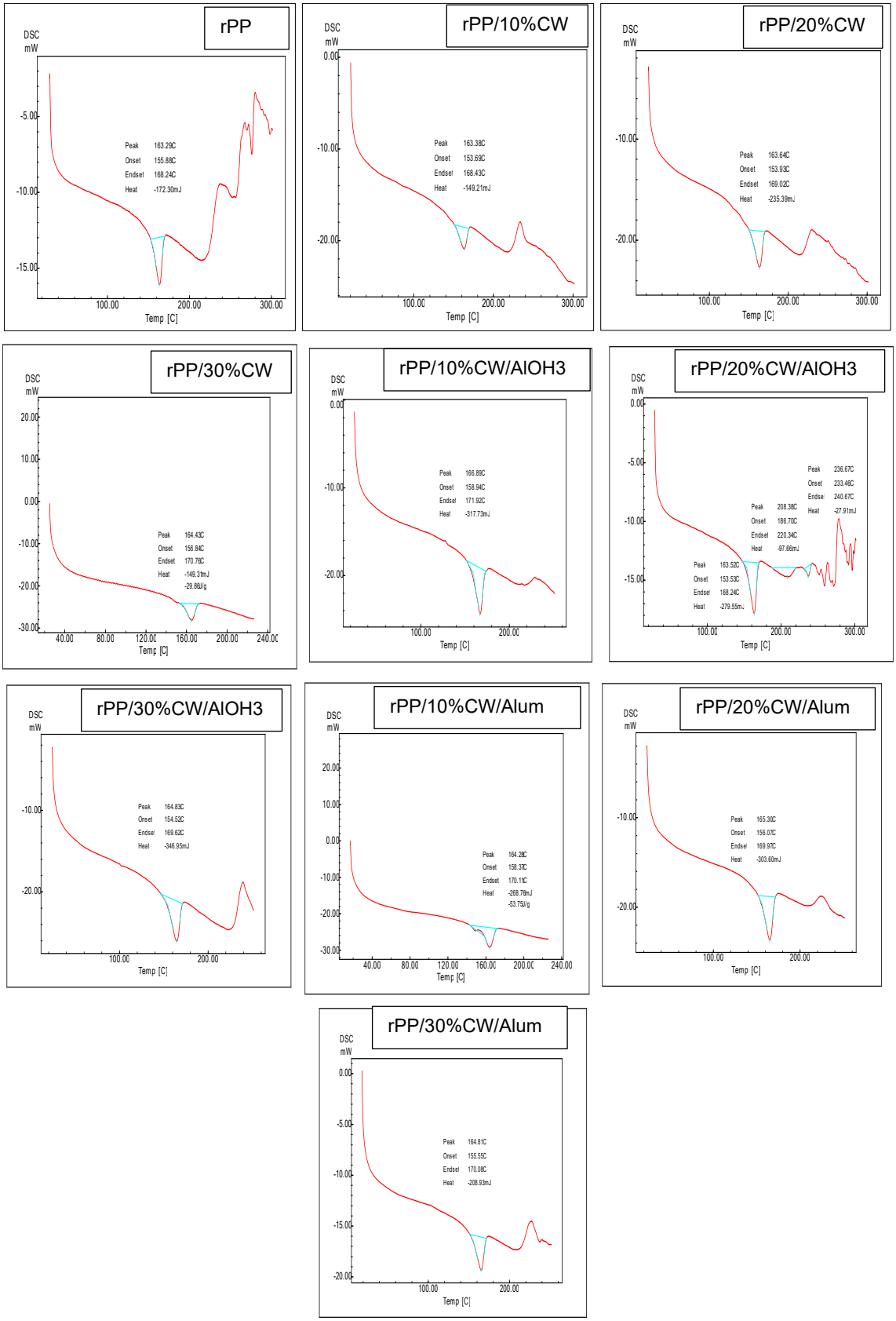

Fig. 8. DSC thermograms of recycled polypropylene (rPP) and rPP/WC composites with different WC contents and additives..

Table 7
DSC results.

Samples	Tm (°C)	ΔHm (mJ)	ΔHm (J/g)	Xc (%)
rPP	163.29	172.3	28.72	13.87
rPP/10%CW	163.38	149.21	29.842	14.42
rPP/20%CW	163.64	235.39	47.08	18.2
rPP/30%CW	164.43	149.31	29.86	14.43
rPP/10%CW/AlOH3	166.89	317.73	63.55	27.6
rPP/20%CW/AlOH3	163.52	279.55	55.91	21.61
rPP/30%CW/AlOH3	164.83	346.95	69.39	23.5
rPP/10%CW/Alum	164.28	268.76	53.75	23.4
rPP/20%CW/Alum	165.30	303.6	60.72	23.5
rPP/30%CW/Alum	164.81	208.93	41.79	20.2

The degree of crystallinity (Xc) increased due to the nucleating effect of cellulose fibers and the stabilizing role of inorganic additives

4. CONCLUSION

The effective production of recycled polypropylene/waste cellulose (rPP/WC) composites was obtained based on the obtained results. Addition of WC in various weight fractions resulted in a significant increase in mechanical properties, especially tensile strength and Shore D hardness, as compared to pure rPP. These mechanical properties recorded slight differences after UV exposure, and it shows improved resistance to degradation caused by UV. Also, the thermal behaviors of the prepared composites, as validated by the DSC study, were enhanced significantly, as indicated by higher melting temperature, melting enthalpy, and crystallinity. On the whole, the findings indicate that waste cellulose, along with inorganic additives, can be used as an effective reinforcement strategy for improving the mechanical performance, thermal stability, and durability of recycled polypropylene composites, thereby supporting their potential application in sustainable and environmentally responsible material systems.

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