

Article

Transforming Bale Twine into Useful Products with an Affordable Melting Machine: Closed-Loop for Recycling Plastics

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Abstract: The escalating use of plastic materials in agricultural practices has substantially increased the amount of plastic waste directed to landfills, leading to significant environmental and ecological challenges. Conventional disposal methods have been found to release hazardous pollutants, including microplastics and toxic chemicals, exacerbating these concerns. This study aims to address the environmental impact of agricultural plastic waste by exploring advanced reprocessing technologies and characterising the processed waste to assess its physical, mechanical, and thermal properties. Synthetic polymer-based bale twine (BT) waste, commonly used in livestock farming, was processed using an economically viable melting machine developed by Ritchie Technology. The BT and processed bale twine (PrBT) were analysed to understand their properties. Fourier transmission infrared spectroscopy revealed that the waste primarily consisted of polypropylene (PP). Thermal analysis indicated that the melting temperature of the PrBT was 162.49 °C, similar to virgin PP. Additionally, tensile testing revealed that the PrBT had an ultimate strength of 13.06 MPa and a Young's modulus of 434.07 MPa. The PrBT was further transformed into a bench that can be applicable in outdoor applications. Furthermore, the PrBT was extruded into 3D printable filament. Therefore, it is evident that bale twine waste can be given a second life through an economically viable technology.

Keywords: bale twine waste; recycling; agricultural plastic waste; extrusion



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1. Introduction

Plastic waste generated in the agricultural sector has become a significant environmental concern, as the widespread use of plastic materials such as mulch films, irrigation tubing, greenhouse covers, and bale twine has led to substantial accumulation of plastic debris in the environment [1]. This continuous increase is expected to persist, creating environmental challenges that must be addressed. Although plastics are essential for specific farming tasks, their environmental impact is increasingly concerning [1]. These plastics, often termed “agropastics”, have revolutionised modern farming practices [2]. As of 2024, the global agriculture sector generates approximately 220 million tons of agroplastic waste annually, posing risks to soil health, water quality, and broader ecological systems [3,4].

The management and disposal of agroplastic waste are not just environmental issues but potential health hazards [4,5]. Conventional disposal methods, such as landfill burial and incineration, often release hazardous pollutants [1]. These pollutants, including microplastics [6] and toxic chemicals [7] seep into the soil and water systems [8,9] leading to contamination [10]. This contamination can infiltrate the food chain, posing direct threats to the health of plants, animals, and humans. Moreover, the persistent nature of plastics means they remain in the environment for extended periods, exacerbating the global plastic pollution crisis, which is both an environmental concern and a potential health crisis. Moreover, incinerating plastic to reduce landfill waste requires costly power generators, making plastic waste-to-energy systems expensive to maintain [11,12].

Recycling offers a practical and economically viable solution to mitigate the environmental impact of agroplastics [13]. Effective recycling procedures can convert waste into significant secondary raw materials, conserving resources and reducing ecological footprints. Various methods, including mechanical [14,15], chemical [16], and energy recovery [17], are employed for recycling agricultural plastics. Each method has its unique advantages and limitations, but they all contribute to the economic sustainability of farming practices.

Despite the potential advantages, recycling agroplastics is fraught with significant challenges. Contaminants such as soil, pesticides, and organic matter complicate the recycling process, driving up costs and diminishing the quality of the recycled materials [18,19]. Furthermore, the diversity of agricultural plastic types, spanning from polyethylene (PE) to polyvinyl chloride (PVC), necessitates sophisticated sorting and processing technologies [18]. Economic factors, including the volatile market value of recycled plastics and the high costs of collection and transportation, further impede the widespread adoption of recycling practices.

Bale twine plays a crucial role in livestock farming by providing the means to package and secure agricultural products, mainly hay and straw. Traditionally, bale twine has been produced from natural fibres such as sisal or hemp [20]. However, in recent decades, the increased use of fossil fuel products has led to the manufacturing of bale twines using synthetic polymers like PP. Each material offers its own set of advantages and disadvantages. For example, natural fibre twines are biodegradable and digestible, making them an environmentally friendly choice that reduces the ecological footprint associated with disposal [21]. On the other hand, natural fibre twines tend to have lower tensile strength than their synthetic counterparts. This reduced strength can result in product loss during transportation and packaging, as the twine may break or degrade prematurely. PP twines offer high strength and durability [22]. They also provide a smooth binding system, minimising friction under adverse conditions. These twines are often manufactured with UV stabilisers and pigments, significantly improving their resistance to sunlight and weathering, thus extending their usability [23]. Despite their advantages, PP-based twines raise notable environmental concerns. Due to their non-biodegradable nature, disposing of them in landfills or burning them after use poses significant ecological risks. PP twines can survive in the ecosystem for a long time, contributing to the growing issue of plastic pollution and challenging waste management systems. Alternatively, farmers often burn the waste bale twines in fields, releasing harmful pollutants such as dioxins and furans, which can contaminate air, soil, and water, posing hazards to human health and ecosystems.

Recycling PP-based twines is crucial to reduce the ecological footprint of livestock farming and ensure a sustainable future for agricultural operations [24]. However, recycling baling twines is challenging due to their high contamination with soil and other residues, such as animal skin or faeces. Additionally, the cost of accepting agricultural waste at waste management facilities leads the farmers to burn the waste in fields rather than dispose of it at waste centres. Addressing these challenges requires a multifaceted approach integrating technological innovations and policy interventions.

Advancements in recycling technologies, such as developing of more efficient reprocessing, cleaning, and sorting systems, can enhance the viability of recycling agroplastic waste [1,10,25,26]. While biodegradable and photodegradable plastics offer alternative solutions, their environmental benefits are not yet fully understood. Additionally, implementing technologies or equipment for on-site waste collection and processing could improve the efficiency of recycling methods and reduce landfill waste [27]. This study aims to introduce new equipment developed by Ritchie Technology (Rtec™) to address significant challenges and opportunities in the field and improve the efficiency of recycling efforts. It also involves processing BT waste using Rtec™ equipment and analysing the thermal and mechanical properties before and after processing. Furthermore, products were developed using the extruded bars from the BT waste to create opportunities to provide a second life to plastic waste. This innovative technology promises to significantly

reduce the environmental impact of agroplastics and bale twines, making recycling more efficient and cost-effective.

2. Results and Discussion

2.1. Fourier Transform Infrared Spectroscopy (FTIR)

Quantitative and qualitative analyses of BT, PrBT, and pure PP is shown in Figure 1. The commercial PP spectrum was used as a reference to confirm the BT and PrBT spectra. The spectra peaks of the all the samples were significantly similar. Bending and stretching vibrations assigned to CH, CH₂, and CH₃ groups that were observed in the 3000 to 2000 cm⁻¹ and 1500 to 1000 cm⁻¹ ranges for all the samples [28]. Similarly, all samples exhibited comparable vibrations in from 900 to 750 cm⁻¹, indicating the presence of double bonds [28]. However, the presence of a few smaller peaks in the range of 800 to 700 cm⁻¹ suggests the oxidative degradation of the samples or the existence of additives with such functional groups in the BT and PrBT. BT displayed a peak of around 3500 to 3000 cm⁻¹ that corresponds to the moisture content (hydrogen bonding functional group) [29–31]. This peak was slightly smaller in the PrBT and pure PP due to lower moisture content compared to the BT. The transmittance peaks at 2952 cm⁻¹, 2917 cm⁻¹, 2870 cm⁻¹, and 2839 cm⁻¹ were related to the C–H stretching functional group [30,32,33]. The peak at 1457 cm⁻¹ corresponded to bending vibration mode of the CH₂ functional group. FTIR peaks displayed at 1376 cm⁻¹ were related to the symmetrical formation of the CH₃ group [34]. Furthermore, the peaks observed at 973 cm⁻¹ and 841 cm⁻¹ were attributed to isotactic PP bonds [29–31,34,35]. In addition, the BT and PrBT spectra were compared with supplementary FTIR library data for qualitative analysis using Agilent's polymer library and Open Specy spectra analysis tool [36]. The quantitative and qualitative search indicated that the obtained spectra were similar to those of polypropylene (PP) pellets. Therefore, it is evident that the samples are composed of PP and are recyclable based on their melting temperatures.

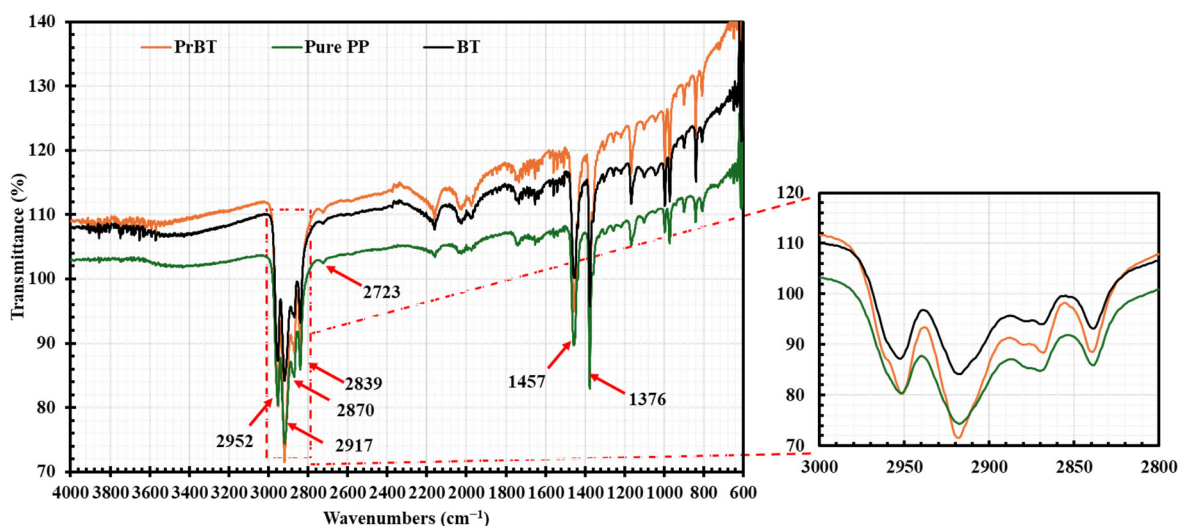


Figure 1. FTIR spectra of the pure PP, BT and PrBT (the insert shows the peaks of 3000 to 2800 cm⁻¹).

2.2. Thermogravimetric Analysis (TGA)

The TGA curves of the pure PP, BT and PrBT are shown in Figure 2a. Figure S1 shows the TGA curve of the orange haybale. The graphs displayed a one-step degradation with 100% weight loss for all the samples. The decomposition of the pure PP began at around 350 °C. Similarly, PrBT exhibited a comparable initial thermal decomposition starting point. However, BT showed a slightly higher decomposition temperature compared to PrBT (Figure 2a inset). The maximum degradation rate was observed at 480 ± 5 °C for all the samples with the process completing at 500 ± 5 °C. As the temperature increased

further, the high molecular weight molecules broke down into lower molecular weight compounds, which then evaporated, leaving almost no char once temperature exceeded 500 °C. According to Jung et al. [37], the active degradation in the samples was primarily due to the fact that half of the carbons in a PP chain are tertiary carbons, which can lead to the formation of tertiary carbonation during degradation. This phenomenon contributes to faster degradation in all samples [37]. The complete degradation of PrBT and BT occurred at 509 °C and 513 °C, respectively. This suggests a minimal presence of inorganic compounds in the samples and indicates the presence of contaminants or fillers.

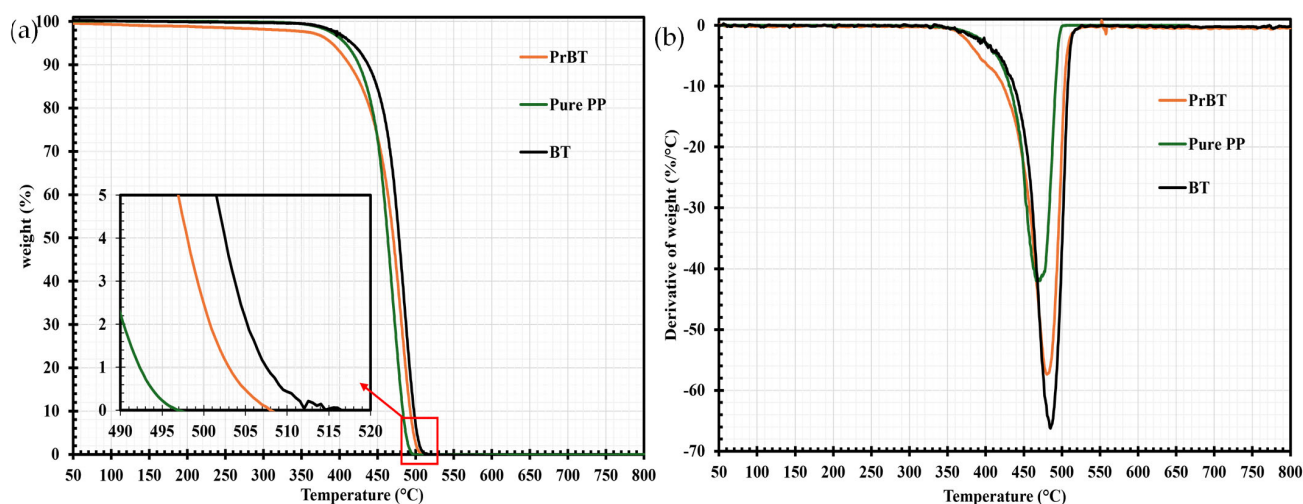


Figure 2. (a) TGA curves of pure PP, BT, and PrBT samples (inset: the thermograms during total degradation) and (b) DTG graphs of pure PP, BT, and PrBT samples.

In line with the TGA, the DTG curves (Figure 2b) of pure PP, BT, and PrBT are shown in Figure 2b, indicating that the major decomposition appeared within the range of 350 to 400 °C for all the samples. The sharp peaks demonstrated the rapid degradation and breakdown of the molecules in the samples. As reported in the literature [35,38–41], recycled PP may contain varying percentages of impurities, which significantly affects its properties. Therefore, it is evident that the thermal stability behaviour of BT and PrBT slightly varies.

2.3. Differential Scanning Calorimetry (DSC)

The thermograms obtained for pure PP, BT, and PrBT are shown in Figure 3 and summarised in Table 1. The DSC curve of the orange haybale is shown in Figure S2. The endothermic heat flow curves of the samples resulting from the second heating run are shown in Figure 3a, while the curves from the cooling run are presented in Figure 3b. The results demonstrated that the melting temperature of pure PP was recorded at 152 °C. However, the melting temperature of BT and PrBT were up to 10 °C higher than pure PP. This increase could be due to the higher molecular mass of polymers in the recycled samples. The broader melting point observed in pure polypropylene indicated a wide range of molecular weight distribution, unlike the sharper peaks in recycled polymers, which reflected a narrower molecular distribution [42].

Table 1. Thermal properties of pure PP, BT, and PrBT.

Sample	T _m (°C)	T _c (°C)	ΔH _m (J/g)	X _c (%)
Pure PP	152	113	54.2	26.6
BT	164	118	149.5	72.2
PrBT	164	116	76	36.7

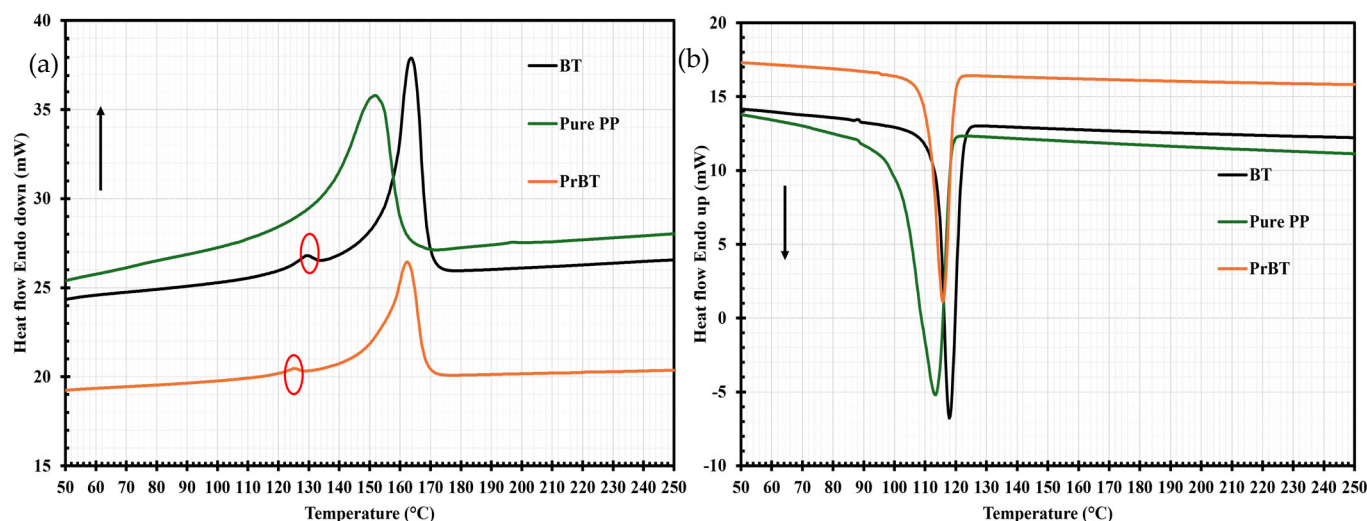


Figure 3. DSC curves of pure PP, BT and PrBT: (a) melting temperature curves (the small peak identified with red circle) (b) crystallisation curves.

According to the literature reports [43,44], industrial PP, virgin PP, or stable PP typically melts around 150 to 160 °C.

For the melting enthalpy, the results showed that pure PP and PrBT had values of 54 J/g and 76 J/g. In contrast, the post-consumer product BT exhibited a higher melting enthalpy of 149 J/g compared to both pure PP and PrBT. Moreover, BT and PrBT displayed a small melting event at high temperatures of 132 °C and 125 °C, respectively, as highlighted by the red circle in Figure 3a. The smaller peaks in BT and PrBT corresponded to a small melting enthalpy of 1 ± 0.5 J/g. These smaller peaks in the recycled samples may result from contaminants such as fillers or additives, a phenomenon frequently reported in post-consumer plastics [28].

The crystallisation data are shown in Figure 3b. All samples exhibited similar crystallisation patterns. The crystallisation of pure PP was determined to be around 113 °C while BT and PrBT crystallised at 118 °C and 116 °C, respectively. The higher crystallisation temperatures in BT and PrBT compared to pure PP suggests the presence of nucleating agents [45]. Vidakis et al. [46] reported that recycled PP typically crystallises around 116 °C, which is similar to PrBT in the current study. The degree of crystallinity for pure PP and PrBT was 26.2% and 36.7%, respectively, whereas BT showed a higher degree of crystallinity at 72.4%. The increased crystallinity can be attributed to the higher molecular weight of BT, which acts as a nucleating agent [38,39,45]. According to Mihelčič et al. [38] the presence of nucleating agents enhances the crystallisation of semicrystalline polymers by facilitating chain unfolding and forming larger crystal structures. While the current study observed the differences between pure PP, BT, and PrBT, these differences may not exclusively result from reprocessing of the BT and PrBT. Furthermore, the pure PP used for testing differs from the BT and PrBT, which limits direct comparability. However, the observed trends in BT and PrBT are consistent.

2.4. Melt Flow Index (MFI) Analysis

MFI analysis measures polymer flow through a die for 10 min at a set temperature and load [47]. Figure 4a represents the MFI values at varying temperatures from 180 to 230 °C for pure PP, BT, and PrBT. As depicted in Figure 4a, pure PP exhibits a higher MFI compared to BT and PrBT at 230 °C, with an MFI of 8 g/10 min. In contrast, the MFI for BT and PrBT were 6 g/10 min and 7 g/10 min, respectively, at 230 °C. MFI increased with temperature across all samples. According to Ferg et al. [48], MFI values for virgin PP ranged from 4 to 16 g/10 min at 230 °C, with variations depending on the molecular weight distribution of different virgin PP samples. Luna et al. [49] demonstrated that lower MFI values indicate higher molecular weight and viscosity. In this study, BT showed the lowest MFI compared to pure PP and

PrBT, indicating it has the highest viscous and molecular weight. Conversely, PrBT did not demonstrated significant changes in molecular weight and polydispersity compared to pure PP. This suggests that the post-consumer product BT may contain polar contaminants or fillers used during its manufacturing. Additionally, the Arrhenius relationship (Figure 4b), determined via Equation (1), was used to compute the flow activation energy of PrBT. The activation energy (E_a) was approximately 34 kJ/mol, reflecting the thermal stability of the recycled plastic. Considering the obtained MFI of PrBT is within the range of standard MFI values for commercially available PP, PrBT is suitable for processing via injection moulding, compression moulding, and other extrusion-based applications.

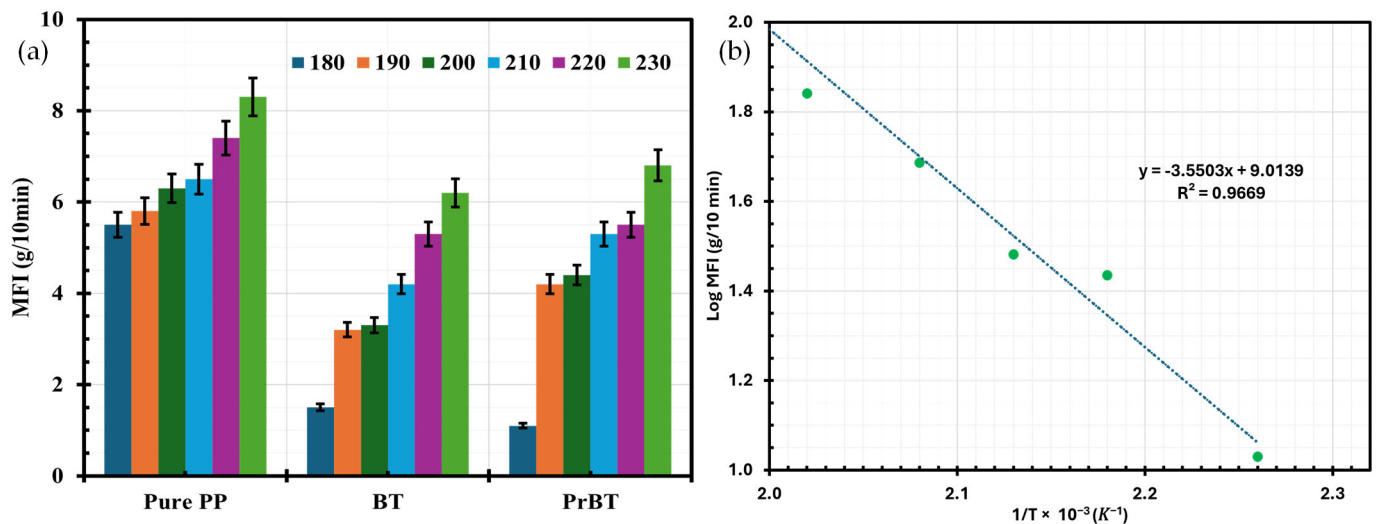


Figure 4. (a) MFI values of pure PP, BT and PrBT and (b) $\ln$ MFI vs. $1/T$ of PrBT MFI values.

2.5. Mechanical Properties

The stress–strain curve of PrBT is shown in Figure 5 and the compressed PrBT tensile samples are shown in the inset of Figure 5. From the graph, the tensile strength and Young's modulus of PrBT were calculated to be 13 MPa and 434 MPa. Gall et al. [33] reported that the tensile strength of virgin polypropylene is typically around 20 MPa. In contrast, the commercial polypropylene used in this study has a reported tensile strength of 28 MPa, according to the supplier's specifications. In this study, PrBT exhibited lower tensile strength compared to the virgin PP. Similarly, the literature reports indicate that the Young's modulus of virgin PP was approximately 600 MPa [50,51]. The observed lower tensile strength and Young's modulus for PrBT distinct to the literature values may be due to the deterioration of molecular chains, leading to increased brittleness [35,52,53]. Additionally, studies by Zdiri et al. [54] and Bourmaud et al. [55] have demonstrated that recycling polymers often displayed a minimal reduction in mechanical properties, which may be attributed to physical ageing and a decrease in molecular weight. In this context, the thermograms and melt flow data indicate that PrBT has a lower melting point compared to BT, reflecting changes in molecular weight.

The hardness of the PrBT indicates its ability to resist deformation. The hardness value of the processed plastic waste was determined to be 98 ± 2 MPa, based on the average of three tested samples. Krishna Satya et al. [52], reported a hardness of 107 MPa for recycled PP while Berdjane et al. [56] demonstrated hardness of 83 MPa for recycled PP. In the present study, the hardness value for PrBT indicates greater brittleness compared to these literature reports. This brittleness could potentially be mitigated with further surface treatments or coatings to enhance the microhardness of the material.

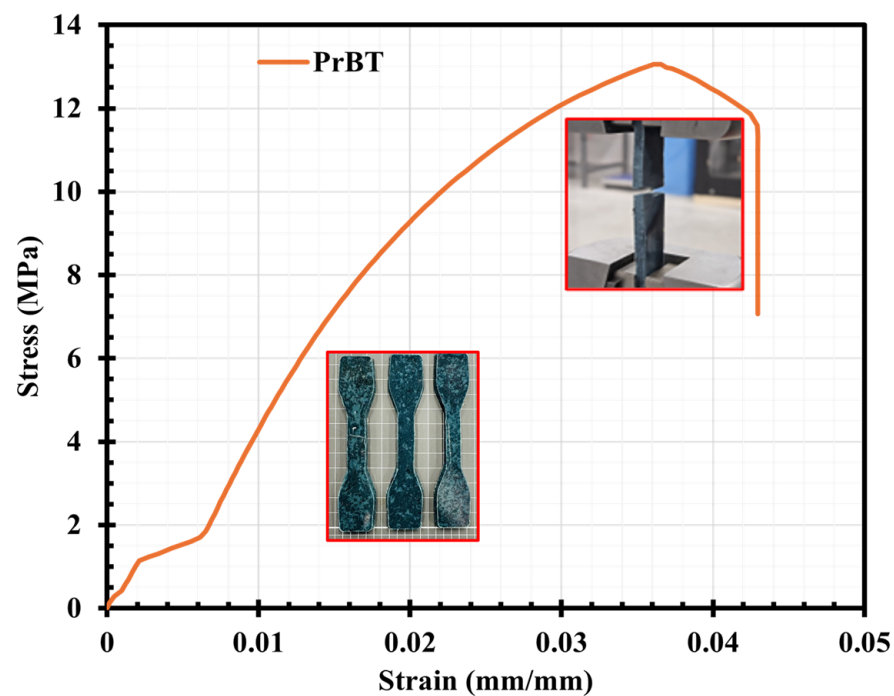


Figure 5. Stress–strain curve of PrBT (the inset shows the hot-pressed tensile test samples, $n = 3$).

2.6. Creep Analysis

The creep compliance over time at elevated temperatures in Figure 6a–c shows the unshifted short-term creep compliance and corresponding master curve of processed BT at all the tested temperatures, plotted against the test time on a logarithmic scale. The shift factor for the PrBT was obtained using the William–Landel–Ferry (WLF) and the Arrhenius equations [57]. Therefore, the WLF method was applied to determine the shift-factor according to Equations (1)–(3).

$$\log \alpha_T = \frac{-C_1(T - T_{ref})}{(C_2 + T - T_{ref})}, \quad (1)$$

$$C_1 = \frac{C_{1g}C_{2g}}{(C_{2g} + T_{ref} - T_g)}, \quad (2)$$

$$C_2 = C_{2g} + T_{ref} - T_g, \quad (3)$$

where α_T denoted the horizontal shift-factor, T_{ref} represents the temperature reference, T denotes the test temperature, C_{1g} and C_{2g} are constants. The shift factor for the PrBT at 45 °C was 3.025×10^{-3} , calculated using C_1 (10.5 °C) and C_2 (85.70 °C). According to this calculation, the creep curves were shifted to the right along the time axis as the temperature increased from 45 to 90 °C. A higher creep strain was observed with increasing temperature due to the greater macromolecular flexibility of the PrBT at elevated temperatures.

$$\varepsilon(t) = \frac{\sigma}{E_m} + \frac{\sigma}{E_K} \left[1 - \exp\left(-\frac{E_K}{\eta_K} t\right) \right] + \frac{\sigma}{\eta_M} t \quad (4)$$

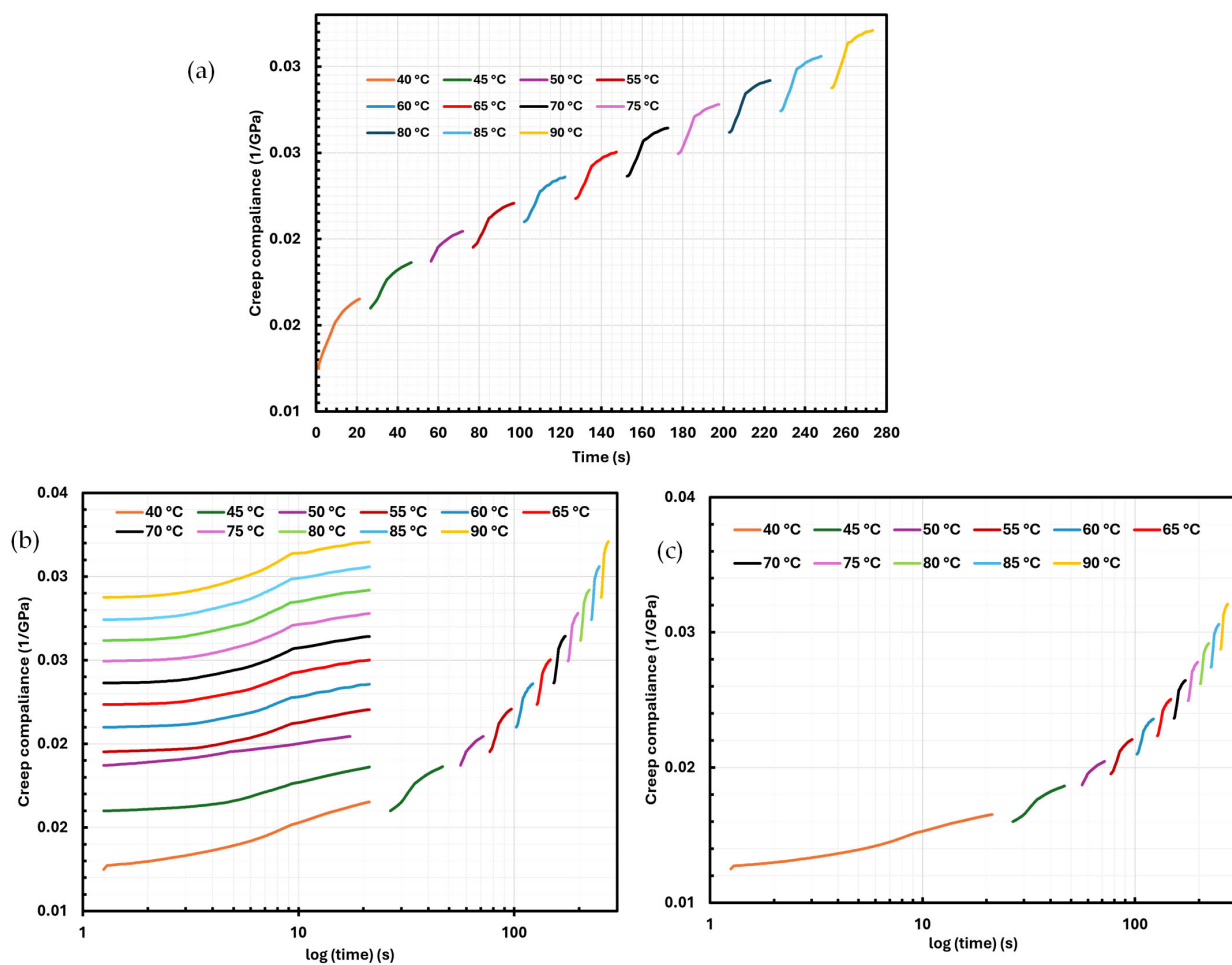


Figure 6. (a) creep compliance of PrBT, (b) unshifted and shifted creep compliance curves of PrBT, and (c) master curve of PrBT at a reference temperature of 40 °C. Many empirical power-law models have been used to describe the nonlinear creep deformation behaviour of plastic materials. Among these, the Burger's [58–60] and Findley power-law models are the most commonly used. Burger's model, which combines elements of the Maxwell and Kelvin–Voigt models [61]. The model effectively illustrates the quantitative correlation between the effects of material matrix interfaces and its relative creep behaviour as stated in Equation (4) [61].

The symbol $\varepsilon(t)$ denotes the strain. E_m and E_K indicate the elastic moduli. η_K and η_M defines the viscoelasticity of the materials. While t represents the creep time and σ denotes the applied stress [61].

Nonlinear creep behaviour is often described using empirical mathematical models such as the Findley power law. The power law has been effectively applied to theoretically the TTSP-predicted creep behaviour for various polymers and polymer composite materials [57,62]. The Findley power law is expressed in the form of Equation (5) [63].

$$S(t) = S_0 + at^b, \quad (5)$$

In this equation, $S(t)$ represents the time-dependent compliance, where S_0 signifies the instantaneous elastic compliance, and a and b denote constant parameters, t represents the elapsed time.

Table 2 presents the parameters for the Findley power law and Burger's models. For Burger's model, the E_m and E_K values for PrBT are 1.0 and 2.3, respectively. Additionally, the viscosity η_K is approximately 70.159, as noted in the literature [64]. These findings suggest increased polymer chain mobility in PrBT. Furthermore, the results indicates that

the spring reaches its balance length in a shorter delay time [64]. Similarly, the other viscosity (η_M) increased up to 3.55×10^3 . This occurrence demonstrated that PrBT has promising creep resistance because of its lower creep rate [65,66]. According to the Findley power law, the elastic compliance and the viscous creep response parameters were recorded 15.9 and 0.25, respectively. The results from both theoretical predications indicated that the PrBT exhibited superior creep resistance [67].

Table 2. PrBT power model parameters obtained using theoretical predictions.

Model	Parameter	Processed ET
Burger's Model	E_m	1.0 GPa
	E_K	2.3 GPa
	η_K	70.1 GPa
	η_M	3.55×10^3 GPa
	τ	15.9
	R^2	0.7
Findley power-law model	S_0	0.3/GPa
	a	0.2
	b	1.0
	R^2	2.3

2.7. Water Contact Angle

The surface wettability of the PrBT was analysed to assess its hydrophobic characteristics. The PrBT demonstrated a hydrophilic nature, with a contact angle of approximately $72.17 \pm 5^\circ$. According to Choi et al. [68], PP shows a contact angle of 104.9° , indicating the polymer's hydrophobic nature. In contrast, the contact angle in the current study was less than 90° , indicating an increase in the wettability of the recycled PP waste. This suggests that recycled plastics may have increased wettability due to factors such as moisture adsorption, ageing or the presence of polar fillers.

2.8. Scanning Electron Microscopy (SEM)

The SEM micrographs of the fractured surfaces of the tensile samples are presented in Figure 7a. The images reveal significant formation and expansion of voids due to cavitation. Furthermore, the EDX analysis indicated that the sample contains a high concentration of carbon elements and small amount of oxygen elements (Figure 7b,c). Furthermore, Figure 7d demonstrates the amount of the carbon and oxygen atom counts. This suggests that the plastic pieces with holes and cracks may undergo further deterioration during recycling process.

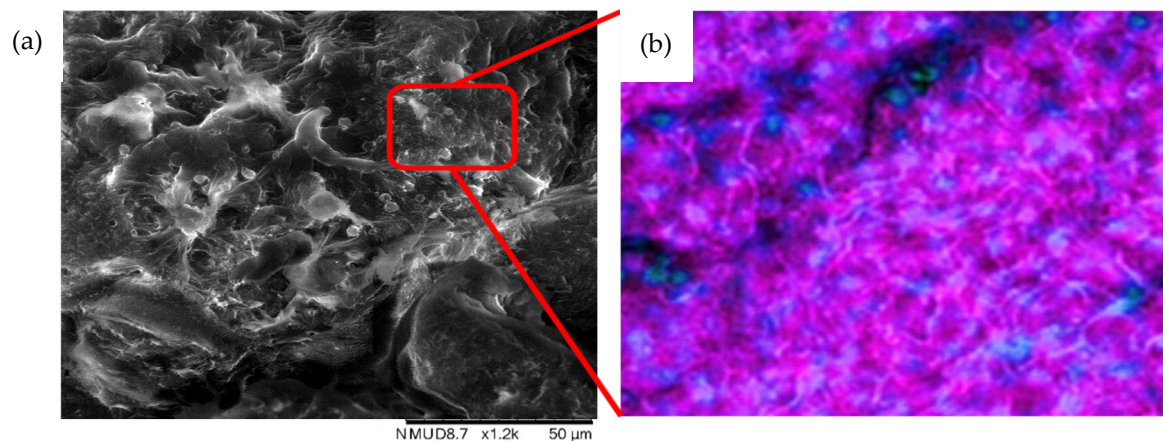


Figure 7. Cont.

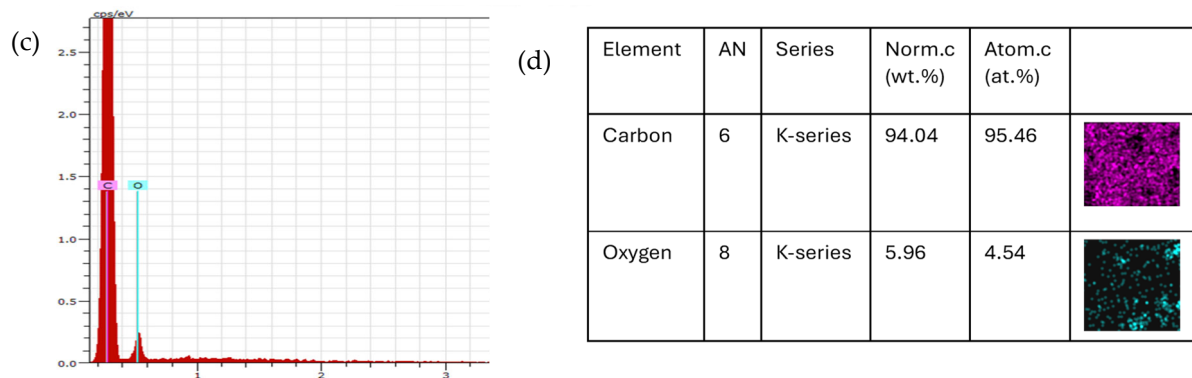


Figure 7. (a) SEM micrograph of PrBT, (b) elemental mapping analysis of PrBT (pink: carbon elements, blue: oxygen elements), (c) EDX spectra analysis of PrBT, and (d) element analysis with total atomic % in PrBT.

3. Materials and Methods

3.1. Materials

The bale twine (BT) waste (Figure 8) used for securing hay bales in Victoria, Australia was collected from farmlands. Commercially available pure polypropylene (PP) (SABIC PPQR6731K, especially used for injection moulding) was purchased from Neo Polymers Pty Ltd., Braeside, VIC, Australia.

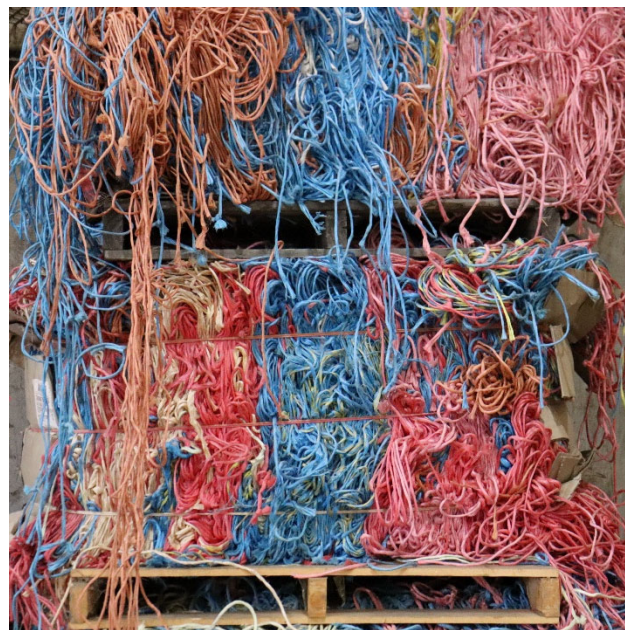


Figure 8. Bale twine waste.

3.2. Preparation of Bale Twine and Processed Bale Twine

The BT waste gathered from various farmlands was processed using the Ritchie Technology (Rtec™) low-cost melting machine (Figure 9a). It consists of a drum compactor and homogenising melter. The BT waste was fed into the drum compactor at 200 ± 5 °C. Consistent compression was applied to the BT in the drum compactor from the top to prevent the formation of voids in the melted plastic during compaction. The drum compactor is connected to an outlet as shown in Figure 9b, to allow the molten processed bale twine (PrBT) to flow out. Finally, the produced PrBT can be moulded into various shapes, such as long bars or ingots. For this study, the obtained PrBT was shredded into granules (Figure 9c) using a plastic crusher (Zhongli Instrument Technology Co., Ltd.,

Dongguan city, Guangdong province, China). These granules were then utilised to develop the characterisation samples.

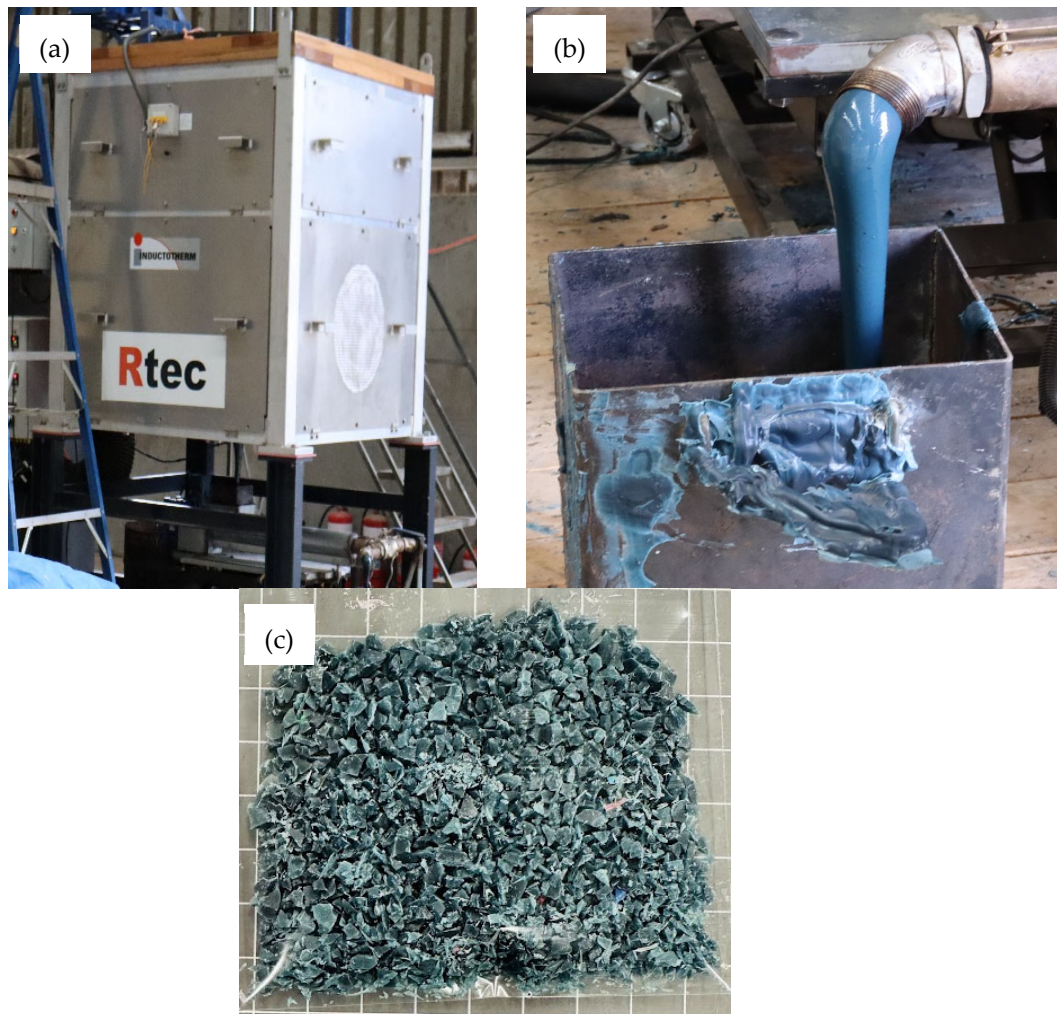


Figure 9. (a) Rtec™ low-cost melting machine, (b) molten BT waste, and (c) PrBT in granule form.

3.3. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier-transform infrared spectroscopy (Cary 630 FTIR (Santa Clara, CA, USA)) provided with an attenuated total reflectance accessory was utilised to perform spectra analysis. The spectra of the bale twine and processed bale twine were obtained using an average of 64 scans between 4000 and 600 cm^{-1} with a resolution of 4 cm^{-1} .

3.4. Melt Flow Index

The *MFI* of the samples was analysed using the TMA-400A-XNR (Test Machines Australia Pty Ltd, Melbourne, VIC, Australia) equipped with an Ohaus Adventure AX analytical NMI-approved weighing scale. The test was conducted according to the ASTM D1238 [69]. BT, PrBT, and pure PP were tested at temperatures varying from 180 to 230 $^{\circ}\text{C}$ with a dead load of 2.16 kg. The molten material was flown through the orifice with a diameter of 2.0 mm and a length of 8.0 mm. The *MFI* values were reported in g/10 min. Furthermore, the activation energy (E_a) was calculated using the Arrhenius Equation shown in Equation (6).

$$MFI = Be^{\frac{E_a}{RT}}, \quad (6)$$

where B = constant, R = universal gas constant (8.314 J/mol), T = the absolute temperature in Kelvin (K), and E_α = slope of $\ln(\text{MFI})$ vs. $1/T$.

3.5. Thermogravimetric Analysis (TGA)

The thermal properties of the BT, PrBT, and pure PP were investigated using a TGA 4000, Perkin Elmer, Waltham, MA, USA in a nitrogen gas atmosphere. The analysis was carried out at temperatures ranging from 35 to 850 °C at 20 °C/min.

3.6. Differential Scanning Calorimetry (DSC)

The melting temperature and crystallinity of the BT, PrBT, and pure PP were analysed using a DSC 6000, Perkin Elmer, Waltham, MA, USA. Crucibles were aluminium pans with lids. A total of 3 mg of samples were pressed in the crucibles. The analysis was conducted in two heating cycles (30 to 300 °C) and one cooling cycle (300 to 30 °C). The initial heating cycle step was used to erase the previous thermal history. In the second step, the samples were cooled down to obtain crystallinity. Finally, the second heating step was carried out to obtain the melting data of the samples. All heating and cooling runs were performed in a nitrogen atmosphere (20 °C/min) to prevent oxidation. Furthermore, the percentage of crystallinity was calculated using the melting enthalpy and crystallisation enthalpy data obtained through DSC graphs and Equation (7).

$$\%X_c = \frac{\Delta H_m}{\Delta H_m^0} \times 100, \quad (7)$$

where ΔH_m are the empirically determined melting enthalpy, and ΔH_m^0 denotes theoretically determined melting enthalpy of 100% crystalline PP (207.1 J/g) [70,71].

3.7. Tensile Properties

The PrBT granules were hot pressed into dumbbell shapes according to ASTM D638 Type IV (10 × 15 mm²) [72] using a compression moulding technique. The compressed moulded PrBT samples were tested using a Universal Testing Machine (Instron 5980, Norwood, MA, USA). The tests were performed at a 1 mm/min crosshead speed with 50 kN load cell to determine the tensile properties. Three samples were utilised to obtain the data.

3.8. Creep Test

Dynamic mechanical analyser (DMA 8000, Perkin Elmer, Waltham, MA, USA) was used to conduct the creep recovery tests in creep extension mode. The PrBT samples with dimensions of 10 × 4 mm ($t = 2$ mm) were prepared using injection moulding. The short-term creep response was recorded in real-time at 1 Hz. Creep recovery cycles were performed isothermally with elevated temperatures ranging from 40 to 90 °C at intervals of 10 °C. For each isotherm, 20% of the average tension was applied for 30 min, followed by a 30 min recovery period. In addition, the creep compliance was determined using Equation (8) [65]:

$$S(T_{ref}, t) = S(T_{elev}, t/\alpha_T) \quad (8)$$

where S = creep compliance, T_{ref} = reference temperature, t = time, T_{elev} = elevated temperature, and α_T = shift factor.

3.9. Hardness Testing

The hardness of the PrBT samples was analysed using a Vickers hardness testing machine (DuraScan G5, Kuchl, Austria). A load of HV 0.3 was applied for 10 s, and the hardness value was recorded. Three samples were tested to determine the average hardness of PrBT.

3.10. Contact Angle

The wettability of the PrBT samples was analysed using the Attention Theta Flex instrument (Biolin Scientific, Västra Frölunda, Sweden). The wettability was observed using the sessile drop technique. A 2 µL dewdrop was disposed on the PrBT flat surface via a Hamilton syringe and results were recorded. Three different samples were analysed to determine the average wettability of PrBT.

3.11. Morphology

The PrBT fractured cross-sectional surface morphology was examined using a scanning electron microscope (Hitachi TM3030Plus, Tokyo, Japan). The sample was sputter-coated with gold to enhance conductivity. In addition, EDX analyses were carried out for the PrBT sample, and each analysis had an acquisition time of 120 s.

4. Conclusions

Thermal, mechanical, and chemical analyses of BT waste and PrBT were conducted to assess contamination and reprocessing parameters. New products were developed to give end-of-life plastic waste a second life, adhering to a cradle-to-cradle approach. Based on the obtained physical and chemical properties, it was estimated that the BT could be recycled with only slight variations in processing temperatures depending on the manufacturing process. The melting point and crystallinity peaks indicated that BT and PrBT are significantly similar to pure PP. In addition, the strength of PrBT was slightly lower compared to the literature reports, suggesting that the addition of fillers or surface coatings could reduce its brittleness. However, this study is limited to mechanical and thermal analyses. Further research on weathering conditions and findings with direct molecular weight measurements of recycled BT will be necessary to better understand the product's durability across a wide range of environmental and reprocessing conditions. This development represents a closed-loop for recycling plastics from agricultural lands. Moreover, the cost effective Rtec™ melter was successfully used to process BT into a wide range of plastic products suitable for household applications as part of commercialisation efforts. The current study demonstrates that agricultural plastic waste, particularly BT, can be recycled and transformed into innovative, value-added products with material properties similar to virgin polymers.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/recycling9060121/s1>, Figure S1: TGA curve of orange haybale; Figure S2: DSC curve of orange haybale.

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