sustainability

MDPI

Article

A Sustainability Study upon Manufacturing Thermoplastic Building Materials by Integrating Chicken Feather Fibers with Plastic Waste

Sebastian Aradoaei [1], Mirela Alina Constantin [2], Lucian Alexandru Constantin [2], Mihaela Aradoaei [1] and Romeo Cristian Ciobanu [1,*]

[1] Department of Electrical Measurements and Materials, Gheorghe Asachi Technical University, Bdul. Mangeron 71, 700050 Iasi, Romania; arsete@tuiasi.ro (S.A.); mosneagum@yahoo.com (M.A.)
[2] National Research and Development Institute for Industrial Ecology—ECOIND, 57–73 Drumul Podu Dambovitei, 060652 Bucharest, Romania; alina.constantin@incdecoind.ro (M.A.C.); lucian.constantin@incdecoind.ro (L.A.C.)
* Correspondence: r.c.ciobanu@tuiasi.ro

Abstract: The article explains how to make thermoplastic construction materials by combining waste from chicken feathers with plastic waste. The initial phase focused on a new and environmentally friendly method of sterilizing raw feathers using microwave radiation inside sealed ovens with circulating air. Additionally, composites containing varying feather amounts using two different polymer matrices were fabricated through an injection process, followed by mechanical and physical tests on the samples. Because of their excellent characteristics, products made from a combination of chicken feather waste and plastic waste could effectively replace traditional wood–plastic composites that are polyvinyl chloride-based. The recycling technology was assessed for its environmental impact, and sustainability was proven economically and environmentally.

Keywords: thermoplastic building materials; mixed chicken feather waste and plastic waste; environmental impact indicators; sustainability analysis

Citation: Aradoaei, S.; Constantin, M.A.; Constantin, L.A.; Aradoaei, M.; Ciobanu, R.C. A Sustainability Study upon Manufacturing Thermoplastic Building Materials by Integrating Chicken Feather Fibers with Plastic Waste. *Sustainability* **2024**, *16*, 9243. https://doi.org/10.3390/su16219243

Academic Editor: Xiaowei Li

Received: 30 September 2024
Revised: 22 October 2024
Accepted: 23 October 2024
Published: 24 October 2024

1. Introduction

It was commonly found that each bird raised for human consumption, like chickens, has around 125 g of feathers [1]. Globally, approximately 3000 tons of feather waste is generated every week, and 3.1 million tons of feather waste is produced annually solely by the EU. That is not only a setting but also a worldwide issue. The dropping of feathers on the ground leads to land pollution, whereas the incineration of feathers results in air pollution. Approximately 40 million tons of these discarded feathers are incinerated each year, releasing sulfur dioxide and carbon dioxide into the atmosphere [2,3]. Moreover, it can also lead to different human health issues like fowl cholera, chlorosis, mycoplasma, and others. Landfill disposal, incineration, and recycling are the three main ways chicken feathers are disposed of, all requiring improved waste management practices in current standards [3–5]. These conventional techniques come with a high cost. Disposing of chicken feather waste requires the allocation of numerous resources, such as fuel for transportation and burning, as well as other resources like water used during the recycling process, are employed. Additionally, these techniques generate substantial levels of greenhouse gases, which are a major danger to the environment and impact the current global warming situation.

In contrast, chicken feathers consist of 90% protein and include alpha and beta keratins, which are valuable raw materials for industrial purposes. At present, using feathers for composting seems to remain the most economical option. Chicken feathers, being a rich source of keratin proteins and amino acids, can be converted into valuable N-rich organic fertilizers, including slow-release fertilizers [6–8]. Secondly, keratinases play a significant role in breaking down feathers for the production of high-quality animal feeds [9,10].

Feathers cannot be spun into thread or woven into cloth due to their short fibers, but when mixed with synthetic long fibers, they could be, e.g., spun into thread or compacted into breathable nonwoven cloths, etc. Researchers have found that various manufacturing processes can produce items with greatly varying characteristics, e.g., plastic films can be created from feather fiber by breaking and then rejoining the bonds between the fiber strands [11,12]. Protein-based plastics may compete with existing biodegradable plastics, which are manufactured from starches derived from carbohydrates. Keratin-based films are capable of degrading naturally, making them a viable option for sustainable material in place of traditional plastics. They can potentially be used for packaging purposes and for creating materials suitable for different biomedical applications. The feathers have also been used in plastics production, where they are mixed with artificial polymers to make durable materials. The structured positioning of keratin boosts the strength of plastics by offering structural support [13–17]. Various types of feather-based materials commonly used for packaging were also examined by filling molds with a mixture of heated hybrid keratin-derived additives combined with plastic matrices to create specific materials [18–24]. Further studies focused on utilizing feathers as a functional filler in nonwoven materials [25–27] or converting them for creating novel plastic compositions for film applications [28–35], though without a specified practical use. However, despite such promising recycling technologies involving keratin, the new plastic materials technologies face significant technical obstacles that hinder their expansion into mass production. End-user sectors and the environment could both profit from a consistent, sustainable, organic fiber source, as chicken farmers may see added worth from their current production and processing of birds for human consumption. Hence, the feather waste issue cannot be adequately addressed with traditional disposal methods. New plans are needed to ramp up production efforts for industrial manufacturing, as well as to evaluate the suitability of feather-based raw materials in various end products. All of these measures are aimed at transitioning to a circular economy, which could see an increase in product demand through the concept of conscious consumerism, where byproducts from one industry are utilized as raw materials in another.

The authors present a method for producing thermoplastic construction materials by integrating chicken feather waste and plastic waste that resemble the traditional method used for making wood–plastic composites (WPC). The processing technology may include traditional methods such as extrusion, injection molding, compression, or thermoforming, as well as some non-traditional methods, such as fused layer and laser sintering. The WPC technology also utilizes some organic materials, specifically wood fibers or wood flour, along with thermoplastic matrices like polyethylene, polypropylene, or polyvinyl chloride, which can be sourced from recycled materials as well [36–39]. Using keratin-derived fibers from feather waste in composites manufacturing is highly beneficial due to their strength properties that can be significantly enhanced when replacing materials like wood flour in WPC compositions [36]. WPC products are increasingly popular with a range of potential uses, with a market size of $7.1 billion in 2023, set to increase to $14.2 billion by 2032, showing an 8.30% compound annual growth rate [40].

Typically, wood–plastic composites are produced using a maximum of 50% wood flour content. The analysis of the composites made from feather waste revealed a similar proportion of organic matter, indicating the potential for absorbing significant amounts of feather waste with varying levels of dirt currently being disposed of in landfills. The literature contains various recipes for bio-composites utilizing feather waste in different ways and for different applications, mainly with a lower content of feathers, as described above, but none focus on feather–plastic thermoplastic composites with a high content of feathers for building purposes. This paper's originality lies in proposing these composites as a potential replacement for conventional WPC technology.

2. Disinfestation, Disinfection, and Sterilization of Chicken Feather Waste

Raw chicken feathers are combined with offal fat, debris, blood, preen oil, and other byproducts of the chicken processing. As a result, feathers are considered dangerous waste due to bacterial contamination as blood-borne pathogens, resulting in an unpleasant odor and making them unsuitable for being valorized in their current state. Before valorization, it is essential to decontaminate them to eliminate any microbial contamination. The current research is centered on assessing the feasible technologies for purifying and preparing chicken feathers for value-added purposes. One disadvantage of these technologies is their challenge to process through machinery because of the light weight of feathers. Some experiments, with relevant results, were conducted to wash waste chicken feathers with sodium dodecyl sulphate, dimethyl dioctadecyl ammonium chloride, mixtures of alcohol and hydrogen peroxide, or polyoxyethylene stearate [41–43]. Other experiments analyzed the thermal decontamination with an autoclave or combined chemical-thermal sterilization [44–47]. In those instances, productivity was negatively affected because a significant amount of water and, respectively, energy was required to process dispersed feathers for an efficient result.

To increase the productivity of the technological process and to avoid human contact with the feathers as much as possible, the authors proposed a new and eco-friendly method of disinfestation, disinfection, and sterilization of feather waste. It uses microwave exposure of feather waste in sealed ovens with circulating air, indeed actually causing feathers to be heated. Disinfestation, often overlooked in the cleaning techniques mentioned earlier, is also essential as feather waste may contain eggs or remnants of typical parasites [48]. The concept is innovative, and it is derived from the use of microwave energy for the specific heating of food materials [49–51]. It is important to note that an additional cleaning of feathers from dust, dirt, etc., is unnecessary, as the thermoplastic composite technology can tolerate very small amounts of micro-particles, whether they are of inorganic or organic origin.

Several feather waste samples from Ross 308 chicken were provided by SAFIR SA, Vaslui, Romania, and all showed a maximum humidity of 40% when tested. The benefit of microwave technology is that it allows radiation to move from the inside of the material to the outside, allowing for maximum preliminary compaction of features and ensuring an efficient process. Exposure to microwave radiation was conducted at various power levels ranging from 800 to 1200 × 10^3 W/kg for higher productivity, but with pre-determined durations of up to 5 min to prevent the feather from exceeding a temperature of 200 °C, where keratin begins to denature, but exceeding 100 °C after about 2 min of exposure. Table 1 displays the most significant findings.

Table 1. Microwave heating technology results.

Experiment 1			Experiment 2			Experiment 3		
Power [10^3 W/kg]	Time [min]	Mass Loss [%]	Power [10^3 W/kg]	Time [min]	Mass Loss [%]	Power [10^3 W/kg]	Time [min]	Mass Loss [%]
800	1	8	1000	1	11	1200	0.5	7
	2	16		2	19		1	15
	3	22		3	26		2	23
	5	29		4	32		3	31
	-	-		5	34		5	36

Observing that 5 min of exposure at a lower microwave power level of 1000 × 10^3 W/kg is sufficient to achieve a reasonable drying of waste to around 5–6% humidity, essential for an effective compounding process.

Regarding the eradication of pests, a minimum of 3 min of exposure is sufficient to eliminate the parasites in all their forms, with findings consistent with the study cited in [52–54]. Zoonotic diseases associated with birds include avian tuberculosis, erysipelas, ornithosis, cryptococcosis, histoplasmosis, salmonellosis, cryptosporidiosis, campylobacterosis, and escherichiosis, but only some of them can be experienced by contact with feathers. The most common germs found upon feathers are Salmonella, Campylobacter, Escherichia coli, mycoplasma, and Chlamydia psittaci, from which people generally experience more severe illness. Viruses and fungi (e.g., Aspergillus) may be found too, but with lower incidence on human health [55–57]. An experiment conducted simultaneously to evaluate the effectiveness of sterilization was not conducted because the use of Bacillus stearothermophilus as a reference and the guidelines outlined in SR EN ISO 6222:2004 [58] are not considered relevant. But, according to the Centers for Disease Control and Prevention (CDC), microwaves can be used to disinfect materials. They may completely kill germs within 60 s to 5 min [59], including *E. coli* and Salmonella, a case implicitly covered by our investigation period. It is worth noting that additional research shows that *E. coli* and Salmonella—which live in the intestinal tract but can accidentally contaminate feathers too—can be eliminated with heat after being exposed to 80 °C for more than 1 min [60], which is surpassed by our experiment in terms of temperature and duration.

Typically, like in previous studies [61], it is noted that sterilization effectiveness increases with longer microwave exposure time, but significantly higher efficacy is seen at higher energy levels, leading us to experiment with feather waste materials exposed to 1200 × 10^3 W/kg microwave power for 5 min. Based on the preliminary data, when exposed to the mentioned electromagnetic conditions, chicken feather waste is considered completely decontaminated and disinfected, with a humidity level even below 5%, suitable for immediate co-compounding with plastic matrices.

3. Manufacturing Process of Thermoplastic Composite Materials

3.1. Materials and Preparation Methods

The feather waste from Ross 308 chicken (provided by SAFIR SA, Vaslui, Romania), after the microwave processing for disinfection and sterilization, was turned into powder by dry grinding with a high-efficiency pulverizer-milling machine (Jiangsu Xinhe, Taizhou, Jiangsu, China), resulting in an average size of 60~100 mesh. Samples of feather and feather powder are presented in Figure 1.

Figure 1. Samples of feather and feather powder.

The waste of polypropylene PP and polyethylene LDPE can be handled by either grinding in one step to produce mixed flakes less than 3 mm in size, using a plastic shredder machine (Henan Gomine, Zhengzhou, Henan, China) or by using pre-processed pellets from PP/LDPE waste sourced from other suppliers, with a size of 2–3 mm. This paper focused on using only in-house raw materials, which were mixtures of ground plastic waste and chicken feather waste, i.e., plastic flakes measuring less than 3 mm and chicken feather waste powder measuring an average size of 60~100 mesh.

To define the composite structures, the following sample codes were used, as shown in Table 2.

Table 2. Composite recipe descriptions.

Code	MatrixType	Matrix [%]	Feather [%]	Additives [%]
I-LDPER	Recycled LDPE	100	0	0
II-LDPER/10FF		83	10	7
II-LDPER/20FF		73	20	7
II-LDPER/30FF		63	30	7
II-LDPER/50FF		43	50	7
I-1 PPR	Recycled PP	100	0	0
II-2 PPR/10FP		83	10	7
II-3 PPR/20FP		73	20	7
II-4 PPR/30FP		63	30	7
II-5 PPR/50FP		43	50	7

A specialized machine (Ningbo Lvhua, Yuyao, Zhejiang Province, China) was used to dehumidify, homogenize, and pre-compatibilize a mixture of flakes and powder with different ratios. Various additives, such as dispersion and anchoring additives, were included to facilitate bonding between the hydrophobic matrix and the feather powder, thereby enhancing mechanical properties: composite stabilizer, dispersing and release agents: Licowax PED 521 granules, 2.7% and HOSTAVIN N30 powder, 0.6% (Clariant, Muttenz, Switzerland); blowing agent: AC7000/ACD-05, 1.2% (Henan Jinhe Ind. Co., LTD., Shangqiu, Henan, China); foam regulator: ZB-530, 0.5% (Shandong Zibo, Zibo, China); modifier/coupling agent: Vistamaxx, 2.7% (ExxonMobil Chemical, Houston, TX, USA) and lead stearate, 0.3%.

The mixtures were immediately submitted to an extrusion process for obtaining pellets by use of a Sj-90/30 single screw extruder (Zhangjiagang Beierman Machinery Co., Ltd., Zhangjiagang, Jiangsu, China). The single screw extrusion process and resulting composite pellets are briefly presented in Figure 2.

Figure 2. Single screw extrusion process and resulting composite pellets.

The Dr. Boy 35A injection molding machine (Dr. Boy GmbH & Co., KG, Neustadt-Fernthal, Germany) was used to carry out the injection of composites from pellets, with the following specifications: a screw diameter of 28 mm, an L/D ratio of 18.6 mm, an injection capacity of 58.5 cm^3 (calculated), a maximum material pressure of 2200 bar, and a minimum real injection capacity of 500 mm. Considering the nature of the polymer matrices (polyethylene and polypropylene, respectively), the following operating parameters were selected: pressure: 550 bars; subsequent pressure: 1000 bars; back pressure: 90 bars; mold temperature: 15–20 °C. The injection machine interface for producing composite materials is shown in Figure 3, along with the temperature regime for each type of polymer matrix in Table 3, to achieve optimal process parameters.

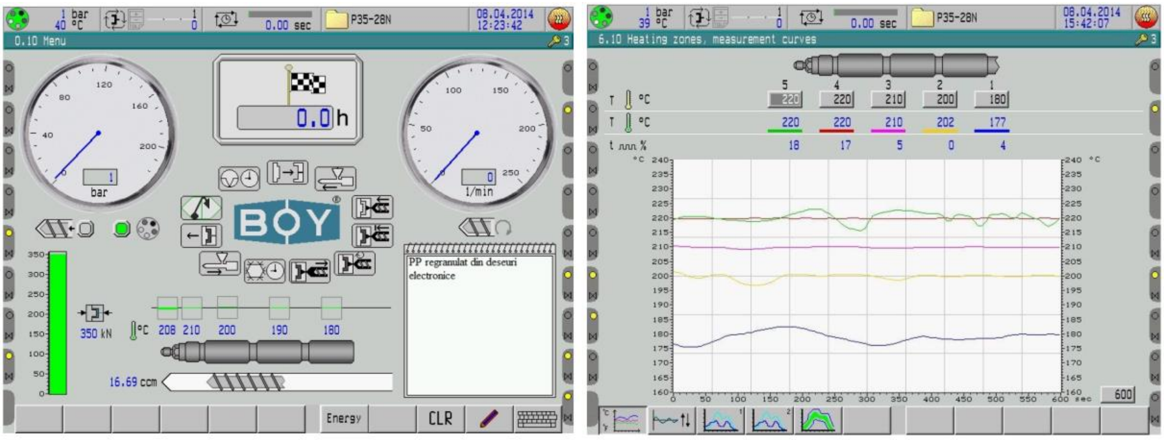


Figure 3. The interface with thermal diagrams of the injection molding machine.

Table 3. Optimal temperatures of the five heating zones of the injection molding machine cylinder.

Zone	5	4	3	2	1
LDPE (°C)	200	190	180	172	162
PP (°C)	220	210	201	192	178

The injection molding method is perfect for creating typical composite samples for mechanical and physical testing purposes, as presented in Figure 4.

Figure 4. Composites sample prepared using injection molding process (I-LDPER; II-LDPER/10FF; II-LDPER/20FF; II-LDPER/30FF; II-LDPER/50FF).

Composite panels for construction were created by extruding pellets containing 50% feather powder with a POEX T40 twin screw extruder (Poex, Nilüfer, Bursa, Turkey) using various molds. The extruder with two corotating screws presents the characteristics: capacity: 150–250 kg/h; main engine: 75 kW, 1500 rpm; heating power: 16 kW; temperature control system with 12 temperature adjustment zones, with separate control for each section. Additional miscellaneous additives were included within the extrusion process to improve product quality: calcium carbonate and talc concentrate 4:1, with a fineness of 800 mesh or more, 4.9%; inorganic pigments for a uniform brown color, UV stabilization additives, and flame retardant additives, 0.1% in all. An example of a resulting composite panel for window frames is presented in Figure 5.

(**a**) (**b**) (**c**)

Figure 5. From the thermoplastic material to building products. (**a**) Example of composite panel obtained at the extrusion equipment. (**b**) Thermal bonding of composite panels at 45°. (**c**) Example of a finalized frame for building purposes.

3.2. Characterization Methods and Related Equipment

(i) Electron scanning microscopy SEM was performed with a field emission and focused ion beam scanning electron microscope (SEM) model Quanta FEG 250 with STEM and EDX detectors (Thermo Fisher Scientific Inc., Waltham, MA, USA). The analysis method was LowVac, with water vapor, which does not allow the samples to be damaged. The SEM charging occurrence was significantly reduced due to the low vacuum in the specimen chamber of the SEM.

(ii) X-ray computer tomography was performed using Skyscan 1174 equipment (Bruker Corporation Billerica, MA, USA).

(iii) A Netzsch STA PC 409 equipment (Erich NETZSCH B.V. & Co. Holding KG, Selbwas, Germany) used for thermogravimetric analysis. The working atmosphere was synthetic air, 100 mL/min in alumina crucibles. The heating program was 35–1200 °C with a heating speed of 10°C/min.

(iv) The hydrostatic density is determined utilizing the XS204 Analytical Balance, characterized by the following specifications: maximum capacity of 220 g, precision of 0.1 mg, linearity of 0.2 mg, internal calibration, equipped with a density kit for solids and liquids, and an RS 232 interface (Mettler-Toledo, Columbus, OH, USA). The measurements were conducted at a temperature of 25 °C.

(v) Shore hardness measurements were made with a common Shore "D" digital durometer.

(vi) The equipment for determining the mechanical features was a specialized PC-controlled universal tensile testing machine (Qiantong, China), with nominal force: min. 20 kN, allowing measurement of tensile strength and elongation.

(vii) CHARPY shock resistance was measured with specialized equipment with the features: test pieces type 1, without notch type A, pendulum 5J.

(viii) The dielectric properties were determined using the broadband dielectric spectroscopy method with a Solartron 1260 A dielectric spectrometer (Solartron Analytical, Farnborough, UK).

(ix) The LFA 447 Nanoflash equipment (Erich NETZSCH B.V. & Co. Holding KG, Selbwas, Germany) was used to measure thermal conductivity. A powerful xenon lamp provided the radiation energy, with a 0.18 ms irradiation time on the front of the sample. The temperature was examined three times in each experiment. Its InSb-type infrared (IR) detector was used to measure the increase in temperature on the sample's opposite surface.

(x) The apparatus for determining the sound absorption coefficient consists of a specialized acoustic interferometer (Hottinger Bruel & Kjaer, Virum, Denmark) with Kundt medium tube type 4206-A, a five-channel simultaneous signal acquisition system with signal generator—PULSE multi-analyzer type 3560-B-030, two microphones type 4187, a signal amplifier 2716 and an acoustic calibrator type 4231 with adapter DP-0775 for microphones. The sound absorption coefficient was measured at a medium-frequency stage (100 Hz–3.2 kHz).

(xi) An inductively coupled plasma mass spectrometer (ICP-MS 7900 by Agilent Technologies, Santa Clara, CA, USA) was used to evaluate the metal concentration in leachates. The levels of sulphate and chloride anions were measured using a DIONEX ICS-3000 ion chromatograph (Thermo Fisher Scientific, Waltham, MA, USA) with an AG23 Dionex column and suppressed conductivity detection.

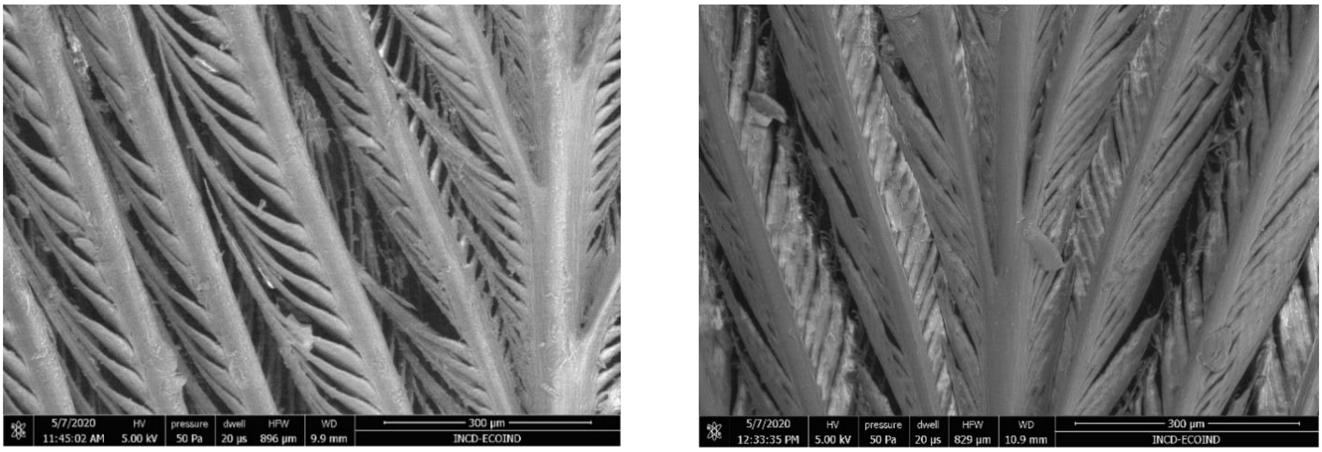
(xii) The levels of dissolved organic carbon (DOC) were assessed with a nitrogen/carbon analyzer (N/C 3100, Analytik Jena, Jena, Germany).

3.3. Results and Discussion

The results provided below take a step-by-step approach to elucidate the scientific findings, beginning with the analysis of feather and feather powder, moving on to composites produced by injection molding, and concluding with the functional attributes of extruded frames for construction applications.

3.3.1. SEM Analysis

The magnitude of 200× was chosen to better emphasize the feather structure before and after microwave exposure, Figure 6. After being exposed to microwaves, it is noticeable that the feather showed redistributed barbs and partially regenerated barbules as a result of drying out. The structure is similar to feathers chemically cleaned and dried in autoclaves but much more pronounced and uniform. The result can also be attributed to the more uniform and deeper removal of the fat layer. There is no damage to the fibers during microwave treatment.



(**a**) (**b**)

Figure 6. Feather structure, (**a**) before and (**b**) after microwave exposure.

The magnitude of 60× was chosen to emphasize the dimension of chicken feather powder from the milling process, Figure 7. It is observed that, except for a few particles from the rachis, which can reach up to 900 microns, most of the particles have an average size of approximately 200 microns, less than the typical size of regular wood fibers used in WPC applications.

In Figure 8, the SEM images of samples with 10%, 30%, and 50% feather powder content are respectively presented. It can be observed that when the amount of feather powder is higher, the injected samples (here, the example for LDPE) exhibit a more consistent structure with evenly dispersed particles. However, in all instances, the particles are well incorporated into the polymer matrix.

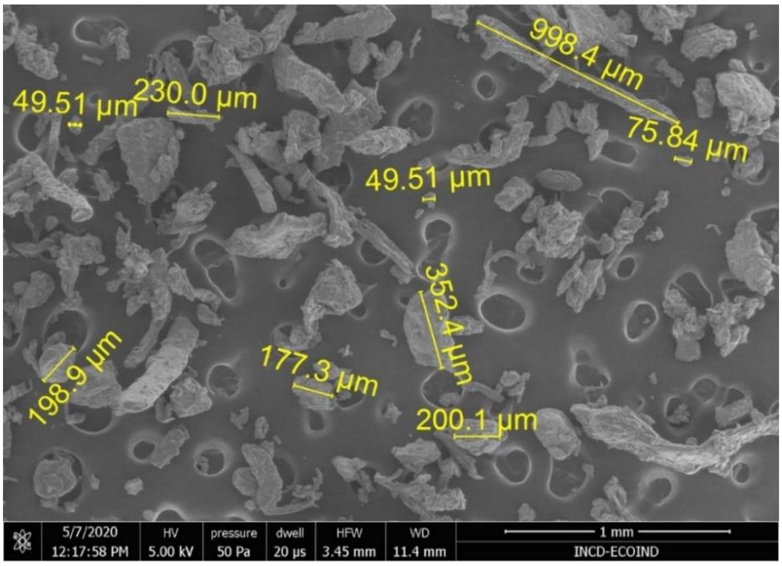
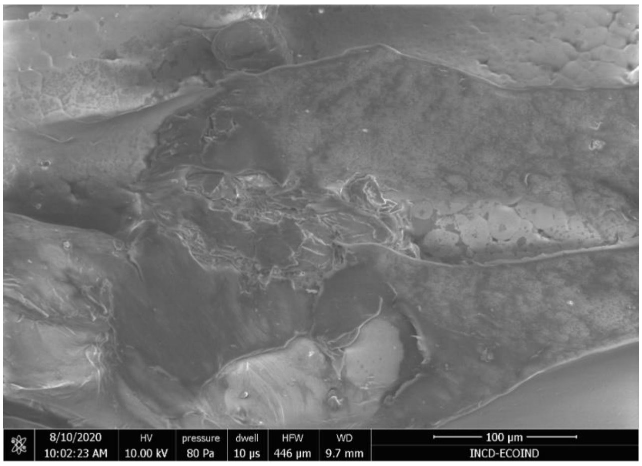
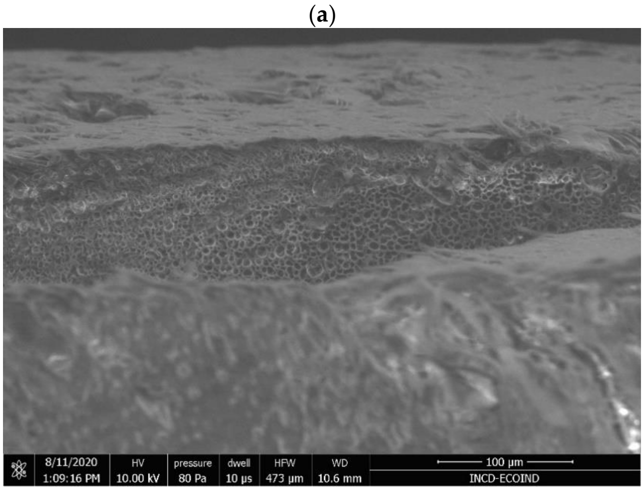


Figure 7. Composite structure showing feather powder size (49.51–998.4 µm range).

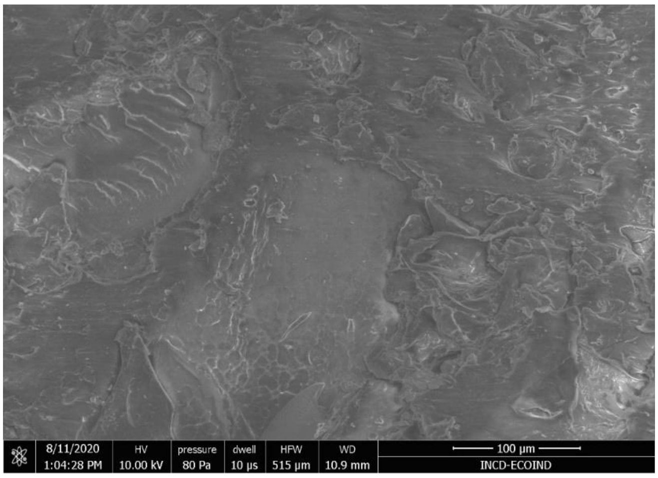


(**a**)



(**b**)

Figure 8. *Cont*.



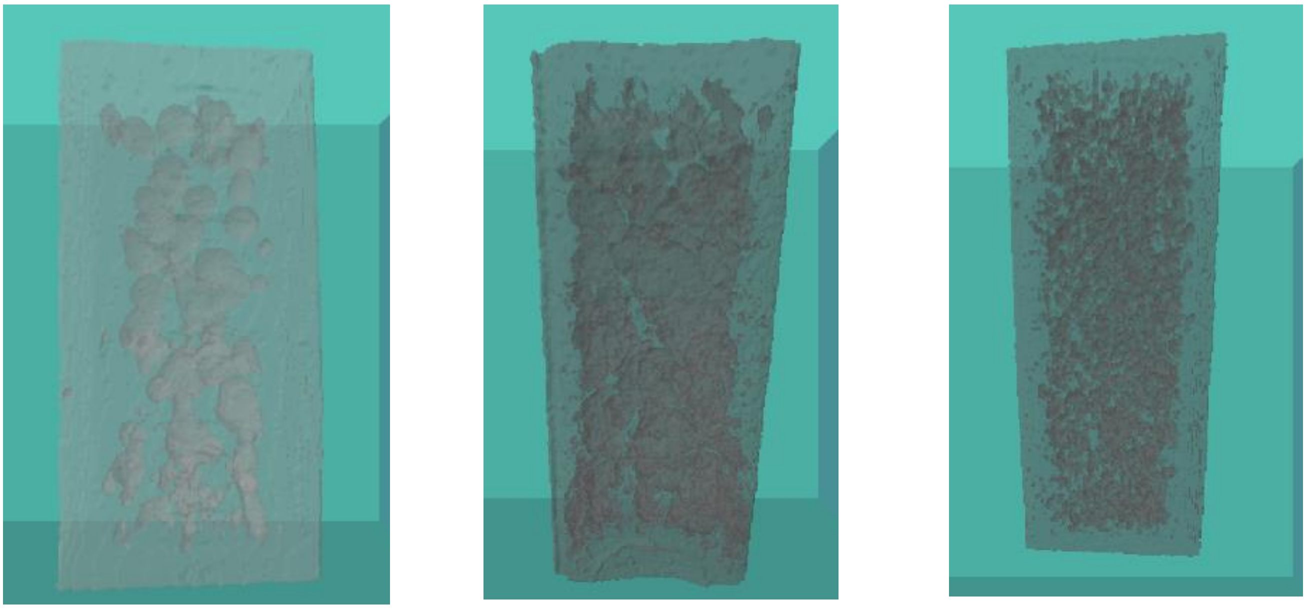
(**c**)

Figure 8. SEM images of composite samples with a feather powder content of (**a**) 10%, (**b**) 30%, and (**c**). 50%.

The injection molding process does not have a particular impact on the alignment of feather fibers in the composite material; however, when feather powder is present in low concentrations, flocculation occurs in the direction of composite flow.

3.3.2. X-Ray CT Analysis

Clearer images of feather powder distribution within a polymer matrix can be achieved by X-ray CT analysis, Figure 9, which considers the structures more in-depth. For example, analysing Figure 9a we can now comprehend why there are some bigger spots present in Figure 8a, when there is 10% feather powder content.



(**a**) (**b**) (**c**)

Figure 9. CT images of composite samples with a feather powder content of (**a**) 10%, (**b**) 30%, and (**c**) 50%.

The X-ray analysis highlights the agglomeration and clumping of feather powder particles despite the presence of technological additives. A flocculation is noticed in the direction of composite flow, based on a rheological effect, visible mainly at lower content of feather powder. The impact is reduced more, and the powder particles of the feather are more evenly scattered when there is a higher amount of powder, leading to a more consistent spatial distribution, as in Figure 9c. Even though the additives were proven effective, they were not specifically designed for keratin.

It may be necessary to create and test new additives for thermoplastic composites with feather powders. In the study, composites with fewer feather powder particles are discussed for scientific purposes, but in reality, composites with more powder are economically beneficial.

3.3.3. Energy Dispersive X-Ray (EDX) Analysis for Feather Powder

The EDX result for feather powder is presented in Figure 10 and Table 4.

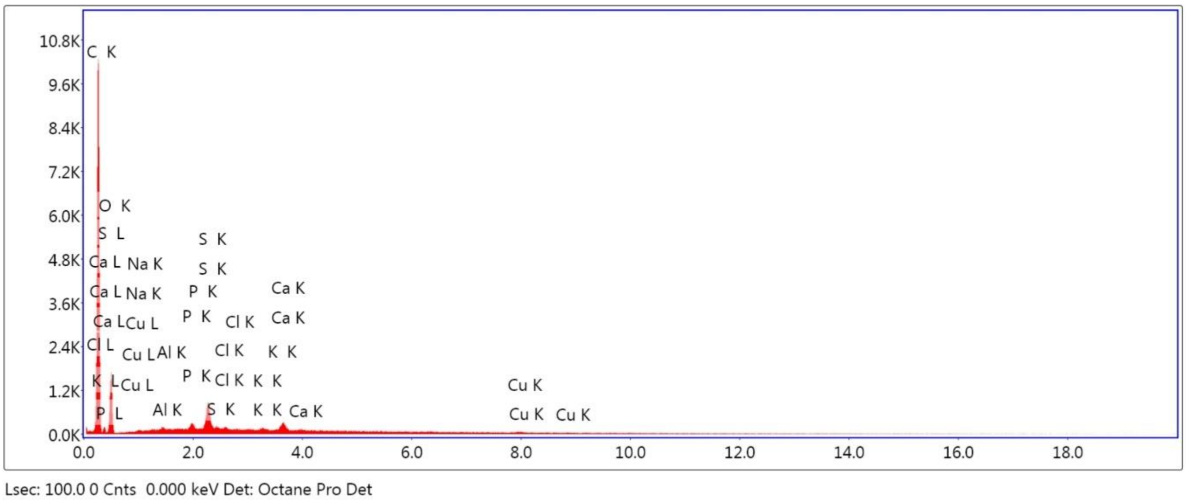


Figure 10. EDX—analysis for feather powder (counts vs. energy/keV).

Table 4. EDX elementary results for feather powder.

Element	Weight %	Atomic %	Net Int.	Error %
C	72.53	78.39	491.16	4.92
O	25.95	21.05	87.02	10.81
Na	0.00	0.00	0.00	99.99
Al	0.00	0.00	0.07	99.99
P	0.13	0.05	7.97	16.56
S	0.81	0.33	57.51	5.02
Cl	0.04	0.01	2.44	57.80
K	0.06	0.02	3.77	41.11
Ca	0.36	0.12	20.76	12.84
Cu	0.12	0.02	4.07	40.87

The dominant elements include, as expected, C, O, S, and P, along with small amounts of Ca, mainly from the feather rachis.

The X-ray (EDX) examination of LDPE and PP waste, as well as its derived composites, was not considered relevant, as the presence of trace elements (such as Ca, Cl, Cu, P, Na, etc.) in addition to the usual C, O, N, and S, can greatly differ based on the origin of the polymer matrix, which can be, e.g., packaging or electronic waste. The analysis related to feathers highlighted that adding feathers does not significantly alter the polymer matrix's basic composition in terms of residual elements.

3.3.4. Thermal Analysis for Feather Powder

The thermogravimetric curve of feather powder is presented in Figure 11. Water evaporates up to 130 °C (both free and bound water), but the powder shows chemical stability up to around the 230 °C point. The processing temperatures shown in Table 3 are fully justified by this thermal stability. In the range of 230–590 °C, an organic decomposition takes place with a significant loss of mass, assimilated to helix denaturation, backbone degradation, and peptide chain bond destruction, as indicated also in [62,63]. After 590 °C, the decomposition of mineral compounds takes place, with traces of gases eventually removed.

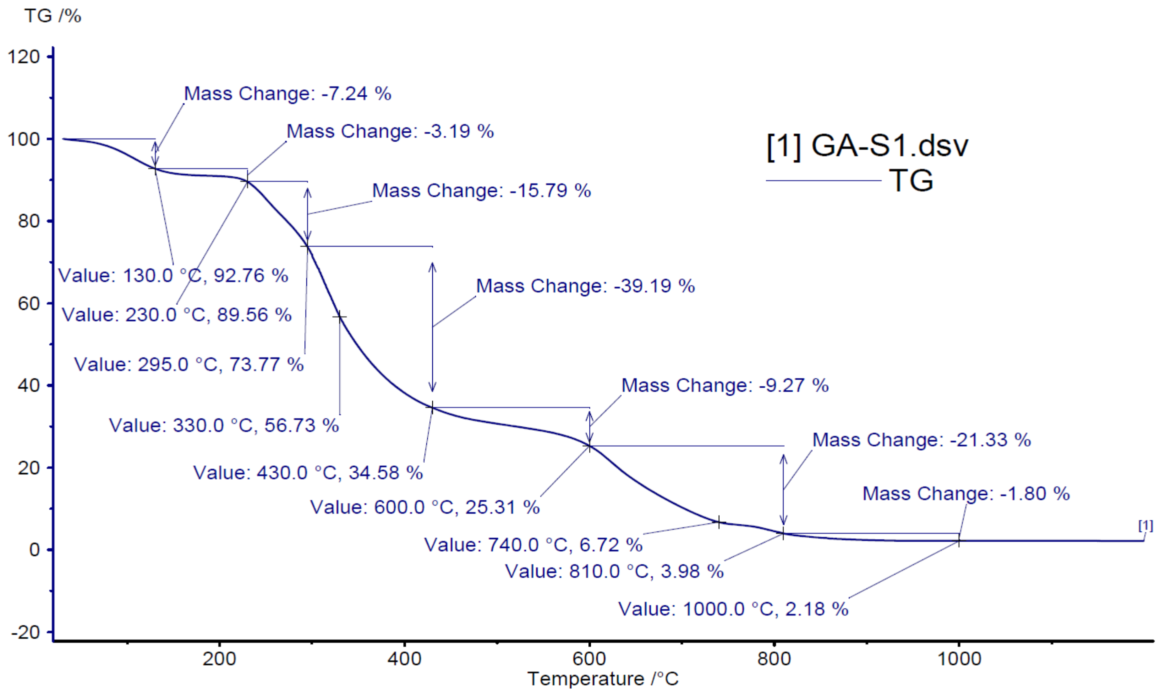


Figure 11. Thermogravimetric curve of feather powder.

A rise in ash content correlates directly with the percentage of feathers in composites, as shown in Table 5, up to a maximum value of about 1%.

Table 5. Thermal analysis of composites made from feather powder and plastic waste.

Sample	Ash Content [%]	Fluidity Index [g/10 min]
II-LDPER/10FF	0.33	14.21
II-LDPER/20FF	0.41	12.37
II-LDPER/30FF	0.78	9.72
II-LDPER/50FF	0.92	4.22
II-2 PPR/10FP	0.32	18.32
II-3 PPR/20FP	0.42	16.23
II-4 PPR/30FP	0.77	13.01
II-5 PPR/50FP	0.94	11.53

The flow-ability of thermoplastic materials is affected by the decrease in the fluidity index (determined at 190 °C; 2.16 kg) as the percentage of feathers in composites increases.

The melting interval is 125—145 °C for 10% and 20% feather content, 126—148 °C for 30% feather content, and 130—150 °C for 50% feather content. A melting range below 150 °C is seen as optimal for the thermal bonding technology used for thermoplastic constructing materials.

3.3.5. Evaluation of Hydrostatic Density of Injected Molded Samples

Table 6 displays the outcomes of hydrostatic density. A decrease in density was observed in composites containing polypropylene when compared to composites containing polyethylene, mainly because of the lower density of the polypropylene matrix. An increased amount of feather powder in composites results in a slightly elevated hydrostatic density value for both types of polymer matrices. The hydrostatic density data align with comparable features found in traditional WPC [64–66].

Table 6. Hydrostatic density values of composites made from feather powder and plastic waste.

Sample	Hydrostatic Density [g/cm^3]
II-LDPER/10FF	0.931
II-LDPER/20FF	0.942
II-LDPER/30FF	0.972
II-LDPER/50FF	0.998
II-2 PPR/10FP	0.932
II-3 PPR/20FP	0.945
II-4 PPR/30FP	0.979
II-5 PPR/50FP	1.017

3.3.6. Evaluation of Mechanical Characteristics of Injected Molded Samples

Average values for Shore hardness and mechanical properties are shown in Table 7, based on six measurements, with polypropylene composites demonstrating higher values compared to polyethylene composites. An increased proportion of feather powder in composites results in a slightly higher Shore hardness value for both polymer matrices; however, the opposite is true for all other mechanical properties. The higher the elastic modulus, the more resistant the composite material is to deformation in the elastic range, so the incorporation of feather powder could facilitate certain cold deformation techniques in construction applications. The outcomes finalize the study discussed in [67].

Table 7. Mechanical characteristics of composites made from feather powder and plastic waste.

Sample	CHARPY Shock Resistance [kJ/m^2]	Shore Hardness [MPa]	Tensile Strength [MPa]	Breaking Elongation [%]	Elastic Modulus [MPa]
II-LDPER/10FF	51.19	61	52.9	44.53	895
II-LDPER/20FF	38.83	66	52,2	26.55	835
II-LDPER/30FF	13.14	74	41.9	15.46	765
II-LDPER/50FF	5.3	76	23.3	11.61	612
II-2 PPR/10FP	54.23	68	76.8	38.07	1604
II-3 PPR/20FP	40.08	73	65.7	24.33	1306
II-4 PPR/30FP	20.19	82	53.4	13.9	1251
II-5 PPR/50FP	7.14	84	26.9	8.95	1121

3.3.7. Dielectric Properties of Injected Molded Samples

Dielectric properties that were examined included dielectric permittivity, loss factor (TgDelta), and conductivity. The findings are displayed in Figure 12 for the recycled LDPE matrix and Figure 13 for the recycled PP matrix, with varying amounts of feather powder. The outcomes finalize the study discussed in [68]. It was commonly observed that, in terms of permittivity, higher amounts of feather powder resulted in higher values for both types of matrices. It is clear that the LDPE matrix material shows slightly higher values compared to those with a PP matrix. The typical trend in evolution with frequency is traditional, and the characteristics decrease as the frequency increases. Similar outcomes were observed in terms of TgDelta, with the significantly elevated values at lower frequencies being caused by the interfacial polarization of the composite. The significant increase in TgDelta observed in both types of matrices with 50% feather waste content is attributed to the greater uniformity of the structure, which aligns with the findings in Figures 8c and 9c.

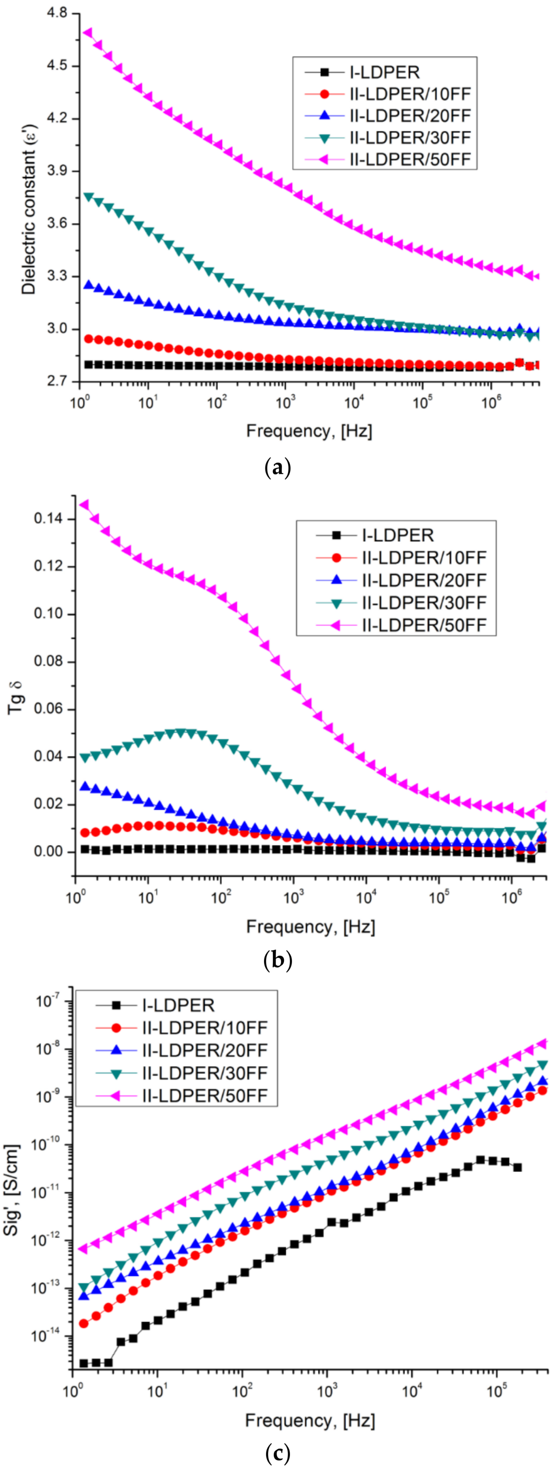
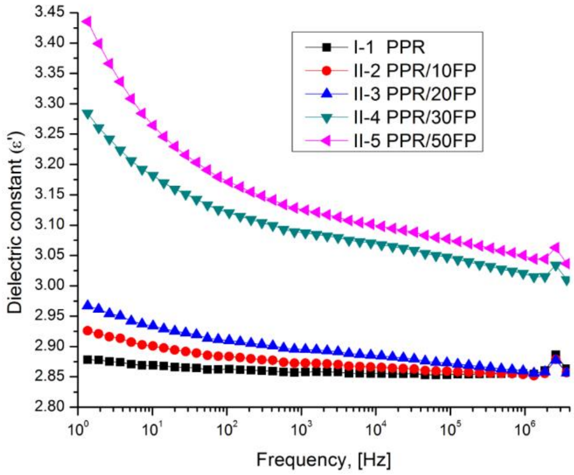
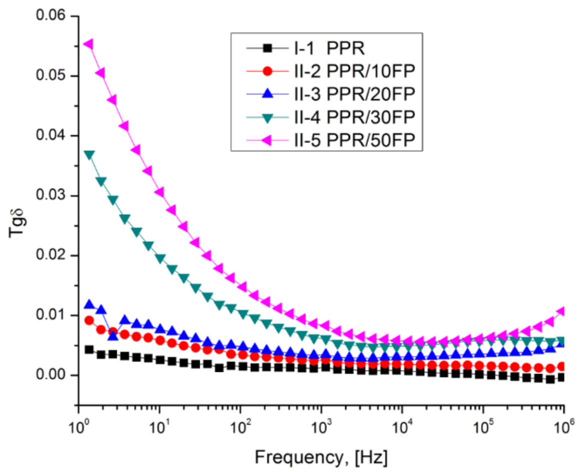


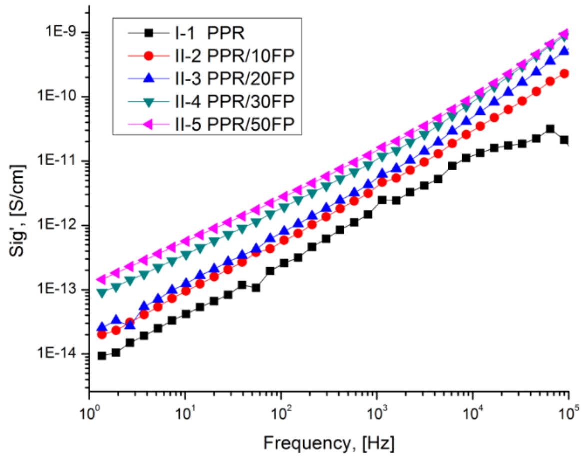
Figure 12. Dielectric properties of composites with recycled LDPE matrix: (**a**) permittivity, (**b**) power loss—TgDelta, and (**c**) conductivity.



(**a**)



(**b**)



(**c**)

Figure 13. Dielectric properties of composites with the recycled PP matrix: (**a**) permittivity, (**b**) power loss—TgDelta, and (**c**) conductivity.

Accordingly, the notable increase in conductivity and TgDelta values when adding feather powder above 30% is a result of improved compatibility between the polymer matrix and the keratin powder. The variation in the shapes of characteristics in Figures 12b and 13b is due to the LDPE matrix incorporating the feather powder differently than the PP matrix, leading to enhanced interfacial polarization and earlier dipolar polarization in the frequency domain. This results in a peak around 80 Hz for the LDPE matrix with 30% powder content, which is still evident with 50% powder content.

Regarding conductivity, it gradually rises with the inclusion of feather powder in both matrices. The value is higher for LDPE-based composites. In terms of how conductivity characteristics change with frequency, there is a common pattern where they steadily rise as the frequency increases.

3.3.8. Evaluation of Thermal Features of Extruded Frames for Building Purposes

In construction, the thermal conductivity typically needs to be reduced to align the absorption and release of heat with the building's heating and cooling process. Greater thermal diffusivity in a material denotes accelerated heat propagation. In our scenario, a higher feather powder content results in decreased thermal insulation. The results are presented in Table 8. The methodology and mathematical model of thermal analysis are according to [69]. The thermal conductivity decreases slightly as more feather powder is added. It was generally noticed that the composites based on polyethylene present marginally better thermal characteristics compared to the ones with polypropylene matrix.

Table 8. Thermal conductivity of extruded frames for building purposes.

Sample	Thermal Conductivity [W/(m·K)]
II-LDPER/10FF	0.262
II-LDPER/20FF	0.257
II-LDPER/30FF	0.248
II-LDPER/50FF	0.241
II-2 PPR/10FP	0.294
II-3 PPR/20FP	0.291
II-4 PPR/30FP	0.286
II-5 PPR/50FP	0.282

The use of extrusion technology resulted in high-quality and adaptable products, similar in characteristics to those made using traditional WPC technology, as described, e.g., in [70,71]. Table 9 presents a comparison of technical features of building composite panels for windows with 50% feather powder, according to the model seen in Figure 5, and a similar composite panel made with WPC containing respectively 50% wood flour (but with 11% calcium carbonate instead of 5% in our case).

Table 9. Comparative technical characteristics.

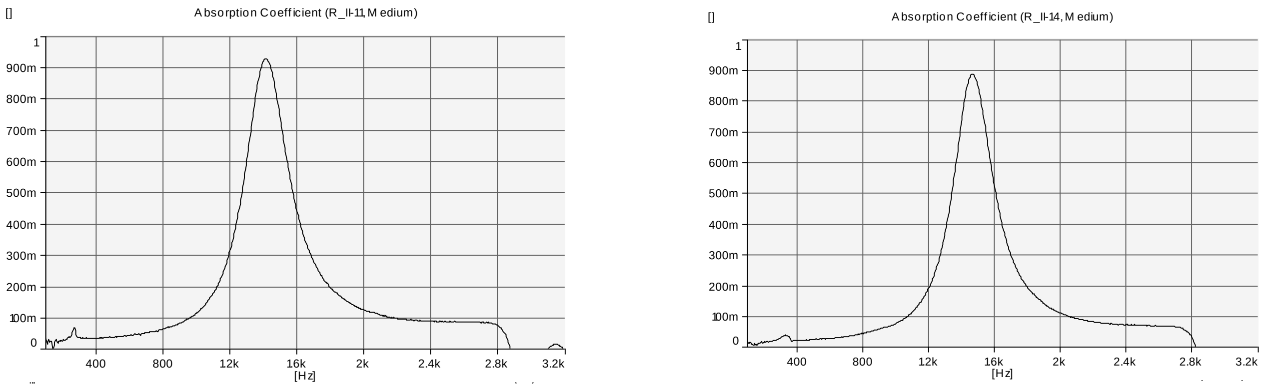
Technical Characteristic	Composite Panel from Feathers & Plastic Waste	WPC Panel with Polyvinyl Chloride Base
Density [g/cm^3]	0.998	0.998
SHORE hardness [MPa]	76	71
Tensile strength [MPa]	23.3	42
Thermal Conductivity [W/(m·K)]	0.248	0.366

It is not surprising to observe an improved thermal conductivity in the panel created using the technology described in the paper, mainly due to the known thermal shielding effect of feathers. Overall, utilizing feather powder as an ingredient in composites results in thermal characteristics that are even with 30% better than the comparable data from commercial WPC. The density and SHORE hardness values are comparable. The increased tensile strength of commercial WPC with a polyvinyl chloride base can also be attributed to the higher resistance of the matrix and increased calcium carbonate content. It is generally accepted that WPC made from a polyvinyl chloride matrix has superior thermal properties compared to WPC made from a polypropylene or polyethylene matrix. However, the manufacturing and usage of polyvinyl chloride-based products are now limited due to their environmental risks. Given that the composites created by the authors demonstrate similar qualities as PVC-based WPCs, the technology proposed in this research could feasibly substitute PVC-based WPCs, resulting in evident environmental advantages from both perspectives.

3.3.9. Determination of Sound Absorption Coefficient of Extruded Frames for Building Purposes

Soundproofing is especially necessary in various uses of composite composite panels within the construction industry. The tests were made according to the SR EN ISO 11654 standard [72]. The outcomes finalize the study discussed in [73]. The standard samples sent for soundproof testing are similar to those shown in Figure 14. The absorption characteristics for the recycled LDPE and recycled PP matrix base, with 10% and 50% feather powder content, are comparatively presented in Figures 15 and 16.

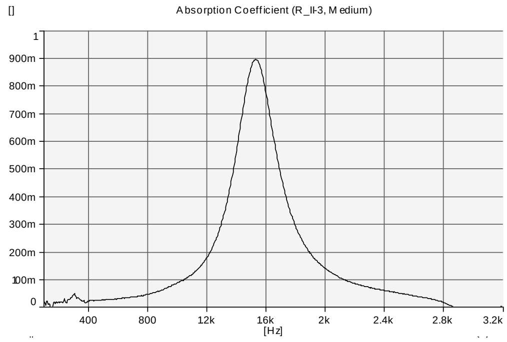
Figure 14. Sample for soundproof testing.



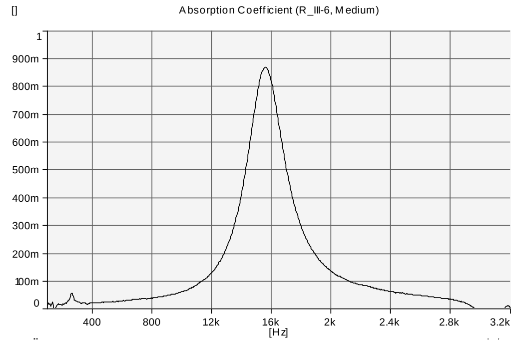
(**a**) (**b**)

Figure 15. Absorption characteristic for LDPE matrix with (**a**) 10% and (**b**) 50% feather powder content.

The values for all analyzed samples are presented in Table 10. An incremental rise in absorbance is seen in all samples beginning at 350 Hz, peaking at around 1500 Hz, but then sharply decreasing as the frequency goes up to 2800 Hz. The gradual inclusion of feather powder raises the peak of the characteristic to slightly higher levels of frequency. However, the differences are not substantial. In short, the absorption coefficient decreases slightly with the addition of more feather powder. It was generally noticed that the composites based on polyethylene present marginally better absorption coefficients compared to the ones with polypropylene matrix. According to [72], due to their very good soundproof characteristics, all materials can be included in the 'absorption class—B'.



(**a**)



(**b**)

Figure 16. Absorption characteristics for the PP matrix with (**a**) 10% and (**b**) 50% feather powder content.

Table 10. Absorption coefficient.

Sample	Maximum Absorption Coefficient
II-LDPER/10FF	0.93
II-LDPER/20FF	0.92
II-LDPER/30FF	0.91
II-LDPER/50FF	0.89
II-2 PPR/10FP	0.90
II-3 PPR/20FP	0.89
II-4 PPR/30FP	0.88
II-5 PPR/50FP	0.86

3.3.10. Environmental Impact of the Feather-Based Building Materials Technology

The durability of a technology can focus on three aspects: replacing non-renewable with renewable resources, including those from waste sources; preventing or eliminating potential pollution and other harmful environmental effects; and improving resource usage efficiency. Our paper focuses on enhancing environmental impact by utilizing raw materials from waste sources, specifically harmful chicken feather waste, to improve resource efficiency with the help of the proposed technology. It also tackles the reduction of carbon footprint and depletion of raw materials indirectly, using waste materials instead of virgin resins for the same technological purpose.

The eight samples of building materials containing two polymer matrices, feather powder, and additives underwent a leaching process after the extrusion process, as outlined in SR EN 12457-2: 2003 [74], to assess the presence of hazardous metals. The leachates were analyzed to determine the values of all indicators defined in Order no. 95/12.02.2005 [75] concerning the criteria for accepting and evaluating stored waste, as well as the national list of approved waste for each waste class. Standardized laboratory analysis was used to determine indicator values for total dissolved solids (TDS) [76]. Table 11 presents the elementary results, and Table 12 presents the results for other chemical indicators. The results for extruded materials were also compared with the results for feather powder (FP).

The results show that none of the analyzed metals exceeded the limit for waste storage in non-hazardous waste deposits, Table 11. It is evident that certain metals show a higher proportion when feather dust is progressively added to composites, but when compared to pure feather dust, the metal levels in the composites are significantly decreased, even greatly eliminated—specifically, Mo, Cr, Se, As. Similarly, a significant decrease in sulfates and chlorides is also noted in Table 12.

Table 11. Elementary results of leachates.

Element	Sample Type/Content (mg/kg)									L.V. * [mg/kg]
	FP	II-LDPER/10FF	II-LDPER/20FF	II-LDPER/30FF	II-LDPER/50FF	II-2 PPR/10FP	II-3 PPR/20FP	II-4 PPR/30FP	II-5 PPR/50FP	
As	0.43	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	<0.15	2
Ba	1.08	0.464	0.678	0.730	1.043	0.447	0.632	0.724	1.020	100
Cd	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	1
Cr	0.106	0.039	0.040	0.049	0.101	0.023	0.028	0.038	0.050	10
Cu	0.76	0.251	0.264	0.356	0.384	0.165	0.304	0.349	0.375	50
Hg	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.2
Mo	0.15	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	10
Ni	0.11	0.048	0.051	0.054	0.055	0.034	0.038	0.048	0.056	10
Pb	0.32	<0.07	<0.07	0.071	0.099	<0.07	<0.07	0.081	0.090	10
Sb	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0.7
Se	0.090	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.5
Zn	2.163	0.635	0.678	1.65	1.82	0.354	0.414	0.790	1.801	50

* L.V.—Admitted limit value according to the standard.

Table 12. Chemical indicators according to [75].

Indicator	Sample Type/Content (mg/kg)									L.V. * [mg/kg]
	FP	II-LDPER/10FF	II-LDPER/20FF	II-LDPER/30FF	II-LDPER/50FF	II-2 PPR/10FP	II-3 PPR/20FP	II-4 PPR/30FP	II-5 PPR/50FP	
Sulfate	10,802	741.3	1031.4	1613.6	1932.7	1696.9	2741.9	3947.4	5208.8	20,000
Chloride	2355	175.7	316.30	1230	1405.8	702.9	808.3	1054.3	1686.9	15,000
DOC	2879	565	640	820	1110	640	795	985	1430	800
TDS	58,600	13,560	16,080	31,230	32,560	22,880	27,320	31,360	39,200	60,000

* L.V.—Admitted limit value according to the standard.

However, the information in Table 12 shows that there is one indicator: Dissolved Organic Carbon (DOC) [77,78], with exceedances above the limit value (800 mg/kg), clearly for feather powder, but as well as products that contain, e.g., more than 30% feather powder. In such situations, storing materials in non-hazardous waste sites is not allowed, but they can still be kept in hazardous waste facilities, which is not ideal.

In hindsight, it is evident that incorporating feather waste into composite materials has a significant positive impact on the environment, as reflected in the noticeable decrease in the evaluated indicators. It is also observed that the values are slightly higher for products related to polyethylene as opposed to those related to polypropylene, with the explanation being linked to the characteristics of the matrix.

If feather waste is deemed hazardous and unrecyclable, the initial decision should be to either prohibit its storage or dispose of it in a hazardous landfill along with related products due to the environmental repercussions of high organic compound levels sensitive to leaching effects.

The positive development is that using thermoplastic processing on feather waste significantly reduces environmental impacts, showing that this technology is environmentally sound. Therefore, the transformation of waste-derived raw materials into composite materials for construction purposes is necessary to stabilize and utilize potentially harmful waste. Extruded products for construction have a strong market and can be easily recycled using the same technology, either by collecting them as building waste or through buy-back policies, in line with the research in [79,80]. This technology complies with European regulations for recycling building materials [81] and is sustainable according to Life Cycle Assessment [82], as the derived building materials integrating chicken feather waste and plastic waste can be fully recycled for construction use using the same thermoplastic technology.

4. Conclusions

The article explains how thermoplastic building materials can be made by combining waste feathers from chickens with plastic waste. The initial stage focused on a new and environmentally friendly method of sterilizing feather waste using microwave radiation in closed ovens with air circulation. The sterilization efficiency increases with longer exposure to microwaves but is more effective with higher energy levels. Experimental results of feather waste exposed to 1200×10^3 W/kg microwave power for 5 min emphasized complete decontamination and disinfection, along with a humidity level below 5%, making the feathers suitable for immediate use for compounding with plastic matrices.

Further, composites with different feather waste content and with two polymer matrices (polyethylene and polypropylene) were obtained by the injection molding process. The samples present a homogeneous structure mostly for larger quantities of feather powder, with feather fibers uniformly distributed and well embedded within the polymer matrix. A lower density of composites with polypropylene compared with the composites with polyethylene was noticed due mainly to the lower density of the polypropylene matrix. A higher content of keratine in composites leads to a slightly higher value for hydrostatic density for both polymer matrices. Higher values of mechanical strength for polypropylene composites, compared to polyethylene composites, were noticed.

A notable increase in conductivity and TgDelta values was noticed when adding feather powder above 30%, confirming the improved compatibility between the polymer matrix and the keratin powder. A specific variation in the shapes of dielectric characteristics was observed for the LDPE matrix, which incorporates the feather powder differently than the PP matrix, leading to enhanced interfacial polarization and earlier dipolar polarization in the frequency domain.

An incremental rise in sound absorbance is seen in all samples beginning at 350 Hz, peaking at around 1500 Hz, but then sharply decreasing as the frequency goes up to 2800 Hz. The gradual inclusion of feather powder raises the peak of the characteristic to slightly higher levels of frequency. The absorption coefficient decreases slightly with the addition of more feather powder. The composites based on polyethylene present marginally better absorption coefficients compared to the ones with polypropylene matrix.

The use of extrusion technology resulted in high-quality and adaptable products that have similar characteristics to those found in the market produced through traditional WPC technology. Furthermore, the products made from waste feathers from chicken and plastic waste can effectively replace traditional polyvinyl chloride-based WPC due to their advanced characteristics, including thermal and soundproof superiority.

Through thermoplastic processing, the environmental impact is significantly reduced. The assessment of thermoplastic technology sustainability is determined by analyzing factors such as Dissolved Organic Carbon (DOC) and Total Dissolved Solids (TDS). The TDS indicator is a major concern in the handling of feather waste, with DOC and TDS levels exceeding hazardous waste deposit limits by two to four times. However, when looking at the process of turning raw materials through injection and/or extrusion into final products (composite materials used in construction), the sustainability indicators return to normal, showing successful consumption and stabilization of potentially harmful chicken feather waste. The technology that utilizes waste feathers from chicken and plastic waste demonstrates full sustainability in terms of European regulations for recycling building materials, as long as the thermoplastic products can be self-recycled through the same technology by collecting them as building waste and reprocessing them through processes like grinding and extrusion, according to Life Cycle Assessment.

Author Contributions: Conceptualization, L.A.C., M.A.C., S.A. and R.C.C.; methodology, R.C.C., L.A.C., M.A.C. and S.A.; validation, R.C.C., L.A.C., M.A.C. and S.A.; formal analysis, L.A.C., M.A.C., S.A. and M.A.; investigation, R.C.C., L.A.C., M.A.C., S.A. and M.A.; data curation, R.C.C., L.A.C., M.A. and S.A.; writing—original draft preparation, R.C.C.; writing—review and editing, R.C.C., S.A. and M.A.; visualization, R.C.C.; supervision, R.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are presented in this study.

Acknowledgments: The research was based on the preliminary results of the Operational Programme Competitiveness 2014–2020, Project ID P_40_300, SMIS 105581, Subsidiary Contract 14352/2019.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Prasanthi, N.; Bhargavi, S.; Machiraju, P.V.S. Chicken feather waste: A threat to the environment. *Int. J. Innov. Res. Sci. Technol.* **2016**, *5*, 16759–16764.
2. Transforming Feather Waste into Sustainable Bio-Based Products, Horizon 2020 Project. Available online: https://unlock-project.eu/transforming-feather-waste-into-sustainable-bio-based-products-farrelly-mitchells-collaborative-role-in-eu-funded-unlock-project/ (accessed on 16 September 2024).
3. McGovern, V. Recycling poultry feathers: More bang for the cluck. *Environ. Health Perspect.* **2000**, *108*, 366–369. [CrossRef]
4. Industrial Feather Waste Valorisation for Sustainable KeRatin Based Materials, Horizon 2020 Project. Available online: https://cordis.europa.eu/project/id/723268 (accessed on 16 September 2024).
5. Feather Meal: A High-Nitrogen Organic Fertilizer. Available online: https://www.epicgardening.com/feather-meal/ (accessed on 16 September 2024).
6. Saba, M.; Akhter, A.; Ahmed, H.; Mehmood, Z.; Khan, A.; Zada, N.S.; Badshah, M.; Hasan, F.; Shah, A.A.; Khan, S. Sustainable Valorization of Chicken Feathers and Grocery Waste as Organic Fertilizer and its Impact on Yield and Quality of Spinach (*Spinacia oleracea*) Plant. *Commun. Soil Sci. Plant Anal.* **2023**, *54*, 2995–3005. [CrossRef]
7. Czech Researchers Find Use for Chicken Feathers as Fertiliser Feedstock. Available online: https://blog.agchemigroup.eu/czech-researchers-find-use-for-chicken-feathers-as-fertiliser-feedstock/ (accessed on 16 September 2024).
8. Feather Meal—Animal Byproduct Obtained by Hydrolysing, Drying and Grinding Poultry Feathers. Available online: https://www.feedtables.com/content/feather-meal (accessed on 16 September 2024).
9. Feather Meal: A Useful Addition to Fish Feed. Available online: https://www.allaboutfeed.net/animal-feed/feed-additives/feather-meal-a-useful-addition-to-fish-feed/ (accessed on 16 September 2024).
10. Zhuang, Y.; Wu, X.; Cao, Z.; Zhao, X.; Zhou, M.; Gao, P. Preparation and characterization of sponge film made from feathers. *Mater. Sci. Eng. C* **2013**, *33*, 4732–4738. [CrossRef]
11. Singh, A.; Maurya, S. Utilization of Waste Chicken feathers as a Sustainable Resource for the Production of Bioplastic film with Keratin and Polyvinyl alcohol. *J. Appl. Mat. Sci. Eng. Res.* **2024**, *8*, 1–15.
12. Ramesh, M.; Rajeshkumar, L.; Balaji, D.; Bhuvaneswari, V. 14-Keratin-based biofibers and their composites. In *Advances in Bio-Based Fiber-Moving Towards a Green Society*; The Textile Institute Book Series; Woodhead Publishing: Sawston, UK, 2022; pp. 315–334. [CrossRef]
13. Qin, C.; Wang, Y.; Gao, H.; Liu, X.; Nie, Y.; Ji, X. Insight into the Keratin Ratio Effect of the Keratin/Cellulose Composite Fiber. *ACS Appl. Polym. Mater.* **2023**, *6*, 265–272. [CrossRef]
14. Prochon, M. Effect of modified keratin from renewable sources on composites properties of synthetic isoprene rubber. *J. Elastomers Plast.* **2020**, *52*, 216–238. [CrossRef]
15. Ali, F.M.; Hossain, S.; Moin, T.S.; Ahmed, S.; Chowdhury, A.S. Utilization of waste chicken feather for the preparation of eco-friendly and sustainable composites. *Clean. Eng. Technol.* **2021**, *4*, 100190. [CrossRef]
16. Kurien, R.A.; Biju, A.; Raj, K.A.; Chacko, A.; Joseph, B.; Koshy, C.P. Chicken feather fiber reinforced composites for sustainable applications. *Mater. Today Proc.* **2022**, *58*, 862–866. [CrossRef]
17. Hu, C.; Reddy, N.; Yan, K.; Yang, Y. Acetylation of Chicken Feathers for Thermoplastic Applications. *J. Agric. Food Chem.* **2011**, *59*, 10517–10523. [CrossRef]
18. Wu, J.; Ullah, A.; Bressler, D. Thermoplastics from Poultry Feathers. Patent US20140060383A1, 6 March 2014. Available online: https://patents.google.com/patent/US20140060383A1/en (accessed on 16 September 2024).
19. Dutta, H.; Bora, D.; Chetia, P.; Bharadwaj, C.; Purbey, R.; Bohra, R.; Dutta, K.; Rajulu, A.V.; Sadiku, E.; Selvam, S.P.; et al. Biopolymer composites with waste chicken feather fillers: A review. *Renew. Sustain. Energy Rev.* **2024**, *197*, 114394. [CrossRef]

20. Aranberri, I.; Montes, S.; Azcune, I.; Rekondo, A.; Grande, H.-J. Fully Biodegradable Biocomposites with High Chicken Feather Content. *Polymers* **2017**, *9*, 593. [CrossRef] [PubMed]
21. Reddy, N.; Yang, Y. Light-weight polypropylene composites reinforced with whole chicken feathers. *J. Appl. Polym. Sci.* **2010**, *116*, 3668–3675. [CrossRef]
22. Vadillo, J.; Montes, S.; Grande, H.-J.; Verstichel, S.; Almqvist, J.; Wrześniewska-Tosik, K. Enhanced Biodegradability in Soil of Chicken Feather by Steam Explosion for Potential Application in Agricultural Biodegradable Plastics. *Polymers* **2023**, *15*, 3701. [CrossRef] [PubMed]
23. Lakhdar, A.; Moumen, A.; Mansouri, K. Recycled PVC with chicken feathers as bio-load. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1126*, 012008. [CrossRef]
24. Jóźwik-Pruska, J.; Wrześniewska-Tosik, K.; Mik, T.; Wesołowska, E.; Kowalewski, T.; Pałczyńska, M.; Walisiak, D.; Szalczyńska, M. Biodegradable Nonwovens with Poultry Feather Addition as a Method for Recycling and Waste Management. *Polymers* **2022**, *14*, 2370. [CrossRef]
25. Dieckmann, E.; Onsiong, R.; Nagy, B.; Sheldrick, L.; Cheeseman, C. Valorization of Waste Feathers in the Production of New Thermal Insulation Materials. *Waste Biomass Valorization* **2021**, *12*, 1119–1131. [CrossRef]
26. Soekoco, A.; Ichwan, M.; Hananto, A.; Mustafa, D. Application of chicken feather waste as a material of nonwoven insulator. *AIP Conf. Proc.* **2018**, *2014*, 020104. [CrossRef]
27. New Process Turns Waste Chicken Feathers into Biodegradable Plastic. Available online: https://phys.org/news/2011-04-chicken-feathers-biodegradable-plastic.html (accessed on 16 September 2024).
28. Colom, X.; Rahalli, A.; Cañavate, J.; Carrillo, F. Properties and Optimal Manufacturing Conditions of Chicken Feathers Thermoplastic Biocomposites. Available online: https://core.ac.uk/download/pdf/41777544.pdf (accessed on 16 September 2024).
29. Chikotsi, P.; Ncube, L.K.; Sibanda, N.R.; Ndlovu, L.N.; Nkomo, N.Z. Development of Starch/Keratin/Chitosan Composite Material as a Substitute for Polystyrene in Food Packaging. *J. Polym. Compos.* **2019**, *7*, 1–7.
30. Sharma, S.; Gupta, A.; Kumar, A.; Kee, C.G.; Kamyab, H.; Saufi, S.M. An efficient conversion of waste feather keratin into ecofriendly bioplastic film. *Clean. Technol. Environ. Policy* **2018**, *20*, 2157–2167. [CrossRef]
31. Oluba, O.; Obi, C.F.; Akpor, O.B.; Ojeaburu, S.I.; Ogunrotimi, F.D.; Adediran, A.A.; Oki, M. Fabrication and characterization of keratin starch biocomposite film from chicken feather waste and ginger starch. *Sci. Rep.* **2021**, *11*, 8768. [CrossRef] [PubMed]
32. Alshehri, W.; Khalel, A.; Elbanna, K.; Ahmad, I.; Abulreesh, H.H. Bio-plastic Films Production from Feather Waste Degradation by Keratinolytic Bacteria Bacillus cereus. *J. Pure Appl. Microbiol.* **2021**, *15*, 6913. [CrossRef]
33. Casadesús, M.; Macanás, J.; Colom, X.; Cañavate, J.; Álvarez, M.D.; Garrido, N.; Molins, G.; Carrillo, F. Effect of chemical treatments and additives on properties of chicken feathers thermoplastic biocomposites. *J. Compos. Mater.* **2018**, *52*, 3637–3653. [CrossRef]
34. Rangappa, S.M.; Parameswaranpillai, J.; Siengchin, S.; Jawaid, M.; Ozbakkaloglu, T. Bioepoxy based hybrid composites from nano-fillers of chicken feather and lignocellulose Ceiba Pentandra. *Sci. Rep.* **2022**, *12*, 397. [CrossRef]
35. Rinaldi, G.; Coccia, E.; Ferrentino, N.; Germinario, C.; Grifa, C.; Paolucci, M.; Pappalardo, D. Effect of Keratin Waste on Poly(ε-Caprolactone) Films: Structural Characterization, Thermal Properties, and Keratinocytes Viability and Proliferation Studies. *Adv. Polym. Technol.* **2024**, *2024*, 3308910. [CrossRef]
36. Najafi, S.K. Use of recycled plastics in wood plastic composites—A review. *Waste Manag.* **2013**, *33*, 1898–1905. [CrossRef]
37. Basalp, D.; Tihminlioglu, F.; Sofuoglu, S.C.; Inal, F.; Sofuoglu, A. Utilization of Municipal Plastic and Wood Waste in Industrial Manufacturing of Wood Plastic Composites. *Waste Biomass Valorization* **2020**, *11*, 5419–5430. [CrossRef]
38. Ribeiro, L.; Stolz, C.M.; Amario, M.; da Silva, A.L.N.; Haddad, A.N. Use of Post-Consumer Plastics in the Production of Wood-Plastic Composites for Building Components: A Systematic Review. *Energies* **2023**, *16*, 6549. [CrossRef]
39. Khan, A.A.; Parikh, H.; Qureshi, M.R.N. A review on chicken feather fiber and its application in composites. *J. Nat. Fibers* **2022**, *19*, 12565–12585. [CrossRef]
40. Global Wood Plastic Composites Market 2024–2033. Available online: https://www.custommarketinsights.com/report/wood-plastic-composites-market/ (accessed on 16 September 2024).
41. Paşayev, N.; Arabacilar, Z.; Çadir, M. Cleaning method of chicken feathers to obtain odorless fibers. *J. Nat. Fibers* **2022**, *19*, 1–12. [CrossRef]
42. Sahin, U. Chemical treatment of chicken feather prior to use as filling material. *Tekst. Konfeksiyon* **2018**, *28*, 547329.
43. Tesfaye, T.; Sithole, B.; Ramjugernath, D.; Ndlela, L. Optimisation of surfactant decontamination and pre-treatment of waste chicken feathers by using response surface methodology. *Waste Manag.* **2018**, *72*, 371–388. [CrossRef]
44. Pourjavaheri, F.; Mohaddes, F.; Shanks, R.A.; Czajka, M.; Gupta, A. Effects of different purification methods on chicken feather keratin. *Adv. Mater. Res.* **2014**, *941–944*, 1184–1187. [CrossRef]
45. Al-Souti, A.; Gallardo, W.; Claereboud, M.; Mahgoub, O. Effects of Autoclaving, Addition of Sodium Hydroxide and Their Combination on Protein Content and in vitro Digestibility of Chicken Feather. *Int. J. Poult. Sci.* **2018**, *17*, 356–361. [CrossRef]
46. Fitriyanto, N.A.; Ramadhanti, Y. Production of poultry feather hydrolysate using HCl and NaOH as a growth medium substrate for indigenous strains. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *951*, 012064. [CrossRef]
47. Said, M.; Yuliati, F.; Sukma, M. The effects of acidic and alkaline hydrolysis process on some physical and chemical properties of broiler chicken feathers. *Iran J. Appl. Anim. Sci.* **2019**, *9*, 529–540.

48. Common Poultry Parasites of Backyard Hens. Available online: https://www.theveterinarynurse.com/content/clinical/common-poultry-parasites-of-backyard-hens/ (accessed on 16 September 2024).
49. Yadav, D.; Anand, T.; Sharma, M.; Gupta, R.K. Microwave technology for disinfestation of cereals and pulses: An overview. *J. Food Sci. Technol.* **2012**, *51*, 3568–3576. [CrossRef]
50. Tamborrino, A.; Berardi, A.; de Lillo, E.; Ragone, G.; De Benedictis, M.; Tufariello, M.; Santino, A.; Leone, A. Using a continuous microwave system for postharvest almond disinfestation. *Postharvest. Biol. Technol.* **2023**, *201*, 112369. [CrossRef]
51. Das, I.; Kumar, G.; Shah, N.G. Microwave heating as an alternative quarantine method for disinfestation of stored food grains. *Int. J. Food Sci.* **2013**, *2013*, 926468. [CrossRef]
52. Microwave Machines for Woodworm Treatment and Sterilisation of Wood Pallets. Available online: https://www.microwavetechnology.com/en/wood-treatment/ (accessed on 16 September 2024).
53. Payette, M.; Work, T.T.; Drouin, P.; Koubaa, A. Efficacy of microwave irradiation for phytosanitation of wood packing materials. *Ind. Crops Prod.* **2015**, *69*, 187–196. [CrossRef]
54. Ciobanu, R.; Ursan, G.-A.; Aradoaei, M.; Batrinescu, G.; Banciu, A.R. Specific Tests Concerning Microwave Sterilization Efficiency of Combined Plastic and Paper Waste. In Proceedings of the 2018 IEEE International Conference and Exposition on Electrical and Power Engineering (EPE), Iasi, Romania, 18–19 October 2018; pp. 1000–1003. [CrossRef]
55. Miskiewicz, A.; Kowalczyk, P.; Oraibi, S.M.; Cybulska, K.; Misiewicz, A. Bird feathers as potential sources of pathogenic microorganisms: A new look at old diseases. *Antonie Leeuwenhoek J. Microbiol.* **2018**, *111*, 1493–1507. [CrossRef] [PubMed]
56. Shawkey, M.; Mills, K.L.; Dale, C.; Hill, G.E. Microbial Diversity of Wild Bird Feathers Revealed through Culture-Based and Culture-Independent Techniques. *Microb. Ecol.* **2005**, *50*, 40–47. [CrossRef] [PubMed]
57. Cason, J.; Buhr, R.J.; Hinton, A. Release of Escherichia coli from Feathered and Featherless Broiler Carcasses in Warm Wate. *Poult. Sci.* **2006**, *85*, 1807–1810. [CrossRef] [PubMed]
58. *SR EN ISO 6222:2004*; Water Quality. Enumeration of Culture Microorganisms. Colony Counting by Seeding in Nutrient Agar Culture Medium. ASRO: Bucharest, Romania, 2004. Available online: https://magazin.asro.ro/ro/standard/89897 (accessed on 16 September 2024).
59. Rutala, W.; Weber, J.D. Healthcare Infection Control Practices Advisory Committee (HICPAC). Guideline for Disinfection and Sterilization in Healthcare Facilities. 2008; p. 71. Available online: https://www.cdc.gov/infection-control/media/pdfs/guideline-disinfection-h.pdf (accessed on 16 September 2024).
60. Biswas, S.; Nazmi, A.; Pitesky, M.; Gallardo, R.; Pandey, P.; Biswas, S.; Nazmi, A.; Pitesky, M.; Gallardo, R.; Pandey, P. Thermal Inactivation of Escherichia coli and Salmonella Typhimurium in Poultry Carcass and Litter at Thermophilic Temperatures. *J. Appl. Poult. Res.* **2019**, *28*, 307–317. [CrossRef]
61. Ciobanu, R.C.; Schreiner, C.; Caramitu, A.R.; Aradoaei, S.; Aradoaei, M. Sustainability of the Technology for Obtaining Thermoplastic Building Materials from Non-Recyclable Mixed Plastic–Paper Packaging Waste. *Sustainability* **2024**, *16*, 3430. [CrossRef]
62. Subramani, T.; Krishnan, S.; Ganesan, S.; Nagarajan, G. Investigation of Mechanical Properties in Polyester and Phenylester Composites Reinforced With Chicken Feather Fiber. *Int. J. Eng. Res. Appl.* **2014**, *4 Pt 4*, 93–104.
63. Ullah, A.; Wu, J. Feather Fiber Based Thermoplastics: Effects of Different Plasticizers on Material Properties. *Macromol. Mater. Eng.* **2013**, *298*, 153–162. [CrossRef]
64. Gozdecki, K.; Wilczynski, A.; Kociszewski, M.; Tomaszewska, J.; Zajchowski, S. Mechanical properties of wood–polypropylene composites with industrial wood particles of different sizes. *Wood Fiber Sci.* **2012**, *44*, 14–21.
65. Murayama, K.; Ueno, T.; Kobori, H.; Kojima, Y.; Suzuki, S.; Aoki, K.; Ito, H.; Ogoe, S.; Okamoto, M. Mechanical properties of wood/plastic composites formed using wood flour produced by wet ball-milling under various milling times and drying methods. *J. Wood Sci.* **2019**, *65*, 5. [CrossRef]
66. Arnandha, Y.; Satyarno, I.; Awaludin, A.; Irawati, I.S.; Prasetya, Y.; Prayitno, D.A.; Winata, D.C.; Satrio, M.H.; Amalia, A. Physical and Mechanical Properties of WPC Board from Sengon Sawdust and Recycled HDPE Plastic. *Procedia Eng.* **2017**, *171*, 695–704. [CrossRef]
67. Aradoaei, S.; Bahrin, V.; Aradoaei, M.; Constantin, M.A.; Constantin, L.A.; Ionescu, I. Analysis of the Physical and Chemical Properties of Biocomposite Materials Obtained from Feather Flour and Polypropylene. *Mater. Plast.* **2020**, *57*, 325–332. [CrossRef]
68. Aradoaei, S.; Bahrin, V.; Aradoaei, M.; Constantin, M.A.; Constantin, L.A. Dielectric Spectroscopy Analysis of Composites Obtained from Thermoplastic with Feather Flour. In Proceedings of the 11th International Conference and Exposition on Electrical and Power Engineering (EPE 2020), Iasi, Romania, 22–23 October 2020; pp. 474–477.
69. *ASTM E-1461-07*; Standard Test Method for Thermal Diffusivity by the Flash Method. ASTM International: West Conshohocken, PA, USA, 2012. Available online: https://www.astm.org/e1461-07.html (accessed on 16 September 2024).
70. WPC—"Wood Plastic Composites". Available online: https://wpcproducts.com/ (accessed on 16 September 2024).
71. WPC Products. Available online: https://www.sundi-wpc.com/wpc-products/ (accessed on 16 September 2024).
72. *ISO 11654:1997*; Acoustics—Sound Absorbers for Use in Buildings—Rating of Sound Absorption. International Organization for Standardization: Geneva, Switzerland, 1997. Available online: https://www.iso.org/standard/19583.html (accessed on 16 September 2024).
73. Constantin, M.A.; Constantin, L.A.; Aradoaei, S.; Aradoaei, M.; Bratu, M.; Vasile, O. Acoustic Properties of a New Composite Material Obtained from Feather Flour and Recycled Polypropylene. *Mater. Plast.* **2020**, *58*, 84–93. [CrossRef]

74. *SR EN 12457-2:2003*; Characterisation of Waste—Leaching. European Standards: Plzen, Czech Republic, 2003. Available online: https://www.en-standard.eu/une-en-12457-2-2003-characterisation-of-waste-leaching-compliance-test-for-leaching-of-granular-waste-materials-and-sludges-part-2-one-stage-batch-test-at-a-liquid-to-solid-ratio-of-10-l-kg-for-materials-with-particle-size-below-4-mm-without-or-with-size-/ (accessed on 16 September 2024).
75. *ORDER 95/2005*; The Criteria for the Acceptance and Preliminary Acceptance Procedures for Waste at Storage and National List of Waste Accepted in Each Class of Waste Landfill, Official Monitor of Romania, Part 1, No. 452/27.05.2005. Available online: https://www.ecotic.ro/wp-content/uploads/2015/07/1e62400fcaa487767564187df6343e669b6f36ad.pdf (accessed on 16 September 2024).
76. Accurate-TDS-Measurement. Available online: https://www.alsglobal.com/es/News-and-publications/2022/11/Enviromail-42-Canada-Accurate-TDS-Measurement (accessed on 16 September 2024).
77. Dautović, J.; Vojvodić, V.; Tepić, N.; Ćosović, B.; Ciglenečki, I. Dissolved organic carbon as potential indicator of global change: A long-term investigation in the northern Adriatic. *Sci. Total Environ.* **2017**, *587–588*, 185–195. [CrossRef]
78. Salguero-Puerta, L.; Leyva-Díaz, J.C.; Cortés-García, F.J.; Molina-Moreno, V. Sustainability Indicators Concerning Waste Management for Implementation of the Circular Economy-Model on the University of Lome (Togo) Campus. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2234. [CrossRef]
79. A Wood Plastic Composite with up to 95% Recycled Materials. Available online: https://www.inno4sd.net/a-wood-plastic-composite-with-up-to-95-recycled-materials-283 (accessed on 16 September 2024).
80. Burgstaller, C.; Renner, K. Recycling of Wood–Plastic Composites—A Reprocessing Study. *Macromol* **2023**, *3*, 754–765. [CrossRef]
81. EU Construction and Demolition Waste Protocol. 2018. Available online: https://single-market-economy.ec.europa.eu/news/eu-construction-and-demolition-waste-protocol-2018-09-18_en (accessed on 16 September 2024).
82. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment. International Organization for Standardization: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 16 September 2024).