Chapter

Advancing Sustainable 3D Printing: Harnessing the Potential of Wastewater Sludge Incineration Ash for Composite Material Development and Practical Applications

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Abstract

This study delves into the unexplored fusion of wastewater sludge incineration ash (WSIA) and 3D printing, uncovering novel possibilities at the crossroads of environmental engineering and advanced manufacturing. The investigation centers on the integration of WSIA within the additive manufacturing framework, specifically material extrusion-fused deposition modeling (FDM). The study focuses on composite materials blending WSIA with commercial thermoplastics like ABS and PC, meticulously analyzing their physical, chemical, and mechanical attributes. Notably, the research highlights the potential for heightened mechanical strength in ABS composite materials, suggesting applications beyond 3D printing. Emphasizing long-term sustainability, the study advocates for the adoption of biodegradable plastics and underscores the importance of continuous research, mass production feasibility, and regulatory adaptations to fully unlock WSIA's potential. This synergy of innovation marries environmental awareness with technological progress, offering a harmonious trajectory to reshape manufacturing paradigms and nurture sustainable development. The study's outcomes present promising avenues for redefining the construction industry and advancing environmental conservation.

Keywords: 3D printing, composite materials, wastewater sludge incineration ash, recycling, sustainable manufacturing, material extrusion-fused deposition modeling

1. Introduction

In the intersection of environmental engineering and cutting-edge technologies, a symphony of possibilities unfolds. This chapter embarks on a journey that delves into the latent potential of wastewater sludge incineration ash (WSIA), unraveling its uncharted connection with the dynamic realm of 3D printing and its implications for the construction industry. As we embark on this exploration, we peel back the layers of complexity surrounding WSIA, unveiling a narrative that embodies both the challenges and prospects embedded within modern environmental concerns.

Metropolitan locales, exemplified by Seoul, house wastewater treatment facilities equipped with sludge incineration units. This incineration process, while crucial for waste management, leads to WSIA as a residual output. Curiously, this seemingly secondary product has evoked interest due to its latent utility. Notably, two wastewater treatment plants (N and S) among four plants annually produce over 12 tons of WSIA each, prompting its incorporation into the production of sturdy cement, thereby reinforcing the infrastructure. Intriguingly, the volume of WSIA and its associated disposal costs have experienced a progressive rise over recent years, attributable in part to a decline in private sector entities involved in its treatment. This confluence of factors underscores the imperative for innovative strategies to navigate the burgeoning landscape of WSIA.

Central to this discourse is the realm of 3D printing, an emerging paradigm within the broader context of environmental engineering and technology. Through an additive manufacturing approach, 3D printing propels a transformative capacity that redefines conventional manufacturing paradigms [1, 2]. This study accentuates the intersection of WSIA and 3D printing, postulating that the integration of WSIA within the additive manufacturing framework may yield pioneering avenues. As we navigate this uncharted terrain, it becomes evident that scant scholarly investigations have delved into the potential of WSIA within the 3D printing domain, except for a preliminary exploratory study conducted by our group [3], which investigated the viability of the binder jet (BJ)-3D printing method.

Intricately interwoven within this investigation is the material extrusion-fused deposition modeling (ME-FDM or FDM) method, a cardinal facet of 3D printing methodology [1, 4, 5]. FDM, revered for its popularity and versatility, predominantly employs thermoplastic materials for its additive manufacturing processes. However, in tandem with evolving needs, novel composite materials have surfaced to enhance the functional attributes of FDM-produced constructs. Remarkably, the use of WSIA within the FDM-3D printing realm remains uncharted. Parameters encompassing filament production, operational requisites spanning printer chambers and nozzles, material interactions, and resultant print quality converge as groundbreaking dimensions shaping the efficacy of FDM-3D printing endeavors [6–8]. This study endeavors to address this void by delving into the synthesis and utilization of WSIA-infused composite materials, with regard to commercial thermoplastics like ABS and PC, within the range of FDM-3D printing.

In sum, the aim of this study was to contribute to new environmental and 3D printing technologies using the potential of WSIA. Ultimately, this research seeks to present new possibilities through the convergence of environmental and technological aspects, suggesting a direction for sustainable development.

2. Review of plastic materials for the development of composite materials using WSIA for FDM-3D printing

The materials used in the FDM-3D printing process are crucial variables at the outset and remain among the most significant factors throughout the entire process [4, 5, 6–8]. In the context of this study, before delving into the development of composite materials using WSIA, it is essential to investigate what materials are available for use. Therefore, a foundational investigation of materials applicable to FDM-3D printing, along with a review of literature related to applied materials, was conducted to ascertain the potential for developing composite materials. The range of materials available for FDM-3D printing is extensive. Primarily, thermoplastic materials (or synthetic resins) in filament form are employed, encompassing not only everyday commodity materials but also engineering materials and high-performance thermoplastic resins. Typically, as the demand for precise and high-performance output increases, the required temperature and associated costs for the printing process also rise [9]. Plastic materials are categorized based on whether they are fossil-based or bio-based and whether they are biodegradable or non-biodegradable. This categorization divides them into four distinct regions, as depicted in **Figure 1** (Sections 1–4). For instance, bio-based and non-biodegradable plastics (Section 2) share nearly identical physicochemical properties with fossil-based and non-biodegradable plastics, differing primarily in production methods and raw materials. Additionally, ongoing research focuses on the development of composite materials beyond the presented individual materials [10–14]. However, a notable absence of research exists regarding the development of composite materials using WSIA.

From the array of plastics corresponding to the four sections (1–4) presented in **Figure 1**, we have selected eight thermoplastic-based materials that can potentially be applied in FDM-3D printing in a composite form when mixed with WSIA. These selections are based on the following criteria: (1) materials that are highly compatible with FDM printing or can be modified to suit printing conditions, (2) materials for which the introduction of WSIA is anticipated to enhance printability or physicochemical properties, and (3) materials that have been researched as composite materials or are deemed to have significant research value. The chosen thermoplastic materials are PP, PE, ABS, PC, PBS, PBAT, PLA, and PHA. Bio-based and non-biodegradable plastics falling within Section 2 (Bio-based & Non-biodegradable) were excluded due to their similarity in physicochemical composition to petroleum-based counterparts.

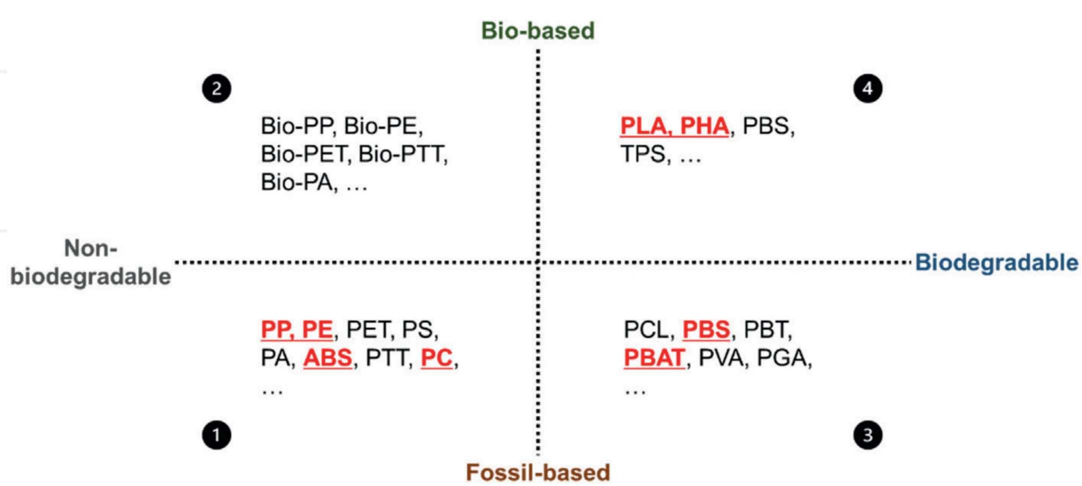

Figure 1.
Classification matrix of plastics based on source (fossil- or bio-based) and biodegradability potential of materials. The red, bold, and underlined ones are selected as potential candidates for composite materials with WSIA. PP, polypropylene; PE, polyethylene; PET, polyethylene terephthalate; PS, polystyrene; PA, polyamide or nylon; ABS, acrylonitrile-butadiene-styrene; PTT, Polytrimethylene terephthalate; PC, polycarbonate; PCL, Polycaprolactone; PBS, polybutylene succinate; PBT, polybutylene terephthalate; PBAT, polybutylene adipate terephthalate; PVA, polyvinyl alcohol; PGA, Polyglycolic acid; PLA, Polylactic acid; PHA, Polyhydroxyalkanoates; TPS, thermoplastic starch.

3. Materials and methods

3.1 WSIA characteristics

Wastewater sludge incineration ash (WSIA) typically appears as a dark brown or gray substance, and its chemical composition may vary depending on additives (e.g., coagulants) used in the wastewater treatment process. In this study, WSIA generated from the N-wastewater treatment plant (N-WWTP) located in Seoul was utilized for the development of composite materials for FDM-3D printing. WSIA samples collected in July 2021 (**Figure 2**) were subjected to analysis of their physical and chemical properties (particle size, oxides, hazardous substances).

The physical properties of the WSIA, specifically the particle size of the ash (powder), were analyzed using a wet analysis method (0.017 ~ 2000 μm) with laser diffraction and scattering analysis using a particle size analyzer (Beckman Coulter Inc., USA). In the process of dispersing the agglomerated ash particles, ultrasonic pre-treatment was carried out using an ethanol-based solvent.

Oxide compounds of the WSIA samples were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES, Perkin-Elmer Optima 8300, UK). There were a total of 20 analysis items, but the main nine components were SiO_2, TiO_2, Al_2O_3, K_2O, Na_2O, P_2O_5, MgO, CaO, and Fe_2O_3. Additionally, there were ten trace components including MnO, V_2O_5, SrO, ZrO_2, ZnO, CuO, BaO, Cr_2O_3, La_2O_3, and SO_3, as well as the loss on ignition.

For the analysis of hazardous substances in the WSIA samples, leaching analysis was conducted for six heavy metals (Cr^{6+}, Cu, Cd, Pb, As, and Hg) and cyanide compounds (CN). This analysis was followed by the Korean Official Wastes Test Method [15].

3.2 Composite materials synthesis

In this study, the base materials for composite material fabrication were selected from the aforementioned eight thermoplastic materials based on their suitability for mass production, easy availability, and immediate commercialization. Among the non-biodegradable and fossil-based plastics that fulfill these criteria,

Figure 2.
Wastewater sludge incineration ash (WSIA) sampled from N-WWTP.

acrylonitrile-butadiene-styrene (ABS) and polycarbonate (PC) were employed (ABS – STARLET from Polystar, China; PC – TEIREX from Samyang Corporation, Korea). The WSIA used as a component was also sampled in July 2021 from the N-WWTP.

The synthesis process of composite materials by mixing WSIA with ABS and PC is as follows: (1) mixing of WSIA with ABS and PC plastics, (2) homogenization of the mixed composite material after drying, (3) filament production by feeding the homogenized composite material into an extruder and cooling it, and (4) machining the filament into chip form. Following this sequence, the mixture of WSIA and ABS/PC was created by mixing WSIA into plastics at weight ratios of 0%, 9%, 17%, and 23% for each. The physical mixing was carried out using an overhead stirrer after measuring the weight according to the mixing ratio. The homogenized composite material was dried to a constant weight ratio, then inserted into an extruder, extruded, cooled, and formed into filaments. The FDM printer used in this study requires polymers to be in chip form; therefore, the produced filaments were further processed into chip form for use (**Figure 3**).

3.3 Physical, chemical, and mechanical properties of composite material

For the characterization of the produced composite material, an analysis of its physical, chemical, and mechanical properties was conducted. In terms of physical properties, density analysis was performed, and the synthesized composite material's surface was observed using a Field Emission Scanning Electron Microscope (FE-SEM) for surface characterization. Chemical properties were investigated through Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) for thermal analysis, Fourier-Transform Infrared Spectroscopy (FT-IR) for analysis of chemical bonds within the material, and leaching analysis of heavy metals (according to the waste process testing standards) to assess its harmfulness. Mechanical properties were evaluated by measuring the tensile strength and load deformation temperature, which are fundamental mechanical attributes of plastics.

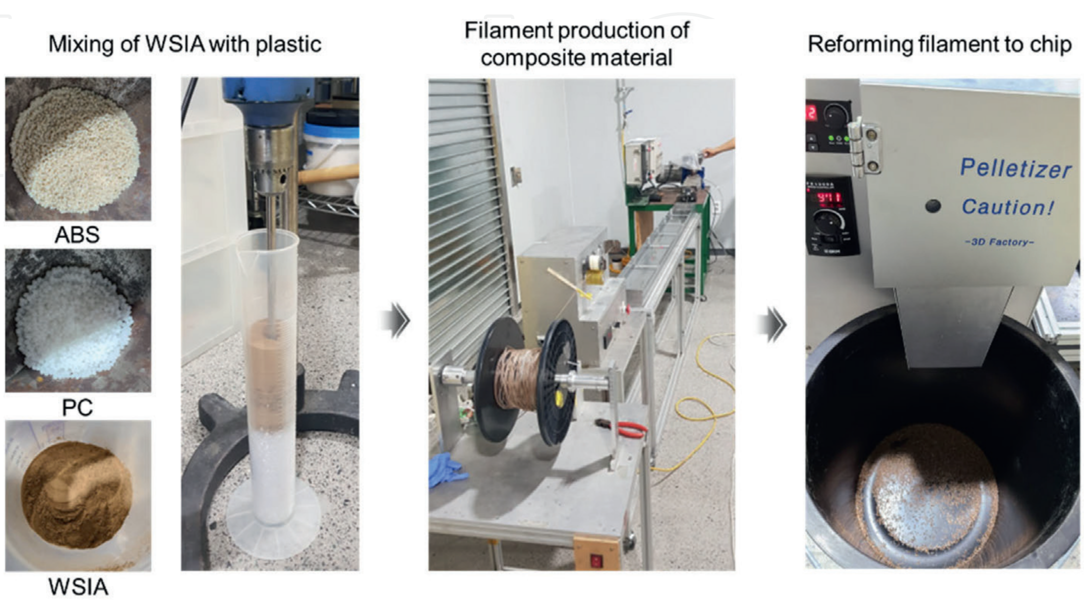

Figure 3.
Process of fabricating composite materials by mixing WSIA with ABS or PC.

3.3.1 Physical properties of composite material

For density analysis, the method B: Liquid Pyknometer Method from KS M ISO 1183-1 "Plastics - Methods for determining the density of non-cellular plastics" was employed. For surface observation of the composite material, analysis was conducted using an FE-SEM following the guidelines of KS I 0051: 1999 method.

3.3.2 Chemical properties of composite material

For the thermal characterization of the composite material, TGA was conducted to observe the mass loss trend with temperature ramping. The analysis conditions were nitrogen (N_2) up to 600°C, followed by air conditions from 600 to 870°C. To observe the calorimetric changes with temperature in the composite material, DSC analysis was performed. This analysis provides information about parameters like the glass transition temperature (T_g) of polymers and can offer references for 3D printing settings. The analysis conditions involved heating up to 230°C under a nitrogen gas atmosphere. FT-IR analysis was carried out to examine any structural changes in the material resulting from chemical bonding and mixing in the composite material. For component analysis of the composite material, ICP-OES was used to analyze both organic content (ignition loss) and oxides. To confirm the toxicity of the composite material, leaching tests were also conducted to measure the six heavy metals (Cr^{6+}, Cu, Cd, Pb, As, and Hg) and cyanide compounds (CN) according to waste process testing standards aforementioned.

3.3.3 Mechanical properties of composite material

To analyze the mechanical properties of the composite material, specimens were produced using FDM-3D printing, which is owned by 3D Factory (Ulsan, Korea). For the tensile strength specimens, they were fabricated according to the ASTM D638 Type 1 standard, and for the load deformation temperature specimens, they were created with an average width of 2.4 mm in accordance with ASTM D648. For tensile strength analysis, the specimens were tested at a crosshead speed of 50 mm/min following the ASTM D638-14 testing method. The results were obtained as the average of two tested specimens. Load deformation temperature, also known as Heat Deflection Temperature (HDT), was measured using the ASTM D648-18 testing method with Method B, which involves withstanding a light load (0.455 MPa) at elevated temperatures. The average width of the specimens used in the HDT test ranged from 2.1 to 2.7 mm.

4. Results and discussion

4.1 Results of WSIA characteristics

When compared with previous research [3], the nine main components did not show significant differences, with SiO_2 (28.2%), Al_2O_3 (24.4%), P_2O_5 (21.4%), Fe_2O_3 (9.4%), and CaO (7.7%) being the predominant constituents in order. The total content of the 10 trace oxides was 1.18%, and the ignition loss was 2.08% (**Table 1**).

The results of leaching analysis for the six heavy metals (Cr^{6+}, Cu, Cd, Pb, As, Hg) and cyanide compounds (CN), just like the measurements taken in June 2020, showed

Total	SiO_2	TiO_2	Al_2O_3	K_2O	Na_2O	P_2O_5	MgO	CaO	Fe_2O_3
96.64	28.2	0.43	24.4	1.7	0.97	21.4	2.45	7.7	9.39

Table 1.
WSIA's chemical (oxide compounds) composition ratio (%) from N-WWTP.

that all substances except for arsenic (As) were not detected, and even arsenic was found to be below the "designated waste" classification standard (**Table 2**).

The particle size distribution of WSIA is presented in **Figure 4**, with an average particle size (mean size) of 20.0 μm, a median size of 18.4 μm, and a mode of 27.9 μm. The minimum and maximum values were 0.445 μm and 67.5 μm, respectively. When compared to the average particle size of WSIA in the previous study [3], the particle size of this ash is less than half, but there is not a significant difference in the distribution size and proportion.

4.2 Composite materials synthesis

ABS and PC are the most common and widely used materials in the FDM printing method, with numerous related studies being conducted [4, 5]. While ABS is more commonly used, the selection of PC is driven by its qualities as an engineering plastic, offering high mechanical strength, heat resistance, and impact resistance, making it suitable for structures that need to withstand loads.

	Cr^{6+}	Cu	Cd	Pb	As	Hg	CN
"Designated waste" classification standard	1.5	3	0.3	3	1.5	0.005	1
WSIA	N.D.	N.D.	N.D.	N.D.	0.107	N.D.	N.D.

Table 2.
Contents of heavy metals and cyanide compound in WSIA (unit: mg/L).

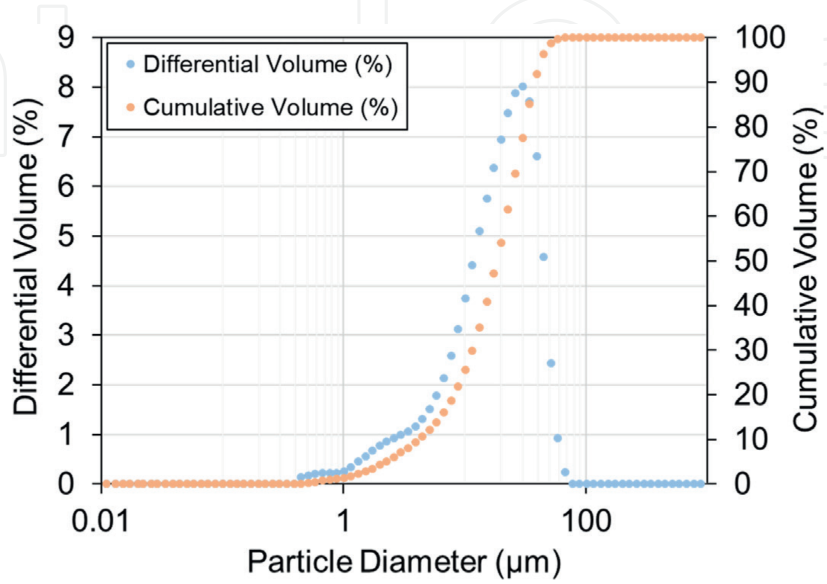

Figure 4.
Particle size distribution of WSIA sampled in July, 2021 from N-WWTP.

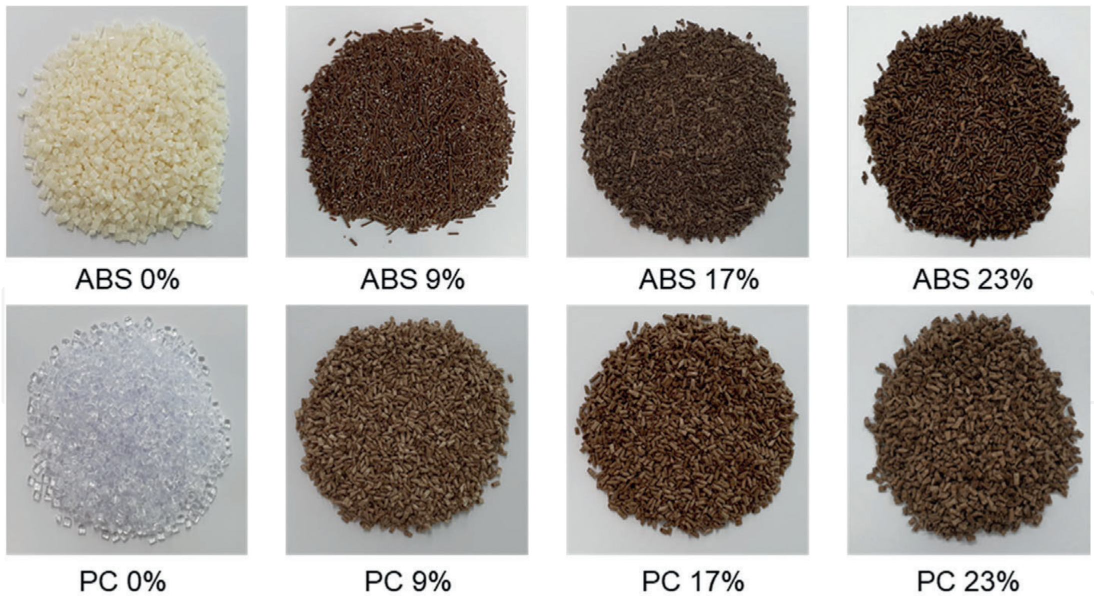

Figure 5.
Composite material chips with varying WSIA mixing ratios (ABS, PC).

The plastic (ABS, PC) and synthesized composite material chips are depicted in **Figure 5**. Pure ABS chips (without WSIA) exhibit an opaque ivory color, gradually transitioning to a darker brown as WSIA is added. Similarly, pure PC chips (without WSIA) appear as transparent white, and as with ABS composite material, the addition of WSIA results in a darker brown hue.

4.3 Physical, chemical, and mechanical properties of composite material

4.3.1 Physical properties of composite material

For ABS without the addition of WSIA, the average density was 1.053 g/cm^3. When WSIA was mixed in at weight ratios of 9%, 17%, and 23%, the measured densities were 1.067, 1.039, and 1.143 g/cm^3, respectively. The density changes after mixing were found to be insignificant. In the case of PC without the addition of WSIA, the average density was 1.193 g/cm^3. With the addition of WSIA at weight ratios of 9%, 17%, and 23%, the densities decreased to 0.736, 0.699, and 0.853 g/cm^3, respectively, representing a maximum reduction of up to 41.4% in density after mixing (**Figure 6**).

For the surface observation of the composite material, an FE-SEM was utilized for analysis. At a low magnification of 500×, the overall sample conditions were observed. The surfaces of pure ABS and PC plastic pellets appeared smooth, while for pellets containing mixed WSIA, a rough surface with WSIA particles of average size 20 μm physically mixed with the polymer was observed (**Figure 7**).

4.3.2 Chemical properties of composite material

Based on the results of thermal analysis (Thermogravimetric Analysis or TGA), for pure ABS (with 0% WSIA content), around 97.9% of the mass decreased around 408°C. As the WSIA content in ABS increased from 9 to 23%, the mass reductions occurred at approximately 90.4%, 78.6%, and 72.5% around 416°C respectively (**Figure 8a**). In the case of ABS composite materials with added WSIA, the

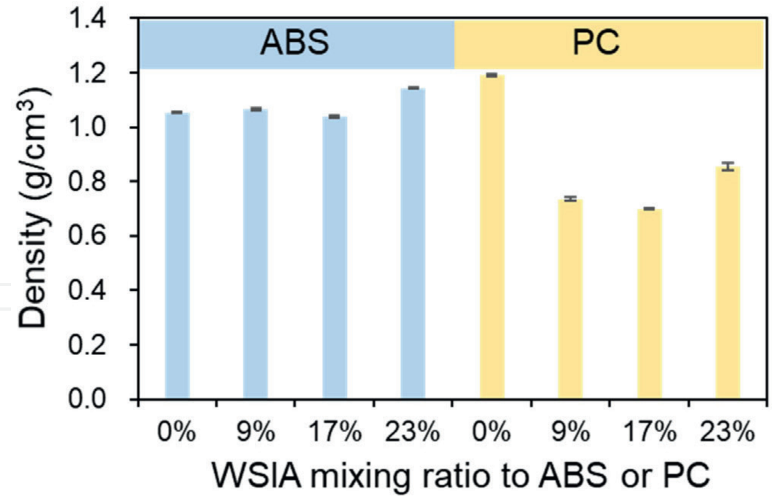

Figure 6.
Density of composite materials with varying WSIA mixing ratio (0–23%).

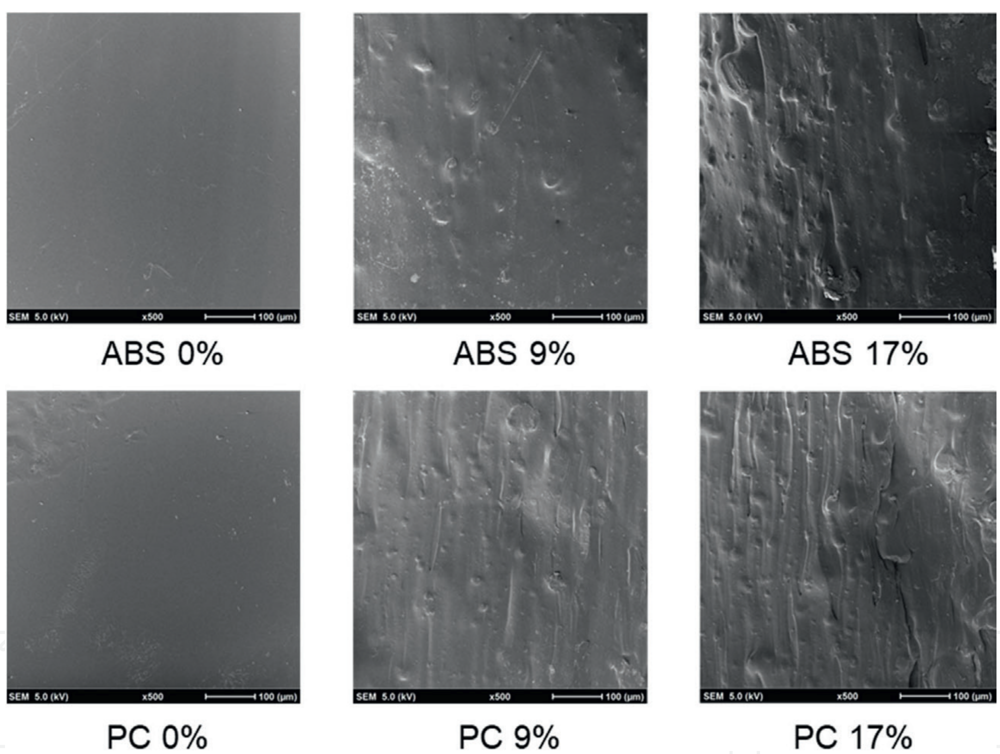

Figure 7.
FE-SEM images of composite materials with WSIA mixing ratio (0–17%).

decomposition temperature increased by about 8°C from 408°C to around 416°C, indicating a slight improvement in thermal stability [16]. For pure PC (with 0% WSIA content), mass reductions of around 98.2% were observed around 514°C and 627°C. When WSIA content in PC was increased to 9%, 17%, and 23%, the mass reductions took place around temperatures ranging from 490 to 500°C and 625°C, resulting in mass reductions of approximately 88.8%, 81.2%, and 77.4% respectively (**Figure 8b**). In the case of PC composite materials with added WSIA, the decomposition temperature decreased from 514°C to the range of 490–500°C, leading to a decrease in thermal stability by a minimum of 13°C to a maximum of 23°C. From the TGA analysis, it was observed that organic polymer materials such as ABS and PC

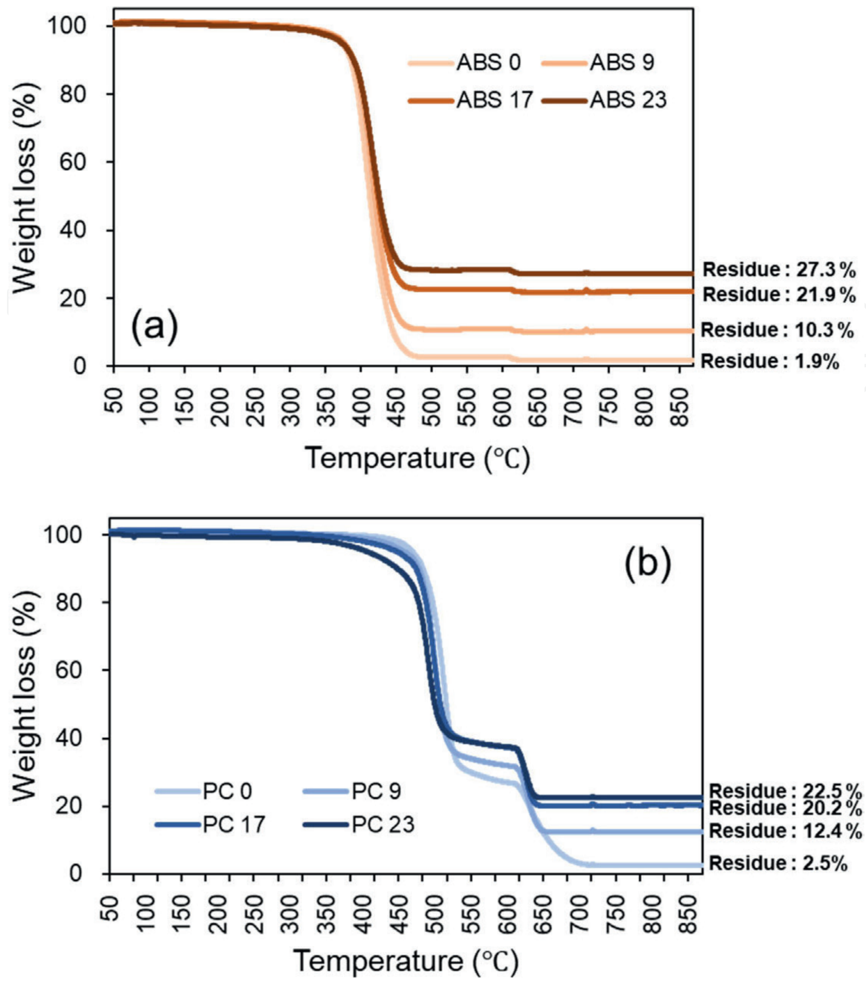

Figure 8.
TGA graphs of composite materials according to WSIA mixing ratios (0–23%) to ABS (a) and PC (b).

undergo thermal degradation at relatively low temperatures below 600°C, while the inorganic WSIA component remains in proportion to the mixing ratio. Additionally, despite the increased decomposition temperature of ABS composite materials after WSIA mixing, PC composite materials exhibited decreased decomposition temperatures. This observation indicates that ABS composite materials have relatively higher thermal stability compared to PC composite materials.

Differential Scanning Calorimeter (DSC) analysis results revealed that in the case of pure ABS, a glass transition temperature (T_g) was observed around 101.1°C (**Figure 9a**) [17]. As the WSIA was mixed in ratios of 9, 17, and 23%, T_g was observed at approximately 102.8°C, 101.2°C, and 100.3°C, respectively. While the main T_g showed no significant change, an additional peak was observed at 75°C, indicating a mixed pattern between the two particles (WSIA and ABS) (**Figure 9a**) [18]. For pure PC, a T_g was observed around 147.2°C (**Figure 9b**) [17], and as the incineration residue was mixed in ratios of 9–23%, T_g values were observed at approximately 141.1°C, 138.9°C, and 136.8°C, respectively. It was confirmed that T_g decreased by 6 ~ 10°C as the WSIA content increased (**Figure 9b**). Through the DSC analysis of T_g influenced by intermolecular interactions, it can be inferred that in the case of ABS composite materials, the main T_g remained relatively unchanged, but an additional peak was observed at the front end, indicating two dispersion patterns between the WSIA and the polymer. Similarly, for PC composite materials, the addition of the WSIA seemed

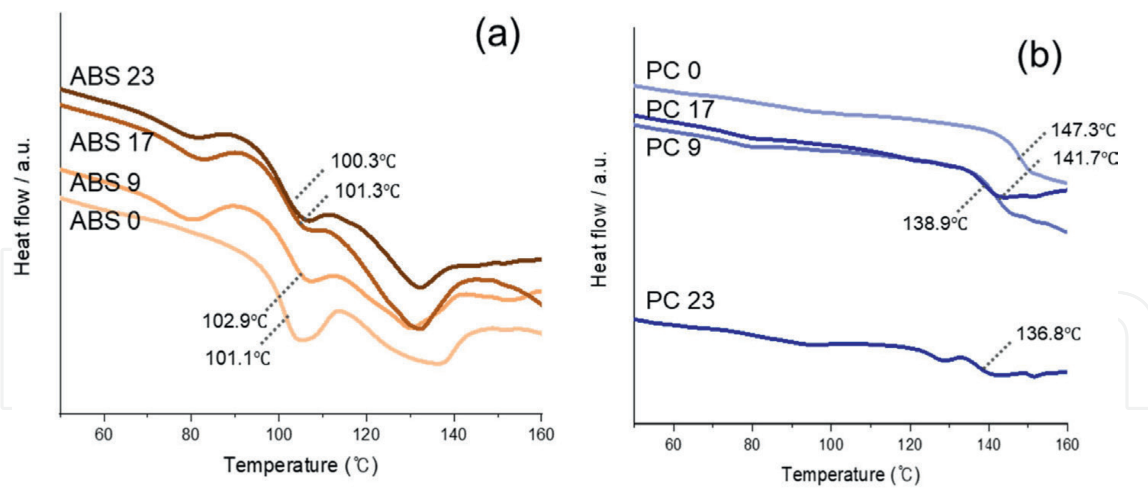

Figure 9.
DSC graphs of composite materials according to WSIA mixing ratios (0–23%) to ABS (a) and PC (b).

to influence the intermolecular interactions between the residue and PC molecules, leading to a decrease in T_g.

The results of FT-IR analysis conducted to assess potential changes in chemical bonding and material structure due to the chemical combination and mixing of WSIA composite materials are shown in **Figure 10**. In the case of pure ABS, distinctive vibrational peaks were observed at 910, 965, 1493, 1639, 2237, 2850, 2920, and 3026 cm^{-1} [19]. When the WSIA was mixed in ratios of 9% and 17%, the same peaks were observed as in pure ABS samples (**Figure 10a**). For pure PC, distinct vibrational peaks were observed at 1220, 1503, 1769, and 2965 cm^{-1} [19]. Similarly, when the WSIA was mixed at 9% and 17%, the same peaks as in pure PC samples were observed (**Figure 10b**). From the FT-IR analysis, it is deduced that the chemical bonding remained unchanged due to the physical mixing of both ABS and PC composite materials with WSIA.

Through compositional analysis of the composite material, it was confirmed that in the case of pure ABS and PC, the result of loss on ignition was determined to be 99.8% and 99.9%, respectively, confirming that they primarily consist of carbon and other organic materials (**Table 3**). As the WSIA was mixed with each plastic (ABS or PC) in the range of 9–17%, an increase in the proportion of inorganic components (such as SiO_2, Al_2O_3, P_2O_5, Fe_2O_3) from the incineration residue was observed. This indicates that the WSIA was appropriately mixed according to the weight ratio. Additionally, the hazardous material analysis results indicated that all parameters of 6 heavy metals (Cr^{6+}, Cu, Cd, Pb, As, and Hg) and CN were below detectable levels, confirming the absence of concerns regarding safety in usage.

4.3.3 Mechanical properties of composite material

The tensile strength analysis results showed that the pure ABS had a strength of 12.8 MPa, while mixing the WSIA from 9 to 23% resulted in strengths of 31.3, 32.1, and 26.5 MPa, respectively, achieving a maximum increase of up to 2.5 times. The highest strength was observed at a mixing ratio of 17%. For pure PC, the initial tensile strength was 32.9 MPa, which was more than twice that of pure ABS. However, as the WSIA was mixed from 9 to 23%, the strengths decreased to 12.7, 8.16, and 9.07 MPa, exhibiting a reduction of over 4 times (**Figure 11a**). In terms of heat deflection temperature (HDT) analysis, pure ABS showed deformation at 90°C. Mixing the ash material from 9 to 23% increased the deformation temperature to 95, 96, and 96°C,

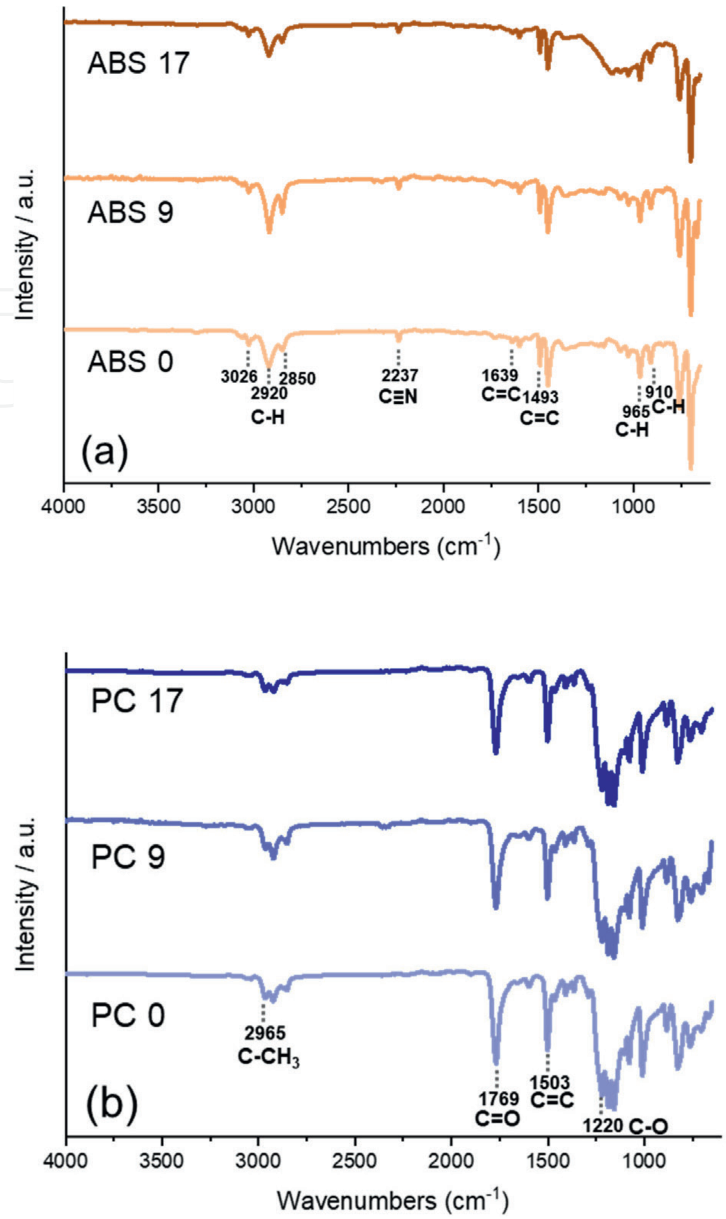

Figure 10.
FT-IR graphs of composite materials according to WSIA mixing ratios (0–17%) to ABS (a) and PC (b).

respectively. On the other hand, pure PC exhibited deformation at 138°C. Mixing the ash material from 9 to 23% led to a gradual decrease in deformation temperature to 124, 116, and 117°C, respectively (**Figure 11b**). Based on the mechanical property analysis results, it was determined that the tensile strength and HDT of the ABS composite material increased as the WSIA was mixed, leading to improved mechanical strength. The optimal mixing ratio was found to be between 9% and 17%. However, in the case of PC, it was observed that the tensile strength and HDT decreased as the WSIA was mixed, indicating that the WSIA composite was not suitable for enhancing the mechanical properties of PC.

4.4 Outlook

In this study, the feasibility of utilizing WSIA as a 3D printing composite material from a material application perspective was examined. However, its applicability extends

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		SiO_2	Al_2O_3	P_2O_5	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	Others	Ig.loss
ABS	0%	0.06					0.06				0.06	99.8
	9%	1.92	1.6	1.66	0.73	0.52	0.25	0.24	0.08	0.04	0.15	92.7
	17%	4.46	4.47	3.85	1.69	1.25	0.43	0.32	0.15	0.1	0.38	82.9
PC	0%										0.07	99.9
	9%	2.30	2.31	1.94	0.91	0.69	0.21	0.25	0.09	0.06	0.17	91.0
	17%	0.06					0.06				0.06	99.8

Table 3.
Chemical (oxide compounds) composition of composite materials according to WSIA mixing ratios (0–17%) to ABS and PC (unit: %).

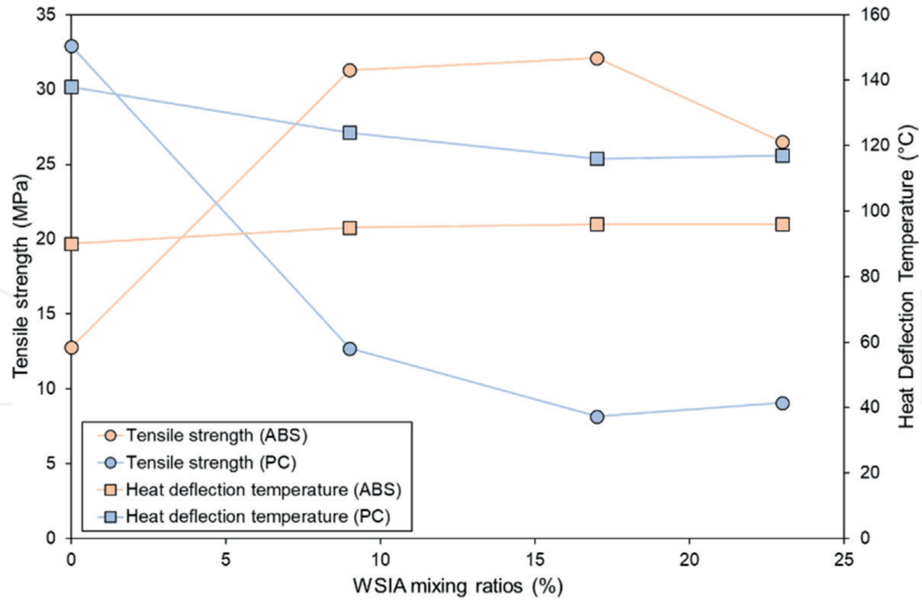

Figure 11.
Results of tensile strength and heat deflection temperature of WSIA composite according to the mixing ratios (0–23%).

beyond 3D printing to general forming processes such as injection molding or extrusion. Moreover, since WSIA can commonly be used as a construction material, its application in the construction field is possible when used as a 3D printing material (e.g., concrete structures, irregular pavilions) [20–22]. Additionally, it can be utilized in outdoor landscaping facilities (benches, pergolas, fences, lighting fixtures, etc.) and other daily life areas (balance bikes, kick scooters, bicycle racks, etc.) (**Figure 12**) [23, 24].

While products using fossil-based and non-biodegradable plastic materials are currently being produced not only through 3D printing but also through general forming processes, the need for research and technological development using more environmentally friendly bio-based/biodegradable plastic materials are increasing. In a long-term perspective, the development of composite materials should also aim at the utilization of biodegradable/bio-based plastics (Section 4 of **Figure 1**). Based on the results of this study, continuous research and development considering mass production and efficient biodegradation are necessary. Furthermore, improvements in the existing legal framework are required to expand the possibilities for WSIA's utilization and commercialization. Initially, this could be achieved by actively leveraging

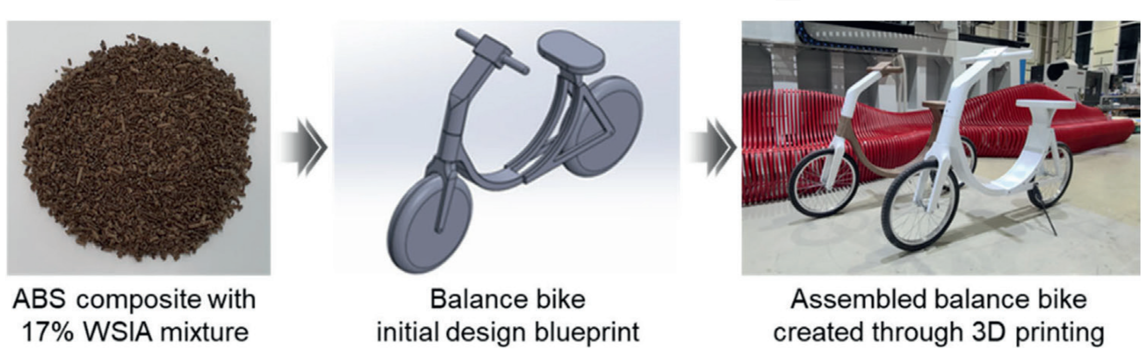

Figure 12.
The initial prototype of balance bike 3D printed using ABS composite material with 17% WSIA mixture (wood color: WSIA composite material, white color: ABS only).

the existing recycling regulations under waste management laws. Subsequently, further improvements could be made to the recognition system for WSIA use within the framework of circular resource management regulations.

5. Conclusions

The exploration of wastewater sludge incineration ash (WSIA) integration with 3D printing uncovers innovative opportunities at the nexus of environmental engineering and advanced manufacturing. The study addresses the uncharted potential of utilizing WSIA in the additive manufacturing framework, particularly within the material extrusion-fused deposition modeling (FDM) method. Focused on composite materials infused with WSIA and commercial thermoplastics like ABS and PC, the investigation meticulously analyzes physical, chemical, and mechanical properties. The findings showcase the potential for enhanced mechanical strength in ABS composite materials, opening avenues for broader applications beyond 3D printing. The study advocates for long-term sustainability by considering the utilization of biodegradable plastics and emphasizes the need for continuous research, mass production viability, and regulatory reforms to fully realize WSIA's potential. In this symphony of innovation, environmental consciousness converges with technological advancement, presenting a harmonious path toward reshaping manufacturing paradigms and fostering sustainable development.

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Conflict of interest

The authors declare no conflict of interest.

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