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Potential of Waste Toner Powder for Sustainable Energy Production: An Assessment of Its Suitability for Bio-Briquette Applications

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Abstract: This study investigates the feasibility of utilizing waste toner powder (WTP) in the energy sector, focusing on its application in bio-briquette production. The research comprised two main phases: the characterization of WTP's structural, morphological, and fuel properties, followed by an evaluation of its potential as a biofuel component in direct combustion processes. WTP samples were collected from a recycling facility specifically established for toner cartridge recycling in the Elazığ Organized Industrial Zone. These samples were stored under appropriate conditions and analyzed using advanced techniques. The structural and morphological properties were examined using FTIR, SEM-EDX, and particle size distribution analyses. Particle size measurements revealed average diameters of 182.6 nm in toluene and 308.4 nm in benzene, with toluene providing a narrower and more uniform distribution. Fuel properties were assessed through proximate and ultimate analyses. The results indicated that WTP contains 88.38% volatile matter, 4.91% ash, and 2.67% moisture, with a higher heating value (HHV) of 35.56 MJ/kg. The ultimate analysis highlighted a significant carbon content (32.12%) and low nitrogen levels (1.98%), reinforcing its potential as a fuel. WTP's dispersion behavior was also evaluated in both media, confirming better stability in toluene. These findings demonstrate that WTP possesses favorable fuel properties, such as a high calorific value and strong binding capabilities, making it a promising raw material for bio-briquette production when mixed with powdered biomass waste sources like furniture factory waste. Producing biofuel pellets with WTP could enhance energy efficiency, reduce emissions, and improve transport and storage convenience. Utilizing WTP as an energy source not only provides a high-value solution for waste management but also supports environmental sustainability and landfill preservation.

Keywords: Waste Toner Powder, Bio-briquette, E-Waste Recycling, Energy Recovery, Sustainable Fuel Development.

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1. INTRODUCTION

The demand for electrical and electronic equipment (EEE) has been rapidly increasing due to urbanization, industrialization, and population growth. Devices such as refrigerators, air conditioners, computers, printers, and cartridges have become integral to daily life and play a significant role in the global economy (Cui and Forssberg, 2003). However, the widespread use of EEEs has led to a surge in e-waste, which contains both environmentally harmful and valuable components (Nnorom et al., 2008).

In 2003, Western Europe generated 6 million tons (Mt) of e-waste, while over 315 million computers in the United States reached the end of their service life in 2004. By 2006, global e-waste production had risen to 20–50 Mt annually, with most contributions from Europe, the United States, and Australia. In the coming years, emerging economies such as China, Eastern Europe, and Latin America are expected to become major e-waste producers (Robinson, 2009). Despite these trends, e-waste was recognized as a significant issue only in 2008, when China implemented the "Waste Electrical and Electronic Equipment Recycling Management Regulation" to address this growing challenge.

Global e-waste production has risen by 9.2 Mt since 2014 and is projected to reach 74.7 Mt by 2030, nearly doubling within 16 years. In 2019, Asia led global e-waste generation with 24.9 Mt, followed by the Americas (13.1 Mt) and Europe (12 Mt), while Africa and Oceania produced 2.9 Mt and 0.7 Mt, respectively. On a per capita basis, Europe topped the list with 16.2 kg per person, trailed by Oceania (16.1 kg) and the Americas (13.3 kg), whereas Asia and Africa lagged significantly at 5.6 kg and 2.5 kg per person, respectively (Forti et al., 2020). The surge in e-waste is driven by increased EEE consumption, shorter product lifecycles, and limited repair options. Recycling and reuse are widely acknowledged as the most effective strategies for managing e-waste. However, in 2019, only 9.3 Mt (17.4%) of e-waste was officially documented as collected and recycled, underscoring the inability of recycling efforts to match the pace of e-waste generation (Forti et al., 2020). While the number of countries adopting e-waste policies has grown from 61 in 2014 to 78, progress in regulation and enforcement remains inconsistent, hindered by limited investment and political will. Consequently, initiatives to improve the collection and recycling of EEE waste are critical at both national and international levels (Devin et al., 2014). Additionally, ongoing research is exploring innovative ways to convert e-waste into high-value-added products (Gaikwad et al., 2018).

Despite efforts by the Chinese government to refill, renew, and remanufacture used toner cartridges under the "Waste Electrical and Electronic Equipment Recycling Management Regulation" enacted in 2008, the global number of discarded toner cartridges has continued to rise. Over the past two decades, even with advancements in digital communication and electronic document management systems, printers and cartridges remain significant sources of e-waste. Globally, approximately 375 million cartridges are added to e-waste annually—equating to around one million cartridges per day. Toner cartridges, composed of 35% low-cost HIPS (High-impact polystyrene) plastic, 39% iron, 8% toner powder, 13% aluminum, and 5% other materials, are largely recyclable and reusable. However, their limited lifespan, resistance to degradation in landfills, and challenges in recycling make them a substantial environmental concern. Improper disposal can result in soil and water pollution, posing significant health risks (Babar et al., 2019). Given their increasing contribution to global e-waste and the environmental hazards they pose, developing sustainable technologies for recycling and reusing waste toner cartridges is critical. This necessity highlights the importance of addressing toner cartridge waste as part of broader e-waste management efforts.

In recent years, international efforts have focused on reclaiming waste toner cartridges and processing solid waste. Studies consistently highlight that landfilling and direct incineration are unsuitable disposal methods for toner cartridges due to several factors: (I) Plastics made from engineering-grade polymers degrade extremely slowly in the environment. (II) Incineration releases toxic gases, such as furans and dioxins, posing severe environmental and health risks. (III) Residual toner can leak during storage or incineration, contaminating the environment. As a result, mechanical recycling methods are widely regarded as the preferred approach for managing e-waste, including toner cartridges, as they minimize secondary pollution during the recovery process (Li et al., 2007; Wu et al., 2008; Veit et al., 2006; Park et al., 2009).

To determine the appropriate storage conditions for waste toner powder and facilitate its conversion into high-value-added products, it is essential to first categorize different cartridge types—inkjet, laser, and duplicator cartridges—and analyze their basic components.

Inkjet Printers: These use inks containing harmful chemicals such as butyl urea, cyclohexanone, ethoxylated acetylenic diols, ethylene glycol, and various sulfur-based dyes. The printing process releases volatile organic solvents, contributing to environmental pollution (Aydemir et al., 2020). Home inkjet printers typically require frequent replacement of cartridges (black, cyan, magenta, and yellow), leading to significant waste generation.

Laser Printers and Copiers: These rely on dry or wet toner formulations. Dry toners are primarily composed of acrylic and styrene powders mixed with pigments, while liquid toners use acrylic resins with added dyes for vibrant colors. Plastic resins, often comprising 45–90% of toner powder, are typically made from styrene and acrylic polymers (Vucinic et al., 2013). Additionally, certain toners contain iron oxide for magnetic properties, along with metals and semiconductors to enhance triboelectric and superflow characteristics.

The combination of organic and inorganic materials in toner powders ensures stability and adhesion to paper but renders them nearly non-biodegradable and environmentally harmful. Their persistence in the ecosystem poses significant environmental threats, highlighting the urgent need for sustainable management strategies (Nakadate et al., 2018; Pirela et al., 2017).

To establish suitable storage conditions for waste toner powder and enable its transformation into high-value products, it is crucial to categorize cartridge types—such as inkjet, laser, and duplicator cartridges—and understand their core components. Inkjet printers use inks containing harmful chemicals like butyl urea, cyclohexanone, ethylene glycol, and sulfur-based dyes, which release volatile organic solvents during printing and contribute to environmental pollution (Aydemir et al., 2020). Additionally, frequent cartridge replacements, especially in home printers with black, cyan, magenta, and yellow cartridges, exacerbate waste generation. Laser printers and copiers, on the other hand, utilize dry or wet toners. Dry toners are composed of acrylic and styrene powders mixed with color pigments, while liquid toners contain acrylic resins and dyes to produce vibrant images. These toners are primarily made up of plastic resins—typically 45–90% styrene and acrylic polymers—and may also include iron oxide for magnetic properties, as well as metals and semiconductors to enhance functionality (Vucinic et al., 2013). While these materials ensure toner stability and strong adhesion to paper, they are highly resistant to biodegradation, posing significant environmental challenges. The persistence of these materials in ecosystems highlights the critical need for effective waste management and recycling solutions (Nakadate et al., 2018; Pirela et al., 2017).

Considering the toner powder composition summarized above, it has been shown that waste toner powder not only poses environmental and human health risks but also possesses valuable properties, making it a waste material worth evaluating (Parthasarathy et al., 2021). Consequently, various studies have been conducted in recent years to explore its potential applications (Saini et al., 2020; Bhongade et al., 2019; Saini et al., 2019; Babar et al., 2019; Akilarasan et al., 2018; Kuma et al., 2018). The scope of these studies includes the following: the production of waste toner-derived carbon/Fe_3O_4 nanocomposites for high-performance supercapacitors (Subramani et al., 2019); the creation of activated carbon as a promising anode for sodium-ion batteries (Uttam et al., 2019; Arjunan et al., 2021); the one-pot conversion of waste toner powder into 3D graphene oxide hydrogel (Tian et al., 2019); the production of micro sorbents from waste toner for use as low-cost magnetic solid-phase extraction adsorbents for Pb analysis (Yu et al., 2022); the development of 3D graphene oxide hydrogels derived from waste toner as adsorbents (Tian et al., 2021); the synthesis of magnetic nanocomposites for the removal of Cr (Zhu et al., 2018); and the creation of low-cost, high-activity, and highly reusable engineered catalysts for persulfate-based advanced oxidation processes in wastewater treatment (Huang et al., 2022). Other applications include the use of waste toner carbon in fully printable mesoscopic perovskite solar cells (Ma et al., 2021) and the design of cheap, environmentally friendly microwave absorbers from waste toner powders (Habib et al., 2021). However, studies focusing on the evaluation of waste toner powder in the energy sector remain limited. No industrial-scale research has been identified; current studies are confined to laboratory-scale R&D efforts. Examples include hydrogen production from waste toner powder activated by Ni under visible light (Zhang et al., 2022), vacuum pyrolysis and the product dispersion/characterization of toner waste powder (Dong et al., 2017), and the production of a high-efficiency 3D solar evaporator derived from waste egg trays and toner for fresh water generation (Ivan et al., 2022).

No studies have been identified on the evaluation of waste toner powder as an energy source in direct combustion processes. However, Patronov and Tonchev (2011) highlighted that toner cartridges and waste toner powder have a high calorific value (approximately 30 MJ/kg), exceeding that of traditional fossil fuels, making them a viable fuel option under controlled combustion conditions. They also cautioned that uncontrolled combustion could result in the release of polycyclic aromatic hydrocarbons (PAH), furans, and dioxins, leading to significant environmental pollution. The increasing environmental concerns associated with fossil fuels, such as greenhouse gas emissions, acid rain, global warming, and climate change, have underscored the growing importance of biofuels as a renewable and clean energy source (Banks et al., 2016). In our country, energy consumption continues to rise alongside improvements in living standards and industrialization, resulting in heavy dependence on fossil fuels. Thus, adopting bioenergy as a renewable resource is crucial to reducing national reliance on foreign energy and enhancing energy security. The furniture factory waste dust planned for use in this study is primarily lignocellulosic biomass, consisting of chopping dust generated during furniture production that can remain suspended in the air. This biomass can be classified as a carbon-neutral fuel and a clean energy source, with significantly lower sulfur and nitrogen content compared to fossil fuels. Combustion of fossil fuels is known to produce minimal SO_x and NO_x emissions (Kemper, 2015), making the use of lignocellulosic biomass a cleaner alternative. In industrialized nations, waste disposal, recycling, and the incorporation of waste into a circular economy play vital roles in ensuring the balanced and sustainable use of national resources. Recycling, recovery, and energy production are increasingly viewed as essential strategies for minimizing the volume of waste sent to landfills.

Plastic-containing wastes, such as those comprising 45–90% of waste toner powder, are a significant component of solid waste management due to their high organic content and environmental impact. These wastes also possess high calorific values compared to traditional biomass and coal. For instance, the calorific values of dry softwood, sub-bituminous coal, and bituminous coal are 19.2, ~20–21, and ~28 MJ/kg, respectively, while polyethylene (PE) and polypropylene (PP) offer calorific values of 41.80 and 30.90 MJ/kg, respectively. Plastic resins are particularly suitable as binders for biomass resources because of their excellent fluidity, tensile strength, and hydrophobicity, enabling the creation of fuel pellets with enhanced physical strength.

However, while direct combustion of high-calorific plastics or plastic-containing wastes can be an effective waste management strategy, it generates significant pollutants, including gases, particulates, and solid residues (ash), that contribute to air pollution. Major acidic gases such as HCl, SO_2, and even HF or HCN are released during combustion, along with other pollutants like NOx (NO and NO_2), CO, and volatile organic compounds (Takasuga et al., 2003; Werther, 2007). Particulates, including PM2.5 and PM10, pose direct health risks by entering the respiratory systems of humans and animals (Xing et al., 2016). Additionally, the combustion of plastics produces toxic chemicals such as polychlorinated dibenzo-p-dioxins (PCDD), dibenzofurans (PCDF), polycyclic aromatic hydrocarbons (PAH), pentachlorophenols (PCP), polychlorobenzenes (PCB), hexabromocyclodecanes (HBCD), and polybrominated diphenyl ethers (PBDE), further exacerbating environmental concerns (Verma et al., 2016). Metal pollutants can also arise due to metal-containing additives used in plastic production. Nevertheless, co-burning plastics with biomass have been shown to produce fewer pollutants compared to burning plastics alone (Emadi et al., 2017; Distler and Sitzmann, 2018; Tomsej et al., 2018).

This study aims to address the identified gaps in the current literature by investigating the usability of waste toner powder as an energy resource, particularly in the production of bio-briquettes. It seeks to evaluate its combustion characteristics under controlled conditions, assess its environmental impacts, and explore its potential to contribute to renewable energy solutions. By doing so, the study provides practical insights into integrating waste management with sustainable energy production.

2. EXPERIMENTAL SECTION

2.1. Materials and Sample Preparation

WTP samples (Figure 1) were obtained from a facility (Filling Market Information Technology, Education, Electrical Electronics, E-Commerce, Security Systems, Import-Export, Marketing, Industry, and Trade Limited Company) in the organized industrial zone of Elazig, specifically established for recycling toner cartridges. The waste toner powder (WTP) structure was characterized to investigate its potential applications. The samples were stored under suitable conditions to preserve their properties for subsequent analysis. The structural, morphological, and fuel properties of the WTP were analyzed comprehensively, and the obtained results were interpreted to understand its behavior and potential usability.

Figure 1: Supplied waste toner powder sample used in the study.

Structural and Morphological Characterization

The structural and morphological properties of WTP were analyzed using Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDX), atomic absorption spectroscopy (AAS), and particle size distribution analyses.

- ✓ **FTIR Analysis:** To identify the functional groups in the WTP structure, measurements were conducted in the 400–4000 cm^{-1} range with 45 scans per sample using a Shimadzu IRSipirit FTIR spectrometer. This method provided insights into the chemical bonds and compounds present in the toner powder.

- ✓ **SEM-EDX Analysis:** Surface morphology and elemental composition of WTP were determined using a JEOL JSM 7001F scanning electron microscope. High-resolution imaging enabled the visualization of particle shapes, sizes, and surface characteristics, while EDX provided elemental analysis of the material.

- ✓ **AAS Analysis:** To quantify the iron content, which is crucial for evaluating the material's magnetic properties, a Perkin-Elmer AAS 3100 Atomic Absorption Spectrophotometer was employed. This ensured precise and accurate measurements of metallic components.

- ✓ **Particle Size Distribution:** Particle size analysis was conducted in two different dispersive media (toluene and benzene) to assess the dispersion behavior of WTP in sedimentary environments. A PSS Nicomp Zeta Potential/Particle Sizer 380ZLS was used to measure the size distribution, providing critical information on the material's granularity and distribution uniformity.

2.3. Fuel Property Characterization

The fuel properties of WTP were analyzed through proximate and ultimate analysis, as well as higher heating value (HHV) determination, to evaluate its energy potential.

✓ **Proximate Analysis:** This included the assessment of ash content and volatile matter following ASTM standards. Moisture content was determined using a Mettler LJ16 moisture analyzer, providing insights into the material's combustion characteristics.

✓ **Ultimate Analysis:** Elemental analysis for carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) content was performed using a LECO CHNS-932 elemental analyzer. This allowed for the evaluation of the chemical composition and combustion efficiency of the material.

✓ **Higher Heating Value (HHV):** The energy content of WTP was determined to assess its viability as a biofuel. HHV measurements provided a quantitative understanding of its calorific value, essential for energy recovery applications.

2.4. Experimental Design and Conditions

To ensure reliable and repeatable results, all analyses were performed under controlled laboratory conditions using calibrated instruments. Standard methodologies and protocols were adhered to throughout the study, ensuring compliance with international standards. Dispersive media were selected based on their compatibility with toner powder particles to achieve accurate dispersion behavior analysis.

3. RESULTS AND DISCUSSION

3.1. Suitability for Thermal Conversion Processes

The moisture content of waste toner powder (WTP) (Table 1) was measured at 2.67%, which was significantly below the maximum threshold of 10% required for effective thermal conversion processes such as pyrolysis and combustion. This low moisture level ensured minimal energy loss during the drying phase, making WTP a highly suitable candidate for thermal transformation without the need for energy-intensive pre-drying. This characteristic supported its economic feasibility for energy recovery applications.

3.2. Combustion Characteristics and Proximate Analysis

The high volatile matter (VM) content of 88.38% by weight indicates excellent combustion properties, as volatile components facilitated rapid ignition and flame stability. The low ash content (4.91% by weight) further enhanced the suitability of WTP for combustion processes by minimizing operational issues such as slagging, fouling, and residue management. Low ash fuels were also desirable for reducing post-combustion disposal costs and maximizing energy recovery efficiency. The fixed carbon (FC) content of 4.04% suggested that the primary combustion process relied more on the release of volatile gases rather than prolonged carbon combustion. Additionally, the HHV of 35.56 MJ/kg positioned WTP as an intermediate energy source, suitable for applications requiring medium calorific value fuels, such as biomass co-firing systems.

3.3. Ultimate Analysis and Environmental Considerations

The carbon content (32.12%) was a significant parameter in determining the energy density of the examined material, and it was typical for biomass or low-carbon fuels. The hydrogen content (9.245%) provided insight into volatile components and combustion characteristics, representing a moderate-to-high level that significantly contributed to energy potential. The nitrogen content (1.975%) was quite low, which was an environmentally favorable indicator as it implied reduced NOx emissions during combustion.

The oxygen content (53.35%) was relatively high, commonly observed in biomass or oxygen-rich materials, although its contribution to energy value was limited. The sulfur content (3.289%) was a parameter of environmental concern, considered relatively high, potentially leading to SOx emissions during combustion. The proportion of other elements (0.024%) was very low and could be considered negligible in the analysis.

3.4. Iron Content and Ash Composition

To evaluate the inorganic composition of WTP, samples were calcined at 950 °C in a muffle furnace, and the iron content was measured using atomic absorption spectroscopy (AAS). The results indicated an iron content of 0.56%, which was relatively low and comparable to traditional biomass compositions. The low iron content can simplify the fuel preparation workflow by eliminating the need for additional pretreatment processes, such as iron recovery. Minimal iron content ensures that the ash produced during combustion will not pose significant environmental risks, aligning WTP with sustainable waste management practices. Low metallic content reduces the risk of slag formation during combustion, ensuring smooth operational efficiency.

Table 1: Proximate and ultimate analysis result of toner powder (*: determined by the difference).

Ultimate analysis	Value (wt. %)	Proximate analysis	Value (wt. %)
C	32.12	**Volatile matter (VM)**	88.38
H	9.245	**Ash (A)**	4.91
N	1.975	**Moisture (M)**	2.67
O*	53.35	**Fixed carbon* (FC)**	4.04
S	3.289	**HHV (exp.) MJ/kg**	35.56
Other	0.024		

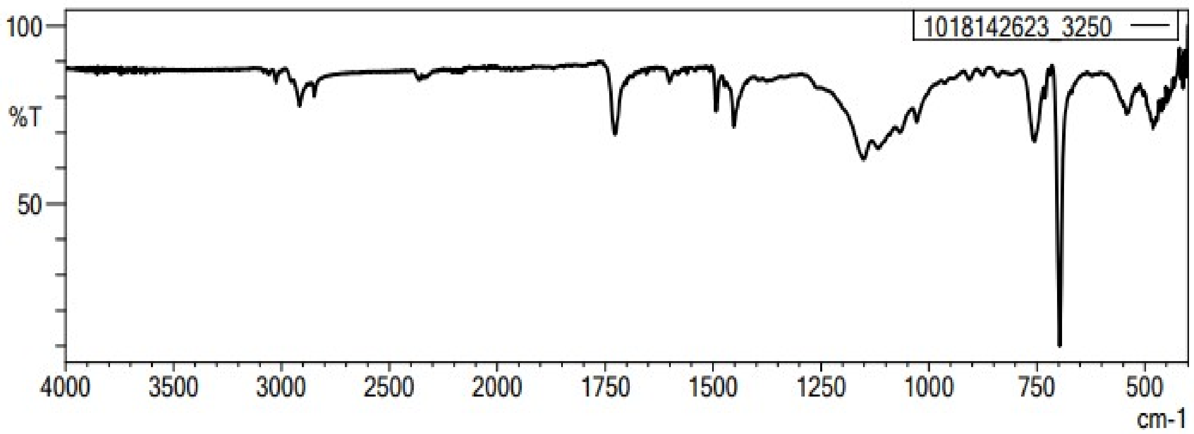
3.5. Insights from Particle Composition and Behavior

Plastic and inorganic components in WTP may play an important role in combustion behavior, with plastic resins potentially contributing to its calorific value and providing effective binding properties when blended with other biomass sources for fuel pellet production. This is because toner powder is known to contain carbon black, polymethyl methacrylate, styrene acrylate copolymer, and polypropylene, as well as inorganics such as iron oxides, manganese, titanium, and silicon (Yordanova et al. 2014). Although toner powder is highly hydrophobic, the presence of polymeric materials like polymethyl methacrylate, polypropylene, and styrene acrylate copolymer makes it a potential filler or binding agent. However, the polarity difference between hydrophilic waste biomass sources and hydrophobic polymers like polyester may lead to weak interfacial bonding, which can affect the tensile behavior of composites (Daniel et.al 2022).

These results collectively demonstrated that waste toner powder was a promising alternative energy resource. Its low moisture and ash content, combined with high volatile matter and HHV, made it suitable for thermal conversion processes, particularly combustion and pyrolysis. While the nitrogen and sulfur content highlighted a need for emission control measures, the overall composition of WTP aligned well with sustainable energy recovery objectives. The absence of significant iron content further enhanced its practicality by reducing the need for pre-treatment and minimizing environmental risks. Future studies should focus on optimizing combustion parameters and exploring co-firing opportunities with conventional biomass to maximize the efficiency of WTP as a renewable energy source.

3.6. FTIR Analysis of Waste Toner Powder: Functional Groups and Composition

The FTIR spectrum of waste toner powder (WTP) (Figure 2) revealed key absorption bands that provided critical insights into its chemical composition, supported by a corresponding library analysis. A broad band around 3250 cm^{-1} corresponded to O–H stretching vibrations, indicating the presence of hydroxyl groups, likely originating from residual moisture or additives. These polar functional groups contributed minor hydrophilic characteristics to the toner powder. The peaks at 2920–2850 cm^{-1} were characteristic of C–H stretching vibrations in aliphatic hydrocarbons, such as CH_2 and CH_3 groups, which suggested the presence of polymer backbones like styrene and acrylate. A sharp peak at 1750 cm^{-1} was associated with C=O stretching vibrations, indicative of ester or ketone functional groups, confirming acrylate-based polymers, such as styrene-acrylate copolymers, commonly found in toner formulations.



	Score	Library	Name	Comment
1	853	169 - ATR-Polymer2	D_Styrene_AllylAlcohol	Styrene/Allyl Alcohol Copolymer(Hydroxyl content 5.4-6.0%) DuraSamplIR-II
2	799	1 - ATR-Polymer2	D_ABS	Acrylonitrile-butadiene-styrene(ABS) DuraSamplIR-II
3	797	158 - ATR-Polymer2	D_PS2	Polystyrene DuraSamplIR-II
4	782	25 - ATR-Polymer2	D_PS	Polystyrene(PS) DuraSamplIR-I
5	776	170 - ATR-Polymer2	D_Styrene_ButylMethacrylate	Styrene/Butyl Methacrylate 50/50 Copolymer
6	771	26 - ATR-Polymer2	D_SBS	Styrene-Butadiene-Styrene(SBS) DuraSamplIR-II
7	763	167 - ATR-Polymer2	D_SA-2	Styrene/Acryonitrile(SA) Copolymer(Acrylonitrile content 30%) DuraSamplIR-II
8	724	92 - ATR-Polymer2	D_ABS2	Acrylonitrile/Butadiene/Styrene(ABS) Resin(High Butadiene content) DuraSamplIR-II
9	721	53 - IRs Polymer2	PS	Polystyrene ATR/diamond ATRcorrected
10	719	25 - T-Polymer2	PS	Polystyrene(PS) Transmission(Microscope)

Figure 2: FTIR spectrum of toner powder.

In the 1600–1500 cm⁻¹ range, distinct peaks represented C=C stretching vibrations from aromatic rings, highlighting the aromatic backbone structure characteristic of polystyrene and its derivatives. These features contributed to the rigidity and thermal stability of the material. Further, the bands in the 1450–1400 cm^{-1} region corresponded to C–H bending vibrations from CH_2 and CH_3 groups, supporting the presence of aliphatic hydrocarbon chains. The 1250–1000 cm^{-1} region displayed strong C–O stretching vibrations, typical of ester groups, accompanied by aromatic C–H bending, confirming the existence of acrylate and ester functionalities. Lastly, the absorption bands between 900–700 cm^{-1} corresponded to out-of-plane C–H bending vibrations, reinforcing the presence of aromatic systems like polystyrene. The experimental results obtained are consistent with the literature (Fernández et. al. 2022; Yordanova et al. 2014).

The library analysis aligned with the FTIR results, confirming the primary components in the toner powder. Styrene/allyl alcohol copolymer was identified by the O–H stretches at 3250 cm^{-1} and aromatic C=C peaks around 1600 cm^{-1}. Acrylonitrile-butadiene-styrene (ABS) was characterized by the C–H stretching vibrations near 2900 cm^{-1} and weak nitrile group peaks around 2200 cm^{-1}. Polystyrene (PS) was supported by aromatic C=C peaks at 1600 cm^{-1} and out-of-plane C–H bending at 900–700 cm^{-1}. Additionally, styrene-butyl methacrylate copolymer was confirmed by the ester C=O stretching peak at 1750 cm^{-1} and aliphatic C–H peaks.

These findings indicated that the toner powder primarily consisted of styrene-based polymers, acrylate-based copolymers, and various additives. Styrene polymers contributed rigidity, thermal stability, and resistance to biodegradation, while acrylate copolymers enhanced flexibility and adhesion properties. Additives like ABS and butyl methacrylate further improved performance characteristics such as heat resistance and print quality.

From an application perspective, the composition highlighted several important implications. The presence of styrene and acrylate polymers confirmed the material's high thermal stability, making it suitable for thermal transformation processes like pyrolysis or combustion. The strong aromatic backbone and low biodegradability emphasized the need for controlled waste management strategies, such as blending with biomass to reduce environmental risks. Additionally, the hydrocarbon-rich composition, coupled with its high calorific value, validated WTP as a promising additive for biofuel production and energy recovery applications.

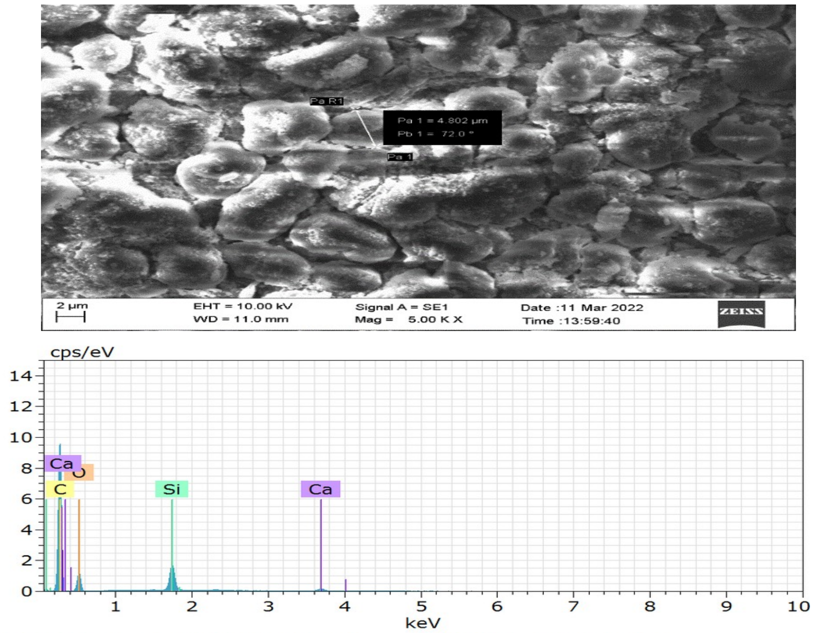
3.7. Hazardous Substances and Environmental Impacts of Waste Toner Powder

Residual toner powder contains hazardous substances, including plastics, heavy metals, and carcinogenic chemicals such as polycyclic aromatic hydrocarbons (PAHs) and resins, which pose significant environmental and health risks (Bhoi et al., 2014). The primary polymeric component, styrene acrylate copolymer, accounts for the majority of the toner composition and is characterized by its high molecular weight. This property makes it highly resistant to biodegradation, allowing the material to persist in ecosystems for extended periods without significant decomposition.

The low water solubility of toner powder further limits its mobility in landfill environments, but it also reduces the likelihood of leaching. However, the heterogeneous morphological and chemical composition of WTP complicates predictions about its degradation behavior under varying landfill conditions (NICNAS, 1991; Yordanova et al., 2012; Yordanova et al., 2019; Kyoseva et al., 2011). Consequently, long-term storage of waste toner powder is considered hazardous due to the potential for unforeseen environmental reactions over time.

The SEM-EDX analysis provided critical insights into the surface morphology and elemental composition of waste toner powder. The SEM micrograph (Figure 3) revealed an irregular granular structure with particle sizes ranging between 4 and 8 µm. This morphology, characterized by a high surface area, could have enhanced combustion dynamics when WTP was used as a fuel.

The EDX spectrum and corresponding data highlighted the elemental composition of WTP. The dominant element, carbon (C), constituting 80.50% by weight, confirmed the organic nature of the toner powder. The high carbon content aligned with the material's high volatile matter content (88.38%) observed in the proximate analysis, makes it a suitable candidate for thermal conversion processes. At 13.76% by weight, oxygen was associated with both the polymeric materials and inorganic oxides present in the sample. Oxygen content was critical for combustion processes, influencing the material's ignition and flame stability. The experimental results obtained are consistent with the literature (Fernández et. al. 2022).



El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
C	6	K-series	61.94	71.29	80.50	6.91
O	8	K-series	14.10	16.23	13.76	1.85
Si	14	K-series	9.11	10.49	5.07	0.40
Ca	20	K-series	1.73	1.99	0.67	0.09
		Total:	86.88	100.00	100.00	

Figure 3: SEM-EDX analysis of waste toner powder, showing its granular morphology and elemental composition critical for evaluating its potential in biofuel applications.

Silicon (Si) and calcium (Ca) elements, present at 5.07% and 0.67% by weight, respectively, originated from fillers and stabilizers commonly used in toner formulations. While low in concentration, these inorganic components may have influenced ash behavior during combustion, such as melting characteristics and slag formation. Given its plastic-rich composition, WTP posed challenges in direct combustion due to the potential release of hazardous emissions such as PAHs and dioxins. However, blending WTP with biomass offered a practical solution to mitigate its environmental drawbacks while leveraging its high energy content. The high carbon and volatile matter content of WTP enhanced its combustion efficiency, while the low ash and moisture content minimized operational challenges and post-combustion residue.

To balance the risks and benefits, it was recommended to limit the proportion of WTP to 8–10% in biofuel mixtures. This dilution strategy ensured that the negative impacts of its plastic composition were mitigated while maintaining desirable fuel characteristics. The low calcium and silicon content observed in the EDX results further supported the material's suitability for blending, as these elements were unlikely to cause significant slagging or fouling during combustion.

The hazardous substances and environmental risks associated with waste toner powder underscored the importance of managing its use in a controlled manner. The SEM-EDX analysis revealed a composition that was highly favorable for energy recovery when integrated with biomass, provided that appropriate blending ratios were maintained. Future research should focus on optimizing the blending process, controlling emissions, and evaluating long-term combustion efficiency to fully realize the potential of WTP as a renewable energy resource.

3.8. Particle Size Distribution Analysis and Solvent Effectiveness

The particle size distribution analysis of waste toner powder (Figure 4) in different solvents revealed significant variations in their dispersive effectiveness. In toluene, the particle size distribution was relatively narrow, with a mean diameter of 182.6 nm and a standard deviation of 147.2 nm. The Gaussian distribution was well-centered, with the majority of particles falling below 400 nm, indicating a uniform dispersion. This suggested that toluene provided favorable interactions with toner components, likely due to better solubility and compatibility with its polymeric structure. In contrast, benzene showed a broader particle size distribution with a mean diameter of 308.4 nm and a much higher standard deviation of 475.2 nm. This indicated the presence of larger particles and significant agglomeration, demonstrating that benzene was less effective as a dispersing medium. The experimental results obtained are consistent with the literature (Fernández et. al. 2022).

The comparison underscored the superior performance of toluene in achieving a consistent and predictable particle size distribution. Toluene's stronger interactions with toner particles facilitated better dispersion, breaking down agglomerates and ensuring more uniform particle sizes. Benzene, while capable of dispersing the toner powder, exhibited limitations such as broader size variability and particle clustering, which may have hindered its applicability in processes requiring precise particle size control. Overall, the findings suggested that toluene should have been prioritized for applications requiring uniform dispersion, while benzene could have been reserved for less critical uses where variability was less of a concern.

The presence of fine toner particles (<10 µm) poses significant health risks, as these particles can remain suspended in the air for extended periods, causing respiratory irritation and long-term damage to living organisms (Salhofer et al., 2011; Nakadate et al., 2018; Pirela et al., 2017). This issue underscores the importance of selecting an appropriate dispersive medium during processing to minimize the generation of respirable particles. Fine particles not only present health hazards but also create challenges in storage and transportation, as they are prone to aggregation, contamination, and dispersion, increasing handling difficulties and safety concerns.

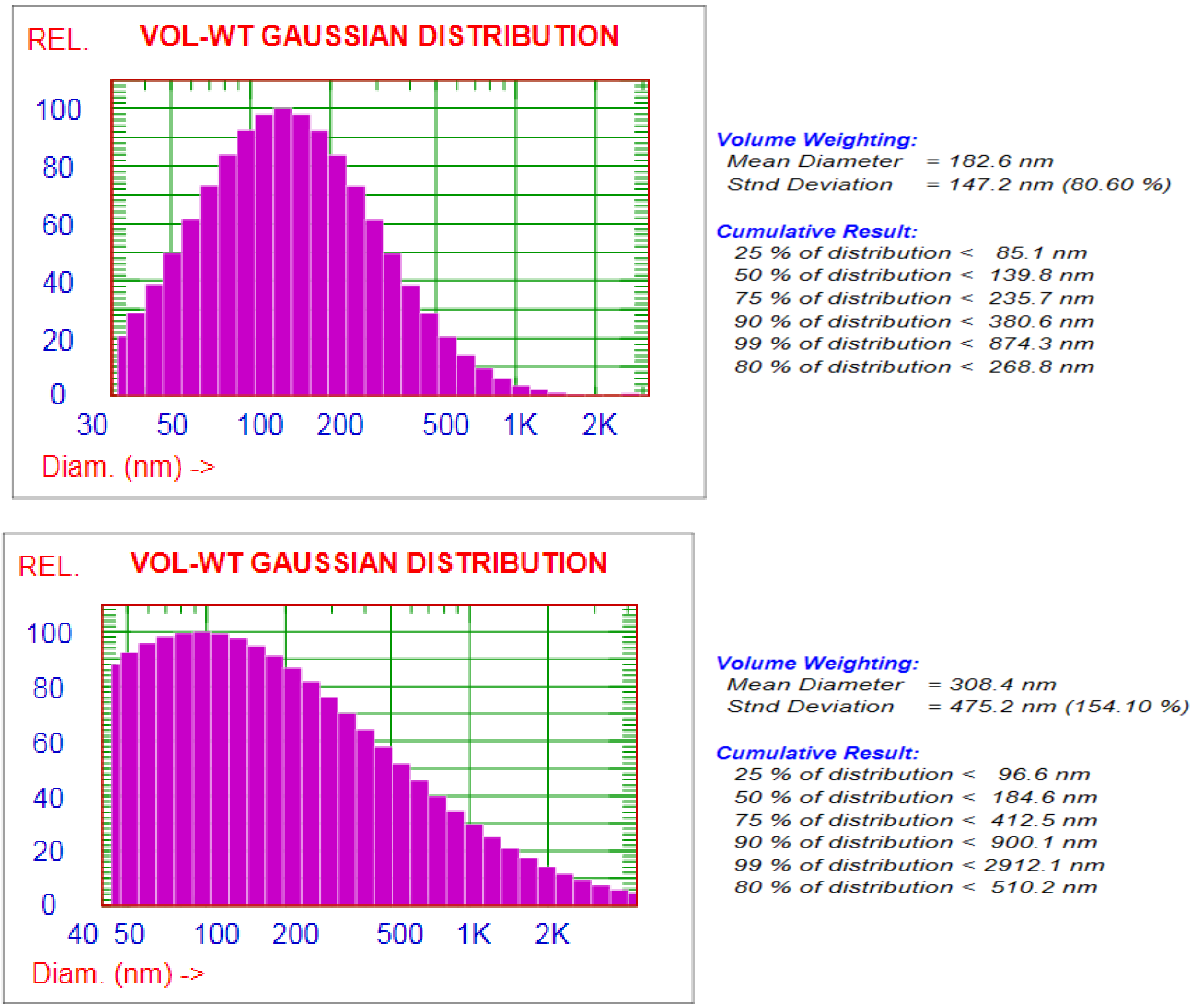


Figure 4: The particle size distribution of waste toner powder (a.Toluene-b.Benzene).

To address these issues, utilizing waste toner powder (WTP) in pellet or briquette form offers a practical solution. By consolidating fine toner particles into larger, denser forms, the risk of airborne particle dispersion is significantly reduced, enhancing safety during handling, storage, and transportation. This approach also improves logistical efficiency by increasing the bulk density of the material, reducing storage space requirements, and lowering transportation costs.

From an environmental and energy recovery perspective, the pelletization of WTP presents further advantages. Structured forms like pellets or briquettes allow for more controlled and uniform combustion, improving thermal efficiency and reducing the emission of fine particulate matter during energy recovery processes. Additionally, blending WTP with biomass, such as powder, not only mitigates the risks associated with WTP's plastic content but also enhances the biofuel's overall performance. The resulting fuel exhibits high calorific value, better thermal efficiency, and cleaner flue gas emissions, making it an environmentally friendly alternative.

4. CONCLUSION

Our study highlights the potential of waste toner powder (WTP) in the production of bio-briquettes for energy generation. Experiments have shown that WTP possesses a high calorific value (35.56 MJ/kg) and exhibits strong binding properties, making it a promising raw material for bio-briquette production. Proximate analysis results indicate that WTP contains 88.38% volatile matter and has low ash (4.91%) and moisture content (2.67%). Additionally, the ultimate analysis reveals a high carbon content (32.12%) and low nitrogen levels (1.98%), indicating its potential for low NOx emissions during combustion. These results demonstrate that WTP is a valuable resource for both environmental sustainability and energy efficiency.

The results have shown that waste toner powder (WTP) is a valuable material to be considered in bio-briquette production. Its high calorific value and strong binding properties highlight its potential as an energy source. Considering the particle size and sulfur/nitrogen contents of WTP, the study concluded that the most effective, suitable, and economical method for utilizing this waste as biofuel is producing biofuel pellets/briquettes by mixing it with powdered biomass waste sources, such as furniture factory waste dust (a lignocellulosic biomass source), in specific proportions.

Finally, utilizing WTP, a material known for causing long-term environmental pollution, as an energy resource would bring significant environmental and economic benefits. Transforming WTP into a high-value-added product not only addresses landfill sustainability but also contributes to the circular economy by reducing waste and promoting energy recovery. This innovative application has the potential to align with global energy and environmental goals through sustainable waste management practices.

5. CONFLICT OF INTEREST

There is no need to obtain permission from the ethics committee to prepare the article. There is no conflict of interest with any person/institution in the prepared article.

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