From Waste Polypropylene to Carbon Dots

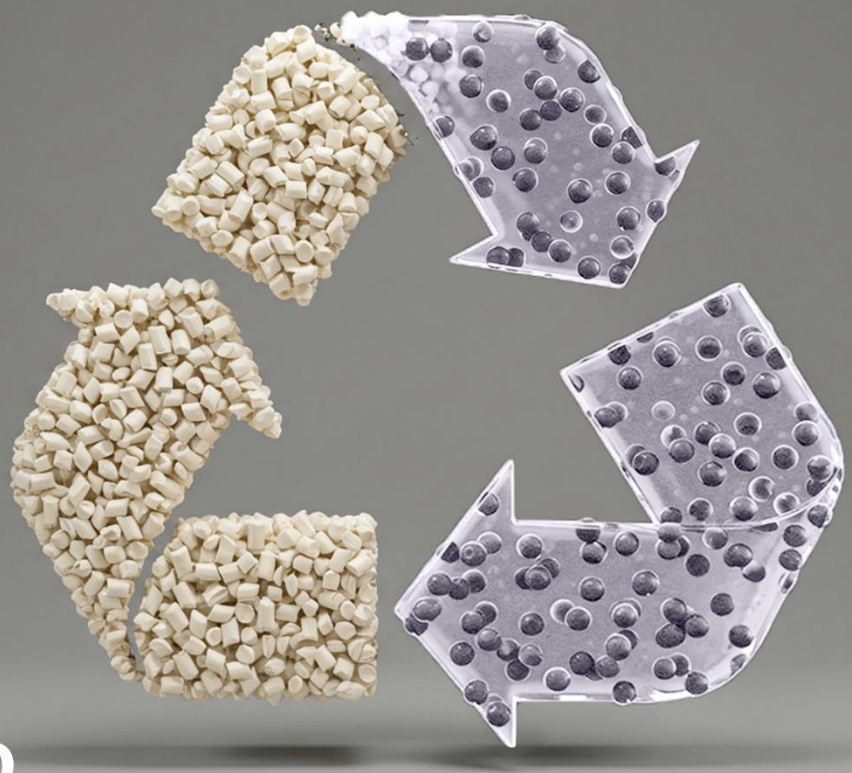
Faezeh Mahdavian, Haleh Naeim, Denis Rodrigue *

Department of Chemical Engineering, Université Laval, Quebec City, QC, G1V 0A6, Canada

Editor's note: Converting plastics into advanced nanomaterials is an effective recycling strategy that addresses the growing problem of polymer waste, making it crucial for environmental sustainability. Mahdavian et al. introduced a two-step method to convert polypropylene waste from food packaging into carbon dots, which can be utilized in bioimaging, energy conversion, and sensing applications.

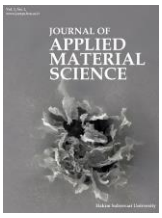
doi: 10.22034/jams.2025.210134

How to cite: F. Mahdavian et al. *Journal of Applied Material Science*, **2025**, *1*, 210134.



JOURNAL OF
APPLIED
MATERIAL
SCIENCE
jams.hsu.ac.ir

Journal of Applied Material Science **2025**, *1*, 210134
How to cite: F. Mahdavian et al., *Journal of Applied Material Science*, **2025**, *1*, 210134.
Journal homepage: **www.jams.hsu.ac.ir**



Original Research

From Waste Polypropylene to Carbon Dots

Faezeh Mahdavian, Haleh Naeim, Denis Rodrigue *

Department of Chemical Engineering, Université Laval, Quebec City, QC, G1V 0A6, Canada

Abstract

This study presents the successful synthesis of carbon dots (C-Dots) from polypropylene (PP) from a two-step method. PP waste from food packaging was converted into C-Dots through a thermal process followed by a solvothermal approach. Thermal analysis of PP waste provided insights into its stability, decomposition, and phase transitions, optimizing its use as the precursor for C-Dots synthesis and impurity identification. FTIR analysis confirmed the presence of oxygen-containing functional groups in the PP-derived C-Dots, highlighting the successful conversion of polymeric waste into a high-value material. The formation of C-Dots nanoparticles was further confirmed via transmission electron microscopy analysis. The particles were characterized by an average size of 43 nm and a standard deviation (SD) of 17 nm. Additionally, the combination of strong UV absorption and a narrow band gap absorption highlights the unique electronic properties of these C-Dots, making them suitable and sustainable candidates for applications such as bioimaging, energy conversion, and sensing.

Keywords: Polypropylene; Waste management; Recycling; Carbon dots.

1. Introduction

Polymers serve as fundamental components in modern life because of their remarkable versatility, durability, and extensive applicability across diverse industrial sectors. However, it is imperative to address the significant drawbacks associated with polymers, especially about sustainability and environmental issues [1]. Minimizing environmental impact, reducing carbon footprints, and decreasing residual wastes are key strategies in polymer waste management [1, 2]. This is why polymer recycling represents a sustainable approach that not only decreases energy consumption compared to the production of virgin polymers, but also substantially reduces greenhouse gas (GHG) emissions, contributing to cleaner and more environmentally friendly manufacturing processes [2].

Recent advancements in recycling technologies catalyzed the development of a variety of innovative techniques for the sustainable management of polymer waste [3]. One of them is mechanical recycling which includes the physical reprocessing of polymers into new materials without changing their chemical structure, making it a straightforward and widely used method [4]. In contrast, chemical recycling involves the depolymerization of macromolecules into their constituent monomers or other fundamental components, enabling the production of high-quality, new polymers

* Corresponding author.
Email address: denis.rodrigue@gch.ulaval.ca (D. Rodrigue)

Received 4 February 2025
Revised 18 February 2025
Accepted 19 February 2025
Available online 20 February 2025

https://doi.org/10.22034/jams.2025.210134

with properties close to virgin materials [5]. Another objective is upcycling which transforms waste polymers into high-value and functional products offering a creative and sustainable approach to polymer reuse [6].

Efforts to upcycle (added-value) plastic waste into lubricants, biofuels, construction materials, and combustible gases often led to inconsistencies, thereby limiting their scalability. The development of a cost-effective methodology for polymer wastes into carbon dots (C-Dots) represents a viable solution to these challenges, enabling the generation of high-value products while concurrently mitigating waste accumulation [7]. Unlike conventional recycling, which often yields lower-grade materials, this approach significantly improves the value of waste polymers. This method offers an innovative and sustainable solution to manage polymer wastes by converting them into non-toxic functional nanomaterials rather than conventional downcycling (fillers) or disposal (landfilling). Moreover, it aligns with sustainable chemistry and materials science principles, contributing to waste reduction and promoting a circular economy. Thus, C-Dots synthesis from waste polymers is in line with green chemistry principles by minimizing waste generation and the optimization of resource efficiency, showcasing a practical and environmentally responsible strategy to address the challenges associated with polymer waste management [8].

The synthesis of C-Dots can be divided into two main approaches: "top-down" and "bottom-up". The top-down technique involves breaking down larger carbon structures into nanoscale materials using methods such as laser ablation, arc discharge, high-energy ball milling, and electrochemical techniques [9, 10]. On the other hand, the bottom-up approach involves synthesizing C-Dots from small organic precursors or polymers through processes such as thermal decomposition, microwave pyrolysis, plasma treatment, and hydrothermal oxidation [11]. Initially, C-Dots synthesis used energy-intensive top-down methods with graphite, carbon nanotubes, or graphene, while more recent strategies use organic molecules or carbon-rich polymers as precursors, requiring less energy [12].

One of the most efficient methods to synthesize C-Dots involves thermal decomposition processes of carbon-rich raw materials at elevated temperatures. For example, Aji et al. studied the synthesis of C-Dots from polypropylene (PP) wastes by heating at 200, 250, and 300 °C for 20 min. Their findings highlighted the significant effect of temperature on C-Dots formation, where higher temperatures led to higher carbon chain rupture and the formation of smaller particles with higher energy levels. The polymerization of carbon chains during the heating process resulted in the creation of new functional groups, a confirmation of the temperature-dependent evolution of C-Dots' structure and properties [13]. This approach offers several advantages, including high yield, cost-effectiveness, shorter reaction times, broader raw material compatibility, and more straightforward syntheses [10].

Since most of the plastics today are derived from carbon, this makes them suitable precursors for the synthesis of C-Dots with precise and tunable properties [10, 14]. The conversion of waste polymers based on polylactide (PLA) [15], polyethylene terephthalate (PET) [16], polystyrene (PS) [17], and polypropylene (PP) [13] into high-value C-Dots nanomaterials represents an advanced form of upcycling for different polymer waste management approaches [18]. In particular, PP gained attention as a precursor to synthesize C-Dots due to its widespread availability, low cost, and high thermal stability [19].

Unlike most polymers, such as polyethylene (PE) or PS, PP has a relatively higher melting point (around 160 °C) and a stable carbon backbone, making it suitable for high-temperature carbonization processes [20-22]. Studies on PP as a precursor also showed promising results of 10.3% C-Dot yield and optical properties like UV-Vis absorption and fluorescence emission for catalyst-free methods [7, 12, 13]. However, compared to more commonly used polymers such as PET, which has been widely explored for C-Dot synthesis due to its higher aromatic content [16], PP's lack of aromaticity may influence the size and surface functionality of the resulting C-Dots. In contrast, polymers such as PS, which are rich in aromatic rings, tend to form C-Dots with high photoluminescence (PL) quantum yield (around 20%), but often require harsher conditions (high temperature), or the use of surface passivating agents such as ethylenediamine, to achieve high yields [23].

Although PP is a promising precursor for sustainable C-Dot production, it may not offer the same optical properties or ease of synthesis as more aromatic polymers. Nonetheless, its use in C-Dot synthesis from waste plastics presents significant advantages in terms of cost-effectiveness and scalability for commercial

applications. Thus, recycling PP wastes into polymer-based carbon nanomaterials represents an opportunity to use waste materials for high-value and cutting-edge applications. These C-Dots exhibit remarkable versatility, making them promising candidates for several advanced technological fields including photocatalytic materials, water treatment [24], bioimaging agents, energy storage [25], and sensors [26, 27].

Although a growing interest in the synthesis of C-Dots from plastic waste was observed, the number of studies remains limited, often relying on microwave heating or the introduction of catalysts (metals, acids, and bases) leading to difficult scalability [10, 28]. This is why the catalyst-free production of C-Dots from available precursors offers a promising step toward sustainability [15]. This study highlights the critical role of waste management in reducing environmental pollution, while creating new opportunities for technological advancements by the transformation of PP wastes into valuable C-Dot nanomaterials. Beyond their technical applications, the results of this study hold broader implications for environmental sustainability. By providing an innovative and scalable approach to PP recycling, this work addresses one of the most pressing environmental challenges of our time: the accumulation of non-biodegradable plastic waste. The successful transformation of plastic residues into valuable polymer C-Dots represents a practical and impactful strategy to mitigate environmental pollution. Moreover, this approach highlights the promising potential of waste recycling, turning discarded materials into functional resources, thereby contributing to a circular economy and advancing global efforts toward environmental protection and conservation.

2. Experimental

2.1. Materials

The recycled polypropylene (PP) was obtained from bags daily used in food-related applications (Figure 1). Ethanol was purchased from Greenfield Global Inc. (Canada) and sodium hydroxide (NaOH) was obtained from Fisher BioReagents (USA).

2.2. Carbon Dots preparation

A step-by-step scheme of C-Dots production is shown in Figure 1. The PP bags were first cleaned by soaking

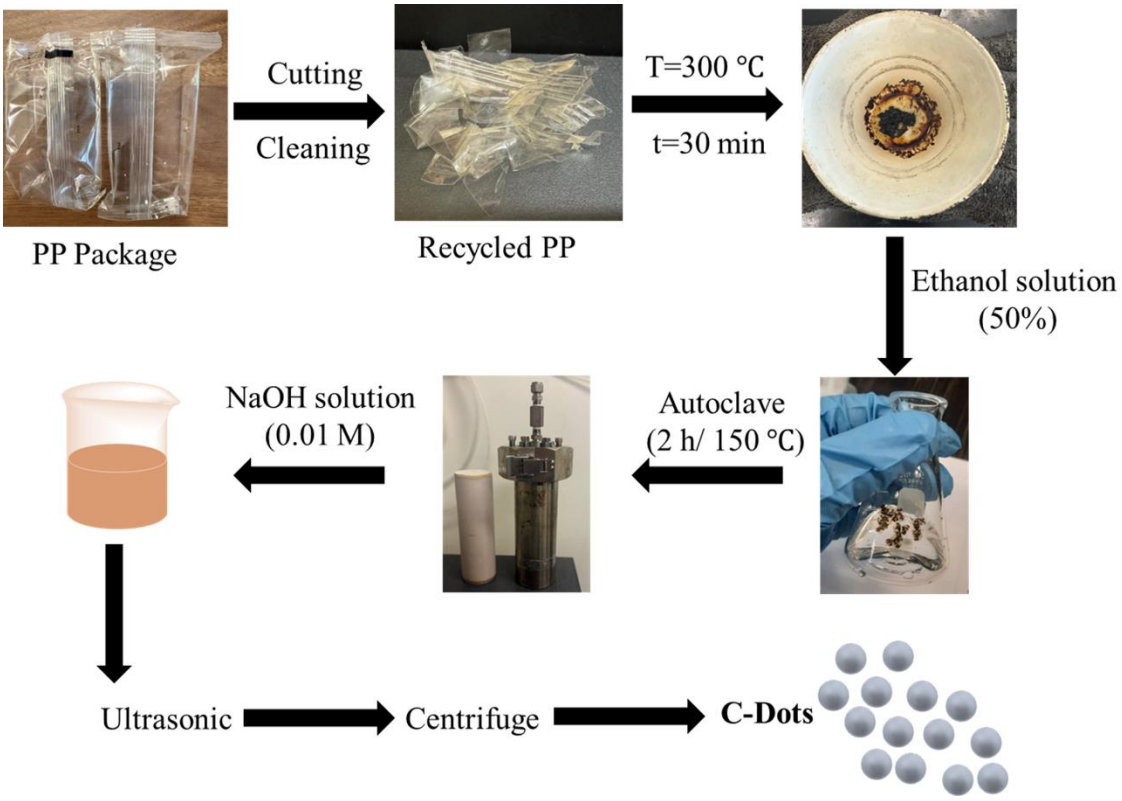


Figure 1. Steps leading to the preparation of C-Dots preparation from waste PP.

them in warm water containing a small amount of liquid soap for a short period. It was then thoroughly rinsed with clean water to remove the detergent and any remaining contaminants. Following this step, the PP was rinsed with distilled water and dried at room temperature, then cut into parts having smaller dimensions. They were then heated in an oven at 300 °C for 30 min. The resulting dark brown solid was added to a 50% ethanol solution and stirred continuously for 2 h. Then, the material was transferred to a 450 ml Teflon-lined autoclave and heated for 2 h at 150 °C. Upon cooling to room temperature, 0.1 M NaOH was added to the solution while stirring. Then, the particles were dispersed and the solution was homogenized using an ultrasonic water bath (model 75T, VWR Scientific Products, USA) for 2 h. Finally, the solution containing C-Dots was carefully extracted from the upper layer following centrifugation at 4000 rpm for 30 min. An ultrasonic cleaning process was performed using a VWR Scientific Products Aquasonic Ultrasonic Cleaner Water Bath (model: 75T).

2.3. Measurements

Thermogravimetric analysis (TGA) was performed on a Q5000 IR (TA Instruments, USA) with a heating ramp of 10 °C/min from room temperature to 850 °C under air. To confirm the composition of the recycled material, differential scanning calorimetry (DSC) analysis was carried out using a Discovery DSC 25 (TA Instruments, USA). The analysis involved a single heating and cooling cycle over a temperature range of 0 °C to 250 °C under a nitrogen atmosphere at a rate of 10 °C/min. The chemical structure of PP bags and C-Dots was characterized using a Nicolet iS50 Fourier transform infrared (FTIR) spectrometer (Thermo Fisher Scientific, USA). A JEOL JEM-1230 transmission electron microscope (TEM) (JEOL, Japan) detected the formation, morphology, and size distribution of C-Dots. UV-Vis absorption spectra were recorded using a Cary 7000 universal measurement spectrophotometer (UMS, Agilent Technologies, USA), with a wavelength range of 200–800 nm. Moreover, the band gap energy was calculated as:

$$(\alpha\, h\nu)^{1/n} = A(h\nu - E_g) \qquad (1)$$

where α is the absorption coefficient, hν is the photon energy, A is a proportionality constant, and E_g is the band gap energy. The exponent n depends on the type of electronic transition. For direct transitions, the band gap was determined by plotting $(\alpha\, h\nu)^2$ as a function of hν and extrapolating the linear region of the curve to the hν-axis at α = 0 [29, 30].

3. Results and discussion

The thermal behavior of waste PP was investigated using TGA and DSC, as shown in Figures 2(a) and (b). These analyses provide insights into the thermal stability, decomposition characteristics, and phase transitions of waste PP, to facilitate and optimize its use as a precursor for C-dots synthesis. Additionally, these tests offer valuable information to identify any additives or impurities in the waste plastic, which could influence the final properties.

In the TGA analysis (Figure 2(a)), the material exhibits a thermal onset at 250 °C, with the decomposition process completing around 354 °C. This indicates that the material remains stable up to 250 °C, then the degradation process starts progressively, with complete decomposition occurring at 354 °C. The DSC analysis (Figure 2(b)) shows no significant thermal degradation within the temperature range of 0 °C to 250 °C, with a melting temperature of around 167 °C. By correlating the DSC and TGA results, it can be concluded that the material undergoes softening (onset) around 154 °C, followed by thermal degradation starting at 250 °C. These results suggest that 300 °C is an optimal temperature for the synthesis of C-Dots, as it allows for controlled thermal degradation while avoiding the complete decomposition of the material around 354 °C. This temperature ensures controlled degradation, promoting carbonization, while preventing complete material decomposition, thus facilitating the formation of C-Dots.

The FTIR analysis of the PP and C-Dots is shown in Figure 2(c). The peak around 2951 cm^{-1} is associated with the asymmetrical stretching of the $-CH_3$ group, and its intensity decreased in the C-Dots spectrum, indicating that PP conversion occurred [12]. The less intense symmetrical bending peaks at 1455 cm^{-1} and 1376 cm^{-1}, attributed to the $-CH_3$ group, provide evidence for the substantial reduction of PP into C-Dots. The FTIR spectrum of C-Dots reveals distinct new absorption peaks compared to PP, suggesting the formation of new functional groups or structural modifications associated with the conversion process.

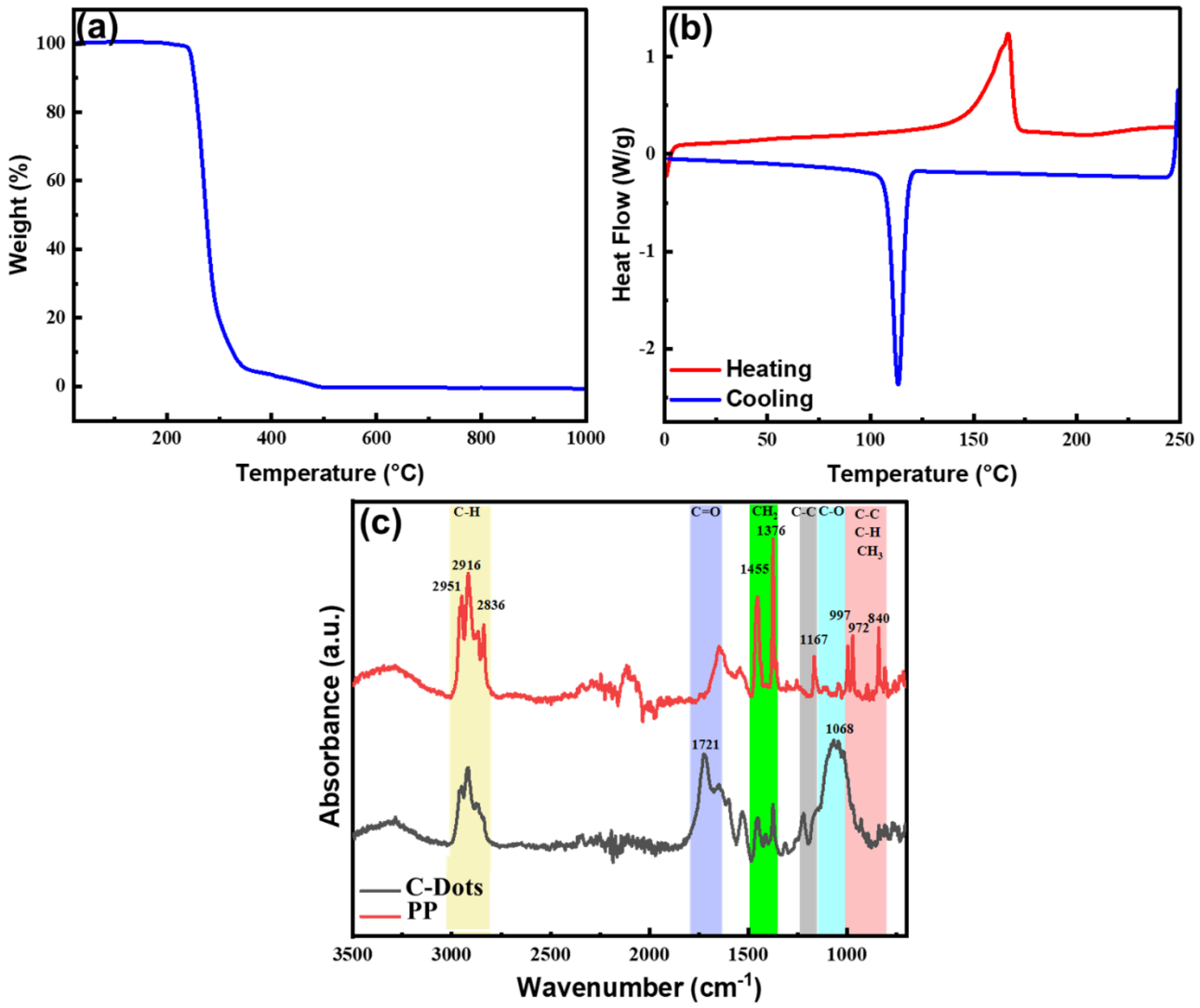


Figure 2. Characterization of waste PP and synthesized C-Dots: (a) TGA and (b) DSC of waste PP, as well as (c) FTIR spectra of waste PP and synthesized C-Dots.

During PP waste heating, the carbon chains react with oxygen from the surrounding environment. This interaction results in the formation of carbonyl groups (C=O), which are observed at 1721 cm^{-1}. These carbonyl groups are a key structural component of polymer C-Dots. A peak around 1068 cm^{-1} is typically attributed to the stretching vibrations of C-O bonds, especially in molecules with hydroxyl (-OH), ether (C-O-C), or ester (-COO-) functionalities [31]. This peak reflects the presence of oxygen-containing functional groups on the C-Dots surface, which are commonly introduced during the thermal treatment involving the polymerization, oxidation, and carbonization of PP [32]. Surface oxygen-containing groups play a crucial role in determining the solubility, stability, and photophysical properties of C-Dots. For instance, hydroxyl or ether groups contribute to hydrophilicity and facilitate interactions with different surrounding media, making the C-Dots suitable for bioimaging or sensing applications. These methods introduce functional groups enhancing fluorescence and modulating electronic properties.

High-resolution TEM analysis of C-Dots can provide valuable insights into their morphology and size distribution. TEM images shown in Figure 3(a) revealed that the carbon particles are spherical and well dispersed (no agglomeration). The conversion method used in this

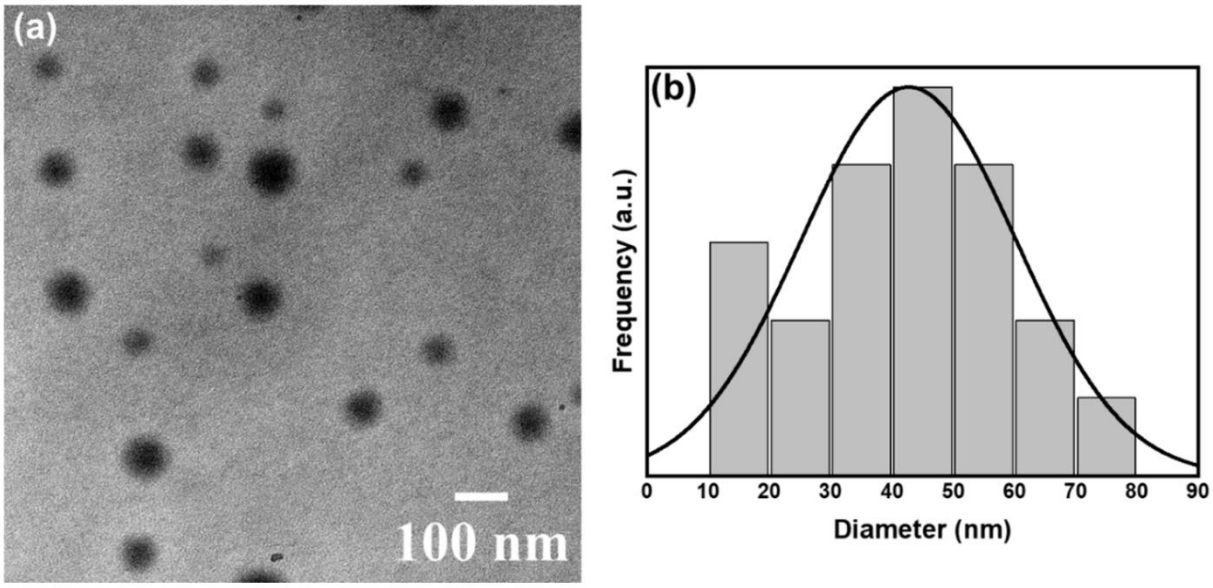


Figure 3. Morphological analysis of the C-Dots: (a) TEM image and (b) particle size distribution.

study successfully produced particles with minimal aggregation and a uniform size distribution with diameters ranging from 11 to 73 nm. The particles exhibit an average size of 43 nm with a standard deviation (SD) of 17 nm, suggesting good uniformity in the synthesis process (Figure 3(b)). The combination of structural and chemical analysis indicates that these particles are well-suited for advanced applications, such as electrode materials in lithium-ion batteries or as supports in catalysis.

Figure 4(a) presents the UV-Vis absorption spectrum of the synthesized C-Dots. An absorption peak around 250 nm is observed, which is commonly attributed to π-π* electronic transitions of aromatic sp^2 domains in the carbon core [16]. This feature is characteristic of graphitic domains within the C-Dots structure, which significantly contributes to their optical properties. The weak absorption peak around 280 nm is associated with n-π* transitions. This peak also provides valuable information about the surface chemistry of the C-Dots, which plays a

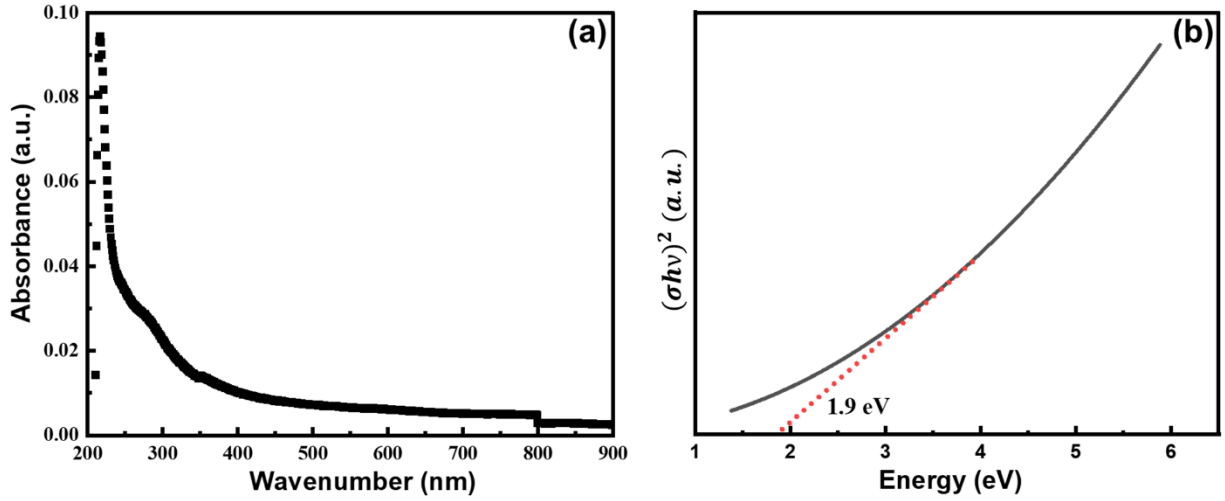


Figure 4. (a) UV-Vis absorption spectrum and (b) band gap energy estimation of C-Dots derived from waste PP.

crucial role in determining their photophysical behavior and interaction with their environment. These transitions arise from non-bonding electron pairs present in surface functional groups, such as carbonyl (C=O) or hydroxyl (-OH), commonly introduced during the C-Dots synthesis [32].

In addition, the band gap energy of the C-Dots shown in Figure 4(b), estimated at 1.9 eV. This suggests a significant quantum confinement effect which is influenced by the size, surface functionalization, and chemical composition of the C-Dots [33]. Aji et al. showed that decreasing the size of C-Dots from 15 nm to 8 nm increased the band gap energy from 2.8 eV to 3.45 eV [13]. In microwave radiation techniques, increasing the power results in a smaller size of the material and increases the C-Dots' energy band gaps (2.47–2.53 eV), remaining within the typical range of 1.5–3.5 eV [34]. In addition, the band gap energy decreases with different dopant types, reaching 2.14 eV for pyridine N, 1.94 eV for amino N, and 1.54 eV for C=O groups [35].

The narrow band gap is indicative of the nanometer-scale dimensions of the C-Dots and the electronic structure modulated by both core size and surface states. A band gap of this magnitude implies that the C-Dots can absorb visible light and positions them as versatile materials for light-harvesting and imaging applications, suggesting potential for optoelectronic, photocatalysis, and bioimaging. The combination of π-π* transitions, surface-related n-π* features, and the observed band gap energy underscores the interplay between the intrinsic core structure and the surface chemistry of the C-Dots. This unique optical profile makes them promising materials for diverse applications requiring tunable electronic and photonic properties. Table 1 compares the C-dots prepared from various polymeric waste materials and techniques.

4. Conclusions

This work investigated the synthesis of carbon dots (C-Dots) from polypropylene (PP) waste (flexible food packaging), presenting an energy-efficient and sustainable approach to plastic waste management. The conversion process was characterized by FTIR analysis,

Table 1. Synthesis of C-Dots from different sources of waste materials

Precursor	Method	Absorption peaks (nm)	Size (nm)	Functional groups	Application	Reference
Plastic waste (polybags, cups, bottles)	Thermal calcination	260	5-30	-OH, -COOH	Analytical applications/ selective Cu^{2+} ions sensing	[31]
Plastic wastes (PP, PE, PS, etc.)	Oxidative acid treatment	-	4-7	-OH, C=O, C-O, C–O–C, -COOH, $-SO_3H$	O_2 harvesting	[36]
PE plastic waste	Acid-mediated plastic charring/chemical oxidation	209, 215, 300, 350	5–7	-OH, -COOH, Sulfate/ Sulfonate	Photocatalyst/ O_2 harvesting	[37]
PET bottles	Pyrolysis/ hydrothermal	-	1.3–4.0	Oxygen-containing groups	Nano-priming agents	[38]
Medical plastic waste	Thermal calcination/ hydrothermal procedure	220-280	5-10	-OH, -COOH, C=O, $-NH_2$	Fe^{3+} ions sensor	[39]
HDPE plastic bags	Pyrolysis-sonication-hydrothermal	290	1-4.5	-OH, -COOH, C=O	Fe^{3+} ions sensor	[40]
Polylactide	One-pot hydrothermal	240, 280	2.5-3.5	-OH, -COOH	-	[15]
Nylon 66 waste fibers	Hydrothermal	251	2.3-8.2	-OH, -COOH, $-NH_2$	Fe^{3+} and pH sensors/ fluorescent inks for encryption and information storage	[41]
PP plastic waste	Thermal/solvothermal process	250, 280	11-73	-OH, -COOH	Bioimaging, energy conversion, and sensing	This work

Notes: PE: Polyethylene; PET: Polyethylene terephthalate; HDPE: High-density polyethylene.

which confirmed the presence of oxygen-containing functional groups in the C-Dots. The carbon-based spherical dots with an average particle size of 43 nm were observed via TEM which validated the formation of nanoparticles. Based on the UV-Vis results, this material exhibits unique optical properties with an electronic band gap energy of 1.9 eV making it suitable for a wide range of applications in optoelectronic, photocatalysis, and bioimaging. The bottom-up synthesis described here is straightforward, free of catalysts, and relies on available recycled materials, offering a practical and scalable option for industrial applications.

Conflict of Interest

The authors declare no conflict of interest.

References

1. N. Evode, et al. Plastic waste and its management strategies for environmental sustainability. *Case Studies in Chemical and Environmental Engineering*, **2021**, *4*, 100142.
2. N. Singh and T.R. Walker. Plastic recycling: A panacea or environmental pollution problem. *Npj materials sustainability*, **2024**, *2*, 17.
3. I. Vollmer, et al. Beyond Mechanical Recycling: Giving New Life to Plastic Waste. *Angewandte Chemie (International ed. in English)*, **2020**, *59*, 15402.
4. R. Kumar, et al. Mechanical, chemical, and bio-recycling of biodegradable plastics: A review. *Science of The Total Environment*, **2023**, *882*, 163446.
5. H. Ahmad and D. Rodrigue. Upcycling of recycled polyethylene for rotomolding applications via dicumyl peroxide crosslinking. *Journal of Applied Polymer Science*, **2024**, *141*, e56236.
6. T.H. Epps, et al. Sustainability of Synthetic Plastics: Considerations in Materials Life-Cycle Management. *JACS Au*, **2021**, *2*, 3.
7. M. Abdelhameed, et al. High-yield, one-pot upcycling of polyethylene and polypropylene waste into blue-emissive carbon dots. *Green Chemistry*, **2023**, *25*, 1925.
8. T. Kuang, et al. Functional carbon dots derived from biomass and plastic wastes. *Green Chemistry*, **2023**, *25*, 6581.
9. A. Vibhute, et al. Fluorescent carbon quantum dots: Synthesis methods, functionalization and biomedical applications. *Applied Surface Science Advances*, **2022**, *11*, 100311.
10. Arpita, et al. Plastic Waste-Derived Carbon Dots: Insights of Recycling Valuable Materials Towards Environmental Sustainability. *Current pollution reports*, **2023**, *9*, 433.
11. Z. Feng, et al. Carbon dot/polymer nanocomposites: From green synthesis to energy, environmental and biomedical applications. *Sustainable Materials and Technologies*, **2021**, *29*, e00304.
12. Y. Yang, et al. Polypropylene-Derived Luminescent Carbon Dots. *ACS Materials Letters*, **2024**, *6*, 1968.
13. M.P. Aji, et al. Polymer carbon dots from plastics waste upcycling. *Environmental Nanotechnology, Monitoring & Management*, **2018**, *9*, 136.
14. H. Jung, et al. Review of polymer technologies for improving the recycling and upcycling efficiency of plastic waste. *Chemosphere*, **2023**, *320*, 138089.
15. A. Lauria and E. Lizundia. Luminescent carbon dots obtained from polymeric waste. *Journal of Cleaner Production*, **2020**, *262*, 121288.
16. R. Wang, et al. Preparation of Carbon Dots from PET Waste by One-step Hydrothermal Method and its Application in Light Blocking Films and LEDs. *Journal of Fluorescence*, **2023**, *33*, 1305.
17. J. Huang, et al. Solid protonic acids and luminescent carbon dots derived from waste expanded polystyrene. *Materials Letters*, **2014**, *117*, 112.
18. Z. Hallaji, Z. Bagheri, and B. Ranjbar. The role of fluorescent carbon dots in the fate of plastic waste. *Journal of Environmental Chemical Engineering*, **2023**, *11*, 110322.
19. A. Alsabri, F. Tahir, and S.G. Al-Ghamdi. Environmental impacts of polypropylene (PP) production and prospects of its recycling in the GCC region. *Materials Today: Proceedings*, **2022**, *56*, 2245.
20. L. Baltes, et al. Differential scanning calorimetry—a powerful tool for the determination of morphological features of the recycled polypropylene. *Journal of Thermal Analysis and Calorimetry*, **2019**, *138*, 2399.
21. C. Budiyantoro, H. Sosiati, and J.W. Joharwan. The influence of the number of recycling cycles on the thermal and physical properties of polypropylene. *Jurnal Polimesin*, **2023**, *21*, 2023.
22. J. Gong, X. Chen, and T. Tang. Recent progress in controlled carbonization of (waste) polymers. *Progress in Polymer Science*, **2019**, *94*, 1.
23. V. Ramanan, et al. Green Synthesis of Multifunctionalized, Nitrogen-Doped, Highly Fluorescent Carbon Dots from Waste Expanded Polystyrene and Its Application in the Fluorimetric Detection of Au3+ Ions in Aqueous Media. *ACS Sustainable Chemistry & Engineering*, **2018**, *6*, 1627.
24. S. Singh, N. Shauloff, and R. Jelinek. Solar-Enabled Water Remediation via Recyclable Carbon Dot/Hydrogel Composites. *ACS Sustainable Chemistry & Engineering*, **2019**, *7*, 13186.

25. F. Mahdavian, et al. Polyethylene glycol-impregnated carbon quantum dots-phenolic phase change composites for highly efficient thermal energy storage. *Carbon*, **2024**, *219*, 118840.

26. N.K. Khairol Anuar, et al. A Review on Multifunctional Carbon-Dots Synthesized From Biomass Waste: Design/ Fabrication, Characterization and Applications. *Frontiers in Energy Research*, **2021**, *9*, 626549.

27. M. Das, et al. Repurposing the domestic organic waste into green emissive carbon dots and carbonized adsorbent: A sustainable zero waste process for metal sensing and dye sequestration. *Journal of Environmental Chemical Engineering*, **2021**, *9*, 106312.

28. X. Li, et al. Green synthesis of carbon quantum dots from wasted enzymatic hydrolysis lignin catalyzed by organic acids for UV shielding and antioxidant fluorescent flexible film. *Industrial Crops and Products*, **2022**, *188*, 115568.

29. C.S. Pathak, et al. Blue light emission from barium doped zinc sulfide nanoparticles. *Ceramics International*, **2012**, *38*, 5497.

30. J. Dharma and A. Pisal, *Simple Method of Measuring The Band Gap Energy Value of TiO2 in the Powder Form Using a UV/Vis/NIR Spectrometer*. **2009**, PerkinElmer. p. 1.

31. S. Chaudhary, et al. Upcycling of plastic waste into fluorescent carbon dots: An environmentally viable transformation to biocompatible C-dots with potential prospective in analytical applications. *Waste Management*, **2021**, *120*, 675.

32. K. Tungare, et al. Synthesis, characterization and biocompatibility studies of carbon quantum dots from Phoenix dactylifera. *3 Biotech*, **2020**, *10*, 540.

33. B. Zhao, et al. Narrow-bandwidth emissive carbon dots: A rising star in the fluorescent material family. *Carbon Energy*, **2022**, *4*, 88.

34. H. Sutanto, et al. High green-emission carbon dots and its optical properties: Microwave power effect. *AIP Advances*, **2020**, *10*, 055008.

35. J. Yu, et al. Luminescence Mechanism of Carbon Dots by Tailoring Functional Groups for Sensing Fe(3+) Ions. *Nanomaterials*, **2018**, *8*, 233.

36. B. Kommula, et al. Landscaping sustainable conversion of waste plastics to carbon dots and enormous diversity in O2 harvesting, hypoxia, autophagy. *Carbon*, **2023**, *213*, 118304.

37. B. Kommula, et al. A two-step strategy for residue-free chemical conversion of plastic waste to carbon dots: Upscaling and solvent recycling prospects. *Carbon*, **2025**, *234*, 119960.

38. L. Liang, S.C. Wong, and G. Lisak. Effects of plastic-derived carbon dots on germination and growth of pea (Pisum sativum) via seed nano-priming. *Chemosphere*, **2023**, *316*, 137868.

39. M. Kumari, G.R. Chaudhary, and S. Chaudhary. Transformation of medical plastic waste to valuable carbon dots: A sustainable recycling of medical waste to efficient fluorescent marker. *Journal of Molecular Liquids*, **2024**, *395*, 123910.

40. R. Lestari, et al. Transforming high-density polyethylene plastic bags into eco-friendly carbon dots for detecting ferric (Fe3+) ions. *Diamond and Related Materials*, **2023**, *139*, 110271.

41. R. Wang, et al. Simple and Green Synthesis of Carbonized Polymer dots from Nylon 66 Waste Fibers and its Potential Application. *ACS omega*, **2021**, *6*, 32888.