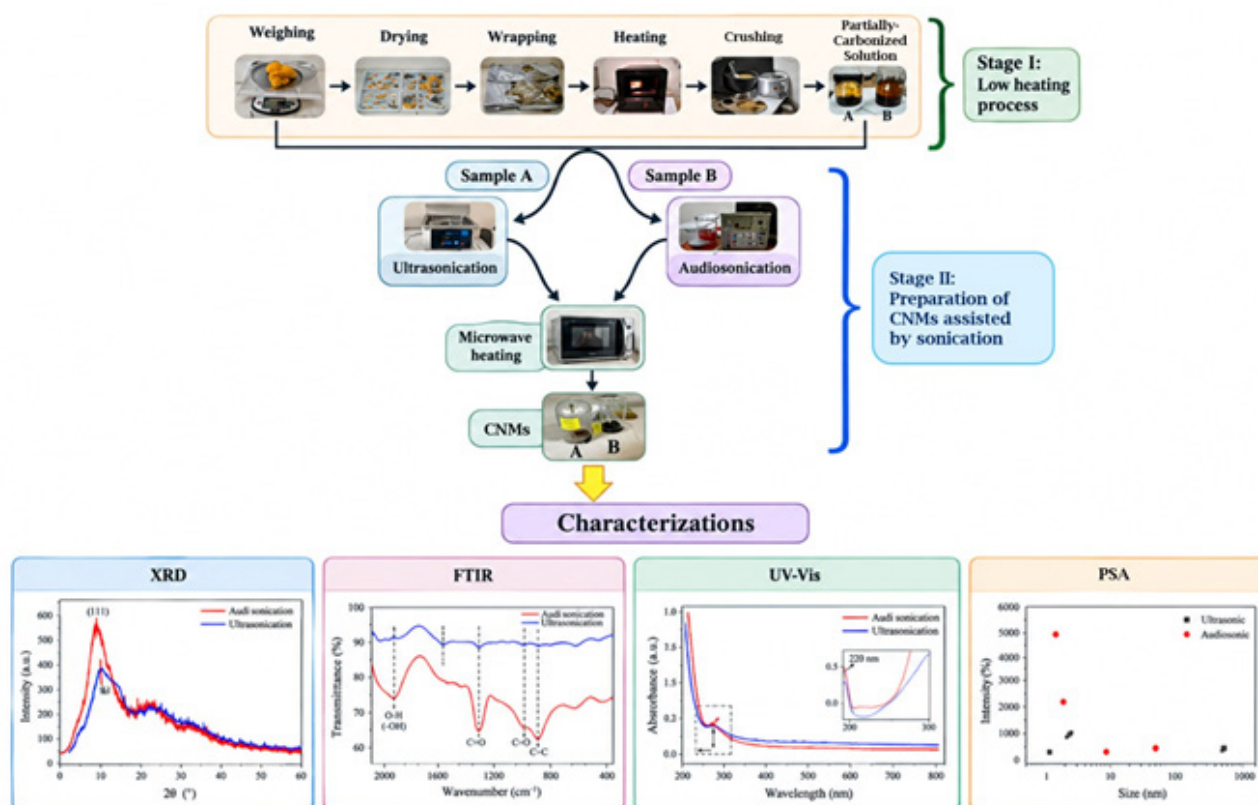


## RESEARCH ARTICLE

# Sonication Effects on the Formation of Carbon-based Nanomaterials via a Two-Step Low-Heating Method

A. Aprilia, M. Solaiman, N. Mantika, A. S. Sulhan, W. S. B. Dwandaru and Ariswan

## Graphical Abstract



## Highlights

- Mango seed waste was used as a precursor for carbon-based nanomaterials.
- A two-step low-heating method was used with acoustic treatments.
- Both samples exhibited cyan luminescence under 405 nm laser excitation.
- Ultrasonic treatment produced smaller particles with lower Raman  $I_D/I_G$  ratios.

# Sonication Effects on the Formation of Carbon-based Nanomaterials via Two-Step Low-Heating Method

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## Abstract

This study aimed to prepare, characterize, and compare carbon-based nanomaterials (CNMs) produced using a two-step low-heating (TSLH) method, with mango seed waste as the precursor. The preparation involved oven- and microwave-based low-heating processes, with audiosonic and ultrasonic treatments applied at intermediate stages. Two CNM samples were produced using audiosonic and ultrasonic treatments. Both samples were characterized using X-ray diffraction (XRD), Fourier-transform infrared (FTIR) spectroscopy, ultraviolet-visible (UV-Vis) spectroscopy, particle size analysis (PSA), and Raman spectroscopy. Both samples exhibited green-to-blue (cyan) luminescence when excited using a violet/UV laser pointer (405 nm). The XRD patterns indicated that both CNM samples were amorphous. The FTIR results suggested the presence of C–H, C=C, CO<sub>2</sub>, and OH functional groups. The UV-Vis absorption peaks occurred at 259.2 nm and 257.8 nm for the samples prepared using ultrasonic and audiosonic treatments, respectively. Particle size analysis indicated a smaller particle size distribution for the CNMs produced using ultrasonic treatment than for those produced using audiosonic treatment. Raman spectroscopy revealed  $I_D/I_G$  values of 1.06 and 0.96 for the audiosonic- and ultrasonic-treated samples, respectively, suggesting a higher degree of structural disorder or defects in the audiosonic-treated sample. These findings indicate that the choice of intermediate treatment influences the characteristics of CNMs produced using the TSLH method.

**Keywords:** Audiosonic treatment, CNMs, Mango seed waste, TSLH method, Ultrasonic treatment

## INTRODUCTION

One of the urgent environmental problems in the world is waste. As an example, Indonesia is the second-largest waste producer in the world after Saudi Arabia, with around 300 kg of waste per person per year (Yuriandala et al., 2020). Waste is divided into organic and inorganic wastes. The former can be naturally decomposed, while the latter cannot (Ardiyanti, 2021). An example of organic waste is mango seeds. Generally, the part of the mango fruit that is usually consumed is the fleshy part, while the seeds are thrown away and become organic waste because they are considered to have no value and are often considered leftovers that cannot be reused. On the other hand, mango seeds are a rich source of carbon. Mango seeds contain 70% carbohydrate, 10% fat, and 6% protein. Mango seeds have a strong antioxidant activity because they contain

high levels of phenolic and phytochemical compounds in the form of tannins (Munawaroh, 2017; Legesse & Emire, 2012; Soong & Barlow, 2004). The chemical content in the form of galotanin has an antibacterial effect on several types of Gram-positive and Gram-negative bacteria (Engels et al., 2012). Mango seeds also contain saponins, flavonoids, and triterpenoid compounds (Prihandani et al., 2016). The ethanol extract of mango seeds has strong antibacterial activity against *Propionibacterium acnes* bacteria; thus, it is expected to inhibit the growth of bacteria that cause acne (Munawaroh, 2017). Mango seeds have fairly high antioxidant content, indicating the effectiveness of mango seeds as a bactericide (Prihandani et al., 2016). Furthermore, mango seeds produce high levels of bioethanol (Cristina et al., 2015). In the present study, mango seed waste is used as a precursor for the production of carbon-based nanomaterials (CNMs) having various applications.

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In conjunction with the environmental problem of organic wastes, the reuse of mango seeds for preparing nanomaterials is a novel approach in order to reduce the financial or environmental costs concerning organic waste disposal (Sharma et al., 2024). This is an excellent opportunity to create a circular economy in order to optimize organic waste management and, hence, overcome the aforementioned environmental problem. A functional nanomaterial that exactly fits this task is CNMs. A major reason for this is that organic wastes contain an abundance of carbon (C) elements linked to hydrogen (H), oxygen (O), and nitrogen (N). That is why CNMs encompass a family of nanomaterials, such as activated carbon, carbon black, biochar, graphene and its derivatives, e.g., graphene oxide (GO) and reduced GO (rGO), fullerenes, carbon nanotubes (CNT), and carbon nanodots (C-dots) (Putro et al., 2019; Jumardin et al., 2022). CNMs can be synthesized from household kitchen waste (Dirja & Dwandaru, 2024), cassava peel waste (Putro et al., 2019), durian fruit (Anindita et al., 2021; Nume et al., 2024), and mango skin (Jiao et al., 2019). The advantages of CNMs are low toxicity, biocompatibility, and excellent fluorescence (Bao et al., 2015; Malode et al., 2024). CNMs have been applied in various fields, such as in photocatalysis (Ahmed et al., 2024) and optoelectronics as sensors (Wang & Hu, 2014). In addition, in the field of biology, CNMs can be used in bioimaging (Yang et al., 2009), biosensor carriers (Malode et al., 2024; Shin et al., 2024), and drug delivery systems (Shahazi et al., 2023).

Generally, in order to obtain the carbon elements contained in the organic wastes, heating processes are involved (Chatterjee et al., 2020). Then, various advanced processes are conducted in order to produce the CNMs depending upon the type of CNMs being produced (Krasley et al., 2024). Based on the approach to synthesizing CNMs, there are two methods in producing them, namely top-down and bottom-up (Rao et al., 2020). The top-down method is the synthesis of nanoparticles by breaking large particles into nanometer-sized particles, which includes arc discharge, laser ablation, electrochemical oxidation, chemical oxidation, and ultrasonication processes. On the other hand, the bottom-up method is based on building nano-sized particles from atoms or molecules, which includes microwave synthesis, thermal decomposition, hydrothermal treatment, and plasma treatment (Putro et al., 2019).

In the present study, we use the sonication method in order to prepare the CNMs. Sonication can be used to speed up the process of dissolving a material using the principle of intermolecular reactions to form nano-sized particles. Ultrasound is an acoustic wave with a frequency greater than 20 kHz. The ultrasonic bath method is used to extract anthocyanin pigments in mango seeds as an alternative to natural dyes (Handaratri & Yuniati, 2019). Furthermore, audiosonic sounds use frequencies between 20 Hz and 20 kHz (Hanifa & Dwandaru, 2017). In this case, the audiosonic bath used is custom-made using a horn speaker equipped with an amplifier and an audio

generator apparatus. To the best knowledge of the authors, this study is the first to use the audiosonic bath treatment for preparing CNMs. Another distinctive feature between audiosonic and ultrasonic treatments is the occurrence of cavitation in the latter treatment, which does not happen in the former (Jiang et al., 2024). Cavities are micro-sized bubbles that undergo constant expansion and contraction and, at some point, will explode, releasing thermal energy. If there are bulk materials in the vicinity of the explosion, the bulk materials can break up into nanosized materials. Therefore, an established mechanism for nanomaterial formation via ultrasonication is the occurrence of cavities in the solution.

It is already known that the preparation of CNMs from various biomass via thermal or sonochemical methods is well documented in the literature; see e.g., Al-Harbi & Abd-Elrahman (2025) and Ashour et al. (2025). However, in the present study, we introduce a certain combination and steps of the top-down and bottom-up methods, i.e., sonication and heating processes, respectively. Two main pieces of equipment are used for the heating process, i.e., an oven and a microwave. Between the heating processes, sonication is conducted. Moreover, the heating processes are done at a low temperature, i.e., less than 450 °C. We designate this procedure as the two-step low heating (TSLH) method.

It is generally accepted that the physicochemical properties of the CNMs depend upon the precursor and the methods used to prepare them (Sezali et al., 2024). Hence, different kinds of preparation methods can produce CNMs with different properties. Here, in order to test this assertion, we prepare CNMs from mango peel waste using the TSLH method assisted with two sonication treatments, i.e., ultrasonic and audiosonic baths. We compare the characteristics of the CNMs prepared by the two sonication treatments based on X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectrometer, ultraviolet-visible (UV-Vis) spectrophotometer, particle size analyzer (PSA), and Raman spectrometer. The comparison of CNM properties prepared via various methods is essential in determining the appropriate method for preparing CNMs for specific applications, such as comparing the hydrothermal and microwave methods for C-dots prepared from commercial granulated sugar, which has been conducted by Dwandaru et al. (2019). Hence, the objectives of the present study are to prepare, characterize, and compare CNMs obtained via the TSLH method assisted with ultrasonic and audiosonic treatments.

## MATERIALS AND METHODS

This was an experimental study with CNMs prepared from mango seed wastes via the TSLH method assisted by two treatments, namely ultrasonic and audiosonic baths. The characterization of the CNMs was carried out using XRD (Rigaku Miniflex 600), UV-Vis spectrophotometer (Shimadzu UV3600), FTIR spectrometer (Spectrum Two System L160000A), PSA (Microtac Nanotrac Wave II),

and Raman spectrometer (Horiba Scientific Olympus CX43). The materials used were mango seed waste and 400 mL distilled water. The tools utilized were a 500 mL beaker (Iwaki), funnel, filter paper, kitchen oven (Mitseda CK-12 Electronic Oven), microwave (Sharp R-223MA-BK), mortar, spatula, aluminum foil, ultrasonic bath cleaner (UC-8360), and a custom-made audiosonic device consisting of a horn speaker, amplifier, and audio generator. The ultrasonic bath cleaner produced a frequency of 21 kHz with varying time duration features. The normal mode vibration of the audiosonic bath was determined via the audio generator with the frequency set at 25 Hz. The sonication devices may be observed in Figure 1.

The experimental procedure in this study consisted of two stages in the TSLH method, i.e., low heating (partially-carbonized) process and CMNs preparation assisted by sonication (see Figure 2). The first stage was to wash the mango seed wastes and weigh them. The weight of the

mango seed wastes obtained was 233.5 g. The mango seed wastes were then dried for 3 days in the sun. After the drying, the wastes were weighed again. The weight of the wastes was reduced to 141.8 g, which were then cut into pieces and wrapped in aluminum foil. The wastes in the aluminium foil were then subjected to low-temperature heat treatment inside an oven at a temperature of 250 °C with a time duration of 3 hours. At the aforementioned temperature, the Maillard reaction should take place, with the occurrence of the caramelization process. Moreover, the surrounding temperature of the oven was measured at around 40 °C to 41 °C. The partially carbonized mango peel waste was crushed using a mortar and pestle until it became smooth, divided into two equal parts, and then each part was put into a 500 mL beaker. Then each beaker glass was weighed, and the first (sample A) and second (sample B) glasses weighed 38 g. Then, 400 mL of distilled water was added to each beaker glass.

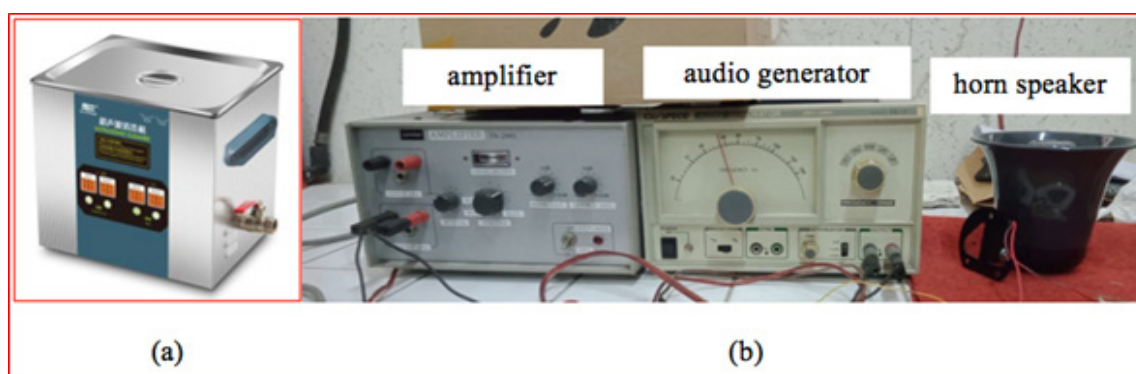


**Figure 1:** Sonication treatments used in the preparation of CNMs: (a) ultrasonic bath and (b) audiosonic bath

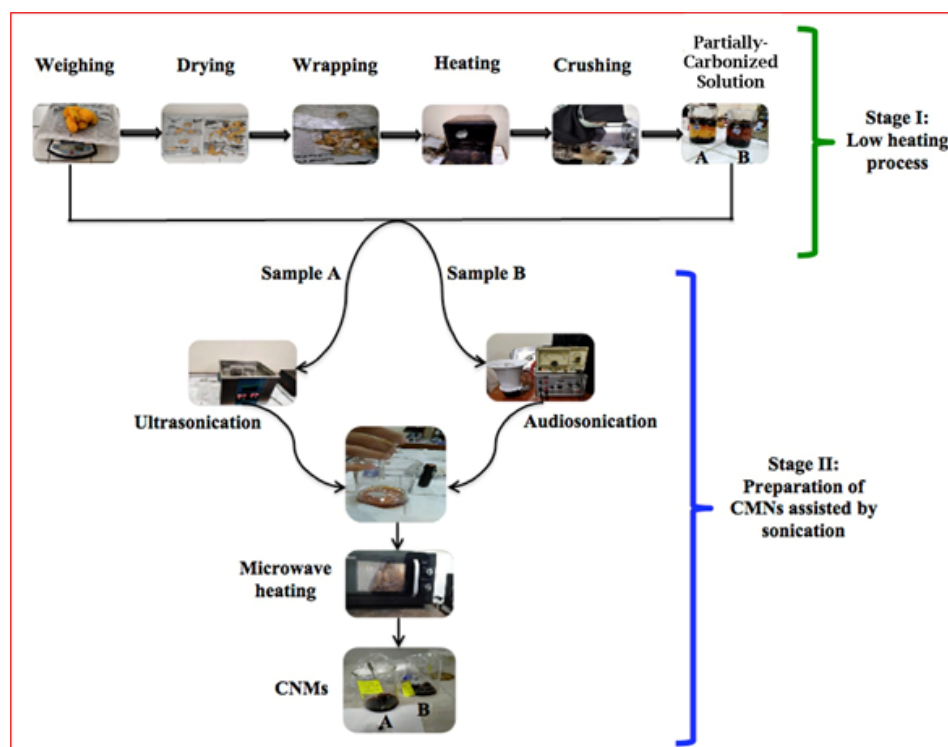


**Figure 2:** Schematic representation of the two-stage preparation process for carbon-based nanomaterials (CNMs) from mango seed waste using the two-step low-heating (TSLH) method

After that, in the second stage, the beaker containing the partially carbonized mango seed solution (sample A) was put into the ultrasonic bath with a frequency of 21 kHz, power density of 20 W/L, and time duration of 1 hour (10 minutes per cycle). Meanwhile, the solution of sample B contained in the beaker glass was put into the horn speaker (audiosonic bath) with the audio generator set at a frequency of 25 Hz for 1 hour. The two sample solutions were filtered using filter paper per 100 mL and put into a microwave at a medium-high temperature until the water content decreased, with a heating duration of 35 minutes. In this case, the objectives of the microwave treatment were twofold, namely, i) to form CNMs through molecular reorientation and ii) to reduce the water content so that the CNMs are in the form of powder or caramel.

The last step was the characterizations of the samples using XRD, UV-Vis spectrophotometer, FTIR spectrometer, PSA, and Raman spectrometer. For the XRD and Raman tests, solidified samples were used. The rest of tests were conducted using the samples in the liquid form.

The data analysis was conducted by comparing the characterization results of the CNMs obtained via ultrasonic (sample A) and audiosonic (sample B) treatments. The results of the data analysis were discussed and then the conclusion was made.

## RESULTS AND DISCUSSION

The precursor material used to prepare the CNMs are wastes of mango seeds. Mango seeds are a part of the fruit that are commonly considered as wastes. Utilization of this waste is an effort to reuse and reduce mango fruit wastes that are scattered around the Faculty of Mathematics and Natural Sciences Laboratory–Universitas Negeri Yogyakarta–[see Figure 3(a)]. Mango fruits that are already rotten and become wastes are cleaned and one part is utilized, namely the seeds [Figure 3(b)] as they contain saponins, flavonoids,

and triterpenoids (Legesse & Emire, 2012). These compounds are secondary metabolites (biologically active compounds - BAC) as a source of rich carbon atoms for the preparation of CNMs. Furthermore, this study uses the low heating treatment using an oven, and then continued by heating using a microwave. This low temperature heating treatment is carried out to partly activate the carbon atoms and simultaneously reduce the water content. The presence of the heating treatment triggers a reorientation of the BAC chemical structures so that the CNMs are formed.

The preparation of the CNMs produces two samples in the form of a liquid emulsion (caramel), as seen in Figures 3(c) and 3(d). It can be seen that there are differences in the surface texture between the CNMs assisted by the ultrasonic [Figure 3(c)] and audiosonic [Figure 3(d)] treatments. It can be observed that the surface texture of the ultrasonic-treated CNMs is smoother than that of the audiosonic-treated CNMs. However, the two CNMs samples have almost the same colour, which is dark brown. The two samples are then diluted again using distilled water to produce CNMs solutions. It can be observed in Figures 4(a) and 4(b) that the two CNMs solutions have a brownish colour. However, the CNMs solution using the ultrasonic treatment [Figure 4(a)] appears to be darker. This shows that the CNMs via ultrasonic treatment are more concentrated, which indicates that the ultrasonic bath produces more CNMs.

The first characterization of the resulting CNMs samples is carried out simply using a purple/ultraviolet (UV) laser pointer. One indicator for the formation of CNMs is the occurrence of luminescence when subjected to a purple/UV laser. The results of the luminescence due to the purple/UV laser upon the two CNMs solutions can be observed in Figures 4(c) and 4(d). The CNMs solution via the ultrasonic treatment produces a green luminescence [Figure 4(d)], while the CNMs solution via the audiosonic treatment produces a blue luminescence [Figure 4(c)].

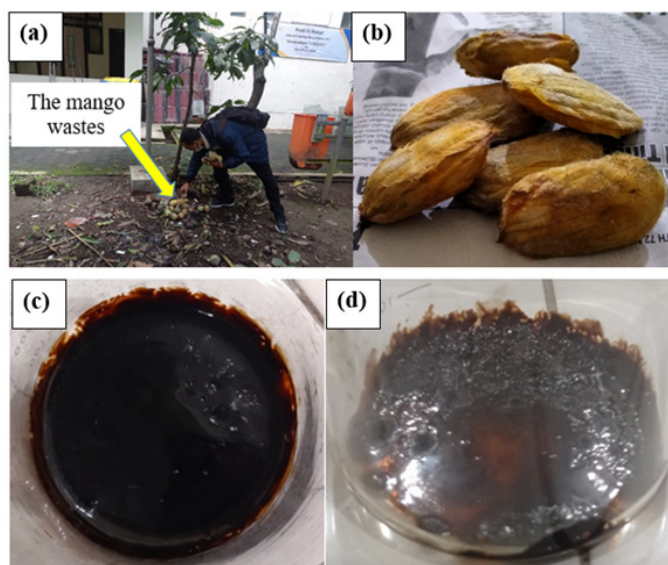


**Figure 3:** Mango fruit waste (a), extracted mango seeds (b), and caramel-like carbon-based nanomaterials (CNMs) produced using ultrasonic treatment (sample A; c) and audiosonic treatment (sample B; d).

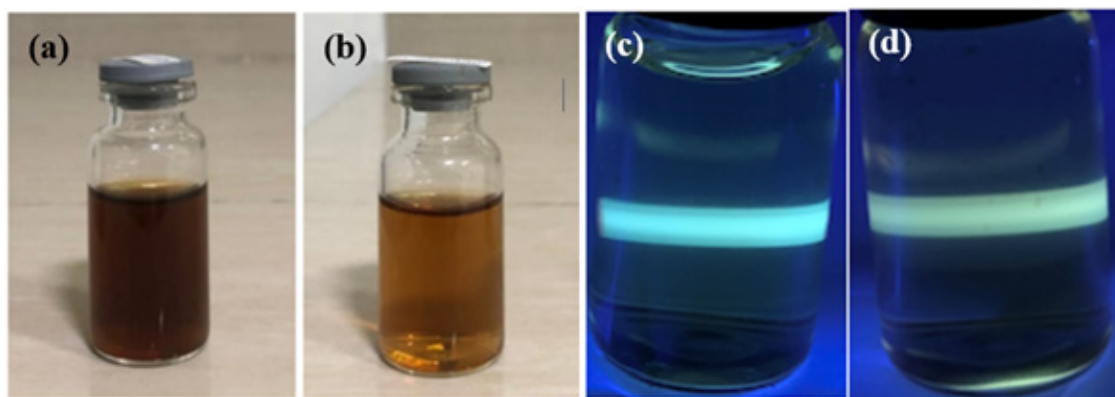


**Figure 4:** Visual appearance of CNM solutions produced using (a) ultrasonic and (b) audiosonic treatments, and their luminescence under violet/UV laser excitation: (c) audiosonic-treated CNMs and (d) ultrasonic-treated CNMs

It may be observed that the luminescence produced by the CNMs via the ultrasonic treatment is qualitatively denser than the CNMs via the audiosonic bath. This is in fact in accordance with the results obtained in Torrisi et al. (2024) where laser ablation was used to prepare CNMs from vegetable carbon in phosphate-buffered saline (PBS) solution. The results of the study show that increasing the laser ablation time increases the concentration of the CNMs produced, and hence increases the luminescence yield. In this case, the CNMs produced via the ultrasonic treatment are more concentrated [Figure 4(a)], hence producing a denser luminescence [Figure 4(d)].

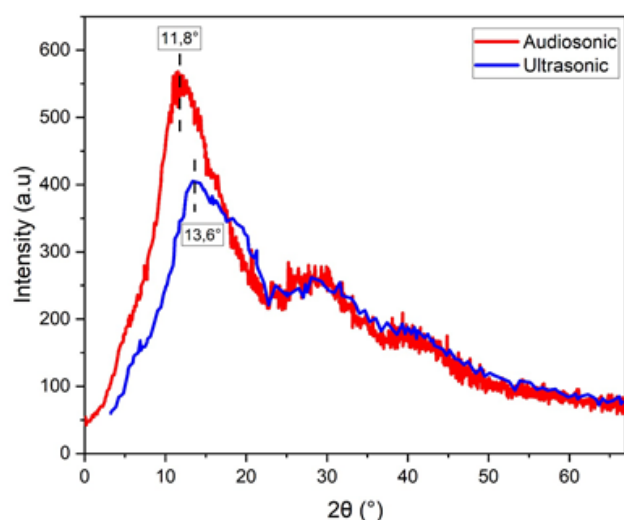


**Figure 5:** X-ray diffraction (XRD) patterns of the CNM samples produced using ultrasonic and audiosonic treatments

The crystallinity of the CNMs samples can be observed in Figure 5. In general, it can be observed that the diffraction spectra for the two CNMs samples show amorphous structures as expected. Sharp peaks do not occur, but rather shallow or low peaks at  $2\theta$  around  $13.6^\circ$  and  $11.8^\circ$  for CNMs obtained from the ultrasonic and audiosonic treatments, respectively. This means that the atomic structures of the CNMs produced do not have a certain pattern (disordered) and tend to be random. The diffraction patterns in Figure 5 are consistent with the amorphous carbon diffraction pattern

obtained by Frolov et al. (2023). It may also be observed in Figure 5 that the CNMs via the ultrasonic treatment have lower intensity with a narrower peak. This indicates that the CNMs via the audiosonic treatment is more amorphous than the CNMs via the ultrasonic treatment.

Quantitative analysis utilizing the Scherrer formula gives the crystalline sizes of the CNMs from ultrasonic and audiosonic treatments around 1.30 nm and 1.27 nm, respectively. This is in accordance with the qualitative analysis that the CNMs are highly amorphous and/or poorly crystalline, having a very limited long-range atomic order. Moreover, the structure of the CNMs contains significant disorder and defects, which are typical for carbonaceous materials produced by low heating temperatures, e.g., the TSLH method.

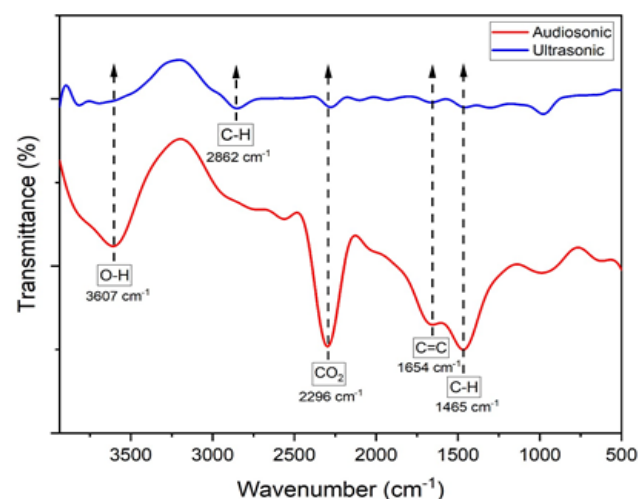


**Figure 6:** Fourier-transform infrared (FTIR) spectra of the CNM samples produced using ultrasonic and audiosonic treatments

The FTIR characterization results for the two CNMs samples can be observed in Figure 6. In general, it can be observed that the FTIR spectra for the two CNMs samples appear to be similar. The two CNMs samples indicate the existence of O-H stretching, carbon dioxide ( $\text{CO}_2$ ) stretching, C=C stretching of cyclic alkene, and C-H bending of alkane functional groups at bands of  $3595 \text{ cm}^{-1}$

<sup>1</sup>, 2291 cm<sup>-1</sup>, 1654 cm<sup>-1</sup>, and 1465 cm<sup>-1</sup>, respectively. The C=C functional group indicates the existence of sp<sup>2</sup> carbon elements in the CNMs samples. Moreover, the existence of O-H and CO<sub>2</sub> suggests that oxygen functional groups are present as well. Another C-H stretching alkane functional group at 2851 cm<sup>-1</sup> occurs for the CNMs produced via the ultrasonic treatment, but is not present in the ultrasonically treated CNMs sample. Thus, the sonication treatments generally do not affect the functional groups produced. The IR spectra of the CNMs samples are in accordance with the IR spectra of fluorescent C-dots loaded nanocomposite chitosan film in Kandra & Bajpai (2020).

The results of UV-Vis characterization can be observed in Figure 7. The absorption profiles of both CNMs samples show the presence of one absorption peak. The CNMs produced via ultrasonic and audiosonic treatments have absorption peaks at wavelengths of 259.2 nm and 257.8 nm, respectively. These absorption peaks are in the UV range, which indicates the existence of carbon elements, i.e., C=C functional groups, as a result of  $\pi \rightarrow \pi^*$  electronic transitions. This is in accordance with the FTIR results obtained in Figure 6, especially at 1654 cm<sup>-1</sup> where the C=C functional group occurs. The wavelength of the absorption peak of the CNMs produced via the ultrasonic treatment is slightly higher, hence indicating a shift to a larger wavelength (red shift) compared to the audiosonic treatment. Furthermore, the Tauc plots of the bandgap energies of the CNMs samples can be observed in the insets of Figure 7. It can be seen that the bandgap energies of the CNMs produced via ultrasonic and audiosonic treatments are 4.87 eV and 4.96 eV, respectively, which means that the ultrasonic treatment decreases the bandgap energy of the CNMs.

The PSA characterization is conducted in order to investigate the size distribution of the CNMs samples.

The results of the PSA characterization can be observed in Figure 8. The CNMs produced via the ultrasonic treatment show particle size distributions of 734 nm, 212.9 nm, and 32.5 nm with volumes of 12.5%, 84.7%, and 2.8%, respectively. Meanwhile, the audiosonic-treated CNMs show particle size distributions of 84.9 nm, 223.9 nm, 2176 nm, and 5120 nm with volumes of 30.6%, 53.6%, 10.6%, and 5.2%, respectively. These results show that the particle sizes of the CNMs produced via ultrasonic and audiosonic treatments with the largest volumes are less than 212.9 nm and 223.9 nm, respectively. These aforementioned particle sizes are larger than 100 nm, the upper-limit criterion for nanomaterials (Vijayaram et al., 2024). Furthermore, as many as 12.5% and 5.2% of the CNMs samples via ultrasonic and audiosonic treatments are particles in bulk with sizes less than 734 nm and 5120 nm, respectively. This means that bulk materials can still be found in the samples, as no further filtration is conducted. The particle sizes that are within the nano-size range are less than 32.5 nm and 84.7 nm, with percentages of 2.8% and 30.6% for the CNMs produced via ultrasonic and audiosonic treatments, respectively. This means that both treatments can produce particle distributions with sizes less than 100 nm, with the audiosonic treatment promoting more nano-sized particles compared to the ultrasonic treatment. On the other hand, the ultrasonic treatment tends to produce smaller nano-sized particles than the audiosonic treatment. Furthermore, this also suggests that the occurrence of large particle size distributions (> 100 nm) in the CNMs samples may be caused by the PSA detecting clumps or groups of these nano-size particles. It can also be observed in Figure 8 that the range of the particle sizes of the CNMs produced via the ultrasonic bath is smaller than that of the CNMs produced via the audiosonic bath. Hence, based on the largest volumes obtained, the CNMs produced via the ultrasonic treatment are more homogeneous.

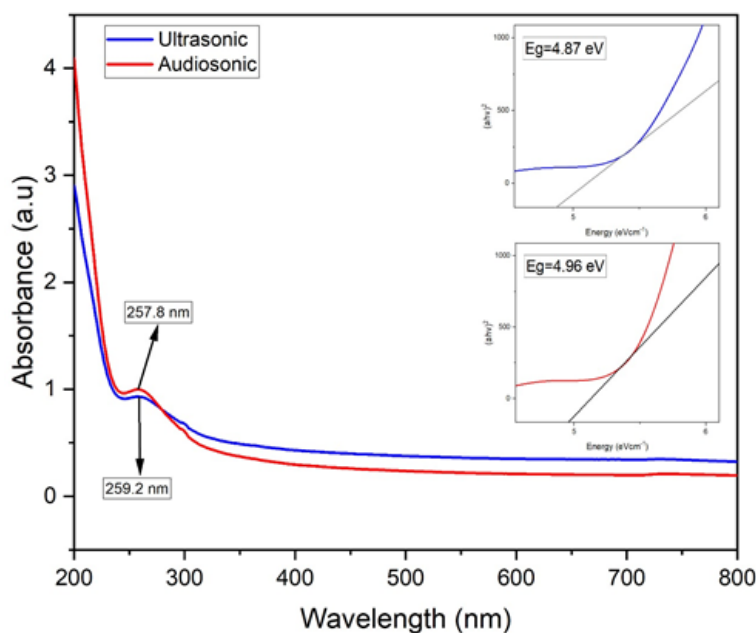


**Figure 7:** Absorption spectra of the CNMs samples

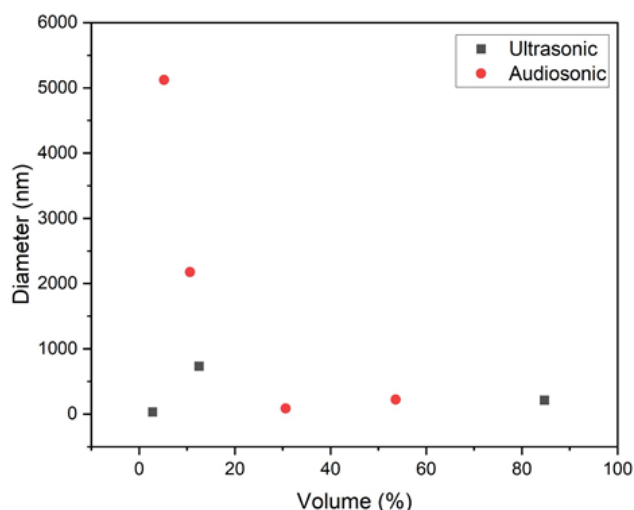


**Figure 8:** Particle size distributions of the CNMs samples

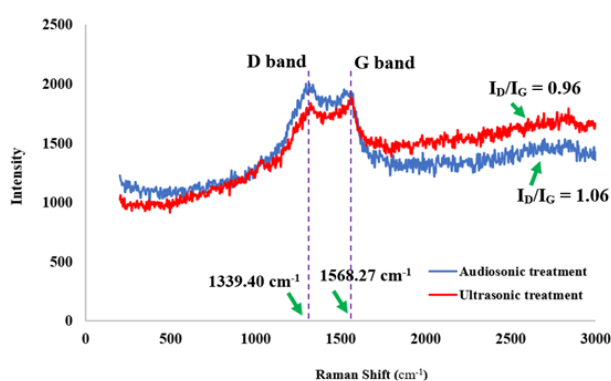


**Figure 9:** Raman shift comparison of CNMs with ultrasonic and audiosonic treatments

A Raman shift comparison of the CNMs obtained from the ultrasonic and audiosonic treatments can be observed in Figure 9. Two dominant bands occur for all the CNMs samples, which are characteristic of carbonaceous materials, i.e., the D and G bands at  $1339.40\text{ cm}^{-1}$  and  $1568.27\text{ cm}^{-1}$ , respectively. It may be observed that the intensity value of the G bands for all CNMs samples is the same around 1871, which indicates vibrational modes of  $\text{sp}^2$ -hybridized carbon atoms (Srivastava et al., 2026). However, the intensity of the D bands is different for the CNMs via audiosonic and ultrasonic treatments. The D band of the CNMs from the ultrasonic treatment is lower than that of the audiosonic treatment, i.e.: 1804 and 1990, respectively. Furthermore, the ratio between the D and G band intensities ( $I_D/I_G$ ) represents a semi-quantitative analysis of the Raman shift. It may be observed in Figure 9 that the  $I_D/I_G$  values for the CNMs via audiosonic and ultrasonic treatments are 1.06 and 0.96, respectively. This indicates that the disorder or defect in the  $\text{sp}^2$  carbon structures of the CNMs from the audiosonic treatment is larger than that from the ultrasonic treatment. In other words, CNMs via ultrasonic treatment produce better crystallinity. This is in accordance with the crystalline size calculation using the Scherrer formula, where the crystalline size of the CNMs from ultrasonic treatment is slightly higher than from the audiosonic treatment.

It is also interesting to compare the XRD, PSA, and Raman spectroscopy results regarding the particle and crystalline sizes of the CNM samples. The XRD and PSA results indicate that the ultrasonic treatment produces larger crystalline size, but a smaller nano-size particle distribution compared to the audiosonic treatment. The smaller nano-size particle distribution from the ultrasonic treatment is expected, as cavitation events lead to further breakage of the  $\text{sp}^2$  carbon planes into smaller particle sizes. On the other hand, both the XRD and Raman spectroscopy results show that audiosonic treatment produces slightly smaller crystalline size. This suggests that the audiosonic treatment produces more disorder or defects on the CNMs although no cavitation events occur because audible sound with low intensity cannot produce them. Therefore, one possible mechanism in which audiosonic treatment produces defects is by assisting and/or promoting the attachment or formation of functional groups upon the  $\text{sp}^2$  carbon structures via mechanical vibrations of the normal modes.

Both sonication treatments may affect surface functionalization of the CNMs, especially through cavitation, shockwaves, and normal modes of standing waves. Ultrasonic treatment breaks down large particles and aggregates into smaller ones (top-down) caused by collapsing cavitation bubbles and intense shear forces (Jiang et al., 2024). The ultrasonic vibrations can also produce acoustic streaming, inducing chaotic mixing (Nguyen et al., 2011; Theodorakopoulos et al., 2024). Smaller particles increase the specific surface area, such that more functional groups can attach to them. On the other hand, audiosonic treatment assists in the attachment of functional groups on the carbon structures via normal modes of standing waves.

The CNMs produced in this study, having prominent properties of amorphous structures, luminescence, and partly nano-size particle distributions (high surface area), can be potentially utilized for various applications. These applications include fillers in rubber, pigments, UV protection, energy storage and conversion, coatings, biosensors, and environmental remediation (Dutta et al., 2022; Ayanda et al., 2024). On the other hand, it is also important to pay attention to the impact or implications of the CNMs produced. These implications include environmental impacts, health impacts, and sustainability of the CNMs.

## CONCLUSIONS

Carbon-based nanomaterials (CNMs) were prepared from mango seed waste using the two-step low-heating (TSLH) method, with ultrasonic and audiosonic treatments applied during the preparation process. The resulting CNMs were obtained as liquid emulsions with a caramel-like appearance. The results showed that the two samples exhibited similar overall characteristics, although differences were observed in their specific measured values. Both samples exhibited green-to-blue (cyan) luminescence when exposed to a violet/UV laser pointer. In addition, the CNM solution produced using ultrasonic treatment was more concentrated.

X-ray diffraction (XRD) analysis indicated that both CNM samples were amorphous, with limited long-range atomic order and substantial structural disorder. UV-Vis spectroscopy revealed absorption peaks at 259.2 nm and 257.8 nm for the samples prepared using ultrasonic and audiosonic treatments, respectively. FTIR analysis indicated the presence of similar functional groups in both samples, including C–H, C=C, OH, and CO<sub>2</sub>, supporting their similar chemical characteristics. Particle size analysis (PSA) showed that the CNMs produced using ultrasonic treatment had a smaller and narrower particle size distribution than those produced using audiosonic treatment. Raman spectroscopy revealed a lower  $I_D/I_G$  value for the ultrasonic-treated sample than for the audiosonic-treated sample, suggesting a lower degree of structural disorder in the former. These findings indicate that both ultrasonic and audiosonic treatments influence the characteristics of CNMs produced using the TSLH method.

Further research should employ scanning electron microscopy (SEM) and high-resolution transmission electron microscopy (HR-TEM) to investigate the surface morphology and particle size of the CNMs, respectively, and compare the findings with the PSA results obtained in this study. In addition, quantitative analyses of the FTIR and UV-Vis spectra would provide further insights into the chemical composition and optical properties of the CNM samples.

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## DECLARATION OF CONFLICT OF INTEREST

The authors have no financial or proprietary interests in any material discussed in this article.

## FUNDING INFORMATION

No funding was received for this work.

## AUTHOR CONTRIBUTION

Conceptualization, Methodology, Data acquisition, Data analysis: **A.A., M.S., N.M., A.S.S.**; Data interpretation, Writing the first draft, Final draft: **A.A., W.S.B.D.**; Manuscript editing and reviewing: **W.S.B.D., A.**; Supervision, Resources: **W.S.B.D.**; Project administration: **A.**

## DATA AVAILABILITY STATEMENT

Data are available upon reasonable requests from the authors.

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