Applied Chemical Engineering (2025) Volume 8 Issue 3
doi: 10.59429/ace.v8i3.5702
ISSN: 2578-2010 (O)

ORIGINAL RESEARCH ARTICLE

Synthesis of carbon nanoparticles from glucose, evaluation of their phenol adsorption capacity, and study their potential as drug delivery systems for treating human pancreatic cancer cells

Maram Ahmed Alaadin[1], Ghufran Ashour Hammood[2], Sahar T. Adday[3], Amer Hamied Hussein[3*], Anmar Haitham Nouri[4]

[1] *Faculty of Production and Metallurgical Engineering, Department of Metallurgical Engineering, University of Technology, Baghdad, 10066, Iraq*

[2] *Department of Chemistry, College of Science, University of Baghdad, Baghdad, 10071, Iraq*

[3] *Department of Chemistry, College of Science for Women, University of Baghdad, Baghdad, 10071, Iraq*

[4] *Shaheed Mustafa Secondary School, Diyala Education Directorate, Baqubah, 32001, Iraq*

***Corresponding author:** Amer Hamied Hussein, amer6600763@gmail.com

ABSTRACT

This research focuses on the synthesis of carbon nanoparticles from glucose through the wet chemical method. The dimensions of the generated particles were evaluated through XRD technology, and the capacity of the synthesized nanoparticles to adsorb phenol particles on their surface was illustrated using UV-VIS and FTIR analysis. The calculation of the loading efficiency (DLE) indicated a remarkably high ratio. The dimensions and morphology of the nanoparticles post-adsorption were assessed through Transmission Electron Microscopy (TEM), revealing the presence of tiny particles within the nanoscale range. To assess the cytotoxic effects on pancreatic cancer cells, various medication doses were prepared utilizing the MTT assay. The results indicate that the generated phenol-loaded nanoparticles exhibit significant potential in eradicating cancer cells.

Keywords: carbon nanoparticles; phenol; drug delivery; MTT assay; pancreatic cancer; cytotoxicity

ARTICLE INFO

Received: 11 July 2025
Accepted: 31 July 2025
Available online: 15 August 2025

1. Introduction

The pancreas, located posterior to the stomach, plays a critical role in digestion and glucose regulation through insulin secretion. Pancreatic cancer is one of the most lethal malignancies worldwide, with risk factors including smoking, chronic pancreatitis, genetic predisposition, obesity, and advanced age—most cases are diagnosed after 65 years of age[1,2]. Epidemiological data indicate a higher incidence in males compared to females[3-5]. Current treatments primarily involve surgical resection, chemotherapy, and radiotherapy; however, these approaches often face limitations such as poor targeting and significant side effects[6-8].

Nanodelivery systems have emerged as promising tools to enhance drug efficacy, reduce adverse effects, and improve selective targeting of cancer cells[9-11]. Their unique properties, including nanoscale size, high surface area, and controlled release capabilities, make them ideal candidates for drug delivery applications[12-14]. Among various nanomaterials, carbon nanoparticles stand out due to

their distinctive chemical and physical properties, offering advantages in drug loading and delivery, especially in oncology[15-17].

In this study, carbon nanoparticles were synthesized via a wet chemical method, which involves chemical reactions in liquid media, using glucose as a carbon source and nickel chloride as a catalyst under acidic conditions[18-21]. These nanoparticles exhibit a large surface area conducive to efficient adsorption[22]. Phenol, a hydroxyl-containing organic molecule with antioxidant properties, was selected for loading onto the carbon nanoparticle surface (**Figure 1**). Phenol's capacity to mitigate oxidative stress caused by free radicals has been linked to protective effects against diseases such as cardiovascular disorders, diabetes, and cancer[23,24]. The adsorption process, involving the accumulation of phenol molecules onto the nanoparticle surface, was utilized to achieve drug loading[25,26].

Cytotoxicity of the phenol-loaded nanoparticles was assessed using the MTT assay, a widely employed, sensitive, and cost-effective method that evaluates cell viability through mitochondrial metabolic activity[27-35]. This study aims to deepen our understanding of nanoparticle-based drug delivery mechanisms in pancreatic cancer treatment and to provide foundational data supporting the development of novel, safer therapeutic strategies.

Recent advances in nanomaterial applications and phenol-based therapeutics highlight the potential of such nanoformulations in oncology, emphasizing the importance of controlled release, targeting efficiency, and biocompatibility[36-41].

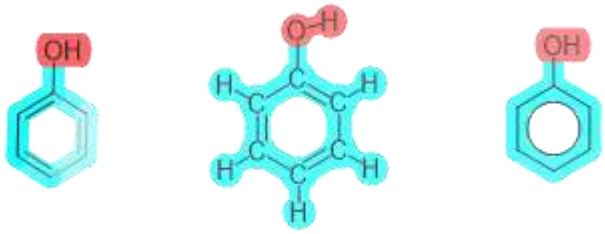

Figure 1. shows the chemical structure of phenol.

2. Experimental section

2.1. Materials and methods

Synthesis of Carbon NPs

To synthesize nanocarbon molecules, 50 grams of glucose were dissolved in 100 millilitres of distilled water in a 500-milliliter flask. After that, one gram of nickel chloride was added as a catalyst, and the flask was placed on a magnetic stirrer. After that, a 70 ml acidic mixture was created using 35 ml of nitric acid and 35 ml of sulfuric acid. As shown in **Figure 2A**, the acid was gradually added to the sugar solution using a pipette while the mixture was continuously stirred in a customized ventilation chamber. After that, we heated the substance to 120 degrees Celsius, and yellow gas emission was observed, indicating the release of nitrogen oxides. After four hours, we saw a color change to black, which suggests that sugar has broken down and carbon has formed, as shown in **Figure 2B**. As seen in **Figure 3**.

To eliminate impurities and acid residues, we then performed the filtering technique shown in **Figure 2C** and washed the precipitate ten times with distilled water. Subsequently, we desiccated it at 100 degrees Celsius in a convection oven.

To ascertain the dimensions and purity of the synthesized particles, we gathered the resultant powder as seen in **Figure 2D** and used the XRD method for analysis.

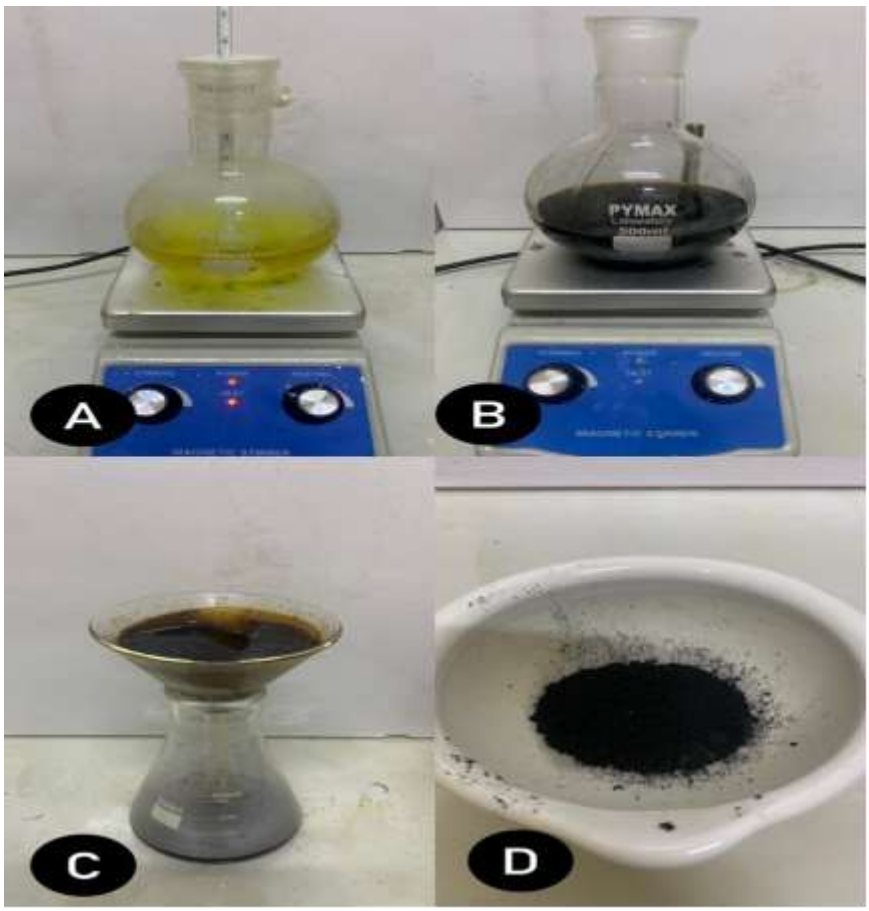

Figure 2. shows the steps of preparing nano carbon.

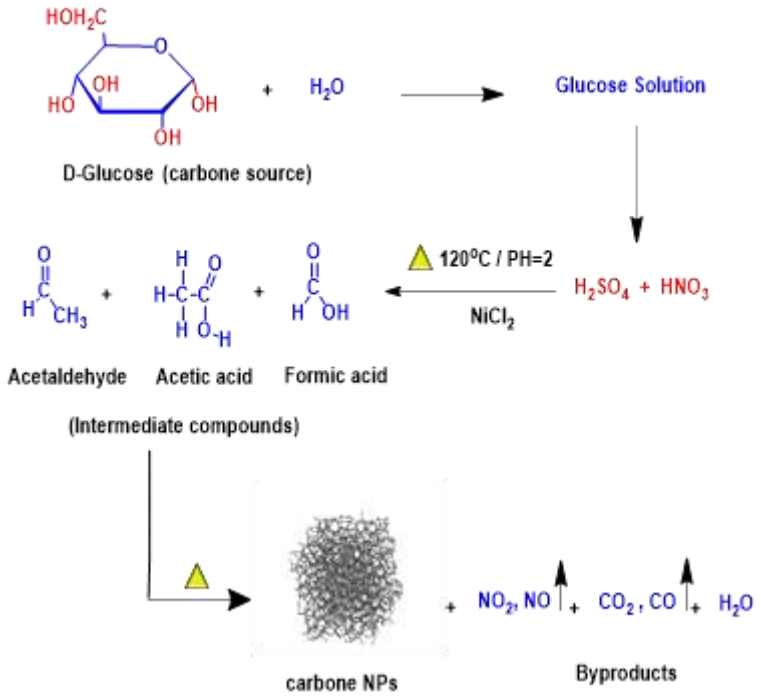

Figure 3. shows the schematic of the process of preparing nanocarbon from glucose.

Drug loading

The drug loading process involved the adsorption of prepared carbon nanoparticles onto the phenol compound. This was achieved by mixing 1.3 grams of phenol in 60 ml of deionized distilled water within a

150 ml beaker, followed by continuous stirring for 5 minutes using a magnetic stirrer.
Subsequently, 5 grams of carbon nanoparticles were incrementally introduced while continuously swirling for 15 minutes. Subsequently, the mixture was allowed to rest in a dark bottle for 24 hours to attain equilibrium. Refer to **Figure 4**.

Figure 4. Shows the components of the mixture: water, nanocarbon, and phenol.

Once the stipulated time had passed, we filtered the precipitate using filter paper, dried it in an air oven set to 80 °C, and prepared it for testing and diagnosis. The filtrate was collected in order to carry out the loading efficiency test in the procedures that follow.

3. Characterization

The following approach was used to confirm that phenol was adsorbed onto the nanocarbon surface after the precipitates had been collected and dried with care:
1- Using a UV-VIS spectrophotometer to read the absorbance.
2- Performing an FTIR study to verify the existence of phenol.
After that, we used an atomic force microscope (TEM) to analyze the form and size of the nano carbon particles after they had been adsorbed.

Drug Loading Efficiency (DLE)

Five different concentrations of phenol solution were prepared: 1%, 3%, 6%, 9%, and 12%. In order to carry out the calibration technique and create the calibration curve, the absorbance of each solution was measured at a wavelength of 285 nm, which is the maximum absorption wavelength of the phenol component. In order to evaluate how well phenol is loaded onto the nanocarbon surface, the residual concentration must be calculated by measuring the absorbance of the solution (the solution that remains after adsorption).

Cell culture and cytotoxicity

The cytotoxic potential of nanoparticles was assessed using the MTT assay. Pancreatic cancer cells were chosen to evaluate cell viability using the MTT assay following treatment with phenol-loaded carbon nanoparticles. The cells were inoculated in a 96-well plate at a density of 1 × 10^4 cells per well and incubated at 37 °C with 5% CO2 for 24 hours to promote optimal stability and adherence. The culture medium was discarded, and the cells were subsequently cultured with fresh medium containing different concentrations of phenol-loaded carbon nanoparticles (10, 20, 30, 40, 50, and 60 µg/ml) for a duration of 48 hours. After 48 hours of cell culture, 10 µl of MTT (5 mg/ml) was added to each well. The incubation lasted

for 4 hours, followed by the addition of 100 µL of DMSO to each well to solubilize the MTT crystals. The responses were measured with an ELISA reader at a wavelength of 570 nm.

4. Results and discussion

XRD analysis

The produced carbon nanoparticles were subjected to XRD examination in order to ascertain the atoms' particle size. The outcomes are displayed in **Figure 5**.

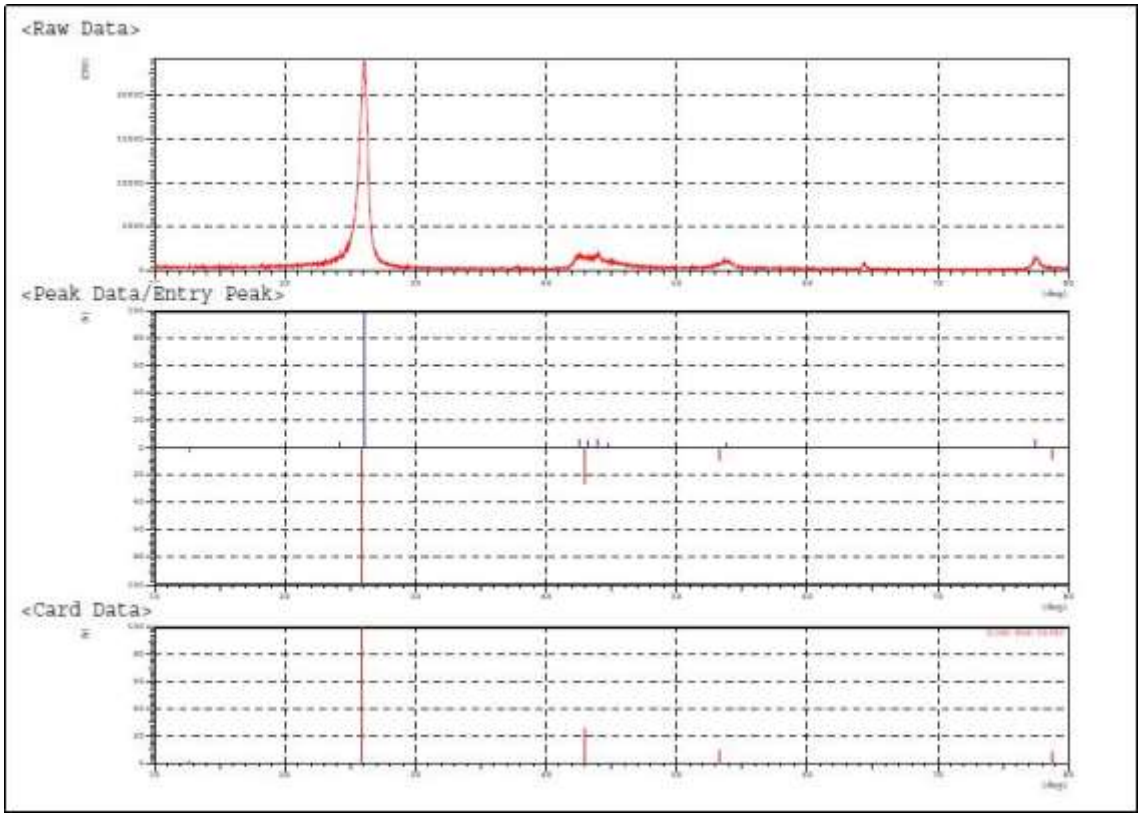

Figure 5. shows the analysis result of the prepared carbon npt using XDR technology.

The crystallite size of the synthesized nanoparticles was estimated based on the X-ray diffraction (XRD) pattern using the Scherrer equation, which is widely applied for determining average crystallite dimensions in the nanometer scale. The equation is expressed as:

$$\tau = \frac{K\lambda}{\beta \cos\theta}$$

where:

τ: average crystallite size (nm)

K: shape factor, typically = 0.9

λ: X-ray wavelength (typically 0.15406 nm for Cu-Kα)

β: full width at half maximum (FWHM) of the diffraction peak = 0.00285 radians

θ: Bragg angle (degrees) = 14°

Using the diffraction data, we calculated the crystal size to be approximately 50.12 nm, confirming that the particles are within the nanoscale range. It should be noted that this method is valid for estimating sizes less than 100–200 nm, due to the effects of peak broadening in X-ray diffraction.

UV-VIS Spectrometer

The presence of phenol on the surface of the carbon nanoparticles was confirmed using UV–Vis spectroscopy. A characteristic absorbance peak was observed at 285 nm, which corresponds to the maximum absorbance wavelength (λ_{max}) of phenol. The sample was prepared by dispersing 0.1 g of phenol-loaded carbon nanoparticles in 5 mL of distilled deionized water, and the measured absorbance at 285 nm was 1.536. This result confirms the successful loading of phenol onto the nanoparticle surface.

FTIR Spectrum

FTIR analysis was carried out to identify the functional groups present on the surface of the nanocarbon particles after phenol adsorption, as shown in **Figure 6**.

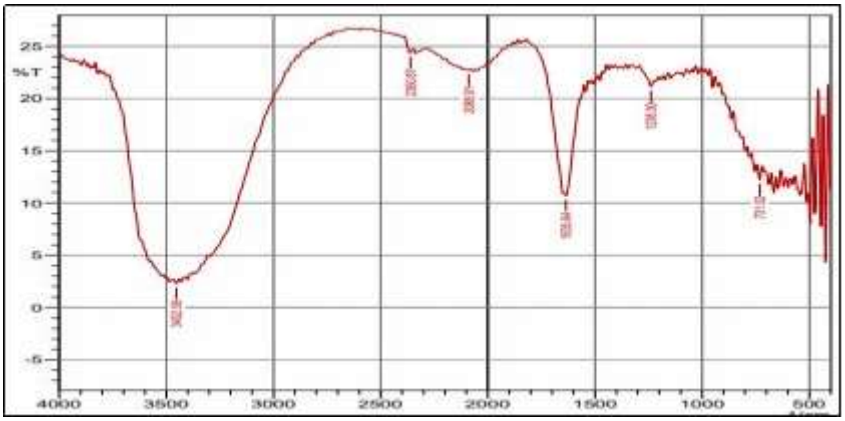

Figure 6. shows the FTIR spectrum of the carbon nanoparticles after adsorption and loading of phenol molecules onto their surface.

A broad absorption band at 3452.58 cm^{-1} corresponds to the O–H stretching of hydroxyl groups attached to the aromatic ring. The peak at 1645.64 cm^{-1} is assigned to C=C stretching vibrations in the aromatic structure. A band at 1238.30 cm^{-1} is attributed to C–O stretching, while the peak at 731.02 cm^{-1} corresponds to O–H bending vibrations.

These characteristic peaks are consistent with the structure of phenol and indicate successful adsorption onto the carbon nanoparticle surface. Although only qualitative FTIR analysis was conducted, the appearance and positions of the functional group bands strongly support the presence of phenol.

TEM Analysis

In order to analyze the nanostructure and determine the size of the carbon nanoparticles, as well as to investigate the geometric form after phenol has been successfully loaded onto the surface and adsorbed. We performed an atomic force microscope study, which provided us with a clear image by demonstrating that all of the particles were smaller than 100 nanometers and inside the nano scale.

It also demonstrated the geometric form of the particles, which were minuscule and had a variety of shapes that were not defined. As seen in **Figure 7**.

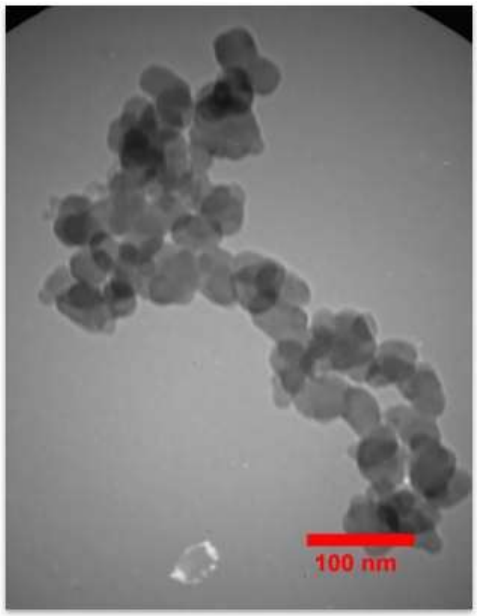

Figure 7. shows the shape and size of the carbon nanoparticles after adsorption as analyzed by TEM.

Drug Loading Efficiency (DLE)

The absorbance was measured for all prepared phenol concentrations and the results were as shown in **Table 1**.

Table 1. shows the concentration and absorbance values.

Concentration	Absorption
1	0.514
3	0.587
6	0.663
9	0.773
12	0.873
1	0.514

Based on the concentration versus absorbance data in **Table 1**, the calibration curve and the equation of the straight line were plotted as shown in **Figure 8**.

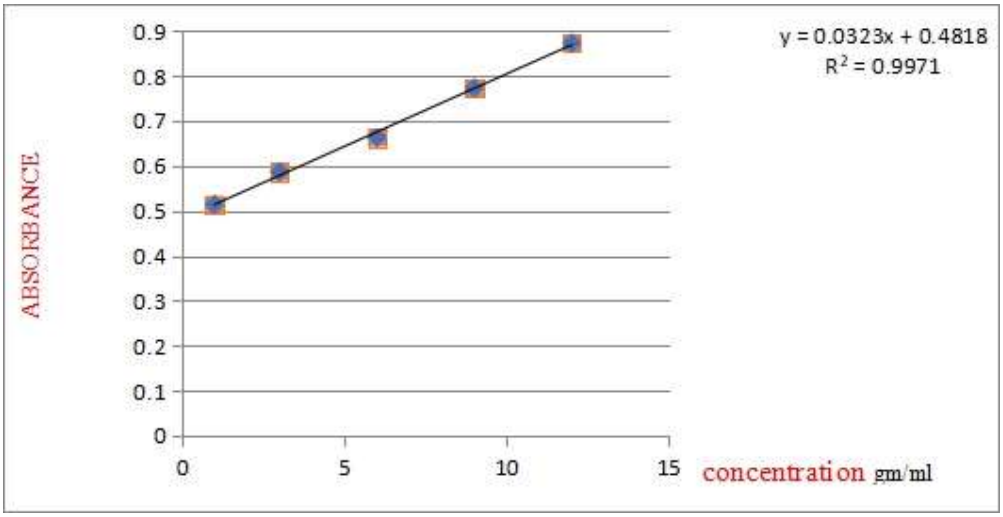

Figure 8. shows the standard curve plot, straight line equation calculation, and R value for the prepared phenol concentrations.

Following the measurement of the absorbance of the residual filtrate from the adsorption process at a wavelength of 285 nm, the concentration value was obtained by referencing the standard calibration curve, yielding a concentration of 0.002 g/mL. To calculate the phenol loading efficiency on the surface of the carbon material, the following equation was applied:

Loading Efficiency (%) =(C_0 - C_e / C_0) × 100

C_0=Phenol concentration before adsorption and it was equal to 0.026 g/ml

C_e=Phenol concentration after adsorption and it was equal to 0.002 g/ml

The drug loading efficiency (DLE) was extracted and it was equal to 92%

Cytotoxicity of phenol-loaded carbon nanoparticles on pancreatic cancer.

Following the successful cultivation of pancreatic cancer cells and the MTT assay to evaluate the cytotoxicity of the prepared concentrations, the cell viability percentage and cytotoxicity percentage were determined using the following formulas

% Cell viability = Sample absorbance / absorbance * 100

% Cell viability for control sample = Control absorbance / Control absorbance * 100

% Cytotoxicity = 100 - Cell viability

Control experiments were conducted to isolate the contribution of each component to the observed cytotoxicity. Pancreatic cancer cells treated with unloaded carbon nanoparticles exhibited minimal cytotoxicity, with a cell viability of approximately 98.99%, indicating negligible toxicity. In contrast, treatment with free phenol at a concentration of 50 µg/mL reduced cell viability to 48.86%, suggesting moderate cytotoxic potential.

The phenol-loaded carbon nanoparticles exhibited the highest cytotoxic effect at concentrations of 50–60 µg/mL, where cell viability dropped to 0%. The lowest observed toxicity was at 10 µg/mL. The average inhibitory concentration was calculated to be 21.983 µg/mL, at which approximately 50% of the cancer cells were no longer viable.

These results suggest that the combined system has enhanced cytotoxic activity compared to either component alone, indicating a potential synergistic effect between phenol and the nanocarrier.as seen in **Figure 9**.

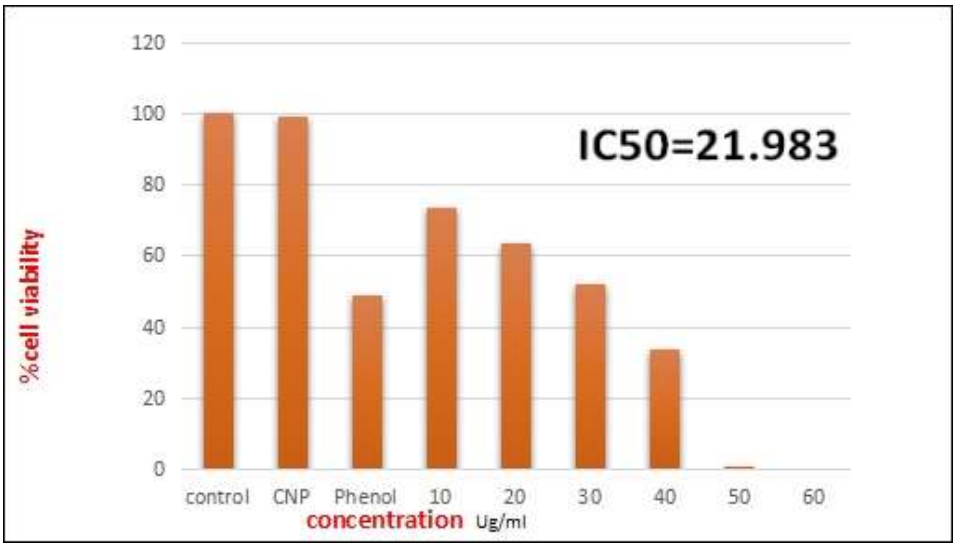

Figure 9. presents the viability of pancreatic cancer cells treated with phenol-loaded carbon nanoparticles at various concentrations, compared to cells treated with free phenol and unloaded nanoparticles.

The enhanced cytotoxicity of the phenol-loaded nanoparticles may be attributed to biochemical mechanisms involving oxidative stress and intracellular damage. Phenol is known to generate reactive oxygen species (ROS), which can compromise mitochondrial integrity, cause DNA fragmentation, and trigger apoptosis pathways. These cellular disruptions collectively reduce viability and contribute to the observed effect. However, further mechanistic investigations are necessary to confirm the precise cellular pathways affected in pancreatic cancer cells.

5. Conclusion

This work concludes the successful synthesis of carbon nanoparticles from environmentally efficient molecules, such as glucose, utilizing wet chemistry with an acidic mixture. The prepared carbon nanoparticles exhibited a significant capacity for phenol absorption on their surface, attributed to their extensive surface area, resulting in a remarkably high loading efficiency. This material exhibits significant toxicity towards pancreatic cancer cells, with increased toxicity observed at higher concentrations. The prepared particles have the potential to be utilized as a drug for cancer treatment in the future, following comprehensive study and clinical evaluation.

Ethics Information:

None.

Fundings

No fundings.

Author Contribution Statement

Ghufran Hammood: Conceptualization, methodology, investigation, writing- original draft; Mustafa Allawi: Visualization, project administration, writing- reviewing and editing; Mina Faris: Supervision, visualization, project administration, writing- reviewing and editing; Shahad Hammad: Investigation and resource.

Acknowledgements

The authors acknowledge to everyone who contributed to this research and work hard to develop it.

Conflict of interest

The authors declare no conflict of interest.

References

1. F. Nugen, D. Garcia, S. Sohn, J. Mickley, C. Wyles, BJ Erickson, M.J. Taunton. Application of natural language processing in total joint arthroplasty: opportunities and challenges. The Journal of Arthroplasty. 2023 Oct 1;38(10):1948-53.
2. D.S. MICHAUD, Epidemiology of pancreatic cancer. Minerva chirurgica, 2004, 59.2: 99-111. https://europepmc.org/article/med/15238885
3. A.H. Alhammer, S.I. Al-juboori, S.A. Mudhafar. APR-246 enhances the anticancer effect of doxorubicin against p53-mutant AsPC-1 pancreatic cancer cells. Baghdad Sci J. 2024 Aug 1;21:2551-60.
4. Prevention I. Standards of medical care in diabetes—2011. Diabetes Care. 2011 Jan 1;34:S11.
5. A. Araszkiewicz, E. Bandurska-Stankiewicz, S. Borys, A. Budzyński, K. Cyganek, K. Cypryk, A. Czech, L. Czupryniak, J. Drzewoski, G. Dzida, T. Dziedzic. 2021 Guidelines on the management of patients with diabetes. A position of Diabetes Poland. Clinical Diabetology. 2021;10(1):1-13.
6. Y. Cinthya S.; WINTER, Jordan M. Pancreatic cancer: a review. Gastroenterology Clinics, 2016, 45.3: 429-445. doi: 10.1016/j.gtc.2016.04. 003.
7. Hussein, Amer Hamied (2025) "Studying the Effect of Thymol-Containing Nano Emulsion Extracted from Thyme on Angiogenesis Controlling Genes VEGF and VEGFR in a Human Liver Cancer cell Line," Baghdad Science

Journal:Vol.22:Iss.4,Article 8.
DOI: https://doi.org/10.21123/bsj.2024.10591
8. A. Fadhil Z, Mohammad Amin EE, Mohammed Mahmood S, Hamied Hussein A. Preparation of a nanoemulsion from clove oil extract containing phenol and studying its effect on a human MCF-7 breast cancer cell line. Salud, Ciencia y Tecnología [Internet]. 2025 Apr. 11 [cited 2025 May 1];5:1535. Available from: https://sct.ageditor.ar/index.php/sct/article/view/1535
9. P. Ma, R.J. Mumper. Paclitaxel nano-delivery systems: a comprehensive review. Journal of nanomedicine & nanotechnology. 2013 Feb 2;4(2):1000164.
10. J.K. Patra, G. Das, L.F. Fraceto, E.V. Campos, M.D Rodriguez-Torres, L.S. Acosta-Torres, L.A. Diaz-Torres, R. Grillo, M.K Swamy, S. Sharma, S. Habtemariam. Nano based drug delivery systems: recent developments and future prospects. Journal of nanobiotechnology. 2018 Dec;16:1-33.
11. Kinetic of Adsorption and Releasing of Ciprofloxacin Drug in Mesoporous Silica Nanoparticles. Baghdad Sci J [Internet]. 2021 Jun 1 [cited 2025 Jan 21];18(2):0357. Available from: https://bsj.uobaghdad.edu.iq/index.php/BSJ/article/view/4778.
12. M.H. Raheema, G.S. Jaber. Synthesis of Carbon Nanotubes Using Modified Hummers Method for Cathode Electrodes in Dye-Sensitized Solar Cell. Baghdad Science Journal. 2023.
13. G.A. Hamoad, S.A. Sahib. Synthesis and characterization of new graphene oxide nano derivatives, and study of their biological activities. *Int J Drug Deliv Technol* [Internet]. 2021 Jul-Sep [cited 2025 Jan 21];11(3).
14. DE SOUZA SIMÕES, Lívia, et al. Micro-and nano bio-based delivery systems for food applications: In vitro behavior. Advances in Colloid and Interface Science, 2017, 243: 23-45.
15. R. Sinan, S. Abed. Spectrophotometric determination of metoclopramide hydrochloride in tablets by diazotization and coupling reaction with phenol. Iraqi Journal of Science. 2009;50(2):136-43.
16. B.T. Zhang, X. Zheng, H.F. Li, J.M. Lin. Application of carbon-based nanomaterials in sample preparation: A review. Analytica chimica acta. 2013 Jun 19;784:1-7.
17. S.C. Ray, A. Saha, N.R. Jana, R. Sarkar. Fluorescent carbon nanoparticles: synthesis, characterization, and bioimaging application. The Journal of Physical Chemistry C. 2009 Oct 29;113(43):18546-51.
18. B.M. Rosen, K.W. Quasdorf, D.A. Wilson, N. Zhang, A.M. Resmerita, N.K. Garg, V. Percec. Nickel-catalyzed cross-couplings involving carbon− oxygen bonds. Chemical reviews. 2011 Mar 9;111(3):1346-416.
19. E.E. Pérez Ramírez, M. de la Luz Asunción, V. Saucedo Rivalcoba, A.L. Martínez Hernández, C. Velasco Santos. Removal of Phenolic Compounds from Water by Adsorption and Photocatalysis. Phenolic Compounds-Natural Sources, Importance and Applications.
20. R. Das, M.E. Ali, S. Bee Abd Hamid, M.S. Annuar, S. Ramakrishna. Common wet chemical agents for purifying multiwalled carbon nanotubes. Journal of Nanomaterials. 2014;2014(1):945172.
21. J.G. Yu, X.H. Zhao, H. Yang, X.H. Chen, Q. Yang, L.Y. Yu, J.H. Jiang, X.Q. Chen. Aqueous adsorption and removal of organic contaminants by carbon nanotubes. Science of the Total Environment. 2014 Jun 1;482:241-51.
22. A. Borges, V. de Freitas, N. Mateus, I. Fernandes, J. Oliveira. Solid lipid nanoparticles as carriers of natural phenolic compounds. Antioxidants. 2020 Oct 15;9(10):998.
23. H.Y. Jo, Y. Kim, H.W. Park, H.E. Moon, S. Bae, J. Kim, D.G. Kim, S.H. Paek. The unreliability of MTT assay in the cytotoxic test of primary cultured glioblastoma cells. Experimental neurobiology. 2015 Sep;24(3):235.
24. M. Twarużek, E. Zastempowska, E. Soszczyńska, I. Ałtyn. The use of in vitro assays for the assessment of cytotoxicity on the example of MTT test.
25. Y.J. Lee, E.Y. Ahn, Y. Park. Shape-dependent cytotoxicity and cellular uptake of gold nanoparticles synthesized using green tea extract. Nanoscale research letters. 2019 Dec;14(1):129.
26. N. Sanoj Rejinold, M. Muthunarayanan, K.P. Chennazhi, S.V. Nair, R. Jayakumar. Curcumin loaded fibrinogen nanoparticles for cancer drug delivery. Journal of biomedical nanotechnology. 2011 Aug 1;7(4):521-34.
27. M.A. Alqahtani, M.R. Al Othman, & A.E. Mohammed, Bio fabrication of silver nanoparticles with antibacterial and cytotoxic abilities using lichens. Sci Rep **10**, 16781 (2020).
28. D. Mittal, G. Kaur, P. Singh, K. Yadav, S.A. Ali. Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. Frontiers in Nanotechnology. 2020 Dec 4;2:579954.
29. P.C. Ray, H. Yu, P.P. Fu. Toxicity and environmental risks of nanomaterials: challenges and future needs. Journal of Environmental Science and Health Part C. 2009 Feb 17;27(1):1-35.
30. S. Rajabi, A. Ramazani, M. Hamidi, T. Naji. Artemia salina as a model organism in toxicity assessment of nanoparticles. DARU Journal of Pharmaceutical Sciences. 2015 Dec;23:1-6.
31. A.A. Al-Ali, K.A. Alsalami, A.M. Athbi. Cytotoxic effects of CeO2 NPs and β-Carotene and their ability to induce apoptosis in human breast normal and cancer cell lines. Iraqi Journal of Science. 2022 Mar 30:923-37.
32. S.M. Fathi, I.A. Ali. Cytotoxic Effect of the Alcoholic Extract of Conocarpus erectus Leaves on MDA-MB 231 and MCF7 Breast Cancer Cell Lines. Iraqi Journal of Science. 2023 Jan 30:84-90.
33. Z.O. Salman, B.M. Alwash, E.J. Kadhim. Isolation and Identification of Flavonoid Compounds from Euphorbia Milii Plant Cultivated in Iraq and Evaluation of its Genetic Effects on Two Types of Cancer Cell Line. Baghdad Science Journal. 2024.
34. A.H. Alhammer, S.I. Al-juboori, S.A. Mudhafar. APR-246 enhances the anticancer effect of doxorubicin against p53-mutant AsPC-1 pancreatic cancer cells. Baghdad Sci J. 2024 Aug 1;21:2551-60.

35. S. Fatimah, R. Ragadhita, D.F. Al Husaeni, A.B. Nandiyanto. How to calculate crystallite size from x-ray diffraction (XRD) using Scherrer method. ASEAN Journal of Science and Engineering. 2022;2(1):65
36. Yang J, Wang X, Liu L, et al. Advanced multifunctional nanomaterials for cancer therapy. Adv Mater. 2025;37(25):e2508047. doi:10.1002/adma.202508047.
37. Kumar P, Sharma R, Singh A, et al. Recent advances in synthesis and applications of carbon-based nanomaterials. Mater Chem Phys. 2025;295:131098. doi:10.1016/j.matchemphys.2025.131098.
38. Chen L, Zhang Y, Li W, et al. Efficient removal of phenolic compounds using nanostructured adsorbents. Chem Eng J. 2024;460:150356. doi:10.1016/j.cej.2024.150356.
39. Smith T, Johnson M, Lee H. Characterization and cytotoxicity of phenol-loaded nanoparticles. ACS Omega. 2024;9(30):18640-18650. doi:10.1021/acsomega.4c04134.
40. Singh N, Gupta R, Verma P. Wet chemical synthesis of carbon nanoparticles for drug delivery applications. Appl Nanosci. 2022;12:4519-4531. doi:10.1007/s13204-022-02645-w.
41. Zhang Y, Li J, Wang S. Photocatalytic properties of modified carbon nanomaterials. Phys Status Solidi C. 2021;18(2):2100073. doi:10.1002/ppsc.202100073.