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Potential of nanotechnology-based nanomaterials and biochar for tofu wastewater filtration: A review on clean water sustainability

Dionezra Bagus Imanuel[1,*], Faatin Nisriinaa Zain[1], Belvannia Levina Celesta[1], Mochammad Choiril Muna[1]
[1] *Chemical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.*
*Correspondent: dionezraimanuel@students.unnes.ac.id

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ABSTRACT

Background: Water pollution, driven by industrial activities and population growth, increasingly contaminates water sources, threatening clean water supply. Tofu wastewater, rich in organic pollutants, exacerbates this issue, highlighting the need for sustainable, effective water treatment solutions. **Methods:** This study uses a literature review method, analyzing journals, articles, and scientific publications to explore nanomaterials and biochar for efficient tofu wastewater treatment and improving water quality in Semarang City. **Findings:** The filtration system using biochar, CNT, TiO_2, and ZVI significantly reduces contaminants in water, enhancing water quality. Each material contributes uniquely, improving adsorption, photocatalysis, and overall filtration efficiency for heavy metals and organic compounds. Carbon nanotubes (CNTs), zero-valent iron (ZVI), and titanium dioxide (TiO2) exhibit high efficiency in environmental remediation, offering cost-effective, sustainable solutions despite challenges like toxicity and mobility. The study demonstrates the potential of nanomaterials like CNTs, ZVI, and TiO2 for enhanced environmental remediation, particularly in wastewater treatment. Their synergistic use improves contaminant removal, offering sustainable solutions with significant efficiency gains. **Conclusion:** In conclusion, integrating nanotechnology and biochar for tofu wastewater treatment presents a sustainable, scalable solution that advances both environmental remediation and technological innovation, aligning with SDGs and enhancing water quality management efforts. **Novelty/Originality of this article:** The novelty lies in combining nanomaterials and biochar for efficient tofu wastewater treatment, enhancing filtration and sustainability in water quality management.

KEYWORDS: nanomaterials & biochar; tofu liquid waste filtration; clean water.

1. Introduction

Water is a fundamental element used for biological and human activities, and water is often considered an inexhaustible resource, but due to the relatively constant hydrological cycle, its availability is limited. The need for clean water is a major concern, especially to fulfill domestic needs such as water for drinking, bathing, and food preparation at the household level, as well as non-domestic needs (Dewantoro & Sitaresmi, 2022). Domestic water is clean water used for household purposes that can be generated through house connections (SR) and public needs provided through Public Hydrant (HU) facilities (Simanjuntak et al., 2021). Meanwhile, non-domestic water is water that is used on average for facilities and infrastructure purposes. The average water consumption unit needs water for facilities and infrastructure such as hospitals, schools, terminals, and so on (Ramadhan,

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2022). However, concerns about water quality are increasing due to the increasing contamination of water sources caused by population growth and industrial activities, and this has led to a decrease in the supply of clean water (Fajar, 2017). This situation highlights the urgent need for sustainable water management practices to ensure adequate and safe water supplies for future generations.

According to Central Bureau of Statistics (BPS) in 2025, there were 10,683 villages/sub-districts that experienced water pollution. Among them, 6,160 villages/sub-districts experienced pollution due to household waste, 4,496 were polluted by industrial waste, and 27 were affected by other sources. In addition to water pollution, 1,499 villages experienced soil pollution, and 5,644 experienced air pollution. Meanwhile, the majority, of 69,966 villages/sub-districts, were recorded to be free from any type of pollution. (Fig. 1).

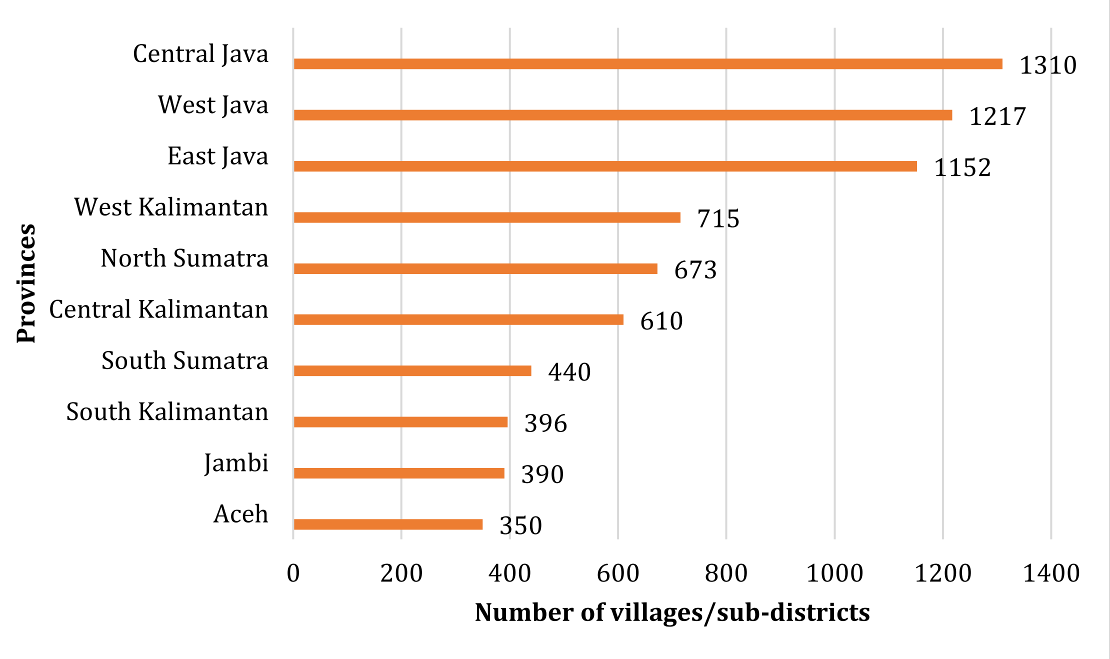

Fig. 1. Ten provinces with villages that experience the most water pollution (BPS, 2025)

Increased industrial activity and population growth have led to water pollution by organic and inorganic pollutants, making access to safe water difficult (Ajith & Rajamani, 2021). One of the widely produced wastes is tofu liquid waste. This waste contains a lot of protein, fat, and carbohydrates, resulting in BOD values of 5000-10,000 mg/L and COD 7000-10,000 mg/L with a low pH of around 4-5. If this waste is discharged directly into the environment, it can have negative impacts, such as polluting waters that cause unpleasant odors and the environment becoming dirty (Aqlys & Cahyanugroho, 2022). The tofu industry in Indonesia annually uses about 2.56 million tons of soybeans for the production process. Of this amount, a significant amount of tofu liquid waste is produced, which on average reaches 20 million m3 per year (Maulana & Marsono, 2021).

The processing of tofu liquid waste has been carried out by many researchers. Research conducted by Lisa et al. (2018) showed that the use of a combination of Moringa oleifera and Tamarindus indica seed powder can reduce COD levels by 31.4%. The main mechanism involves positively charged amine groups that interact with negatively charged organic particles, forming large flocs that can be deposited. However, the effectiveness of reducing TSS levels is still limited due to the high amount of organic material that is not fully coagulated. Meanwhile, according to research conducted by Khuriyah et al. (2023), the aerobic treatment process of tofu wastewater using activated sludge can effectively reduce TSS levels from 92 mg/L to 19 mg/L through aeration for 10 hours with the addition of microorganisms at 1840 mg/L, this method requires a relatively long process time and continuous oxygen supply, which can increase energy consumption.

Nanotechnology has emerged as an innovative solution to address these challenges through the application of nanomaterials in water filtration and decontamination processes (Mukhopadhyay et al., 2022). Nanotechnology can be defined as the science and engineering that involve the design, synthesis, characterization, and application of materials organized in at least one dimension at the nanometer scale (one-billionth of a meter). This technology focuses on manipulating materials with a size ≤100 nm, which fall into at least one-dimensional categories, where their physical, chemical, and biological properties fundamentally differ from those of bulk materials (Prasetiyo, 2020). Meanwhile, nanomaterials refer to materials with external dimensions or internal structures measured on the nanoscale, exhibiting unique or distinct properties compared to bulk materials (Nursanti & Syafira, 2022). Nanomaterials, such as carbon nanotubes (CNTs), titanium dioxide (TiO_2), and zero-valent iron (ZVI), have been shown to be effective in reducing contaminants such as heavy metals and toxic organic compounds (Annan et al., 2018; Yadav et al., 2022). In addition, photocatalysis and adsorption technologies using nanomaterials have shown high efficiency in water filtration (El-Gohary et al., 2025; Reihanifar et al., 2024). In addition, the use of biochar also has the potential to be utilized in water treatment. Biochar (BC) is a carbon-rich solid material produced from pyrolysis of biomass in the absence of oxygen (or with low oxygen content) and at temperatures exceeding 250 °C. Biochar functions as an adsorbent to reduce toxic elements such as heavy metals (Kamali et al., 2021).

One material that has the potential to be utilized as a base material for biochar production is coconut shell. Over the past few decades, coconut shell production has shown steady growth (Wibowo et al., 2019). In recent decades, coconut shell production has shown a steady growth (Wibowo et al., 2019). Based on data released by the (BPS, 2024), national coconut production in 2021 reached 2,822 tons. This figure continues to increase gradually until 2022 and 2023, with total production reaching 2,854 tons. This figure continues to increase gradually until 2022 and 2023, with total production in 2023 reaching 2,854 tons. High coconut production is directly proportional to the coconut shell waste produced. Coconut shell has a highly developed pore structure that can be utilized as an adsorbent. In previous studies, coconut shell-based biochar has been widely used to remove various types of contaminants from the environment, such as harmful compounds such as phenols and heavy metals (Li et al., 2022). The combination of nanomaterials and biochar offers an innovative solution for the effective treatment of tofu wastewater. Nanomaterials, such as carbon nanotubes (CNT), titanium dioxide (TiO_2), and zero-valent iron (ZVI), have been shown to adsorb contaminants such as heavy metals, while biochar, produced from biomass pyrolysis, serves as an adsorbent to reduce toxic elements in water. By utilizing these two materials together, the treatment process of tofu effluent can be enhanced while reducing the impact of pollution and improving the resulting water quality. This approach not only has the potential to address pollution issues but also supports environmental sustainability.

In addition, the use of a combination of nanomaterials and biochar can offer a more environmentally friendly solution compared to traditional waste treatment methods, which often require hazardous chemicals or consume high amounts of energy. This innovative technology has the potential to significantly reduce waste treatment costs in the long term by improving efficiency in filtration and adsorption processes, as well as reducing dependence on more complex, energy-intensive, and expensive technologies. The application of this technology can also accelerate the decomposition of contaminants in water, ultimately speeding up the recovery of ecosystems that have been contaminated by wastewater, such as those from tofu production. In a broader context, this approach supports the principles of a circular economy, focusing on reducing waste, conserving resources, and promoting sustainable resource reuse. Therefore, it not only provides significant ecological benefits but also has the potential to boost industrial competitiveness by minimizing environmental impact and reducing operational costs associated with waste treatment, making it a promising solution for both ecological and economic sustainability. Additionally, this solution has the potential to create new economic opportunities through the development and commercialization of green technologies.

2. Methods

The method used in writing this article is a literature review. The review was conducted by examining several previous journals, articles, and scientific publications to gather comprehensive data and information, analyze successful experiences from earlier studies, and provide a clearer understanding of the subject. This approach involved an extensive exploration of available resources to ensure the inclusion of relevant findings and insights. It specifically focused on identifying literature and factual data related to the research, including advanced materials and innovative water purification technologies. The literature review aimed to identify relevant nanomaterials, such as carbon nanotubes (CNT), titanium dioxide (TiO_2), zero-valent iron (ZVI), and biochar derived from coconut shells, evaluating their efficiency and mechanisms in absorbing heavy metals, breaking down organic pollutants, and reducing metal ions into stable forms. Furthermore, the review explored key applications and breakthroughs in nanotechnology to improve the efficiency of water purification systems, particularly in areas with critical water quality challenges.

The selected location for this study is Semarang City, Central Java, which faces persistent clean water scarcity issues. This issue is clearly illustrated by the clean water deficit ratio map from Food Security Agency (2021), which identifies priority areas with significant deficits, marked in dark colors on the map. The location was chosen not only due to its urgent need for water treatment solutions but also to address a critical environmental problem impacting public health and livelihoods in the area. This decision aligns with both ontological and epistemological research approaches, emphasizing the consideration of social and environmental impacts in developing effective solutions. The selection of Semarang underscores the importance of addressing localized and context-specific issues through innovative, adaptive, and sustainable interventions, ultimately aiming to mitigate the city's clean water challenges.

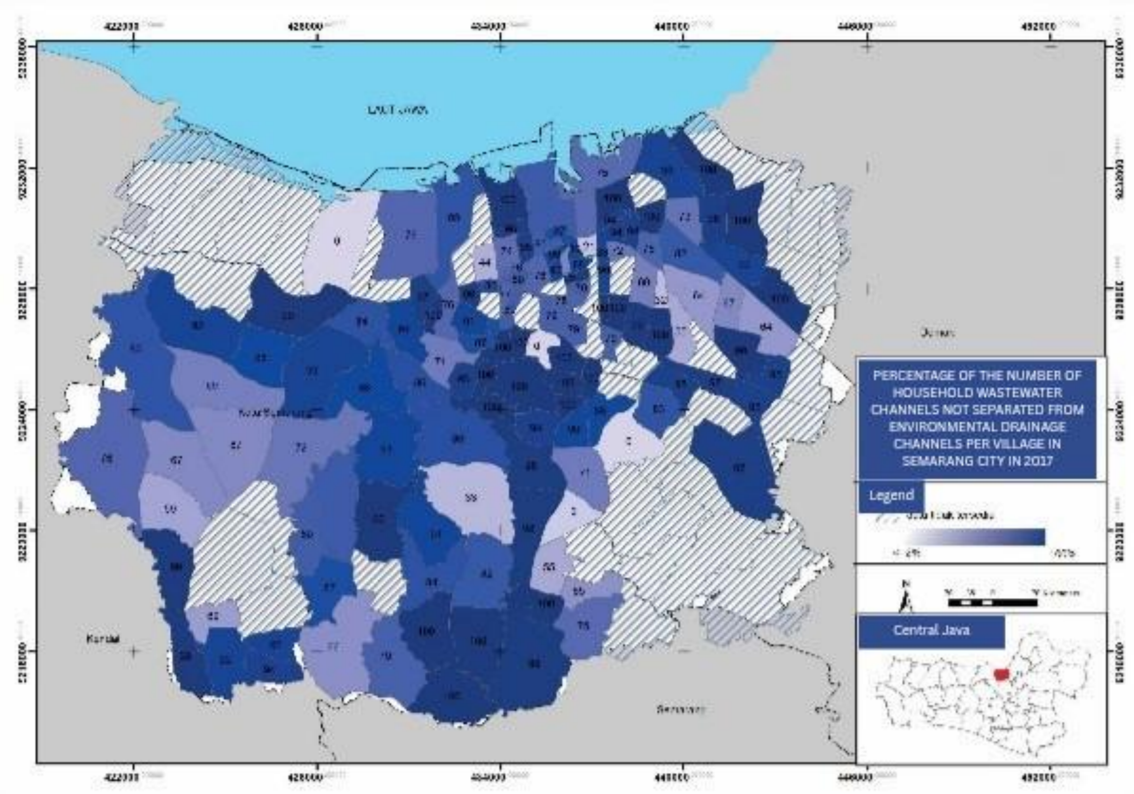

Fig. 2. Non-separated waste water channels in Semarang City
(Artiningsih et al., 2018; Pradana, 2023)

The issue of water scarcity In Semarang is closely linked to the industrial activities that dominate the city and its surroundings. This has led to significant water pollution caused by industrial waste, including tofu waste, which is commonly produced in the Semarang area due to the large number of tofu processing industries. Tofu waste is rich in organic matter, such as proteins, fats, and carbohydrates, which can contribute to severe water contamination if left untreated. These pollutants frequently degrade clean water quality and pose a risk to aquatic ecosystems and public health. This literature review investigates the potential application of nanomaterials, including biochar, in addressing tofu waste through advanced filtration processes. These processes can reduce organic matter content and hazardous compounds in wastewater, presenting a sustainable alternative for pollution management. Moreover, the study examines the integration of nanomaterials into existing filtration technologies, aiming to evaluate their scalability, effectiveness, and cost-efficiency in practical applications.

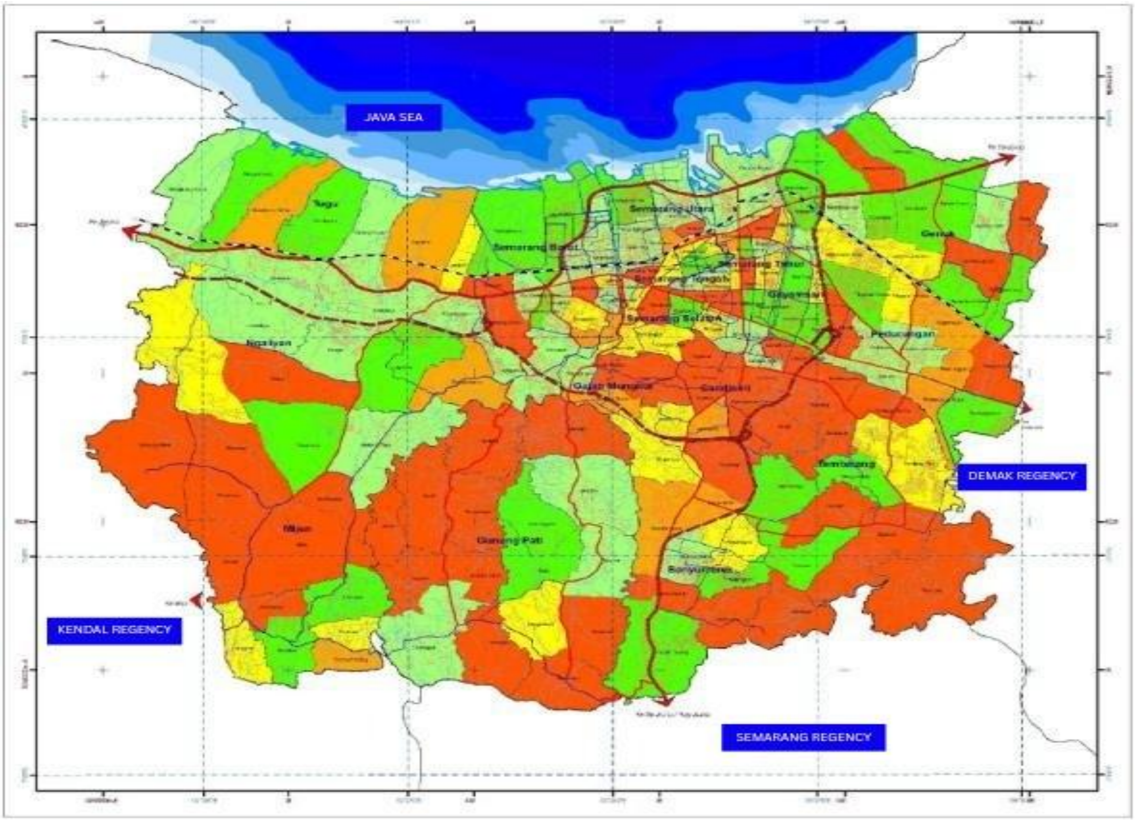

Fig. 3. Map of clean water deficit ratio
(Artiningsih et al., 2018; Pradana, 2023)

Additionally, the criteria for selecting journals and articles were established based on relevance and specificity, with keywords such as “nanomaterials & biochar,” “tofu liquid waste filtration,” and “clean water” playing a critical role in narrowing the focus of the review. This strategic approach ensured that the literature review incorporated high-quality sources and cutting-edge findings, enhancing the overall reliability and depth of the study. By examining the most relevant studies and synthesizing the insights gained, this review provides a robust foundation for understanding the potential of combining nanotechnology and biochar to address water quality issues, particularly in Semarang City.

3. Result and Discussion

3.1 Types of nanomaterials and their efficiency

Based on the literature review, this study was conducted to identify relevant technologies in water treatment. Biochar from coconut shell, carbon nanotubes (CNT), titanium dioxide (TiO_2), and zero-valent iron (ZVI) were selected for their respective advantages in water treatment. Biochar from coconut shell has a high adsorption capacity for heavy metals and organic compounds, making it an effective material for water filtration (Irawan et al., 2016). CNT is known to be effective in adsorbing heavy metals, while TiO_2 serves as a photocatalyst to degrade harmful organic compounds. ZVI has the ability to reduce heavy metal ions to a more stable and non-toxic form (Annan et al., 2018; El-Gohary et al., 2025; Reihanifar et al., 2024). Tests were conducted to evaluate the effectiveness of the filtration system that combines biochar from coconut shells with nanomaterials such as carbon nanotubes (CNT), titanium dioxide (TiO_2), and zero valent iron (ZVI). Table 1 shows the test results of contaminant removal efficiency by each material in the filtration system.

Table 1. Comparison of analysis nanomaterials type

Nanomaterial type	Removal containments	Efficiency	Method
Biochar	Heavy metals, organic compounds	70 – 85%	Adsorption
Carbon Nanotubes (CNT)	Organic compounds and heavy metals	92%	Adsorption
Zero-Valent Iron (ZVI)	Heavy metals (Pb, Cd, Cr)	85 – 95%	Adsorption
Titanium Dioxide (TiO_2)	Methylene Blue, Rhodamine B	76 – 90%	Photocatalysis

(Irawan et al., 2016; Annan et al., 2018)

Test results showed that each component in the filtration system contributed significantly to improved water quality. Biochar served as an effective initial adsorbent, while CNTs and ZVI played a role in further reducing contaminants. The use of biochar from coconut shells not only contributes to filtration efficiency but also supports environmental sustainability by utilizing local biomass waste. And TiO2 acts as a photocatalyst to degrade organic compounds.

3.2 Identification of selected nanomaterials

Nanomaterials can be grouped into: (i) metal-based or inorganic NMs, (ii) carbonaceous NMs, (iii) polymer-based NMs, and (iv) composite NMs (Guerra et al., 2018). (Fig. 3) depicts a schematic representation of various types of NMs used for the removal of environmental contaminants. Metal-based NMs (e.g., Fe-based NPs, Cu-based NPs, BNPs) are widely used in environmental remediation followed by carbonaceous NMs (e.g., CNTs, graphene and graphene oxides), while polymer (e.g., chitosan, alginate) and composite (e.g., clay-polymer nanocomposites, zeolite, and biochar supported nanocomposites) NMs have received considerable research attention but limited practical applications (Guerra et al., 2018; Mukhopadhyay et al., 2022). Each type possesses unique properties and characteristics that make them suitable for various applications. Below is a detailed explanation of these four types.

Metal-based nanomaterials include nanoparticles composed of metals, metal oxides, and other inorganic substances. These nanomaterials exhibit high reactivity, large surface areas, and unique electronic properties. Common examples include silver nanoparticles, titanium dioxide (TiO2), zinc oxide (ZnO), and iron-based nanoparticles such as nanoscale zero-valent iron (nZVI). These materials are widely used for environmental remediation, catalysis, and water treatment because they adsorb, degrade, or neutralize pollutants. For example, due to its high electron-donating capacity, nZVI is highly effective in reducing heavy metals and organic contaminants in groundwater. Similarly, TiO2 nanoparticles are employed in photocatalysis to degrade organic pollutants under UV light, a feature that makes them popular in water purification systems (Mukhopadhyay et al., 2022). However, their potential toxicity and tendency to aggregate can limit their application, necessitating further research into stabilization techniques (Guerra et al., 2018).

Carbonaceous nanomaterials, such as carbon nanotubes (CNTs), graphene, graphene oxide, and fullerenes, are characterized by their high mechanical strength, conductivity, and chemical stability. These materials have been extensively studied for environmental applications, particularly in adsorption and membrane filtration. For example, graphene oxide (GO) exhibits a high surface area and the presence of functional groups that enhance its adsorption capacity for heavy metals and organic dyes. Similarly, CNTs' ability to adsorb pollutants is influenced by their functionalization with carboxyl or hydroxyl groups. Additionally, these materials have demonstrated potential in photocatalysis and sensing applications. However, the hydrophobic nature and high cost of production of CNTs can pose challenges to their large-scale use (Singh et al., 2021). The functionalization and hybridization of carbonaceous nanomaterials with metal oxides, such as TiO2, can enhance their applicability by combining their adsorption and photocatalytic properties.

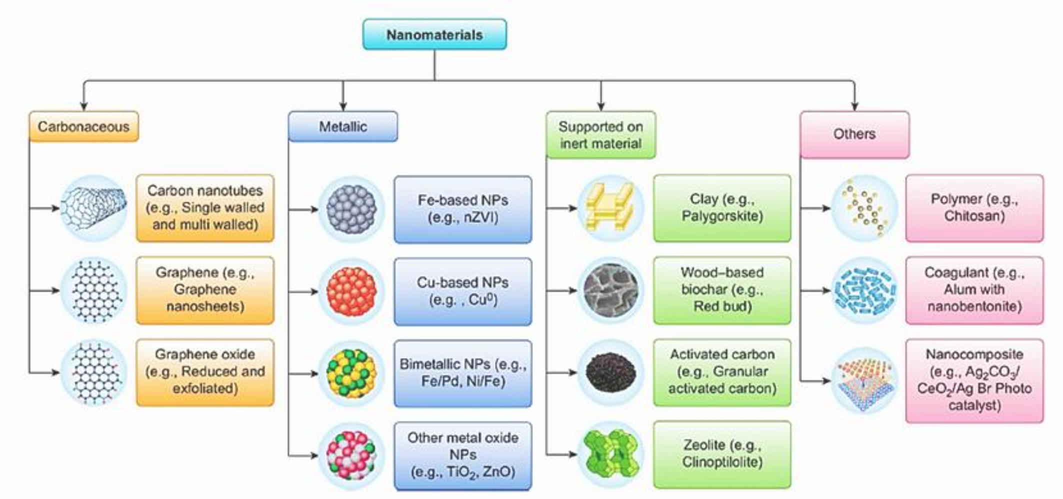

Fig. 4. Types of nanomaterials used for the removal of environmental contaminants (Mukhopadhyay et al., 2022)

Polymer-based nanomaterials include nanoparticles synthesized from natural or synthetic polymers such as chitosan, polyaniline, and polyacrylamide. These materials are widely recognized for their biocompatibility, low toxicity, and tunable properties. Chitosan, for example, is extensively used for water treatment due to its ability to chelate heavy metals and dyes through its amino groups. Another important example is dendritic polymers, such as poly(amidoamine) (PAMAM) dendrimers, which have high surface functionality and can encapsulate metal ions for water purification. Polymer-based nanomaterials are often combined with metal or carbon-based materials to improve their mechanical strength, thermal stability, and reactivity. For instance, nanocomposites of polymer and iron oxide nanoparticles have demonstrated enhanced adsorption of chromium and arsenic from contaminated water sources (Guerra et al., 2018). Despite their advantages, issues such as limited mechanical strength and biodegradability remain concerns.

Composite nanomaterials are a combination of two or more different nanomaterials, designed to enhance the properties of each component. These include clay-polymer nanocomposites, metal-supported carbon nanomaterials, and biochar-based composites. Composite nanomaterials are highly versatile and are often employed in environmental remediation. For instance, biochar-supported nZVI has been shown to effectively remove heavy metals and organic contaminants from water and soil by leveraging the adsorptive capacity of biochar and the reactivity of nZVI (Mukhopadhyay et al., 2022). Similarly, graphene-metal oxide composites, such as graphene-TiO2, have exhibited superior photocatalytic activity compared to their individual components, making them highly effective in degrading persistent organic pollutants. These materials are particularly valued for their stability, high selectivity, and potential for regeneration.

In conclusion, the four types of nanomaterials, metal-based or inorganic, carbonaceous, polymer-based, and composite, offer distinct advantages in terms of reactivity, stability, and environmental applicability. Their use in areas such as water purification, soil remediation, and pollutant degradation underscores their potential to address critical environmental challenges. However, at this stage, to identify relevant technologies, CNT, TiO_2, and ZVI were selected due to their respective advantages in water treatment. CNT is effective in adsorbing heavy metals, TiO_2 acts as a photocatalyst to degrade organic compounds, and ZVI can reduce heavy metal ions to a more stable form (Annan et al., 2018; El-Gohary et al., 2025; Guerra et al., 2018; Mukhopadhyay et al., 2022; Reihanifar et al., 2024).

3.2.1 Carbon nanotube (CNT)

Carbon nanotubes (CNT) are cylindrical macromolecules in which carbon atoms are arranged in the form of hexagonal lattices in tube partitions and closed at the ends with the help of half structures such as fullerenes, CNTs effectively work as adsorbents, easier regeneration, and have an excellent ability to eliminate bacteria and viruses through adsorption and microbial killing (Arora & Attri, 2020). CNTs can be categorized into single-walled (SWCNTs) and multi-walled (MWCNTs) varieties. These nanomaterials possess remarkable physicochemical properties, including high specific surface area, mechanical strength, and electrical conductivity, making them highly effective for environmental remediation applications (Fajar, 2017; Mukhopadhyay et al., 2022).

CNTs are predominantly utilized for the adsorption of organic and inorganic pollutants due to their high adsorption capacity, which is attributed to their large surface area and reactive adsorption sites. Functionalization techniques, such as oxidation or adding -COOH and -NH2 groups, enhance adsorption efficiency for specific contaminants. For instance, functionalized CNTs exhibit superior performance in removing heavy metals like lead (Pb) and cadmium (Cd) from wastewater through mechanisms involving physisorption and chemisorption, achieving adsorption efficiencies exceeding 99% under optimal conditions (Arora & Attri, 2020; Mukhopadhyay et al., 2022; Reihanifar et al., 2024). Combining CNTs with other materials, such as conductive polymers or noble metals, can further improve environmental remediation performance. For example, CNTs modified with silver nanoparticles demonstrate significant improvements in antibacterial and water purification capabilities. However, the production cost of CNTs remains a major barrier. The price of SWCNTs ranges from $25 to $300 per gram, depending on the production method, such as chemical vapor deposition or laser ablation. Additionally, concerns about potential environmental toxicity require further investigation. Despite these limitations, the recyclability and high removal efficiency of CNTs make them a promising nanomaterial for sustainable remediation technologies (Reihanifar et al., 2024).

3.2.2 Zero valent iron (ZVI)

Zero-Valent Iron (ZVI) nanoparticles are widely regarded as a cost-effective and efficient solution for environmental remediation, particularly for groundwater treatment. These nanoparticles leverage strong reducing properties to degrade or immobilize contaminants such as heavy metals, chlorinated organics, and nitrates. ZVI is typically available in two main forms: emulsified ZVI (EZVI) and nanoscale ZVI (nZVI), which provide better distribution within contaminated media. The advantage of nZVI lies in its large specific surface area, which enhances its chemical reactivity (Mukhopadhyay et al., 2022; Reihanifar et al., 2024).

ZVI nanoparticles work by donating electrons to contaminants, facilitating their transformation into less toxic or immobilized forms. Modified ZVI, such as bimetallic compositions or polymer-coated variants, further enhances stability and reactivity. For instance, studies have shown that hydroxyethyl cellulose-coated ZVI exhibits improved dispersion and catalytic efficiency in degrading trichloroethylene (TCE) and other persistent organic pollutants (Mukhopadhyay et al., 2022; Reihanifar et al., 2024).

Despite its effectiveness, the application of ZVI nanoparticles faces challenges related to agglomeration, limited mobility in porous media, and potential ecological risks. Strategies like stabilization using biochar or zeolite matrices show promise in addressing these issues. For example, studies demonstrate that ZVI supported on activated carbon can improve remediation efficiency by up to 30% compared to pure ZVI. The production of nZVI is relatively inexpensive compared to other conventional technologies, costing approximately \$0.05 to \$0.10 per gram, making it an economical solution for large-scale remediation projects (Reihanifar et al., 2024; Yadav et al., 2022).

3.2.3 Titanium oxide (TiO2)

Titanium dioxide (TiO2) is one of the most widely recognized photocatalysts, extensively utilized for its excellent photocatalytic performance, high chemical and biological stability, water insolubility, resistance to both acidic and basic environments, corrosion resistance, non-toxic nature, affordability, and greater availability compared to other materials such as oxides and sulfides (Armaković et al., 2023). TiO2 naturally exists in three crystalline forms: anatase, rutile, and brookite. While the artificial synthesis of brookite is challenging and has limited applications, anatase and rutile are readily available, involve straightforward preparation processes, and are cost-effective and easy to obtain. Synthetic anatase and rutile TiO2 exhibit high chemical stability, resistance to acid and alkali corrosion, and serve as efficient semiconductor photocatalysts, making them suitable for applications like water treatment. These forms generate reactive oxygen species under light irradiation, enabling the degradation of organic pollutants, elimination of microorganisms, and oxidation of heavy metals, significantly improving water quality (Yang et al., 2024).

The mechanism of TiO2 involves the generation of reactive oxygen species (ROS) upon UV activation, which oxidizes contaminants into harmless byproducts such as water and carbon dioxide. Innovations such as doping TiO2 with metals like nitrogen (N) or incorporating it into composite materials have enhanced its photocatalytic efficiency and expanded its active spectrum to the visible light range. Additionally, studies have shown that combining TiO2 with materials like graphene or silver nanoparticles further improves its photocatalytic efficiency. For instance, graphene enhances electron transfer, thereby increasing TiO2's photocatalytic performance. Applications of TiO2 include wastewater treatment, clean energy production through photochemical reactions, and antibacterial applications (El-Gohary et al., 2025; Yadav et al., 2022).

The recyclability and chemical stability of TiO2 nanoparticles further underscore their suitability for long-term environmental applications. However, their efficiency can be limited by high recombination rates of electron-hole pairs and dependency on UV light. Recent advancements in Z-scheme photocatalytic systems, integrating TiO2 with other semiconductors, offer improved performance and broader applicability. Environmental impacts, such as ecotoxicity, require ongoing assessment to ensure safe deployment (El-Gohary et al., 2025; Yadav et al., 2022).

3.2.4 Potential combinations of nanomaterials

Integrating various nanomaterials, such as CNTs, ZVI, and TiO2, holds immense potential for synergistic applications in environmental remediation. For instance, combining CNTs with TiO2 can enhance photocatalytic degradation by leveraging the high surface area of CNTs to support TiO2 nanoparticles, increasing light absorption and reducing electron-hole recombination rates. Similarly, embedding ZVI particles into CNTs can improve the stability and reactivity of ZVI by preventing agglomeration and enhancing contaminant reduction efficiency (Mukhopadhyay et al., 2022; El-Gohary et al., 2025). Another promising approach involves the use of ZVI-TiO2 composites. TiO2 can act as a photocatalyst to degrade organic contaminants, while ZVI contributes to the reduction of heavy metals, offering a dual-function remediation system. Such combinations not only enhance overall efficiency but also expand the range of contaminants addressed, including complex mixtures of organic and inorganic pollutants (Reihanifar et al., 2024; Yadav et al., 2022).

Future research should focus on optimizing these composite materials for scalability and cost-effectiveness. Exploring green synthesis methods and evaluating long-term environmental impacts will be critical to their sustainable implementation. Carbon Nanotubes, Zero-Valent Iron, and Titanium Dioxide represent distinct yet complementary solutions for environmental remediation. While CNTs excel in the adsorptive removal of contaminants, ZVI offers cost-effective reduction capabilities, and TiO2 serves as a robust photocatalyst. Addressing challenges related to cost, environmental impact, and scalability through continued research and innovation will enhance the deployment of these nanomaterials for sustainable environmental applications.

3.2.5 Biochar

Biochar is a biomaterial that supports environmental sustainability through various functions, such as reducing organic pollutants, stabilizing heavy metals, improving soil quality with slow nutrient release, increasing soil microbes, and improving moisture and oxygen levels, with physical properties such as porosity and high surface area, and chemical properties including high pH, large carbon sequestration capacity, and the presence of active functional groups, making it effective for climate change mitigation, air quality improvement through benzene sequestration, soil nutrient recovery, and wastewater management (Wibowo et al., 2019). The process of making biochar can go through various processes including Pyrolysis, gasification and self-sustained carbonization (Ajien et al., 2023). Biochar has a wide range of applications in the agricultural and environmental sectors which include improving soil fertility, use as a base material in the synthesis of functional materials, and aiding in the degradation of biological and abiotic contaminants. In addition, biochar is also utilized in the composting process, soil amendments to improve land productivity, and as a medium for efficient carbon sequestration. The use of biochar can reduce greenhouse gas emissions that have a positive impact on climate change mitigation. With its wide-ranging benefits, biochar makes a major contribution to environmental sustainability, while offering innovative solutions for healthier and more efficient ecosystem improvement (Liu et al., 2023). Furthermore, biochar contributes to sustainable agriculture by enhancing crop yields, reducing fertilizer dependency, and minimizing nutrient leaching into water bodies. Its application in water treatment systems helps remove contaminants, providing safer and cleaner water for communities.

3.3 Synthesis of biochar from coconut shell with modified zero-valent iron (ZVI)

Compared to other agricultural and forestry wastes, biochar produced from coconut shells through the pyrolysis process has high carbon content and a large specific surface area. These characteristics make it an eco-friendly adsorbent that can be widely used for various environmental applications. However, unmodified coconut shell biochar tends to lack an optimal pore structure and is less rich in functional groups. As a result, its ability to absorb heavy metals is limited (Gu et al., 2024). Therefore, modification using other materials is required, one of which is Zero-Valent Iron (ZVI). ZVI is a material that has a low cost and high level of reactivity, and is known for its efficiency as a reducing agent in various applications in the environmental field (Nguyen et al., 2024) The Synthesis of Biochar from Coconut Shell with Modified Zero-Valent Iron (ZVI) process can refer to 2 previous journals, namely Gu et al. (2024) and Nguyen et al. (2024), Biochar from coconut shell was modified using zero-valent iron (ZVI) through an integrated procedure. First, coconut shells were washed thoroughly, dried, and activated using sodium bicarbonate ($NaHCO_3$) with a mass ratio of 1:4. The pyrolysis process was carried out at 550°C for 2 hours in a nitrogen atmosphere to produce biochar with high porosity. The pyrolyzed biochar was then washed with a dilute HCl solution to remove Na_2CO_3 residue, rinsed using deionized water until neutral and dried at low temperature. Modification was carried out by soaking the biochar in $FeCl_3$ solution with a certain concentration, followed by a reduction process using $NaBH_4$ solution to precipitate ZVI particles evenly on the biochar surface. This mixture was dried in a vacuum oven to minimize ZVI oxidation.

Modification of coconut shell biochar with Zero-Valent Iron (ZVI) significantly improved its performance in removing Cr(VI) from aqueous solution. Through the modification process, ZVI particles were evenly dispersed in the carbon matrix of biochar, which expanded the contact area and strengthened the interaction between ZVI and carbon. This modification reduces the aggregation and passivation of ZVI particles, thereby enhancing electron transfer and maintaining their reactive activity. With an adsorption capacity of up to 307.8 mg/g and an elimination capability lasting up to 144 hours, this material exhibits much higher efficiency than unmodified biochar (Yu et al., 2024).

3.4 Data analysis and evaluation

The data from prototype testing were analyzed using statistical methods, including analysis of variance (ANOVA), to ensure the significance of the test results. Measurements were conducted using a spectrophotometer to evaluate the effectiveness of pollutant removal (Yadav et al., 2022). The analysis results revealed that the developed filtration system could reduce heavy metal concentrations by more than 90% in contaminated water samples. The use of biochar as a base material in the filtration process proved to enhance adsorption capacity and exhibited a synergistic effect when combined with carbon nanotubes (CNT) and zero-valent iron (ZVI). Furthermore, the system demonstrated consistent performance even under varying pH and temperature conditions, thereby increasing its reliability for practical applications in diverse environmental settings, including industrial wastewater treatment.

3.5 Working mechanism in water treatment technology

The nanomaterial-based tofu wastewater treatment technology operates through a series of carefully designed stages, each contributing to the effective purification of contaminated water. This multi-stage process begins with the entry of tofu wastewater into a filtration system that incorporates carbon nanotubes (CNTs). These CNTs play a crucial role in adsorbing residual heavy metals and organic pollutants due to their exceptionally large surface area. The extensive surface area allows CNTs to trap a significant quantity of pollutant molecules, enhancing the overall efficiency of the filtration process by removing contaminants that might otherwise bypass traditional methods. Following this initial filtration stage, the partially treated water is transferred into a reactor containing titanium dioxide (TiO_2). This step leverages the photocatalytic properties of TiO_2, which are activated under ultraviolet (UV) light. When exposed to UV light, TiO_2 initiates a series of chemical reactions that break down remaining organic pollutants into safer, non-toxic compounds such as water and carbon dioxide. This advanced oxidation process effectively eliminates even stubborn organic contaminants, ensuring that the water is further purified to a high degree.

The final stage of the treatment process involves passing the water through a reactor containing zero-valent iron (ZVI) that has been modified with coconut shell-derived biochar. This stage is critical for addressing pollutants such as Cr(VI), which are challenging to remove with conventional treatments. The integration of biochar with ZVI significantly enhances the system's overall performance. Biochar serves as a support matrix that disperses ZVI particles uniformly, preventing the aggregation and passivation that typically reduce the reactivity of ZVI over time. This uniform dispersion ensures that the ZVI remains active for longer periods, maintaining its effectiveness in reducing pollutants. Additionally, the biochar contributes to the process by increasing the adsorption capacity due to its high porosity and acting as an electron mediator. This mediation facilitates more efficient electron transfer from ZVI to the pollutants, thereby accelerating the reduction and removal of contaminants. By combining these complementary mechanisms, this stage achieves superior pollutant removal efficiency compared to the use of ZVI alone (Yu et al., 2024). Overall, this multi-stage technology ensures that the treated tofu wastewater is not only free from harmful contaminants but also meets safety standards for consumption and reuse. Its innovative design addresses the pressing need for effective and sustainable water treatment solutions, particularly in areas with limited resources, offering a robust and environmentally friendly approach to wastewater management.

3.6 Formula calculation

Several models commonly used to describe the adsorption process in water and wastewater treatment applications were developed by (i) Langmuir, (ii) Brunauer, Emmet, and Teller (BET), and (iii) Freundlich. The Langmuir model applies to monolayer adsorption, while the BET model represents isotherms that reflect true multilayer adsorption. This means that when adsorption is limited to a single layer, the BET isotherm simplifies to the Langmuir expression (Annan et al., 2018). Both equations are based on the assumption that adsorption energy is uniform across the surface. The Langmuir isotherm applies to systems with homogeneous adsorption sites, whereas the Freundlich model incorporates surface heterogeneity using an empirical equation. The Freundlich isotherm is thus more appropriate for systems with non-uniform adsorption behavior. These models provide valuable insights into adsorption mechanisms and are widely used to optimize adsorption processes for specific pollutants.

Adsorption is a critical process in water and wastewater treatment, widely applied for the removal of heavy metals, dyes, organic compounds, and other contaminants. Understanding the principles described by adsorption isotherm models allows for the design of efficient treatment systems. For example, the Langmuir model is often utilized in scenarios where the maximum adsorption capacity is crucial, while the Freundlich model is preferred for heterogeneous adsorbents, such as activated carbon or clay-based materials. The Langmuir and Freundlich equations are given as follows:

$$\frac{qe}{qm} = \frac{bC}{1 + bCe} \qquad \text{(Eq. 1)}$$

Where q e (mg/g) is the amount of adsorbate per mass unit of adsorbent at equilibrium, C e is the liquid-phase concentration of the adsorbate at equilibrium (mg/L), q m is the maximum adsorption capacity (mg/g) and b is the Langmuir constant related to the energy of adsorption (L/mg):

$$qe = KfCe^{\frac{1}{n}} \qquad \text{(Eq. 2)}$$

Where K F (mg/g) (L/mg)1/n is the Freundlich capacity factor and 1/n is the Freundlich intensity parameter. The constants in the Freundlich isotherm are determined by plotting log(qe) versus log(C e). Differences between these isotherm models highlight the importance of selecting the most suitable model based on the characteristics of the adsorption process. The BET model, which extends adsorption theory to multilayer adsorption, is particularly useful for characterizing porous materials. By applying these models to experimental data, adsorption efficiency and contaminant removal performance in water treatment systems can be enhanced.

3.7 Environmental analysis

Utilizing nanomaterials in the treatment of tofu wastewater represents a promising innovation that can enhance both environmental sustainability and the quality of effluent filtration. Several materials have shown great potential in handling complex contaminants. These include carbon nanotubes (CNTs), titanium dioxide (TiO_2), and zero-valent iron (ZVI). CNTs, with their enormous surface area, are effective in absorbing heavy metals, while TiO_2

serves as a photocatalyst that breaks down organic compounds into safer products such as carbon dioxide and water. When modified with biochar derived from coconut husks, ZVI has shown an enhanced ability to reduce heavy metals by preventing the aggregation of particles, which in turn boosts its reactivity (Annan et al., 2018; El-Gohary et al., 2025; Reihanifar et al., 2024).

This combination not only enhances the efficiency of effluent treatment but also contributes to a circular economy through the utilization of agricultural by-products. Biochar contributes to pollutant removal through its high porosity and surface area, making it an important component in nanotechnology-based systems. This approach is particularly effective in dealing with new contaminants that are often difficult to address by conventional water treatment methods (Sajid et al., 2022; Yu et al., 2024). However, the application of this technology requires careful management and regulation to ensure its safety and sustainability. It is essential to thoroughly evaluate potential risks, including the release of nanoparticles into the environment and their effects on aquatic ecosystems. If managed properly, technologies utilizing nanomaterials and biochar could revolutionize tofu wastewater treatment, providing effective and environmentally friendly solutions to pollution while aligning with global sustainable development goals (Annan et al., 2018; El-Gohary et al., 2025; Sajid et al., 2022; Yu et al., 2024).

4. Conclusion

The development potential of a combining nanotechnology-based nanomaterials and biochar as an innovative solution for addressing tofu wastewater treatment in Semarang has made significant contributions to advancing filtration systems in wastewater management, especially in the context of achieving the Sustainable Development Goals (SDGs). The integration of biochar derived from agricultural waste, such as coconut shells, with advanced nanomaterials like carbon nanotubes (CNT), titanium dioxide (TiO_2), and zero-valent iron (ZVI), has proven to be highly effective in enhancing filtration efficiency. This method not only supports environmental remediation but also enhances the broader development of science and technology in addressing global challenges related to water quality. By providing a practical and scalable solution, this approach meets critical public health and environmental needs, aligning with the broader objectives of sustainable development. This review's adoption of such cutting-edge solutions reflects a significant step forward in achieving a balance between technological advancement and environmental sustainability, offering a model for future initiatives in water treatment and resource conservation.

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Author Contribution

All authors contributed to the conceptualization, literature review, data analysis, drafting, and final approval of the manuscript, ensuring accuracy, coherence, and adherence to scientific and ethical standards.

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Biographies of Authors

Dionezra Bagus Imanuel, Chemical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: dionezraimanuel@students.unnes.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Faatin Nisriinaa Zain, Chemical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: fatinnisrina5@students.unnes.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Belvannia Levina Celesta, Chemical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: belvanniacelesta@students.unnes.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Mochammad Choiril Muna, Chemical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Semarang, Central Java 50229, Indonesia.

- Email: mchoirilmuna@students.unnes.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A