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Review

Review on the synergistic mechanisms in harnessing rice residue-derived cellulose nanocrystals for sustainable water purification and wastewater treatment

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ABSTRACT

The review explores the innovative use of rice residue for developing Cellulose nanocrystals and reinforcement applications of CNCs for wastewater treatment. Rice residue, rich in lignocellulose components like cellulose, hemicellulose, and lignin, presents a sustainable resource for biocomposite fabrication. The review highlights the significant challenges of managing rice residue, particularly the environmental impact of its open field burning, which contributes to severe air pollution and health risks. By examining recent advancements in the extraction of cellulose nanocrystals (CNCs) from rice residue, the review emphasizes their potential for enhancing water treatment technologies and contributing to Sustainable Development Goal 6 (Clean Water and Sanitation). The review provides a comprehensive analysis of the current state of research such as facts and challenges related to using CNCs for water treatment, and suggests future directions for developing eco-friendly, high-performance water filtration and its reinforcement perspectives, underscoring the importance of integrating waste valorization with sustainable practices.

1. Introduction

Water scarcity and contamination are among the most pressing global challenges, driven by industrialization, population growth, and inadequate waste management systems [1]. The increasing prevalence of waterborne pollutants, including heavy metals, synthetic dyes, organic pollutants, and emerging contaminants such as microplastics and pharmaceutical residues, poses significant threats to human health and aquatic ecosystems [2]. Traditional water treatment technologies, such as coagulation, activated carbon adsorption, and reverse osmosis,

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often face limitations, including high costs, energy demand, and reduced efficacy for removing certain pollutants [3]. In parallel, agricultural residues like rice husk are underutilized, despite their potential for value addition. With global rice husk production exceeding 150 million tons annually, regions such as China, India, and Southeast Asia are the largest contributors [4]. Rice husk, rich in lignocellulosic content, is often discarded or burned, causing environmental pollution and inefficient resource utilization. This surplus of rice husk presents a unique opportunity to address both environmental and water treatment challenges [5].

Cellulose nanocrystals (CNCs), derived from lignocellulosic biomass such as rice husk, have emerged as a promising solution for sustainable water purification. CNCs possess remarkable properties, including a high surface area, exceptional mechanical strength, and abundant hydroxyl groups that can be functionalized for specific applications [6]. These attributes enable CNCs to target diverse water contaminants through mechanisms such as adsorption, catalytic degradation, and antimicrobial action [7].

This review examines the production, properties and advance application of agricultural residue especially rice residue and the potential of CNCs extracted from rice waste in addressing critical water treatment challenges by leveraging their unique physicochemical properties. It also explores their role in advancing sustainable technologies through innovative applications, particularly in contaminant adsorption, degradation of organic pollutants, and antimicrobial treatments. By integrating insights into global rice residue production, existing water treatment limitations, and CNCs' multifunctionality, this work aims to bridge knowledge gaps and highlight future directions for CNC-based water purification systems.

1.1. *Chemical composition and structural characteristics of rice residue*

Rice waste is a rich source of lignocellulose including a complex of cellulose, hemicellulose, and lignin that provide structural integrity to rice plants [8]. Each of them has different qualities such as cellulose providing strength and stability [9]. Rice residue has two main parts in terms of residue such as rice husk (RH) and rice straw (RS) (Fig. 1). Rice husk ash (RHA) is made by burning RH in the absence of oxygen with a controlled temperature [10]. Rice residue, particularly RS, is characterized by its fibrous structure and high silica content [11]. The fibrous nature of RS makes it a suitable candidate for reinforcement in the composite. It has a high cellulose content of approximately 64 %, contributing to its strength and making it suitable for use as a reinforcement in composite materials [12]. RH is composed of 75–90 % organic matter, including cellulose and lignin, with the remainder being mineral components like silica, alkali, and trace elements [13].

The properties of RH include a bulk density ranging from 86 to 114 kg/m^3 and a hardness on the Mohs scale of 5–6 [15]. It contains 22–29 % ash, around 35 % carbon, 4–5 % hydrogen, 31–37 % oxygen, 0.23–0.32 % nitrogen, 0.04–0.08 % sulfur, and 8–9 % moisture [16]. RS has a particle size of approximately 3 cm and may be useful as an adsorbent for heavy metal removal from wastewater or energy storage in supercapacitors [17]. Before deliberating the residue engendered from rice crops, the chemical constituents in crops, such as paddy, can vary depending on several factors, including the plant variety, weather patterns during growth, soil chemistry, and the use of fertilizers and manures [18]. These factors can affect the mineral content of rice grains, for example, as well as other nutrients and compounds. Environmental factors such as temperature, humidity, and rainfall can also affect crop chemistry [19]. Therefore, it is crucial to consider all these factors when growing crops to ensure that they develop the desired chemical constituents [20]. Observing the lignocellulose constituents and other bio

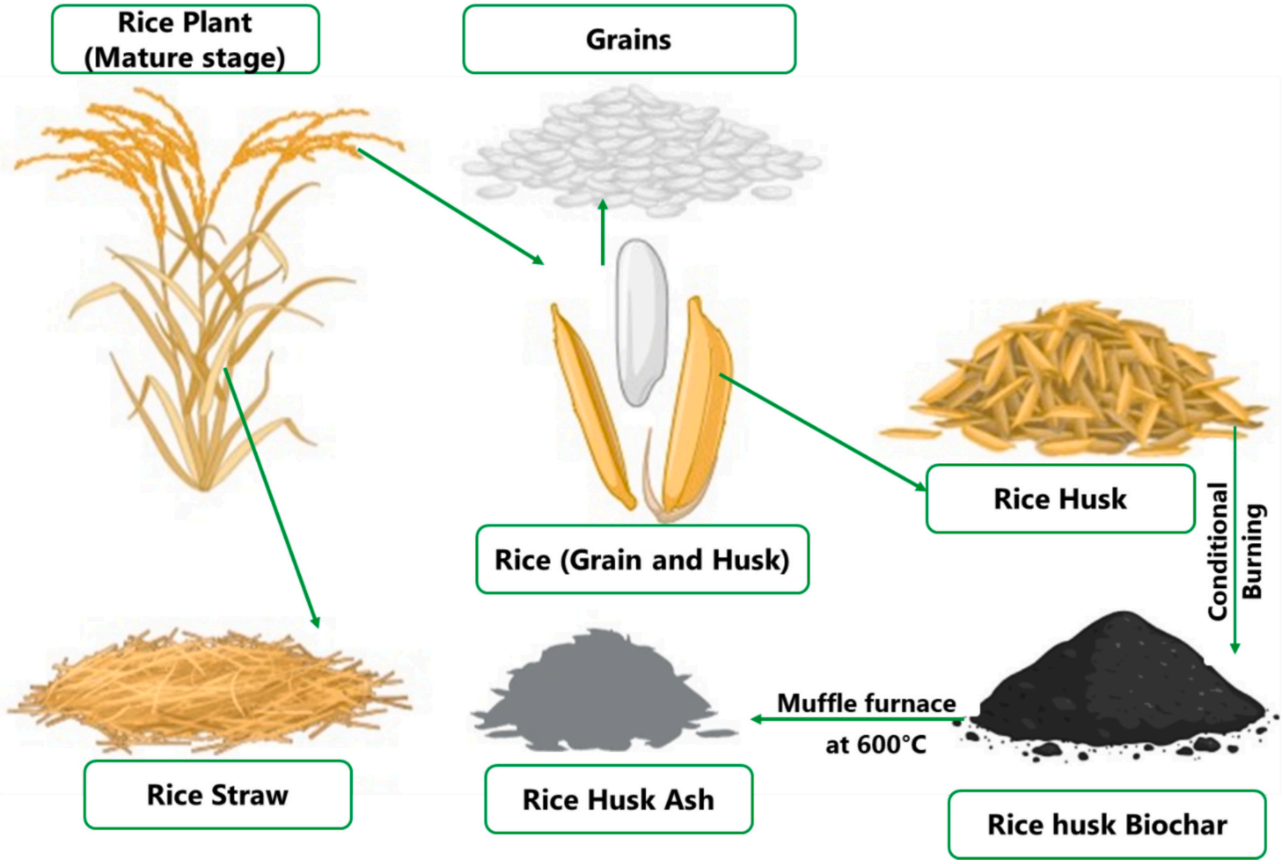

Fig. 1. Rice residue components [14].

content of rice residue Table 1 is shown below which includes the presence of lignocellulose along with Silicon dioxide (SiO_2) which is important for the extraction of CNCs.

The bulk density of RS varies, with loose straw around 13 to 18 kg/m^3 and baled straw ranging from 60 to 90 kg/m^3 [28]. By weight, raw rice husks are composed of 35 % cellulose, 25 % hemicelluloses, 20 % lignin, 17 % ash, and roughly 3 % moisture [29].

Particle size is critical to rice husk ash's pozzolanic action. The greater the surface area and reactivity, the smaller the particle size. However, research found that milling had no substantial effect on the chemical makeup of RHA. Milling, on the other hand, can reduce particle size while increasing RHA surface area [30]. Different properties of RHA are elaborated in tabular form in Table 2 Where it can be used according to its properties. RHA is a byproduct of rice milling, and its properties make it a valuable resource for various industries.

In rice husks and black rice husks mostly the content of SiO_2 is at an extremely important level. Black RHA holds 96.2 % silica followed by RH having 89.39 % SiO_2. Only the bagasse other than rice by-products has high silica content [16].

2. Rice production and its residue impact on environment

With the increase in population, the demand for food has risen dramatically, making rice one of the most favored staple foods worldwide [36]. The production of rice results in a significant amount of agricultural residue, which is often left as waste and frequently burned in many countries [37]. This practice in context with agrifood wastes, not only leads to loss of potential resources but also has severe environmental impacts, including air pollution and increased greenhouse gas emissions [38]. This section discusses the demographic aspects of rice production and the associated waste, highlighting its environmental consequences on a global and national scales particularly India and its neighboring countries.

2.1. Rice residue generation in the world

Rice is one of the most important cereal crops worldwide, with production steadily increasing over the past few decades [39]. Global rice consumption in 2023/2024 increased to 538.9 million tonnes (milled basis). The top producers of rice in 2024 were China (151.3 million tonnes), India (106.6 million tonnes), Bangladesh (38.8 million tonnes), Indonesia (36 million tonnes), and Vietnam (22.4 million tonnes) [40].

The global generation of rice residues is estimated to be in the range of 781 million tonnes of rice straw [41]. Along with this 150 million tonnes RH generated annually in the world out of 750 million tonnes of grain [42]. This significant amount of residue presents both a challenge and an opportunity for sustainable management [43].

Asia is the dominant region in rice production, accounting for over 86.9 % of the global output [44]. Major Asian rice-producing countries include China, India, Indonesia, Bangladesh, and Vietnam (shown in Fig. 2) The management of this residue poses unique challenges due to the high volume and the prevalent practice of open-field burning [45]. This practice is largely driven by the need to quickly clear fields for subsequent crops, particularly in the densely cultivated regions of Punjab and Haryana. The lack of adequate infrastructure and awareness regarding sustainable residue management methods further exacerbates the problem.

Table 1

Chemical constituents of rice residue.

Cellulose%	Hemicellulose%	Lignin%	SiO_2	Soluble	References
25–35	18–21	26–31	15–17	2–5	[21]
25–48	18–25	12–31	15–17	2–5	[22]
35.2	18	24.5	18.8	NA	[23]
39.4	27.7	15.8	17.1	NA	[24]
34.42	21.53	17.93	NA	NA	[25]
31.9	56.3	3	8.8	NA	[26]
26–36	12–32	15–23	13–23	NA	[27]

Table 2

Properties of Rice Husk Ash (RHA).

Properties	Descriptions	References
Silica content	RHA has approximately 90 % pure silica, making it an excellent source of silica for CNCs extraction.	[31]
Bulk density	RHA has a low bulk density, making it a good insulating material.	[32]
Pozzolanic activity	RHA has high pozzolanic activity, which makes it a useful additive in cement and concrete production.	[16]
Surface area	RHA has a high surface area, making it an effective adsorbent for various pollutants such as heavy metals and organic compounds.	[33]
Carbon content	RHA has a low carbon content, making it an eco-friendly material for various applications.	[34]
Cost	RHA is a low-cost material, making it an attractive possibility for industrial applications.	[33]
Color	RHA has a light color, making it an ideal additive for white or light-coloured products.	[35]

In East Asia, countries like China and Vietnam are among the largest rice producers. In Vietnam alone produce 45.2 million metric tonnes of rice from which 39 million tonnes of rice residues are generated annually [46]. In China, there were 254.57 million tons of "available-field-residue" (AFR). The largest amount of AFR (95.00 Mt) came from maize, which was followed by rice (78.90 Mt) [47]. In Vietnam with about 70 % being burned either fully or partially. This practice contributes to severe air pollution and greenhouse gas emissions, accounting for approximately 13 % of the total $PM_{2.5}$ emissions in the country, making it the second highest source of $PM_{2.5}$ combustion after fuelwood burning [48]. The burning process releases not only carbon dioxide but also particulate matter (PM), volatile organic compounds (VOCs), and other pollutants that severely degrade air quality. For instance, during the rice straw burning season, cities like Hanoi experience significant increases in air pollution levels, impacting public health and visibility. Studies indicate that burning rice straw can release over 141 million tonnes of CO_2 annually in Vietnam alone, contributing to climate change and local health crises related to air quality degradation [49]. The life-cycle-assessment-based metrices for utilizing rice-straw with various approaches employed in India as elucidated in the study [49].

In South Asia, particularly in the Indo-Gangetic Plains (IGP) encompassing parts of India, Pakistan, and Bangladesh, the situation is similarly dire producing 28 % of rice worldwide [50]. An estimated 150 million metric tons of rice leftovers are produced yearly by Southeast Asian nations combined [51]. India, as the world's second-largest producer of rice, significantly contributes to the global rice residue. The burning of roughly 92 Mt. of agricultural waste annually in India leads to significant particulate matter emissions and severe air pollution [52]. The region witnesses the burning of approximately 23 million tonnes of rice residue each year. This practice not only contributes to local air pollution but also leads to soil degradation by destroying beneficial soil microbes and organic matter essential for soil health. Research indicates that burning reduces soil organic carbon levels significantly; for example, it has been reported that burning rice residues can lead to a loss of about 2.0–2.1 t of carbon per hectare [5]. This reduction is critical for maintaining fertility and productivity in agricultural systems. The health implications of such practices are profound. In Punjab, India, crop residue burning has been linked to increased respiratory ailments among local populations due to the release of harmful pollutants like benzo[*a*]pyrene (BaP), a carcinogenic compound associated with higher lung cancer risks. Crop burning contributes significantly to particulate matter (PM) levels in the atmosphere; in Delhi, it has been estimated that PM emitted from burning crop residues is 17 times greater than that from all other sources combined. Furthermore, crop residue burning accounts for about 40–60 % of peak pollution during winter months in

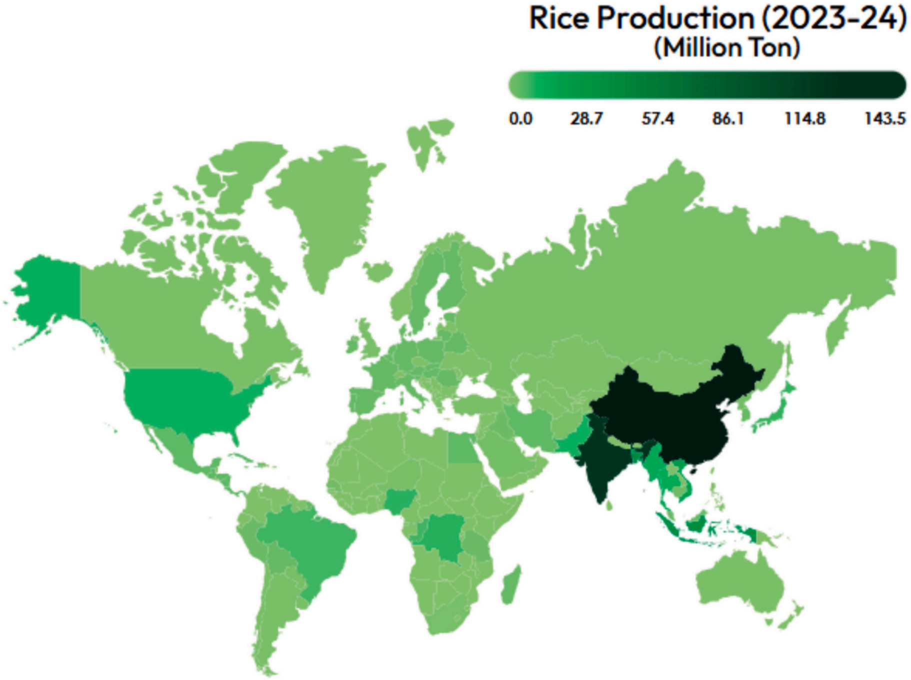

Fig. 2. Rice Production in the World (Million tonnes) [40].

South Asia, resulting in approximately 2 million deaths each year due to air pollution-related health issues. This practice contributes substantially to both local air pollution and greenhouse gas emissions [5].

In Africa, notable rice-producing countries include Nigeria, Egypt, and Madagascar [48]. Although Africa's total rice production is smaller than Asia's, the continent still faces challenges in managing rice residue sustainably. In the Americas, the United States and Brazil are key producers. The United States, for instance, produced around 7.3 million tonnes of rice in 2022, generating an estimated 7–11 million tonnes of RS and 1.5–2 million tonnes of RH [42]. These countries have developed advanced technologies for managing rice residue, including its use in bioenergy and animal feed with the utilization of environmental-friendly Composites [53]. Countries like Italy and Spain contribute to rice production in Europe, albeit on a smaller scale [54]. European countries often adopt stringent environmental regulations that promote sustainable residue management practices. Australia, in Oceania, is a minor yet significant rice producer, known for its high-efficiency farming practices and innovative approaches to residue management [55]. Each region faces distinct challenges and opportunities in managing rice residue.

The 'Global Yield Gap Atlas' and agricultural input data from 32 rice cropping systems in 18 rice-producing nations account for 51 % of global rice harvested land [56]. Understanding the global and regional dynamics of rice production and residue generation is crucial for developing effective and sustainable management practices [48]. Asia, particularly India, stands out as a major producer of both rice and its associated residue, presenting unique challenges that require tailored solutions [36]. By comparing the practices and advancements in other major rice-producing regions, valuable insights can be gained to inform policies and technologies that promote sustainable agriculture and environmental health.

2.2. Rice residue generation in India

Each year, India produces approximately 196 million tonnes of rice residue, with significant surpluses remaining after accounting for its use in fodder, fuel, and other applications. Major rice-producing states such as Punjab, Uttar Pradesh, and Haryana contribute the most to this surplus, which often leads to environmental concerns due to the prevalent practice of burning straw in the fields. [34]. The end use of stubble by farmers for rice crops includes burning, fodder, soil incorporation, rope making, and miscellaneous purposes. In Fig. 3. It was given the amount of surplus residue generated in which Punjab state plays a major role. In the case of rice, 80 % of the total stubble production is burnt [57], 7 % is used as fodder, 1 % is incorporated into the soil, and 4 % is used for rope making [58], Stubble refers to the residual part of crops that stays in the field after harvesting, including crops such as rice, wheat, and maize.

Burning stubble harms the environment by emitting hazardous gases, such as carbon monoxide, nitrogen oxides, and particulate matter, which can lead to air pollution [59]. Another current way rice farmers use stubble is by feeding it to their livestock, accounting for 7 % of the total stubble produced for biofuels [60]. This is an eco-friendly way to use stubble as a source of feed for the animals, reducing the amount of stubble that needs to be burnt or discarded.

In conclusion, farmers need to explore and adopt sustainable alternatives to stubble management to minimize burning practices. Biocomposite made from rice residue can be decomposed into natural components [61]. Biodegradable and eco-friendly materials are gaining popularity among polymer and composite researchers [62]. CNCs are extracted from the RH which delivers strength to the biocomposite material [63]. Excellent tensile strength can be achieved by adding 5 % of NCC, beside this, the water absorptivity of biocomposites also increased [64].

2.3. Air pollution in India and neighboring countries and Punjab State

Burning of rice residue is a critical problem in the South Indian continent. Due to the high population, the agricultural land becomes broad enough to fulfill the food necessities of people. As a result of the fast pace of agricultural activities which promotes the burning of agricultural burning Fig. 4. showing residue burned in India in millions of tonnes. India alone produced over 105 million tonnes of rice residue each year [52]. Uttar Pradesh leads with the highest residue burning (21.92 million tonnes), followed by Punjab (19.65 million tonnes) and Maharashtra (7.42 million tonnes). Overall 33 % of agricultural residue

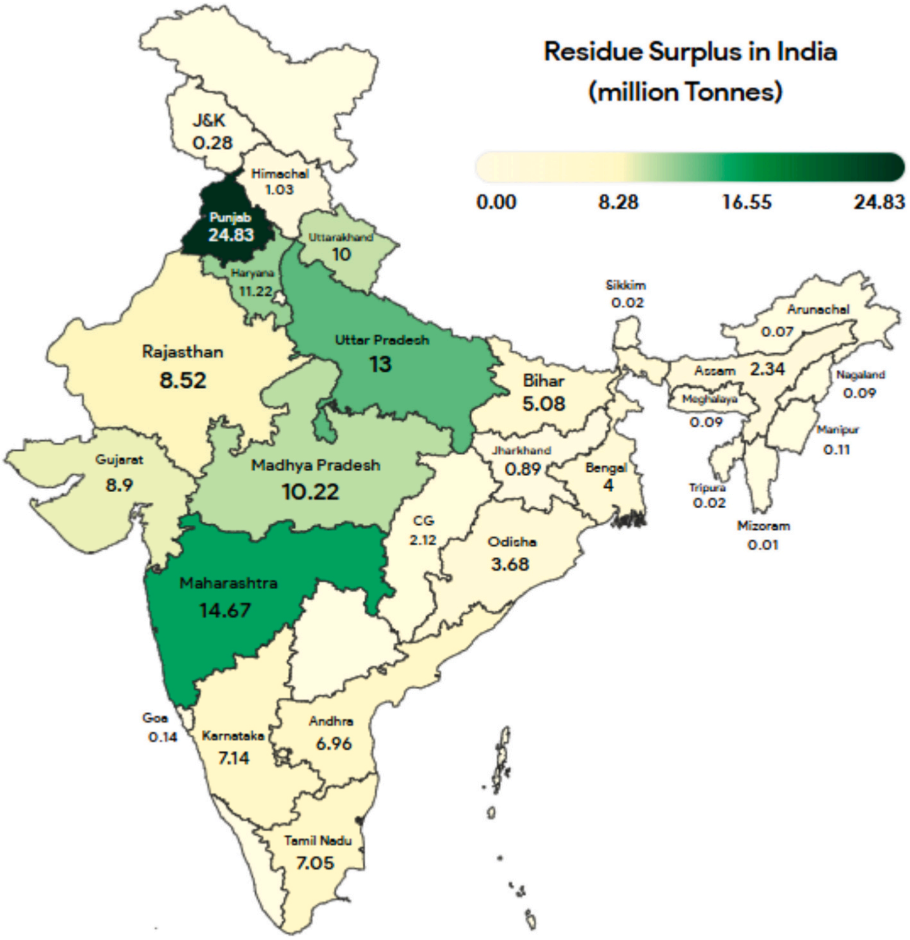

Fig. 3. Surplus residue in India.

produced from rice production in India [65]. In India specifically, the combined burden of residential combustion and household air pollution (HAP) results in 0.72 million deaths, with 68 % attributed.

to HAP and 32 % to ambient $PM_{2.5}$ from residential sources. This underscores the need for targeted interventions to reduce dependability on traditional fuels and address both indoor and outdoor air pollution in India and other nearby regions [66]. Several key sectors primarily drive air pollution in Punjab, each contributing significantly to the deteriorating air quality in the region [67]. In Fig. 5, the graph shows the major sectors that contribute to the AQI of South Asia including India, Pakistan, Nepal, Myanmar, Sri Lanka, and Bangladesh particulate matter ($PM_{2.5}$) pollution poses a significant threat to human health globally, contributing to millions of premature deaths annually.

Residential combustion is the leading cause of $PM_{2.5}$-related mortality in South Asia, accounting for 28 % of all fatalities in the region [66]. The impact is particularly severe in states like Delhi, Uttar Pradesh, and Haryana, where residential combustion accounts for 35 % to 39 % of $PM_{2.5}$-attributable mortality. Industry and power generation also play critical roles, contributing 15 % and 12 % respectively to $PM_{2.5}$-related deaths in South Asia. In Punjab, with a total installed capacity of 2640 MW across major thermal power plants, the annual utilization of crop residues for 7 % blending amounts to 726,000 t. Fig. 6. showing (AQI) of Punjab in August (2024). AQI across different districts of Punjab, highlighting variations in air quality. Faridkot reports the highest AQI of 303 followed by Moga and Bathinda, indicating hazardous air quality, while Pathankot has the lowest at 74. Agricultural burning is a fourth major source of pollution, particularly during the harvest season.

Every year, approximately 20 million tonnes rice straw are burnt in the agricultural fields of Punjab, leading to air pollution in the state and nearby areas [68]. In 2022, 93 % of the stubble burning incidents in India were reported from Punjab and a study in 2020, 70 % to 80 % of the stubble disposed by burning in Punjab [69]. This practice affects local air quality and contributes to regional smog that impacts neighboring states. The transport sector also plays a crucial role in air pollution along with the growth of industries in Punjab, often without adequate pollution control measures, which has led to increased emissions of various harmful pollutants. This includes emissions from small and medium-sized enterprises, such as brick kilns and steel re-rolling mills, which contribute disproportionately to air pollution relative to their economic output [70]. Additionally, construction activities and open burning of waste materials further contribute to overall pollution levels [71]. These activities release dust and other particulates into the air, compounding the challenges faced in managing air quality in Punjab.

The burning of RS contributes to poor air quality and significantly impacts public health in India, causing 44,000 to 98,000 premature fatalities annually due to particulate matter exposure [57]. The states of Punjab, Haryana, and Uttar Pradesh account for 67–90 % of these fatalities [72]. In a study, a multicity campaign was carried out during the crop residue burning season to investigate the impacts on ambient air quality [73]. The Indo-Gangetic Plain (IGP) region is a major contributor to air pollution due to crop residue burning, which significantly impacts ambient air quality and human health. Along with residue synthetic plastic is made from petroleum ore plays a major role in polluting the air as well as land [74]. It is estimated by the Punjab Pollution Control Board report (2022) that the average plastic generation is 128,744.64 t per annum in Punjab only. Thus, the current situation demands the use

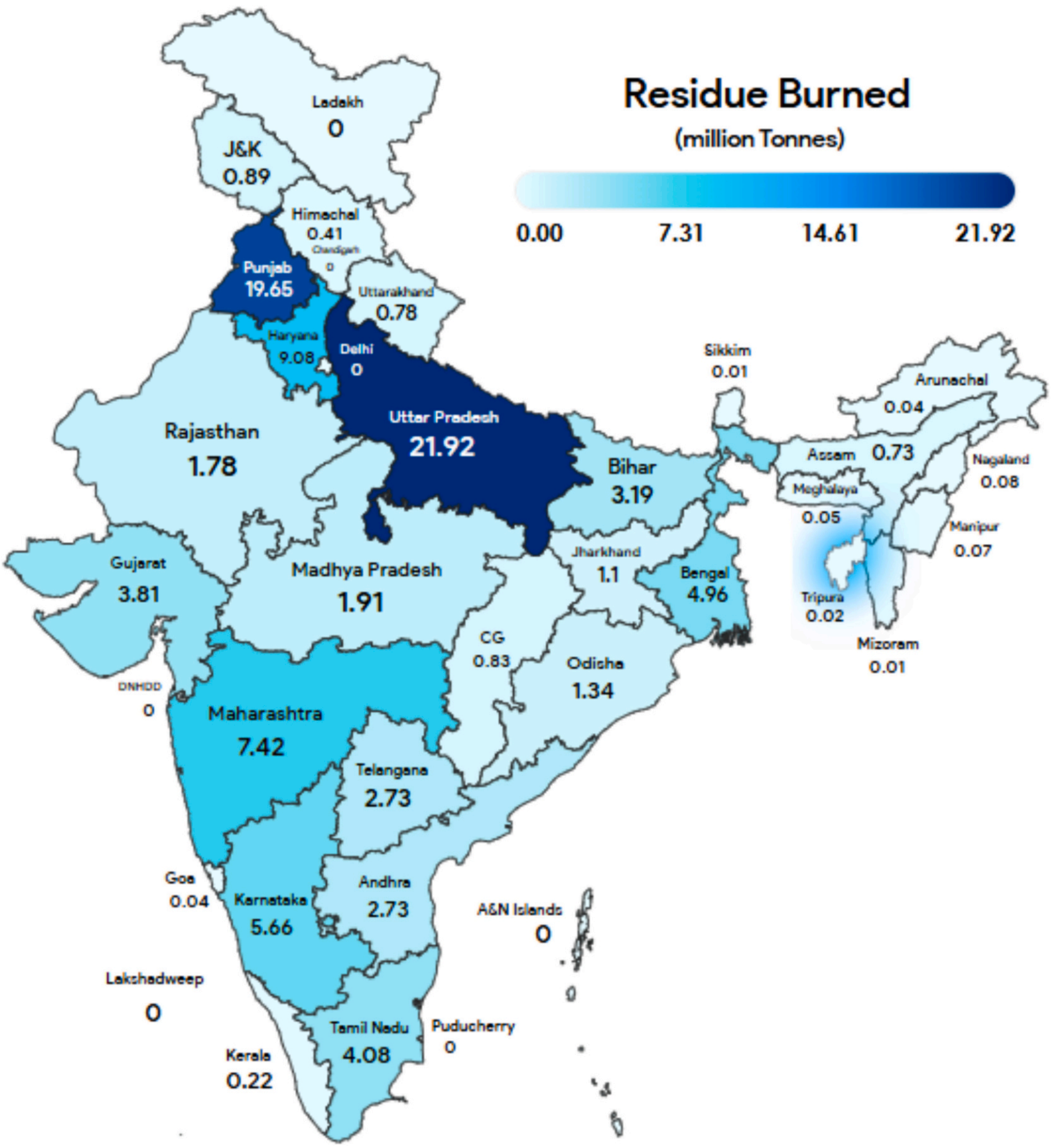

Fig. 4. Map representing residue burned in major states of India.

of natural biodegradable polymers. To make a sustainable hybrid biocomposite, various natural polymers obtained from the starch are used as matrix materials including, PLA [75]. Polylactic Acid (PLA) is a biopolymer derived from renewable resources, primarily corn starch or sugarcane, and has gained significant attention due to its environmentally friendly properties [76]. While PLA is non-toxic, biodegradable, and compatible with other materials, it is a potential substitute for traditional polymers made from petroleum [77].

3. Advanced application of rice residue application as CNCs

CNCs are derived from various sources such as plant biomass, oils, and seeds [78]. However, processing CNCs from such types of sources is not a cost-effective process [79]. CNCs are garnering significant attention in various fields due to their exceptional mechanical, thermal, and optical properties, as well as their renewability and biodegradability [80]. These biopolymeric materials, derived from the abundant natural resource of cellulose, exhibit a high surface area and aspect ratio, making them ideal candidates for a wide range of applications across multiple industries, including, biomedical as well as food sectors [81]. CNCs can be utilized in composite materials, where they serve as reinforcing agents that enhance the mechanical strength and durability of polymers [82]. For instance, when incorporated into biodegradable polymers, CNCs improve tensile strength and stiffness, which is particularly beneficial for sustainable packaging solutions that reduce reliance on conventional plastics [83]. Their high aspect ratio and surface area contribute to strengthened strength and stiffness in composite materials, making them suitable for packaging, automotive, and construction applications [84]. In addition to their role in composites, CNCs have been extensively explored for their potential in electronic applications. They can be combined with conducting polymers to create flexible and lightweight materials suitable for use in sensors and energy storage devices [85]. Recent studies highlight the development of CNCs based sensors capable of detecting hazardous gases and heavy metals, showcasing their versatility in environmental monitoring [86]. CNCs are increasingly used as fillers in polymeric-films to enhance mechanical characteristics [87]. The integration of CNCs with conductive materials not only enhances the mechanical properties but also improves the electrical conductivity of the resulting composites, opening new avenues for applications in wearable electronics and smart devices. Moreover, CNCs are making strides in biomedical applications due to their biocompatibility and ability to function for specific uses [88]. They have

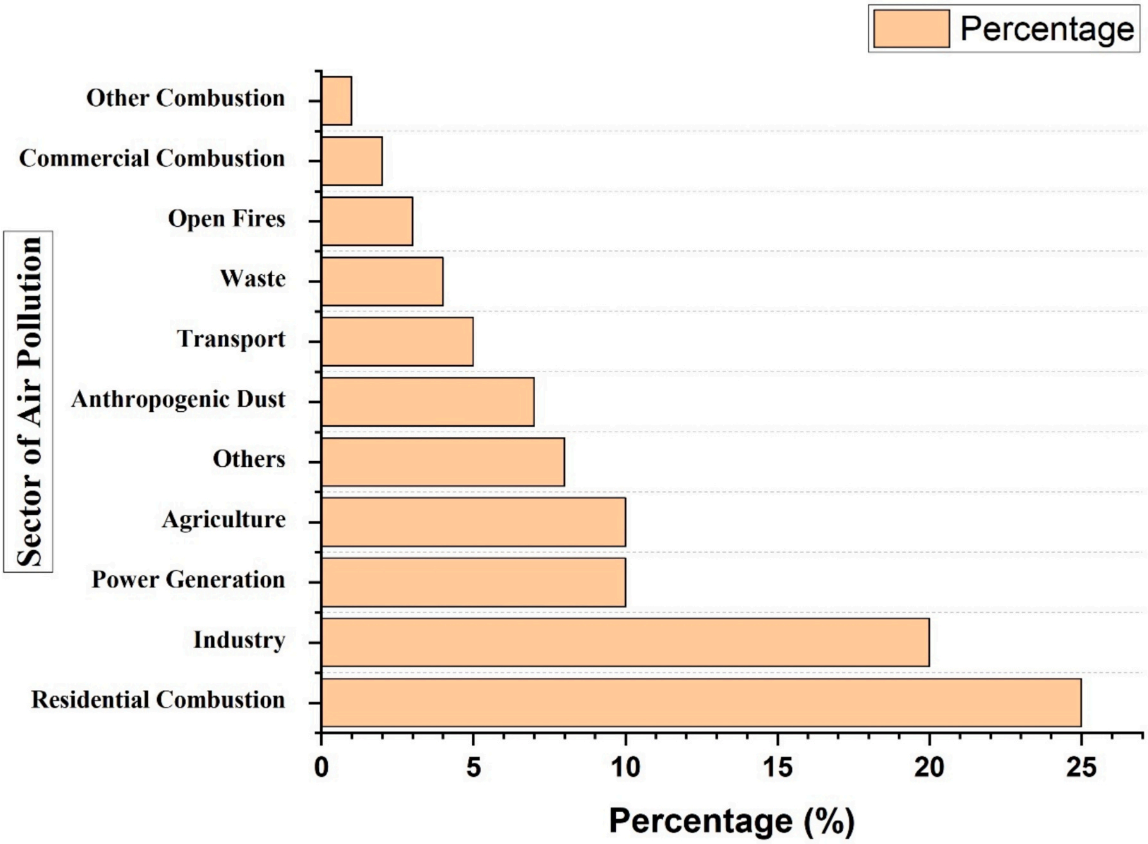

Fig. 5. Air pollution sectors of India and neighboring countries (India, Pakistan, Nepal, Myanmar, Sri Lanka, and Bangladesh).

been employed in drug delivery systems, where their large surface area allows for efficient loading and controlled release of therapeutic agents [89]. CNCs have potential uses in drug delivery systems and tissue engineering due to their biocompatibility and ability to form hydrogels [90]. CNCs can be utilized in food packaging to enhance barrier properties and prolong shelf life, as well as in food additives to improve texture and stability [91].

Additionally, CNCs are being investigated for use in tissue engineering scaffolds that promote cell adhesion and growth, providing a promising platform for regenerative medicine [92]. The potential interdisciplinary impacts of CNCs extend beyond materials science into fields such as environmental science, biology, and engineering [93]. Their application in water purification systems exemplifies this interdisciplinary approach; by utilizing CNCs in filtration membranes, researchers can effectively remove contaminants from water while promoting sustainable practices [94]. Furthermore, the combination of CNCs with other nanomaterials like graphene enhances the performance of sensors and energy devices by improving sensitivity and reducing material agglomeration [95]. CNCs represent a versatile and sustainable material with a broad spectrum of applications ranging from advanced composite materials to innovative biomedical solutions [88]. Their unique properties facilitate interdisciplinary collaboration among scientists and engineers aiming to develop next-generation technologies that address current challenges in sustainability and health [93]. As research continues to evolve around CNCs, their role as a cornerstone of sustainable innovation is expected to expand significantly across various sectors [96].

When compared to other water treatment technologies such as membrane filtration and ion exchange, CNCs offer unique advantages that enhance their suitability for advanced applications [97]. These include biodegradability, low cost, renewability, non-toxicity, and high chemical stability. Their high surface area (300 m^2/g) and functionalization potential, stemming from the hydroxyl groups on their surface, set CNCs apart from other filtration materials by employing recent novel techniques [98]. Membrane filtration, while highly effective at removing a broad range of contaminants, often suffers from high energy requirements approximately (0.5–1 kWh/m^3) and fouling issues, leading to increased maintenance costs [99]. Similarly, while ion exchange is effective for specific ions, its high environmental footprint due to resin disposal (30 % annual waste generation) and chemical regeneration processes presents challenges [100]. CNCs, on the other hand, are environmentally friendly and can be engineered for tunable selectivity, allowing them to target specific contaminants like heavy metals, dyes, and organic pollutants [101]. CNCs exhibit superior adsorption capacities, up to 50 mg/g for heavy metals and 60 mg/g for organic dyes, making them highly effective for targeted contaminant removal (70 % removal efficiency). Moreover, CNCs can enhance the performance of hybrid systems, such as CNC-polymer membranes, by improving mechanical strength and contaminant removal efficiency [102]. This makes CNCs a promising component in hybrid water treatment technologies, combining sustainability with high performance.

3.1. Economic feasibility of CNCs for advanced applications

The economic feasibility of CNCs plays a pivotal role in determining their potential for large-scale applications [103]. While their remarkable properties make them attractive for diverse uses, an assessment of their production costs, market value, and a cost-benefit analysis compared to traditional adsorbents provides a clearer understanding of their practicality. The production cost of CNCs is a critical factor influencing their commercial viability. Recent studies indicate that CNCs can be produced at approximately \$4.69 to \$4.89.00 per kilogram, depending on the production method employed (e.g., with or without acid recovery) [104]. The production process typically involves acid hydrolysis of

Fig. 6. Air Quality index (AQI) of Punjab state in August 2024 [66].

cellulose, which, while effective, is both capital and operationally intensive [105]. Costs can vary based on factors such as raw material sources, energy consumption, and processing methods. Employing acid recovery processes can enhance profitability but requires higher initial investments. Using agricultural waste like rice residue as a raw material provides an opportunity to reduce costs and increase sustainability, offering competitive advantages over conventional sources.

A study evaluating the production of a cellulose nanocrystal/polydimethylsiloxane (CNC/PDMS) hybrid membrane highlighted its economic feasibility and environmental benefits. With a production capacity of 10 MT/day, the plant's capital cost is $136 million, annual operating costs are $139 million, and projected annual revenue is $198 million. The minimum selling price for an 80 μm thick CNC/PDMS membrane is estimated at $3.68/m^2, which is cost-competitive with market alternatives. Environmentally, the hybrid membrane reduces global warming potential by 12 % compared to conventional PDMS membranes [106]. A research highlighted manufacturing costs ranging from USD 3632 to USD 4420 per ton of CNC (dry equivalent), with 95 % certainty that costs would remain below USD 5900 per ton [107].

The market for CNCs is experiencing rapid growth, driven by increasing demand for sustainable materials across multiple industries. Projections indicate that the market value of CNCs will grow from $430 million with growth rate of 24.7 % by 2028 [104]. Another research representing a compound annual growth rate (CAGR) of 2.9 %. The versatility of CNCs, especially in applications such as drug delivery systems and water purification, is a significant driver of their market expansion [108]. Their renewable and biodegradable nature aligns well with global sustainability trends, further enhancing their market potential [92]. The Comparison of CNCs to the traditional absorbents is given in Table 3. When compared to traditional adsorbents like activated carbon or synthetic polymers, CNCs present several advantages.

Scaling up CNCs production faces challenges due to high initial investments in infrastructure and technology [109]. However, integrating CNCs production into biorefineries that utilize agricultural waste, such as rice residue, can significantly reduce costs and increase economic feasibility [110]. Such advancements could further enhance CNCs' competitiveness in the market, ensuring their adoption across various industries [96].

While the initial production costs of CNCs may be slightly higher, their properties, and alignment with eco-friendly policies that make them highly valuable for practical applications such as water filtration [111]. CNCs can be categorized based on their surface properties [112]. Hydrophilic CNCs, with diameters ranging from 4 to 30 nm and lengths between 50 and 300 nm, are available as water dispersions or dry

Table 3
Comparison of CNCs to Traditional Adsorbents [92].

Factors	CNCs	Traditional Adsorbents
Production Cost	\$4.69 - \$4.89/kg (varies by production method)	\$2.00 - \$5.00/kg (varies widely)
Production Process	Acid hydrolysis of cellulose (capital & operationally intensive)	Typically, less capital intensive; varies by material
Raw Materials	Agricultural waste (e.g., rice residue) for reduced costs	Often derived from non-renewable resources
Market Growth	Rapid growth projected CAGR of 24.7 % by 2028	Stable market with growth driven by environmental concerns
Manufacturing Costs	\$3632 - \$4420 per ton (dry equivalent)	Varies; generally lower for traditional adsorbents
Environmental Impact	Low impact; renewable and biodegradable	Higher impact; potential leaching of harmful substances
Revenue Potential	Projected annual revenue of \$198 million for CNC/PDMS hybrid membrane	Generally lower revenue due to limited market expansion
Cost Competitiveness	Competitive with a selling price of \$3.68/m^2 for CNC/PDMS membrane	Generally lower production cost but requires more chemical treatments
Sustainability & Versatility	Renewable, biodegradable; high versatility in applications (drug delivery, water purification, composites, etc.)	Often derived from non-renewable sources, primarily used in water treatment and air purification
Scaling Challenges	High initial investment in infrastructure and technology; can be mitigated by integrating into biorefineries	Lower initial costs but may face regulatory challenges

powders and can be functionalized with carboxyl, carboxymethyl, epoxy, hydroxyl, or phosphate groups [113,114]. Conversely, hydrophobic CNCs, such as ester-functionalized types, exhibit similar dimensions (5–30 nm in diameter and 50–300 nm in length) and are also available as water dispersions or dry powders [115,116]. These classifications highlight the versatility of CNCs, enabling their use in diverse environments and enhancing their potential for sustainable water treatment applications. [86].

3.2. Production of CNCs from rice residue

Also, agricultural waste such as rice residue rich with lignocellulose content is best to provide for CNCs. Due to their exceptional qualities, CNCs can serve as reinforcement and water treatment applications [117]. Lignocellulosic-based waste plays a significant role in the synthesis of emerging nanomaterials for wastewater treatment, leveraging the inherent properties of lignocellulose present in plant biomass [118]. Lignocellulosic biomass, such as agricultural residues (e.g., rice husk, straw), is a rich source for extracting nanocellulose, which includes CNCs and cellulose nanofibers (CNFs) [119].

3.2.1. Basic CNCs extraction process

The extraction of CNCs from rice residue involves several key steps designed to produce high-purity nanocrystals suitable for diverse applications. Rice residue, abundant after harvesting, provides a sustainable raw material source. The basic extraction process, as shown in Fig. 7, begins with pretreatment using specific chemicals, such as alkalis or acids, to break down the biomass and isolate cellulose fibers from non-cellulosic components.

The choice of pH and temperature during the alkali or acid pretreatment is crucial as they directly influence the removal of lignin and hemicellulose while preserving the integrity of cellulose [90]. Studies indicate that pH values around 7 to 8 during neutralization [120]. Temperatures of 45 to 95 °C during acid hydrolysis, optimize the reaction kinetics without causing degradation of the crystalline structure.

Following pretreatment, the cellulose undergoes acid hydrolysis which typically using sulfuric acid under controlled conditions, such as a concentration of 64 %, a reaction temperature of 45 °C, and a duration of 30 to 60 min [6]. These conditions are chosen to selectively hydrolyze amorphous regions of cellulose while preserving crystalline regions, resulting in CNCs with high crystallinity and desired nanoscale dimensions [121]. Lower acid concentrations or shorter durations often yield incomplete hydrolysis, while excessive conditions can cause over-

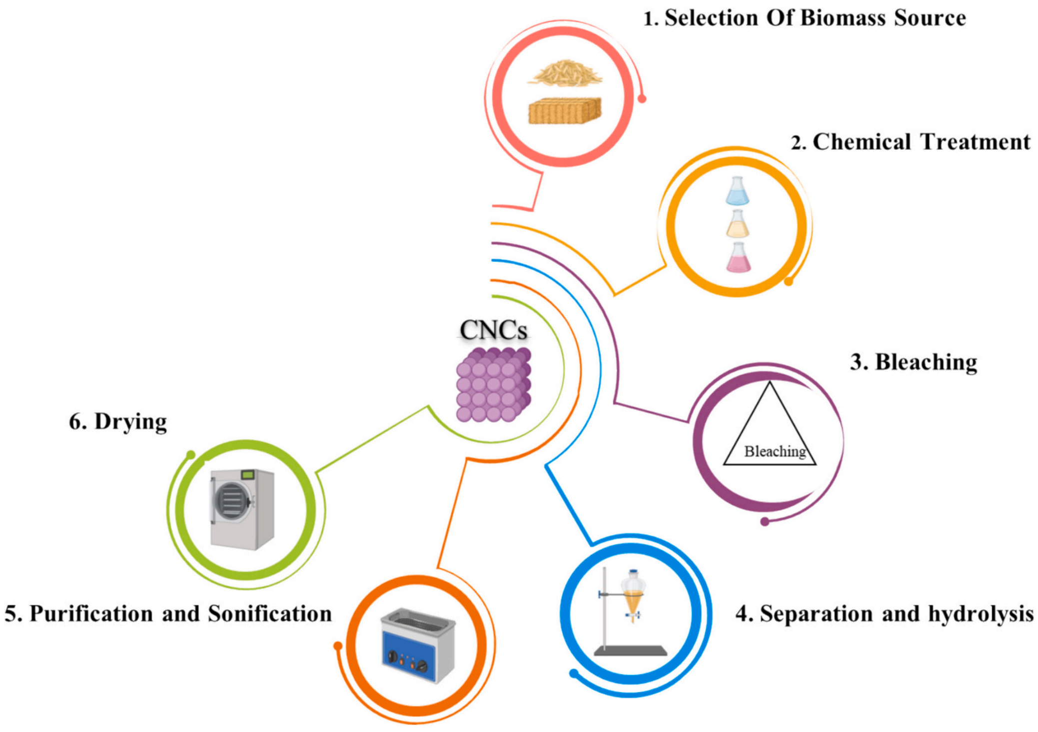

Fig. 7. CNCs basic extraction process [125].

fragmentation and reduce the mechanical properties of the final product.

The washing and filtration stages involve maintaining a neutral pH (~7) to eliminate residual chemicals, ensuring high purity [8]. Ultrasonic waves are employed to enhance fiber dispersion, which increases purification efficiency. Parameters such as ultrasonic frequency and power are optimized to achieve consistent results without damaging the CNCs [122].

The bleaching step uses hydrogen peroxide, potassium hydroxide (KOH) or sodium hypochlorite. In a research conditions like 1.4 % acidified sodium chlorite ($NaClO_2$) and 5 % potassium hydroxide (KOH) at 90 °C for 2 h are specifically selected to efficiently remove lignin residues while minimizing cellulose degradation [123]. Final drying steps, including freeze-drying or spray-drying, transform the CNCs into a stable powder suitable for long-term storage [121]. Freeze-drying, performed at −70 °C and 0.08 mbar, is preferred as it prevents agglomeration and preserves nanoscale morphology [124].

Following pretreatment, the cellulose fibers undergo acid hydrolysis, typically using sulfuric acid, which effectively breaks down the cellulose into nanocrystals while preserving their crystalline structure [105]. After hydrolysis, it is essential to purify the CNCs by washing and filtering to eliminate any residual chemicals, ensuring a high purity of the final product. Techniques like ultrasonic waves can be employed during this stage to help disperse the cellulose fibers and enhance purification efficiency [125].

Once purified, the CNCs are further processed using bleaching agents such as hydrogen peroxide or sodium hypochlorite to remove any remaining lignin and hemicellulose, which can affect the quality and properties of the final product. Finally, the purified CNCs are dried using methods like freeze-drying or spray-drying. This step transforms the CNCs into a stable, powdery form that is suitable for storage and subsequent applications [126].

The process parameters of extracting CNCs are different in some cases. A detailed research process is shown in Table 4 Along with methods and references. Studies have shown that CNCs from RH can achieve crystallinity indices of up to 70 % [131].

Alkali treatment combined with bleaching and sulfuric acid hydrolysis is an effective method for producing CNCs from rice residues. This process involves removing non-cellulosic materials through washing, sonication, and dehydration steps. Similarly, rice husk cellulose can be transformed into CNCs using sulfuric acid hydrolysis, followed by dilution, centrifugation, and drying to ensure a consistent and pure final product. Another approach involves treating dried cellulose with sulfuric acid, followed by neutralization, centrifugation, dialysis, and freeze-drying, resulting in high-quality CNCs. These methods highlight the effectiveness of chemical treatments in isolating and purifying cellulose nanostructures for various applications.

3.3. *CNCs extraction methods*

CNCs are typically produced through various methods, including acid hydrolysis, enzymatic processes, and mechanical treatments. Each method has its advantages and limitations, influencing the properties and applications of the resulting CNCs.

3.3.1. *Enzymatic processes*

Enzymatic hydrolysis presents an environmentally friendly alternative for extracting CNCs from rice residue. This process utilizes cellulases to break down cellulose into nanocrystals without harsh chemicals, making it more environmentally friendly. Enzymatic methods yield CNCs that are easier to functionalize and possess high thermal stability. Although it is less explored than acid hydrolysis, recent research has shown that combining enzymatic treatment with mechanical processes can enhance the efficiency of CNCs production while minimizing energy consumption [132].

Table 4
Various CNCs extraction experiments from rice residue.

Ref.	Experiment Details related to rice waste	Methods	Final Products
[118]	Cellulose Nanostructures Fabrication: - Alkali treatment followed by bleaching (27 g NaOH, 75 mL acetic acid in 1 L water, 1.7 % NaClO at 95 °C for 1 h. - Filtration, washing with distilled water, and drying at 60 °C (repeated twice). - Mixed with 60 % H_2SO_4 (0.2 g/10 ml) at 45 °C for 30 min. - Added tenfold water, centrifuged, dialyzed to neutral pH, and ultra-sonicated at 20 kHz, 750 W for 10 min. - Dehydrated for further studies.	Alkali treatment and acid hydrolysis	Cellulose nanostructures
[6]	Production of CNCs: - RH cellulose treated with 64 % sulfuric acid (1:20 ratio) at 45 °C for 30 min. - Diluted with 1000 mL distilled water to neutralize. - Centrifuged at 4000 rpm for 10 min (twice with water, thrice with ethanol). - Dried at 80 °C until constant mass; yield calculated from RH starting weight.	Acid hydrolysis	CNCs
[127]	Preparation of CNC: - Dried cellulose mixed with 64 wt% H_2SO_4 (1 g cellulose per 8.75 ml acid) with mechanical stirring at 45 °C for 30 min. - Diluted with 10-fold deionized water to stop the reaction. - Centrifuged, diluted again and centrifuged until the supernatant was turbid. - Dialyzed for a week to achieve pH 6.5–7.	Acid hydrolysis	CNCs
[124]	Nanocellulose Extraction: - Integrated sonication and acid hydrolysis using ultrasound equipment. - Three independent parameters: sulfuric acid concentration (40, 55, 70 %), ultrasound power (50, 200, 250 W), and reaction time (30, 75, 120 min). - 4 g RS cellulose in 100 mL beaker; 35 mL sulfuric acid added. - Preheated to 38 °C, treated with ultrasound, quenched with ice water, and centrifuged until neutral pH. - Dialyzed, sonicated for 20 min, freeze-dried at −70 °C and 0.08 mbar.	acid hydrolysis	CNCs
[128]	Nanocellulose Production: - Dried cellulose from RS hydrolyzed in 62 wt% H_2SO_4 at 45 °C for 1 h. - Reaction quenched with 5 times water, centrifuged, neutralized with NaOH, and washed thrice. - Frozen at −5 °C for 24 h, freeze-dried to obtain nanocellulose powder.	Acid hydrolysis	Nanocellulose powder
[129]	CNFs were produced using a bench-top planetary mill. Around 3 % (*w*/*v*) at a ball-to-material ratio of 80:1 and a speed	Alkaline extraction and bleaching	Cellulose nanofibers

(*continued on next page*)

Table 4 (*continued*)

Ref.	Experiment Details related to rice waste	Methods	Final Products
	of 300 rpm for periods of (3.21 h). After milling, the balls were separated, and the material was collected		
[130]	Preparation of CNCs The slurry obtained after the alkaline process and chlorine-free bleaching sequence was mixed using H_2SO_4 at 25 °C for 30 min. A centrifuge was used to filter and wash the suspension. 1200-W sonication treatment (30 min), vacuum filtered and placed in a freeze dryer to prepare the CNCs powder.	Alkaline process and bleaching	Nanocellulose powder

3.3.2. *Mechanical treatments*

Mechanical methods involve physically breaking down cellulose fibers in rice residue into nanoscale dimensions using techniques such as high-pressure homogenization, grinding, or ultrasonication [6]. These methods can produce CNCs without the use of chemicals, making them suitable for applications requiring biocompatibility. However, mechanical treatments often require significant energy input and may result in lower yields compared to chemical methods [133].

3.4. *Rice residue based CNCs in waste-water treatment*

Nanocellulose exhibits exceptional properties making it suitable for various applications, including water purification [134]. Its rich hydroxyl groups allow for easy modification and functionalization, enhancing its effectiveness as an adsorbent for pollutants [135]. Lignin, a complex biopolymer found in lignocellulosic waste, can be processed into lignin nanoparticles [136]. Lignin nanoparticles can act as adsorbents for heavy metals and organic pollutants in wastewater [137]. Their ability to Chelation of metal ions and their antimicrobial properties further enhances their utility in treating contaminated water. RH and straw can be converted into activated carbon through carbonization and activation processes [138]. This method yields a high surface area and porous structure, which are critical for effective adsorption for biomimicking applications [139]. Activated carbon derived from lignocellulosic waste is widely used for removing inorganic and organic contaminants from wastewater, including dyes, heavy metals, and other pollutants [140]. Its high porosity and surface area make it an efficient absorbent [105]. The functionalization of nanocellulose and lignin nanoparticles can improve their adsorption capabilities and stability in aqueous environments [42]. These materials can be incorporated into composite materials to enhance their performance in wastewater treatment applications [141].

Due to their high surface area and functional groups, CNCs derived from rice waste can be effective adsorbents for pollutants in wastewater treatment. They can remove heavy metals and organic contaminants, contributing to eco-friendly water purification technologies. CNCs are used in a variety of ways as filters as shown in Fig. 8. Nanocellulose is increasingly recognized for its potential applications in water purification due to its unique properties and versatility. One primary application is membrane filtration, where nanocellulose-based membranes effectively remove suspended solids, microorganisms, and dissolved contaminants from water. [100]. These membranes leverage the material's high surface area and mechanical strength to provide efficient filtration solutions [142].

Additionally, functionalized nanocellulose can serve as an effective adsorbent material in water treatment processes, targeting specific pollutants through adsorption-based purification methods [97]. This capability is enhanced by the rich hydroxyl groups on the nanocellulose surface, allowing for various chemical modifications to optimize its adsorption properties [143]. Nanocellulose can also be incorporated into composite materials, such as hydrogels or aerogels, to improve their adsorption and filtration characteristics [144]. This integration enhances the performance of these materials in removing contaminants from water, making them suitable for diverse water treatment applications [145]. Furthermore, nanocellulose can be combined with antimicrobial agents to develop advanced water treatment systems that effectively eliminate pathogenic microorganisms [146,147]. This combination not only addresses the removal of chemical pollutants but also enhances the safety and quality of drinking water [147]. The application of CNCs in wastewater treatment has garnered significant attention due to their unique physicochemical properties [135]. Further review is needed to discuss the role of CNCs in contaminant adsorption, degradation of organic pollutants, and antimicrobial applications in detail [134].

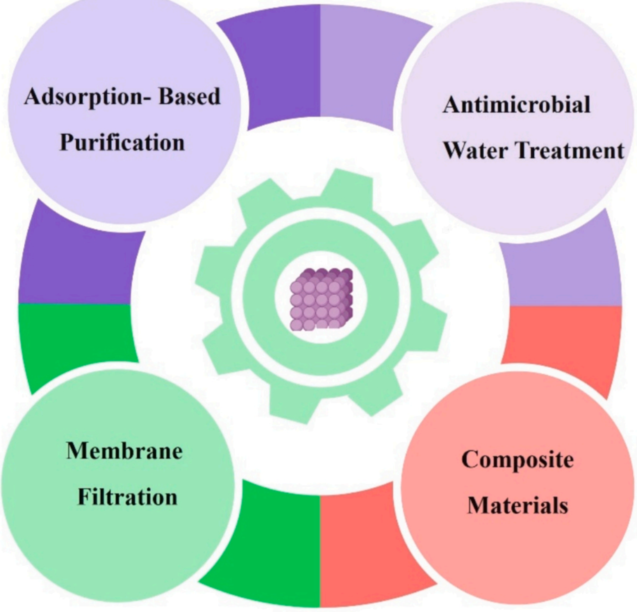

Fig. 8. CNCs in various water purification applications.

3.4.1. *Contaminant adsorption*

CNCs exhibit remarkable adsorption capabilities due to their high surface-to-volume ratio and the presence of functional groups, such as hydroxyls, which can interact with various contaminants through hydrogen bonding, electrostatic interactions, and Van der Waals forces [148]. Numerous studies have demonstrated the efficiency of CNCs in removing heavy metals, dyes, and organic pollutants from wastewater. Functionalized CNCs, particularly those modified with carboxyl, amine, or thiol groups, have shown exceptional capacity to adsorb heavy metals like lead (Pb), cadmium (Cd), and arsenic (As). For instance, CNCs modified with ethylenediaminetetraacetic acid (EDTA) have been reported to exhibit up to 90 % removal efficiency for Pb ions at low concentrations. Additionally, a study highlighted that CNCs functionalized with thiol groups achieved a maximum adsorption capacity of 472.59 mg/g for Pb^{2+} ions, demonstrating their potential as effective adsorbents in environmental remediation [149].

CNCs based materials are also effective in adsorbing synthetic dyes such as *methylene blue* and *rhodamine B*. The porous structure of CNCs composites enhances dye entrapment, while electrostatic interactions between dye molecules and functionalized CNCs contribute to high adsorption rates [150]. A recent study found that CNCs composites could remove over 95 % of methylene blue from aqueous solutions due to their large surface area and favorable interaction mechanisms [151]. The adsorption kinetics were rapid, reaching equilibrium within just a few hours. CNCs can absorb organic pollutants, including phenols and pesticides. Studies have shown that CNCs functionalized with surfactants or polymers improve the adsorption efficiency of hydrophobic organic molecules. For instance, research indicated that CNCs modified with polyacrylic acid enhanced the removal efficiency of phenolic compounds from wastewater by facilitating stronger interactions between the adsorbent and the pollutants [152].

3.4.2. *Degradation of organic pollutants*

In addition to adsorption capabilities, CNCs have been explored as catalysts or catalysts supports in the degradation of organic pollutants. Their ability to immobilize active species and enhance catalytic reactions has been widely studied. CNCs functionalized with photocatalytic agents like titanium dioxide (TiO_2), or zinc oxide (ZnO) exhibit enhanced degradation of organic pollutants under UV or visible light. These hybrid materials leverage CNCs' high dispersibility and stability to optimize light absorption and pollutant interaction. For example, a study demonstrated that TiO_2/CNCs composites significantly improved the photocatalytic degradation rates of methylene blue and ciprofloxacin under UV light irradiation [153]. The incorporation of CNCs increased the surface area available for photocatalytic reactions, leading to higher degradation efficiencies.

CNCs-based composites embedded with iron nanoparticles facilitate Fenton-like reactions for the oxidation of organic compounds. Such systems achieve high degradation rates for dyes, phenols, and other refractory pollutants. Recent research has shown that these composites can effectively degrade up to 85 % of phenolic compounds within 60 min, highlighting their potential for treating industrial wastewater [63]. CNCs are also used as carriers for enzymes like laccase and peroxidase, which degrade the lignin-derived pollutants and other organic contaminants. These biocatalytic systems are sustainable and effective under mild environmental conditions. A study reported that laccase-immobilized CNCs could degrade lignin model compounds efficiently while maintaining enzyme activity over multiple cycles and the related-study on the Cellulose-Ag composites has been unraveled by Salama et al., (2021) [154].

3.4.3. *Antimicrobial applications*

The antimicrobial properties of CNCs, particularly when functionalized or combined with antimicrobial agents, provide an additional avenue for water treatment applications. CNCs loaded with silver nanoparticles (AgNPs) exhibit potent antimicrobial activity against a broad spectrum of pathogens, including *Escherichia coli* and *Staphylococcus aureus*. AgNPs synergize with CNCs to create durable and effective antimicrobial surfaces. Recent studies indicate that these composite films can reduce bacterial counts by over 99 %, making them suitable for applications in water disinfection [155]. The combination of CNCs with chitosan as natural polymer with intrinsic antimicrobial properties enhances bacterial inhibition and biofilm disruption. Such composites are particularly valuable for treating biologically contaminated water. Research has shown that chitosan/CNCs films can inhibit bacterial growth effectively while remaining biodegradable [156]. CNCs functionalized with quaternary ammonium compounds demonstrate effective microbial inactivation by disrupting cell membranes. These materials are promising for applications in disinfection and microbial load reduction in wastewater treatment systems. A recent study found that quaternary ammonium-modified CNCs exhibited significant antibacterial activity against both gram-positive and gram-negative bacteria [146].

4. Pre-treatment on rice residue for CNCs extraction

The characteristics of biomass can be changed through chemical treatment. The heating rate during the pyrolysis process can influence the thermal stability of RH. Methods like isoconversational FWO and KAS can be used to estimate the energy activated during pyrolysis. Higher heating rates have been found to upgrade thermal stability. Also, treatment like hot water treatment is given to the rice residue to remove impurities from RR. The analysis of characteristics on the alkaline-treated RH biomass using techniques like field emission scanning electron microscopy (FESEM), thermogravimetric analysis (TGA), derivative thermogravimetric analysis (DTG), and confirms the desired enhancements [157].

The results of tensile and flexural tests revealed that the PLA composite reinforced with alkaline-treated RHF particles of 100, 200, and 500 μm sizes showed higher strength than those reinforced with water-treated RHF particles [158]. Thermogravimetric analysis results showed that the treatment decreased the thermal stability of the PLA when used as matrix. Biodegradable packaging films combining rice straw (RS), montmorillonite clay (Mt), and polyvinyl alcohol (PVA) showed enhanced tensile strength (69.39 MPa) with 6 wt% cellulose nanocrystals (CNC), enhancing the mechanical and thermostability, while raw/treated RS fibers reduced optical transparency and mechanical performance [159]. FESEM images of the PLA-matrix adjacent to the fiber because of the PLA resin's brittle-nature [160]. However, the bulk properties of rice husk (RH) biochar had no discernible impact after plasma treatments. Interestingly, oxygen plasma treatment showed effective surface-level etching, leading to an increase in nano-porous structure [161]. These findings suggest that plasma treatments can be a promising method to tailor the surface properties of hybrid silica/carbon particles synthesized from RH [161]. The potassium permanganate solution ate away at the RH. Pyrolysis of RH revealed that the treated RH thermally degraded quicker than the untreated RH, while analytical data indicated the presence of more amorphous silica in the treated RH [35].

The extraction of CNCs from rice residue involves pretreatment processes aimed at isolating cellulose by removing lignin, hemicellulose, and other impurities [6]. Effective pretreatment ensures a high yield and improved quality of CNCs with enhanced mechanical, thermal, and structural properties.

Alkaline treatment is one of the most widely used methods for the delignification and removal of hemicellulose in rice residues before CNC extraction. In a research study, rice residue is treated with sodium hydroxide (NaOH) solutions (4 % NaOH, *w*/*v*) at temperatures 165 °C for 90 min under constant stirring. Then solid washed several times to remove the remaining NaOH [63].

The biomass-to-solvent ratio is typically maintained at 1:20 *w*/*v*. NaOH disrupts ester bonds and cleaves hydrogen bonds in lignin and hemicellulose, resulting in the exposure of cellulose fibers. The treated fibers are thoroughly washed with deionized water until a neutral pH is achieved and then dried at 60 °C. This process significantly increases the cellulose content (up to 80 %–85 %) while removing impurities. NaOH treatment is given mostly for making nanofibers. Hence, the acid hydrolysis is necessary for the next process to extract CNCs from oil-fibers [162].

Acid hydrolysis is the core method for isolating CNCs from purified cellulose, usually following alkaline pretreatment. Concentrated sulfuric acid (H_2SO_4) 64 wt% is used at 45–45 °C for 30 min under continuous stirring. A controlled acid-to-cellulose ratio (typically 1:20 w/v) ensures proper hydrolysis without excessive degradation [163]. The hydrolysis reaction is quenched using a large volume of cold water to stop further reaction. Sulfuric acid selectively hydrolyzes the amorphous regions of cellulose, leaving behind crystalline domains as CNCs. Post-hydrolysis, the suspension is centrifuged (5 min at 4000 rpm) and dialyzed against deionized water until a neutral pH is achieved throughout this ultra-sonic technique [164]. This process yields CNCs with dimensions of 5–10 nm in diameter and 100–300 nm in length, depending on reaction conditions. Excessive acid concentrations or prolonged reaction times may degrade CNCs or lead to reduced crystallinity [6].

Bleaching removes residual lignin and enhances cellulose purity before CNC extraction. Rice residue is treated with a mixture of sodium hypochlorite ($NaClO_2$, w/v 4 %) [123] or hydrogen peroxide (H_2O_2, 2 %) at 70 °C for 2 h for rice straw-derived cellulose (RSC) [165]. These agents oxidize the lignin, breaking its aromatic rings and converting it into soluble products that can be washed away. The residue is washed and dried to obtain pure cellulose with a high whiteness index. The process enhances the thermal stability of the extracted CNCs by removing residual lignin, which is thermally unstable.

A hydrogen peroxide (H_2O_2) pre-treatment technique was adjusted to improve the biodegradation efficiency of RS and boost biogas generation [166]. It was discovered that the thermos-plasticity of products was greater than that of starting materials [166]. TGA and TMA thermograms reveal that chemically-processed RS are more thermally stable and thermoplastic than beginning materials [167]. RH has been investigated as a potential filler for biocomposites in engineering applications, but their hydrophilic nature has limited their use. Overall, this study suggests that pH 10.5 could lead to the development of biocomposites with improved mechanical properties and adhesion characteristics, suitable for use in engineering applications. In paper and pulping industries, mercerization had achieved general acceptance for creating material suitable for manufacturing writing papers. Hence, the natural fibers can serve as reinforcement in composites or can be further compressed into sheets for paper production [168].

The researchers found that pre-treatment resulted in increased pore volume in the solid waste residues, which enhanced the efficiency of enzymatic hydrolysis to 70 %. They attributed this increase to the release of (acid soluble lignin), which generated extra pore volume. The pre-treatment had a limited effect on the crystallinity index of the RS, which was consistent with Fourier transformer infrared (FTIR) analysis results. A maximum sugar yield of 83 % was obtained when rice straw underwent pretreatment with 1 % (*w*/w) sulfuric acid for 1–5 min at temperatures of 160 °C or 180 °C, followed by enzymatic hydrolysis. The complete release of sugars (xylose and glucose) enhanced the pore volume of the pretreated solid residues, leading to a 70 % efficiency in enzymatic hydrolysis [169]. HCl was found to be the most effective reagent compared to the other options in a study. The hydrolysis of RH using HCl was optimized based on three parameters, HCl-concentration, pre-treatment duration, and temperature. The optimal conditions (0.5 % *w/v* HCl, 125 °C, 1.5 h) were relatively mild and yielded approximately 22.3 mg TRS/ml in the hydrolysate [170]. In a study, RH was used as the filler material, while epoxy resin was used as the matrix. An increase in filler loading led to a decrease in fracture toughness. The effect of fiber treatment on toughness was also examined by pre-treating RH fibers with NaOH, which resulted in significant improvement. The concentration of the treatment media was found to affect fracture toughness as well. Fracture toughness significantly raised from 2.7465 MPa to 2.876 MPa after treatment with 20 %-reinforcement [171]. Additionally, the effect of hybridization was examined by adding RHA as a secondary reinforcement, which led to a remarkable increase in fracture toughness.

4.1. Some additional pretreatment methods for CNCs extraction

Acid hydrolysis is a process that uses acid to break down the cellulose (35–50 %) and hemicellulose (20–35 %) in rice husk (RH) into simpler sugars such as glucose and xylose. Cellulose $(C_6H_{10}O_5)_n$ reacts with water (H_2O) and an acid catalyst (H^+) to produce glucose ($C_6H_{12}O_6$)). Hemicellulose $(C_5H_8O_4)_m$, in the presence of water and an acid catalyst, produces xylose ($C_5H_{10}O_5$), along with other sugars like arabinose and galactose. Xylose ($C_5H_{10}O_5$) undergoes hydrogenation to form xylitol ($C_5H_{12}O_5$), a sugar alcohol, with the byproduct of water. In addition, prior literary-study has exhibited the effective utilization of the wastes for the CNCs fabrication for further agricultural crop-yield applications [172]. Xylose, a major pentose sugar derived during this process, can constitute up to 20–25 % of the hydrolyzed components and holds significant industrial importance [173]. Furfural, another derivative of xylose, is a key platform chemical used in manufacturing bio-based resins, solvents, and other industrial materials. Integrating xylose recovery into CNC extraction not only improves the economic viability of the process but also aligns with sustainable practices by maximizing the utilization of rice residue components [173]. Breaking this lignocellulose involve various pretreatment streps which are crucial for the CNCs extraction process. This process typically involves boiling the RH in a dilute acid solution like sulfuric acid for a few hours [162]. Once the desired reaction has taken place, the resulting mixture is neutralized with a base like NaOH to stop the acid hydrolysis reaction and adjust the pH level. This solution can then be used as a source of sugars for fermentation, which can be used in the production of CNCs or other valuable products. While acid hydrolysis of RH has the potential to be a sustainable and environmentally friendly process, the cost, energy inputs required, and environmental impacts of using acid and producing waste streams should be taken into consideration. Thus, natural fibers are subjected to various chemical treatments or modifications [174].

Thermochemical pretreatments like steam explosion, ammonia fiber expansion (AFEX), and organosolv use a combination of heat, pressure, and chemicals to break down the recalcitrant structure of lignocellulosic biomass [175]. Steam explosions use high-pressure steam to disrupt the lignin and hemicellulose, while AFEX employs liquid ammonia. Organosolv uses an organic solvent like ethanol to extract lignin [176]. These different methods are shown in Fig. 9. significantly improve the enzymatic digestibility of cellulose but require high-energy inputs and chemical recovery [177]. In contrast, biological and enzymatic pretreatments use microorganisms or enzymes to degrade lignin and hemicellulose selectively [177]. Fungi like white rot fungi produce ligninolytic enzymes that can efficiently delignify biomass [177]. Enzymes like cellulases, hemicellulases, and ligninases can also be applied to break down the cell wall components [178]. These methods are environmentally friendly, operate under mild conditions, and do not require chemical recovery [179]. However, they are slower and less effective compared to thermochemical methods. To overcome the limitations of the above techniques, advanced pretreatments like ionic liquids and microwave-assisted pretreatments have emerged. Ionic liquids are salts that can dissolve and fractionate lignocellulose at low temperatures. Microwave irradiation can rapidly heat and disrupt the biomass structure [180]. These methods can achieve high delignification and digestibility under milder conditions. However, they require further optimization and scale-up to be commercially viable. The choice of pretreatment depends on factors like feedstock composition, desired products, and economic and environmental considerations [181].

5. Properties of CNCs extracted from rice residue

Along with the various procedures of extracting CNCs, some properties of CNCs impact their application implementation such as crystallinity index (CI) diameter, and length. The yield percentage of CNCs extraction from any source is also directly related to the method or procedure employed in extrication processes. In Table 5 the summary of various research in which the CNCs were extracted or reviewed especially from rice waste. The Crystallinity Index (CI) was noted between 59 % to 77.45 % of rice husk. The diameter of the CNCs also varied from 7 to 32 nm. The maximum yield was found to be 52.8 %.

CNCs extracted from rice husk with a pH of 6.0 have 90.7 % Removal efficiency with 9.7(mg/g) adsorption capability when the concentration of pollutants was 25 mg/g [188]. Also, Rice based CNCs was reported as water absorption capacity to be 402.8 % when used in aerogel form [187]. CNCs exhibit a remarkable array of properties that make them ideal for various advanced applications. Their mechanical properties, thermal stability, and chemical functionality play a crucial role in their performance across diverse fields.

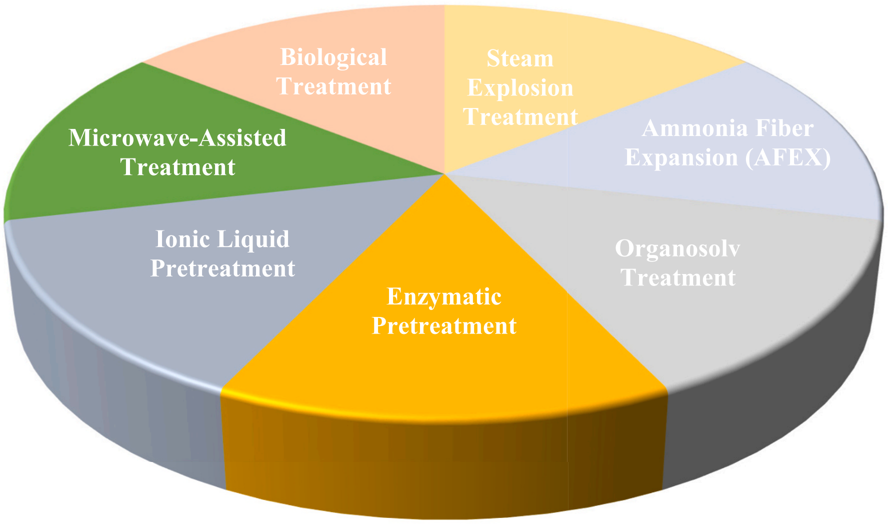

Fig. 9. Type of additional treatment on rice residue.

Table 5
Literature summary of CNCs extracted especially from rice waste.

Sources	Crystallinity Index (CI)	Diameter (nm)	Length (nm)	Methods	Yield (%)	Ref.
Rice Husk	59.00 %	7–15	–	Alkali + Bleaching + Acid Hydrolysis	Cellulose 96 %	[182]
Rice Husk (Chlorine-Free)	CNC1: 77.45 %, CNC2: 66.21 %	30–21	12.5	Alkali + Hydrogen Peroxide + Acid Hydrolysis	CNC1: 52.8 %, CNC2: 45.1 %	[183]
Rice Husk (Australia)	65.00 %	25–27	50–550	Alkaline + Bleaching + Acid Hydrolysis	NCC 95 % from B-RHP	[184]
Rice Husk (vs. Cotton)	62.5 % (rice husk)	11–30	117–270	Acid Hydrolysis	6.43	[185]
Rice Husk (India) vs. Wheat Straw	67.3 % (rice husk)	10–20	120–150	Acid Hydrolysis + Sonication	48.50	[186]
Rice Husk	67.16 %	19.3	195	Alkali + Bleaching + Acid Hydrolysis	28–30	[6]
Rice Husk vs oat husks	75.5	32.1	NA	enzymatic hydrolysis+ mechanical treatment		[187]

5.1. *Mechanical properties of CNCs*

CNCs possess exceptional mechanical properties, including a high tensile strength ranging between 9.2 GPa and Young's modulus of approximately 110–220 GPa [189]. These values are comparable to or even surpass those of other commonly used nanomaterials [95]. This high mechanical strength is attributed to the strong intramolecular hydrogen bonding and crystalline arrangement within CNCs, which provide them with rigidity and load-bearing capacity [190]. In composites, CNCs act as excellent reinforcements by improving the interfacial bonding with polymer matrices, significantly enhancing tensile strength, elasticity, and impact resistance [86].

5.2. *Thermal stability of CNCs*

The thermal stability of CNCs is another critical property, typically characterized by their thermal degradation temperature, which usually falls between 200 and 350 °C. Pristine CNCs tend to degrade due to the dehydration of hydroxyl groups and subsequent decomposition of cellulose chains [191]. Thermal analysis, such as TGA, reveals that functionalized CNCs demonstrate improved thermal behavior, with degradation temperatures shifting upwards by 20–50 °C depending on the modification. This enhanced thermal stability makes CNCs suitable for applications requiring elevated processing temperatures.

5.3. *Chemical functionality of CNCs*

Chemical functionality is one of the most versatile aspects of CNCs, primarily due to their abundant hydroxyl groups. These groups enable chemical modifications like esterification, etherification, oxidation, and grafting reactions, which tailor CNCs for specific applications. For instance, oxidation using TEMPO (2,2,6,6-Tetramethylpiperidine-1-oxyl) produces carboxylate-CNCs with enhanced dispersibility and adsorption capabilities for water treatment applications [2]. Similarly, esterification with fatty acids improves the hydrophobicity of CNCs, making them compatible with nonpolar polymer matrices. Such chemical modifications also enhance CNCs' ability to adsorb contaminants, catalyze reactions, or reinforce materials. [192]

5.4. *Dispersibility properties of CNCs*

Additionally, CNCs exhibit excellent dispersibility in aqueous and organic solvents, which is critical for their application in nanocomposites and coatings. Their surface energy and compatibility with other materials can be further enhanced through surfactant-assisted dispersion or the incorporation of coupling agents. These properties allow CNCs to integrate seamlessly into hybrid materials, extending their functionality to areas such as bioplastics, hydrogels, and nanofibers [193].

5.5. *Crystallinity index and its impact on CNCs in sustainable water treatment*

The crystallinity index of CNCs plays a significant role in determining their effectiveness in water treatment applications [80]. Higher crystallinity typically correlates with an increased specific surface area, providing more active sites for adsorption, which enhances the ability of CNCs to remove pollutants such as heavy metals and organic dyes from water [194]. Additionally, CNCs with a higher crystallinity index exhibit superior mechanical properties, making them more durable and effective when used in composite materials for water filtration systems [195]. This mechanical strength contributes to the longevity of filtration membranes, making them more reliable in long-term applications [196]. Crystallinity also impacts the performance of CNCs when combined with photocatalytic materials [197]. A higher crystallinity index can enhance the photocatalytic degradation of organic pollutants under light irradiation, making the purification process more efficient [198]. Moreover, the crystallinity of CNCs affects their surface charge and hydrogen bonding capabilities, which are crucial in coagulation and flocculation processes [199]. CNCs with higher crystallinity are often more effective in removing turbidity and suspended solids from water due to their improved ability to form stable aggregates [200].

The methods employed to enhance the crystallinity of CNCs, such as acid hydrolysis, sonication, and high-pressure homogenization, significantly influence their characteristics and performance in water treatment applications [132]. Acid hydrolysis selectively removes the amorphous regions of cellulose, leaving behind a more ordered and crystalline structure [201]. This process not only increases the crystallinity index but also exposes a hydroxyl group on the CNC surface, which enhances their ability to form hydrogen bonds with contaminants. Similarly, sonication, and ultrasonication disrupt amorphous regions by applying mechanical forces, thereby raising the exposure of crystalline areas. This results in an enlarged specific surface area, which provides active adsorption sites for pollutants such as heavy metals and organic dyes [202].

Higher crystallinity contributes to strengthened the adsorption efficiency in several ways. The ordered crystalline structure enhances the mechanical strength of CNCs, making them more durable for long-term use in water filtration systems [149]. Additionally, CNCs with higher crystallinity exhibit a more stable surface charge, which improves their interaction with oppositely charged pollutants during coagulation and flocculation processes. This facilitates the aggregation of contaminants, leading to more efficient removal. Moreover, the raised surface area associated with higher crystallinity allows for greater interaction among the CNCs and contaminants, enhancing the adsorption capacity [203].

The hydrogen bonding capabilities of CNCs, which are influenced by their crystallinity, play a critical role in their adsorption mechanism. A higher crystallinity index raises the density of accessible hydroxyl groups, enabling stronger-interactions with waterborne pollutants. Furthermore, the mechanical characteristics of CNCs, enhanced by their crystalline structure, contribute to their integration into composite materials, making them highly effective in advanced water treatment systems [203]. By understanding and optimizing these relationships, the crystallinity of CNCs can be tailored to achieve superior adsorption efficiencies and address specific challenges in water purification [204].

5.5.1. *Methods to optimize CNCs crystallinity*

Optimizing the crystallinity index (CrI) for specific water treatment applications is essential, as the ideal level of crystallinity may vary depending on the targeted contaminants and treatment methods on lignocelluloses [205]. Various techniques can be employed to enhance the crystallinity index of CNCs. Acid hydrolysis can selectively remove amorphous regions by fine-tuning the concentration of the acid, reaction temperature, and duration, leading to a higher crystallinity [206]. Sonication and ultrasonication can disrupt amorphous regions, further exposing crystalline areas, while ionic liquid processing dissolves the amorphous portions while preserving the crystalline structure. Mechanical treatments like high-pressure homogenization and microfluidization are also effective in increasing crystallinity by breaking down amorphous areas [120]. Alkali pretreatment of rice straw followed by high-pressure homogenization increased the CrI from 41.9 % in raw straw to 52.2 % in cellulose nanofibers (CNFs) and microfluidization of cellulose CrI from 45 % in the starting material to 65 % in the final CNFs. In some cases, a combination of these methods can be employed to synergistically enhance the crystallinity index, resulting in CNCs that are better suited for specific water treatment tasks [205]. The crystallinity index of CNCs significantly influences their performance in water treatment by affecting their adsorption capacity, mechanical strength, photocatalytic activity, and coagulation efficiency [207]. By employing various methods to enhance crystallinity, CNCs can be optimized for more effective removal of contaminants from water, contributing to improved purification processes [208].

5.6. *Enhancement of CNCs properties for water treatment*

CNCs derived from renewable sources can be effectively functionalized through various chemical modification techniques, including esterification, etherification, and grafting [209]. These processes enhance the properties of CNCs, making them suitable for diverse applications in wastewater treatment [193]. An illustration of these processes is shown in Fig. 10. Esterification involves the reaction of cellulose hydroxyl groups with carboxylic acids or acid anhydrides to form esters, which significantly enhance the hydrophobicity and adsorption capacity of CNCs for waste-water treatment [210]. The process typically begins with the extraction of CNCs from rice husk through a series of chemical treatments, including alkali treatment, bleaching, and acid hydrolysis [133]. Following extraction, appropriate reagents, such as acetic acid or acetic anhydride, are selected for the esterification reaction, which is carried out under controlled temperature and time conditions in the presence of a catalyst [193]. This modification not only enhances the interaction of CNCs with organic pollutants but also facilitates their aggregation and removal from wastewater, thereby increasing treatment efficiency [209].

Characterization techniques such as Fourier Transform Infrared Spectroscopy (FTIR) are employed to confirm the formation of ester bonds and to assess changes in functional groups [113].

Similarly, etherification modifies CNCs by reacting to hydroxyl groups with alkyl halides or epoxides to form ethers, thereby enhancing their solubility and compatibility with various matrices. The etherification process parallels that of esterification, starting with the extraction of CNCs, followed by the selection of suitable etherifying agents [211]. The reaction is conducted in the presence of a base, which deprotonates the hydroxyl groups, making them more nucleophilic. This modification is particularly beneficial for improving the dispersion of CNCs in nonpolar solvents and enhancing their performance in composite materials used for water treatment [212]. Characterization methods such as Nuclear Magnetic Resonance (NMR) spectroscopy and FTIR are utilized to confirm the successful formation of ether bonds [213]. In addition to these modifications, grafting techniques further enhance the functionality of CNCs by attaching polymer chains to their surfaces [214]. Methods such as Surface-Initiated Atom Transfer Radical Polymerization (SI-ATRP) and grafting from Ring-Opening Polymerization (ROP) allow for controlled growth of polymers [215].

Grafting via Ceric Ammonium Nitrate (CAN) enables grafting in an aqueous medium without strong acids, making it more environmentally friendly [197]. It has been shown to achieve high monomer conversion rates and grafting yields, enhancing the applicability of CNCs [209]. This results in tailored properties that improve the CNCs' hydrophobicity, mechanical strength, and compatibility with various matrices [209]. Grafted-CNCs can be designed to exhibit specific functionalities, including, the responsiveness to environmental stimuli or enhanced adsorption capacity with strengthened thermomechanical characteristics of PLA composites for targeted pollutants [216]. This makes them particularly effective for applications in wastewater treatment, where tailored interactions with contaminants are crucial for achieving high removal efficiencies [121].

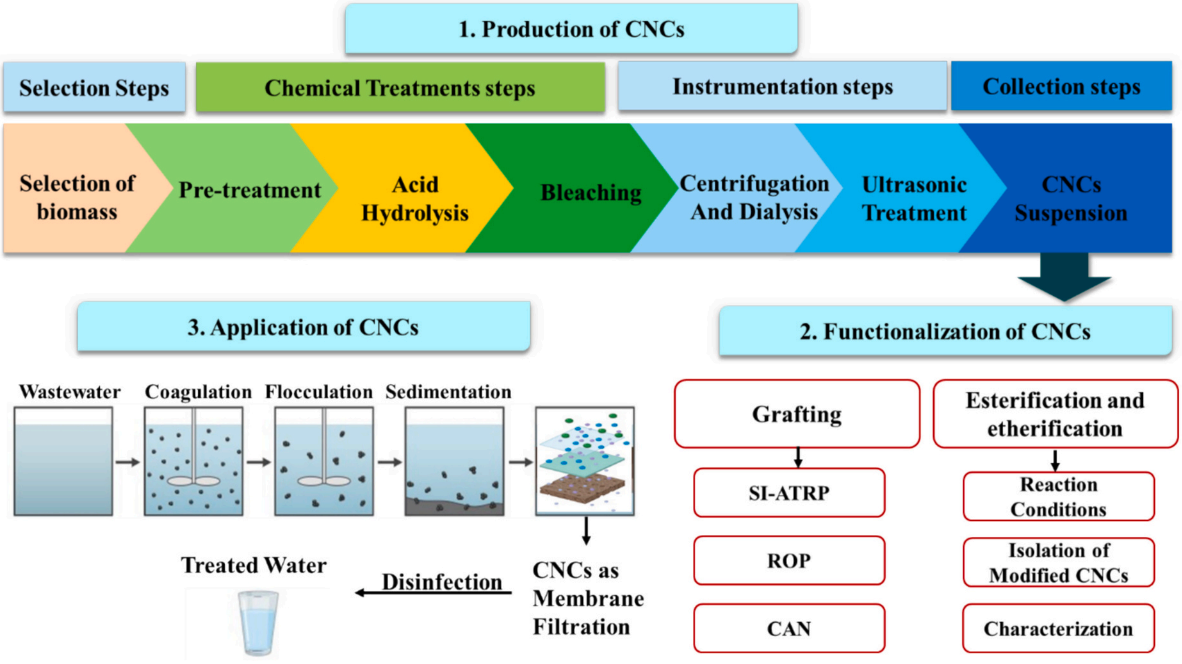

Fig. 10. Production, functionalization, and applications of CNCs as water treatment.

5.6.1. Mechanisms of CNCs in water treatment applications

One of the primary mechanisms by which CNCs aid in water purification is adsorption. The high surface area and surface hydroxyl groups of CNCs facilitate interactions with contaminants such as heavy metals, dyes, and organic pollutants [196]. The adsorption process is driven by hydrogen bonding, electrostatic forces, and van der Waals interactions [217]. The basic rection process is shown in Eq. (1). CNCs effectively adsorb heavy metal ions like lead (Pb^{2+}) and chromium (Cr^{6+}), with the hydroxyl groups on the CNCs surface forming bonds with metal ions, replacing hydrogen atoms.

$$CNC - OH + Pb^{2+} \rightarrow (CNC - O) - Pb + 2H^{+} \qquad (1)$$

This reaction demonstrates the strong affinity of CNCs for metal ions, enabling significant removal of toxic substances from water. In addition to adsorption, CNCs also play a crucial role in coagulation and flocculation processes [100]. Their negatively charged surfaces interact with oppositely charged colloidal particles in water, neutralizing their charges and promoting aggregation. These aggregated particles form larger flocs that settle out of the solution through sedimentation [197]. This mechanism is particularly effective for removing suspended solids, organic matter, and turbidity from wastewater. CNCs thus act as eco-friendly flocculants, offering an alternative to traditional chemical coagulants [218].

However, while the short-term effects of CNCs in removing heavy metal ions and pollutants have been demonstrated, research on their long-term stability and reuse potential is still evolving [109]. Repeated adsorption-desorption cycles often lead to diminished performance due to structural degradation, fouling, or loss of active sites. In a study it was observed that CNCs could retain up to 83.1 % of their adsorption capacity after five cycles, though the specific outcomes varied depending on the type of contaminant and regeneration method used [219]. Further studies are necessary to optimize regeneration techniques, such as thermal treatment, chemical washing, or ultrasonic cleaning, to enhance reusability while minimizing environmental impact.

Additionally, the chemical stability of CNCs in harsh conditions, such as varying pH levels or prolonged exposure to contaminants, remains a critical factor in determining their reliability as an environmentally friendly material for water treatment. CNCs performance decreased in acidic conditions due to partial hydrolysis of cellulose [220]. To address this limitation, future research could focus on surface modifications or hybrid composites that improve durability without compromising adsorption efficiency. These advancements would establish CNCs as a more viable, sustainable option for real-world water treatment systems.

CNCs exhibit negatively charged surfaces, which interact with positively charged colloidal particles in water, facilitating charge neutralization and aggregation [184]. For instance, CNCs derived from sugarcane bagasse were employed as eco-friendly flocculants to reduce turbidity in wastewater, achieving over 99.82 % turbidity reduction for kaolin suspension [221]. The mechanism can be represented by the following interaction Eq. (2).

$$CNC^{-} + Colloidal\ particle^{+} \rightarrow Aggregated\ Floc\ (Neutralized) \qquad (2)$$

These flocs settle through sedimentation, effectively removing suspended solids and organic matter. CNC-based flocculants are an eco-friendly alternative to chemical coagulants such as aluminum sulfate. Another significant application of CNCs lies in membrane filtration. CNCs are used to fabricate composite membranes with improved hydrophilicity, water flux, and contaminant rejection capabilities [99]. Their hydrophilic nature enhances water permeability while preventing fouling, a common issue in conventional membranes. CNC-based membranes have demonstrated high efficiency in removing microplastics, bacteria, viruses, and salts from water. By embedding CNCs into polymeric membranes, the resulting composite structures achieve superior filtration performance, making them suitable for both industrial and municipal water treatment systems [222]. CNCs modified membranes have demonstrated remarkable performance, removing over 99 % of microplastics and 98 % of bacteria and viruses from wastewater [97]. CNCs based composite membranes embedded with silver nanoparticles achieved high antimicrobial activity against *Escherichia coli*, providing dual benefits of filtration and pathogen removal [153]. The reaction between CNCs and contaminants can be generalized as shown in Eq. (3).

$$CNC - OH + AgNO_3 \rightarrow CNC - O - Ag + HNO_3 \qquad (3)$$

To enhance their effectiveness, CNCs can be functionalized through chemical modifications. Esterification and grafting are two common methods that expand the application range of CNCs [223]. Esterification introduces carboxyl groups to the CNCs surface by reacting them with carboxylic acids or anhydrides, thereby increasing their adsorption capacity for heavy metals and dyes [209]. The reaction can be represented in Eq. (4).

$$CNC - OH + R - COOH \rightarrow CNC - O - COR + H_2O \quad (4)$$

Grafting involves attaching functional groups such as amines or polymeric chains to the CNCs structure, enhancing their selectivity for specific pollutants. For instance, amine-functionalized CNCs exhibit improved affinity for negatively charged contaminants like nitrates and phosphates. Numerous case studies demonstrate the efficacy of CNCs in water treatment. For instance, CNCs functionalized with carboxyl groups have been shown to remove over 95 % of lead ions from industrial wastewater [142]. The maximum starch-based nanoparticle exhibits impressive adsorption efficiency, reaching 383.08 mg/g for cationic metal removal [3]. Similarly, CNC-based membranes exhibit high adsorption efficiency for organic dyes like methylene blue due to π-π stacking interactions between the dye molecules and CNCs surfaces.

6. Key considerations for using CNCs in wastewater treatment

Optimizing CNCs for real world applications requires addressing challenges related to material properties, surface modifications, and pollutant-specific treatments to ensure efficiency and sustainability.

6.1. Critical factors in the use of CNCs for wastewater treatment

CNCs extracted from rice husks have significant potential for water purification applications due to their unique properties, such as high crystallinity, large surface area, and ability to modify their surface for enhanced adsorption [3]. However, several factors must be considered to optimize their performance in water treatment systems shown in Fig. 11. [99]. Surface modification is crucial, as CNCs may require functionalization with specific functional groups (e.g., amine, carboxyl, or hydroxyl groups) to enhance their adsorption capacity for targeted pollutants like heavy metals, dyes, or organic compounds [224]. The crystallinity index of CNCs is also important, as high crystallinity improves their mechanical strength and stability, which is essential for filtration systems [100].

Fig. 11. Factor related to CNCs.

Ensuring the appropriate crystallinity level is crucial for optimal performance in water treatment applications. The size and morphology of CNCs also play a significant role in their adsorption potential. Smaller CNCs have a higher surface area-to-volume ratio, which can increase their adsorption capacity [193].

However, too small particles can lead to difficulties in recovery post-treatment, so a balance must be struck between size and ease of separation [137]. The type of pollutants present in the water also affects the adsorption capability of CNCs [144]. Different pollutants, such as heavy metals, organic dyes, or pharmaceuticals, require tailored CNCs for optimal efficiency [197]. Biocompatibility is another important consideration, as CNCs are inherently biocompatible and biodegradable, reducing the risk of secondary pollution [4]. This eco-friendly aspect of Cl-free pulping technique has aligned with green chemistry principles, making CNCs favorable for sustainable water treatment applications [225].

6.2. Challenges of using CNCs as wastewater treatment

CNCs derived from rice husks present promising opportunities for water purification, but several challenges must be addressed for their effective application in this field. Different challenges related to using CNCs are shown on Fig. 12. One significant challenge is the separation and recovery of CNCs from treated water [7]. After the filtration process, retrieving the nanocrystals can be difficult, and while techniques such as incorporating magnetic nanoparticles may facilitate this, they also introduce additional complexity to the system [226]. Scalability is another critical concern. Although CNCs have demonstrated effectiveness in laboratory settings, transitioning to large-scale production and application in water treatment systems poses both technical and economic hurdles. This includes the need for efficient manufacturing processes that can produce CNCs in sufficient quantities without prohibitive costs [63].

Moreover, the functional stability of the CNCs is essential [190]. The performance of the functional groups or surface modifications applied to the CNCs can vary under different water treatment conditions, such as fluctuations in pH, temperature, and ionic strength [63]. Maintaining consistent performance across these varying conditions is vital for reliable water treatment.

Cost and resource availability also play a crucial role in the feasibility of CNCs for water purification. While rice husk is an abundant agricultural by-product, the extraction process for CNCs is energy-intensive and requires chemicals, which can impact the overall cost-effectiveness of the technology. Regulatory approval is a significant barrier to the widespread adoption of CNCs-based water treatment technologies. These technologies must undergo rigorous validation for safety, efficacy, and environmental impact before they can be implemented on a large scale [2]. While CNCs from rice husks hold great potential for water purification, addressing challenges related to separation and recovery, scalability, functional stability, cost, and regulatory approval is crucial for their successful integration into water treatment systems.

6.2.1. Synergistic mechanisms in CNCs for wastewater treatment: advantages and limitations

In synergistic mechanisms of CNCs the primary advantage lies in its ability to integrate with various functional agents, such as photocatalysts, antimicrobial compounds, and polymeric matrices, to achieve multifunctional properties [226]. For instance, CNCs functionalized with photocatalytic agents like TiO_2 or ZnO enhance the degradation of organic pollutants through improved light absorption and catalytic efficiency [227]. Similarly, composites of CNCs with antimicrobial agents, such as silver nanoparticles, demonstrate effective pathogen inactivation while maintaining structural stability [228]. Additionally, CNCs derived from rice residues contribute to sustainability by upcycling agricultural waste and reducing dependency on non-renewable materials [100]. Their renewable nature, combined with high surface area

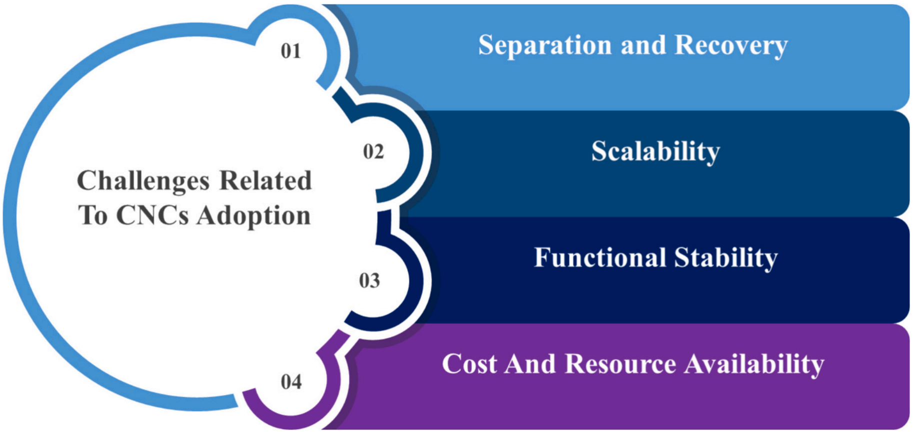

Fig. 12. Challenges related to CNCs adoption for water purification.

and ease of chemical modification, makes CNCs a versatile platform for water purification applications, such as adsorption, degradation, and disinfection [196]. These attributes address the limitations of traditional adsorbents and catalysts, offering eco-friendly and efficient alternatives [229].

However, certain limitations need to be addressed to maximize the potential of these synergistic mechanisms. The scalability of CNCs production from rice residues remains a challenge, particularly in maintaining uniform quality and functionalization at an industrial scale [122]. Furthermore, CNC based composites may face reduced stability and performance in real-world wastewater matrices containing mixed contaminants and competing ions [230]. The regeneration of CNCs systems, particularly those used in adsorption and catalytic processes, is another concern, as it directly impacts the sustainability and cost-efficiency of these systems [139]. To overcome these limitations, further research is needed to optimize CNCs production processes, enhance the selectivity of CNC-based systems for specific contaminants, and develop efficient regeneration methods. Additionally, long-term field trials are essential to evaluate the feasibility and durability of these technologies under practical conditions.

6.3. *Cost and performance comparison of CNCs with other nanomaterials (NMs)*

CNCs, derived from renewable biomass like rice residues, present a sustainable alternative to conventional nanomaterials for water treatment. In terms of cost-effectiveness, CNC production is currently expensive than activated carbon due to the specialized chemical pretreatments and extraction processes involved for the applications of water-treatment as ultra-filtration membranes [231]. However, the raising availability of lignocellulosic waste and advancements in large-scale CNC production methods for sustainable carbon NMs, could reduce costs in the future [232]. The cost analysis revealed that the laboratory-scale production cost of native L–CNCs is approximately AUD 80/kg, which is only 10 % of the cost for purified L–CNCs at around AUD 850/kg. This significant difference indicates a more cost-effective method for producing native L–CNCs/PVA composite films [79].

In comparison, activated carbon, which is produced from coal or biomass through pyrolysis, is more cost-competitive but depends on energy-intensive manufacturing. Synthetic polymers, while initially cost-effective, rely on petrochemical feedstocks, which are subject to price volatility and sustainability concerns [228].

Cellulose nanofibers adsorb Pb^{2+} and Cd^{2+} with capacities of 28.7–37.3 mg/g, while graphene oxide composites achieve up to 1416 mg/g for Pb^{2+} and 544 mg/g for MB via π–π interactions and electrostatic forces [233]. CNCs, with negatively charged surfaces, adsorb 34 mg/g of Ag^{+} and 22.6 mg/g of Pb^{2+}, reducing biofouling [234].

As shown in Table 6, carbon-based nanomaterials like Carbon Nanotubes (CNTs) and Graphene Oxide (GO) possess exceptional properties that enhance their utility across various applications. CNTs, composed of carbon atoms arranged in cylindrical structures, are known for their high electrical conductivity, mechanical strength, and large specific surface area, making them effective in electronics and water filtration systems, with an adsorption capacity of up to 300 mg/g for organic pollutants [235]. The production of carbon nanotubes (CNTs) has achieved a cost of less than $1 per gram through optimized catalysts and natural calcite supports, highlighting significant advancements in cost-effective large-scale synthesis [236]. Graphene Oxide consists of a single layer of carbon atoms with oxygen functional groups, offering high surface area and hydrophilicity, which results in an adsorption capacity of 400–600 mg/g for heavy metals and rapid adsorption kinetics suitable for water purification [224]. Additionally, Nano Hydroxyapatite (nHAp), a biocompatible calcium phosphate mineral, is effective for heavy metal removal with an adsorption capacity of 100–200 mg/g and is utilized in biomedical applications [236]. Lastly, Cellulose Nanocrystals (CNCs), derived from plant fibers, are biodegradable and exhibit a high aspect ratio, making them suitable for drug delivery systems and water purification, with an adsorption capacity of up to 500 mg/g for organic dyes. Together, these nanomaterials represent significant advancements in material science, providing innovative solutions across multiple industries. The cellulose composite with a cellulose/graphene ratio of 3:1 achieved the highest adsorption capacities of 1178.5 mg/g for methylene blue and 585.3 mg/g for (Congo red) dye. Performances in terms of removing mercury ions from water having an adsorption capacity of 178 mg/g. This performance is attributed to the composite's larger surface area and increased adsorption sites [137]. Adsorption capacity can be lower than that of activated carbon, which has a well-developed porous structure ideal for removing a wide range of pollutants, including organic chemicals and gases [85]. Synthetic polymers can be engineered to exhibit high selectivity for specific contaminants, however CNCs show great promise for targeted and sustainable water treatment and more specialized production methods currently limit their large-scale applicability compared to more established materials like activated carbon or other NMs [237].

6.4. *Cycle for reusing CNCs in water treatment*

The reuse of CNCs in water treatment processes can be optimized by designing a cyclic system that enhances sustainability and reduces material waste [238]. The cycle begins with CNCs preparation and functionalization, where CNCs are derived from lignocellulosic biomass, such as rice husk or rice straw, and chemically modified to enhance their adsorption capabilities [6]. Functional groups like carboxyl or sulfonic

Table 6
Comparison of nanomaterials and cellulose nanocrystals (CNCs) as absorbents [235].

Type	Subtype	Composition	Key Properties	Adsorption Capacity (Typical)	Advantages	Applications
Carbon-Based	Carbon Nanotubes (CNTs)	Carbon atoms arranged in cylindrical nanostructures	High tensile strength; excellent electrical conductivity	Up to 300 mg/g for organic pollutants	High surface area; strong mechanical properties	Water treatment; electronics
	Graphene Oxide (GO)	Single-layer carbon atoms with oxygen functional groups	High surface area; hydrophilic nature	400–600 mg/g for heavy metals	High adsorption kinetics; versatile	Water filtration; sensors
Metal Oxide-Based	Nano Hydroxyapatite (nHAp)	Calcium phosphate mineral	Biocompatible; high surface area	100–200 mg/g for heavy metals	Environmentally friendly; effective for ion exchange	Heavy metal removal; biomedical applications
Bio-Based	Cellulose Nanocrystals (CNCs)	Derived from cellulose fibers	High aspect ratio; biodegradable	Up to 500 mg/g for organic dyes	Renewable resource; non-toxic	Drug delivery; water purification

groups can be introduced to CNCs, or nanoparticles such as silver or titanium dioxide can be embedded, depending on the target contaminants [221]. The functionalized CNCs are then applied in water treatment processes, primarily for adsorption or membrane filtration, where they effectively capture pollutants like heavy metals, dyes, and organic compounds [239].

After CNCs become saturated with contaminants, a recovery process is initiated to enable reuse [210]. This involves desorption and regeneration techniques, such as chemical desorption (using acids or bases), thermal treatment, or solvent washing, depending on the nature of the pollutants. Once the contaminants are removed from the CNCs, these pollutants are handled in a separate disposal process where heavy metals can be recycled, and organic pollutants can be safely incinerated or treated to minimize environmental harm [209]. This closed-loop process is illustrated on Fig. 13. which highlights the potential for CNCs to provide a sustainable solution for water treatment applications. Following regeneration, CNCs may undergo re-functionalization to restore their adsorption capacity [238]. This re-functionalization ensures that the CNCs maintain high performance for subsequent cycles. The regenerated CNCs are then reused in water treatment, maintaining their effectiveness without the requirement for additional raw materials, and the related-study has exhibited the effective absorption of corncob-CNCs by employing the ingenious adsorbents [240]. This cycle can continue through multiple iterations until the CNCs reach the end of their usable life. At this point, they can either be safely biodegraded or transformed into other materials, such as CNCs-based composites, for alternative applications.

6.5. CNCs with global standards for wastewater treatment efficiency

CNCs have emerged as an innovative solution for wastewater treatment, demonstrating remarkable efficiency and sustainability. To ensure their widespread adoption, it is essential to evaluate their performance against global standards and benchmarks established by regulatory bodies like the Environmental Protection Agency (EPA), World Health Organization (WHO), and the European Union [143]. These standards outline critical parameters, such as pollutant removal efficiency, chemical and biological oxygen demand (COD and BOD), and pathogen reduction, which serve as the foundation for assessing the efficacy of wastewater treatment technologies.

6.5.1. Key benchmarks in wastewater treatment

Global wastewater treatment standards prioritize the reduction of pollutants to acceptable levels. The EPA recommends COD levels in treated water to be below 250 mg/L for safe discharge, while BOD levels should not exceed 50 mg/L [241]. Similarly, heavy metal concentrations such as lead, cadmium, and chromium must be reduced to below 0.01 mg/L, 0.003 mg/L, and 0.1 mg/L, respectively [188]. Effective disinfection is also essential, with WHO guidelines requiring microbial load reductions of at least 99.99 % for pathogens like *E. coli* and *Salmonella* [242]. These benchmarks not only safeguard public health but also promote sustainable water management practices. Moreover, the

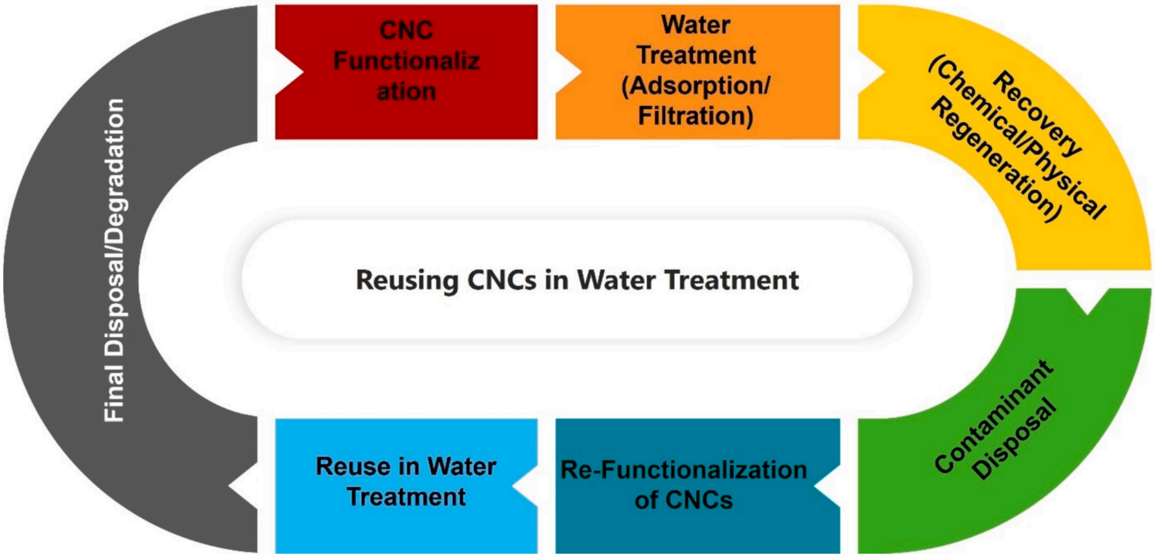

Fig. 13. Cycle illustrates the reusing CNCs in water treatment.

United Nations Sustainable Development Goal (SDG) 6.3 aims to enhance the water quality by reducing pollution and substantially raising the recycling and safe reuse of wastewater by 2030 [243].

6.5.2. *CNCs' performance against global benchmarks*

Sustainable CNCs excel in addressing the key-metrics outlined by global standards [244]. Studies have shown that CNCs functionalized with carboxyl or sulfate groups can adsorb up to 98 % of heavy metals including, lead and cadmium at concentrations of 20–50 mg/L [196]. In Table 7, the performance of the CNCs is illustrated with global benchmark. In dye removal applications, CNCs modified with cationic surfactants have demonstrated efficiencies of over 95 % for methylene blue and reactive black 5 dyes at initial concentrations of 50–100 mg/L [188].

Furthermore, CNC-based treatments have achieved COD and BOD reductions of 85–90 %, often surpassing the limits set by EPA and WHO for treated wastewater [231].These results highlight the potential of CNCs to outperform conventional adsorbents like activated carbon, which typically achieve 60–80 % pollutant removal under similar conditions.

6.5.3. *ASTM and ISO standards relevant to CNCs*

CNCs are increasingly recognized for their potential in wastewater treatment, and several international standards ensure their safe and effective application. One of the key standards is ISO 1762:2019, which provides guidelines for characterizing cellulose nanomaterials, including CNCs [246]. This standard focuses on essential sampling and testing methods that are crucial for evaluating the performance of CNCs in various applications, including wastewater treatment.

Another relevant standard is ISO 21400:2018, which specifies procedures for the laboratory determination of total elemental sulfur and sulfate half-ester content in CNCs [247]. Understanding these characteristics is vital, as they influence the behavior of CNCs in aqueous environments and impact their effectiveness in pollutant removal. Additionally, ISO/TS 23151:2021 describes methods for measuring particle size distributions of CNCs using techniques such as atomic force microscopy and transmission electron microscopy. Another study by Srivastava et al. (2024) have analysed the distinct fabrication approaches, resolving the ecological implications and diverse multifaceted applications of the plant-wastes-based NCs [248]. Accurate characterization of particle size is critical for understanding the adsorption properties of CNCs in wastewater treatment applications.

The ISO/TR 19716:2016 technical report reviews commonly used methods for characterizing CNCs, including sample preparation and measurement techniques. This report serves as a guide for researchers and practitioners to ensure consistency and reliability in CNCs characterization.

Table 7
Global wastewater treatment benchmarks vs CNCs' performance [245].

Pollutants	Global Benchmark	CNCs Performance	Removal Efficiency
COD	≤ 250 mg/L (EPA)	85–90 % reduction	85–90 %
BOD	≤ 50 mg/L (EPA)	85–90 % reduction	85–90 %
Lead (Pb)	≤ 0.01 mg/L (EPA)	98 % removal at 20–50 mg/L	98 %
Cadmium (Cd)	≤ 0.003 mg/L (EPA)	98 % removal at 20–50 mg/L	98 %
Chromium (Cr)	≤ 0.1 mg/L (EPA)	Not specified, but similar removal as Pb and Cd	~98 %
Microbial Load (*E. coli* & Salmonella)	≥ 99.99 % reduction (WHO)	Not specified for CNCs directly, but typically ≥99.99 %	~99.99 %
Dye Removal (Methylene Blue & Reactive Black 5)	Not a standard but relevant for industries	95 % removal at 50–100 mg/L	>95 %

On the ASTM side, ASTM D5907 provides a framework for assessing materials by broadly covering the, "microbial fuel cells", used in water treatment processes [249]. While it does not specifically address CNCs, it can be adapted to evaluate the performance of CNC-based systems in effectively removing contaminants. Furthermore, ASTM E2876 addresses the environmental health and safety aspects of nanomaterials, ensuring that applications involving CNCs comply with stringent safety regulations [250]. This standard is essential for promoting safe practices in the use of nanomaterials within wastewater treatment contexts.

6.5.4. *Challenges and opportunities*

While CNCs hold significant promise, certain challenges must be addressed to unlock their full potential. For instance, surface modifications, such as oxidation or polymerization, are often required to enhance their adsorption and coagulation properties [143]. Research shows that CNCs modified with TEMPO-oxidation exhibit adsorption capacities of up to 250 mg/g for copper ions, compared to 80–120 mg/g for unmodified CNCs. However, scaling up these modifications while maintaining cost-effectiveness remains a challenge [251]. Regulatory acceptance also remains critical, as guidelines for nanomaterial-based wastewater treatment technologies are not yet universally established. Nonetheless, ongoing research into the synthesis and functionalization of CNCs presents opportunities for innovation, enabling them to meet evolving global standards and address emerging contaminants like microplastics and pharmaceutical residues.

7. Future trends and research directions

The future of CNC-based water treatment technologies lies in overcoming current limitations while broadening their applicability and efficiency. One of the primary challenges is the scalable production of CNCs, which remains constrained by high costs and energy-intensive processes. To address this, future research must focus on developing cost-effective and eco-friendly extraction techniques, particularly using waste-derived lignocellulosic biomass like rice husk. Enzymatic treatments and green solvent methods offer promising pathways to minimize environmental impact while enhancing CNCs yield and quality. Additionally, integrating CNCs production with automated processing systems and circular economy models can facilitate large-scale implementation. Optimizing CNCs production processes is crucial to ensure consistent quality and functionalization at an industrial scale, which will facilitate their broader application. Another crucial direction is the development of multifunctional CNCs composites with enhanced adsorption, catalytic, and antimicrobial properties. By incorporating nanoparticles, enzymes, and other active agents, CNC-based hybrid materials can address diverse challenges in water treatment. For instance, integrating CNCs with metal-organic frameworks (MOFs) or carbon nanotubes could provide dual functionalities such as pollutant adsorption and photodegradation. Similarly, future efforts should emphasize combining CNCs with existing technologies like ultrafiltration and nanofiltration membranes, where CNCs can enhance selectivity and reduce fouling. CNCs supported electrochemical systems also hold potential for addressing persistent pollutants in wastewater streams, and research must ensure their operational stability and energy efficiency.

To improve the economic viability of CNC-based systems, regeneration and reusability must be prioritized. Current research should focus on designing CNCs materials capable of withstanding harsh regeneration conditions, such as thermal, chemical, or mechanical treatments, while maintaining high performance across multiple cycles. Environmental and toxicological studies are equally important to ensure the safe and sustainable use of CNCs. Despite their renewable origin, CNCs must be assessed for their potential ecological impact, particularly in aquatic environments. Life cycle assessments (LCA) will help quantify their environmental benefits compared to conventional materials. Expanding the scope of biomass sources for CNCs production is another promising avenue. While rice husk is a widely studied feedstock, other agricultural residues such as wheat straw, corn stalks, and sugarcane bagasse offer immense potential. Diversifying biomass sources can mitigate supply chain constraints and enable region-specific solutions.

8. Conclusions

This review highlights the transformative potential of rice residue-derived CNCs in wastewater treatment applications. The unique properties of CNCs, such as their high surface area, abundant functional groups, and biodegradability, position them as a promising material for addressing global water contamination challenges. Through their application in adsorption, catalytic degradation, and antimicrobial treatments, CNCs demonstrate versatility in removing a wide range of contaminants, including heavy metals, organic pollutants, and pathogens. Moreover, their derivation from agricultural waste such as rice husk and straw align with principles of sustainability and waste valorization, offering a dual benefit of environmental remediation and resource efficiency. The comparative advantages of CNCs over conventional materials, such as their renewable origin, customizable surface functionalities, and eco-friendly nature, make them an attractive alternative for water purification systems. However, the review also underscores critical challenges, including the scalability of CNCs production, the regeneration of CNC-based systems, and their performance in complex wastewater matrices containing diverse contaminants. Addressing these limitations requires a comprehensive approach that integrates advanced functionalization techniques, rigorous performance testing, and lifecycle analysis to ensure both efficiency and environmental compatibility. Overall, rice residue-derived CNCs offer a sustainable pathway to enhance wastewater treatment technologies, addressing the dual imperatives of water quality improvement and agricultural waste management attempt to achieve the sustainable development goal “responsible consumption and production” (Goal 12) along with Goal 6 (Clean Water and Sanitation). By leveraging their inherent properties and focusing on overcoming existing limitations, CNCs can emerge as a cornerstone in the development of innovative, sustainable water treatment systems. This work emphasizes the urgent need for interdisciplinary collaboration and further research to unlock the full potential of these remarkable materials in real-world applications.

CRediT authorship contribution statement

Bhupinder Singh: Conceptualization. **Ravinder Kumar:** Conceptualization. **Shubham Sharma:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **T. Ramachandran:** Conceptualization. **V.K. Bupesh Raja:** Conceptualization. **Abinash Mahapatro:** Conceptualization. **Deepak Gupta:** Writing – review & editing. **Ankit Kedia:** Writing – review & editing. **A. I. Ismail:** Writing – review & editing. **Abhinav Kumar:** Writing – review & editing.

Consent to participate

Not applicable.

Consent to publish

All authors have read and approved this manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available within the manuscript or from the main corresponding author (Bhupinder Singh and Ravinder Kumar) who are primarily responsible for the thorough analysis, characterization testing, and experimentations. As all the characterizations, analysis, testing’s related work and testing’s have solely been responsible by Bhupinder Singh and Ravinder Kumar. Additionally, the raw data can be obtained on request from the corresponding author, Bhupinder Singh and Ravinder Kumar.

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