Vietnam Journal of Science and Technology ***62*** *(5) (2024) 836-858*

doi:10.15625/2525-2518/20843

Copper oxide/biopolymer nanocomposites: synthesis and applications, a comprehensive review

Rajdeep Malik, Nazreen*, Jagram Meena*

Department of Chemistry, Gurukula Kangri (deemed to be) University Haridwar India, 249404, India

*Emails: *1. naazreenali2@gmail.com*, *2. jagram.meena@gkv.ac.in*

Received: 25 May 2024; Accepted for publication: 30 August 2024

Abstract. Copper oxide (CuO) particles have a significant role in various fields due to their many properties like special shape, size, and high surface area. Thanks to their rarity and unique characteristics, such as their large surface area, paramagnetic nature, and ease of separation, CuO nanoparticles (NPs) have received the greatest attention. Chitosan, guar gum, tamarind, alginate, starch, cellulose, polysaccharide, etc. are examples of natural biopolymers that have proven to be excellent hosts for creating CuO nanoparticles. Long-established fabrication techniques for biopolymer-based CuO nanocomposites include co-precipitations, green synthesis, solvent casting method, Alco thermal method, and sol-gel method. Excellent biological characteristics of biopolymer/CuO nanocomposites include their potent antibacterial activity against a variety of diseases as well as bacteria that are resistant to antibiotics. These characteristics have sparked the creation of numerous strategies with direct biological applications, including customized surfaces with antimicrobial effects, wound dressings, and modified textiles. This study aims to provide a comprehensive overview of the very first biopolymer CuO NPs reported within the last ten years as well as its appealing methodology in diverse applications.

Keywords: copper oxide nanocomposites, biopolymers, carboxymethyl tamarind kernel gum, green synthesis.

Classification numbers: 2.9.3, 2.9.4, 2.7.2.

1. INTRODUCTION

Different types of microorganisms that microbially pollute the air, water, and soil cause problems for the living environment and are severe problems in the field of health care. Interesting alternative microbial agents, such as tiny antibiotics, cationic polymers, metal NPs, and antimicrobial peptides, have emerged due to the growth of antibiotic-resistant diseases [1]. CuO is a p-type, narrow bandgap transistor that belongs to the transition metal oxide group. It has a crystalline nature and numerous unique properties: Super thermal resistance, luminous characteristics, and great stability are all features of this material as well as antibacterial properties. CuO is widely employed in a variety of technical domains because of its unique features, including electro catalyst, biosensor, high efficiency, heat conductive materials, magnetic recording media with high selectivity, and photovoltaic applications [2]. When compared to organic antimicrobial agents, the CuO NPs are more stable, stronger, and have a longer shelf life [3]. The discovery of new antimicrobial drugs has been triggered by the well-known concern of harmful bacteria becoming resistant to the multidrug population. In this regard, nano-Ag has undergone extensive research and is presently used in a variety of consumer and medical applications [4]. The CuO is more affordable than silver, simple to bind with polymer, and has generally stable physical and chemical characteristics due to its ability to be generated with exceptionally high surface areas and unique crystalmorphologies. Highly nanoparticulate metal oxide such as CuO may be particularly useful antibacterial agents [5]. The potential application of CuO NPs in the medical field such as therapy for cancer [6], targeted drug carrier [7], wound dressing [8], and antibacterial activity [9] has recently attracted a lot of interest.

Biopolymers are naturally plentiful and environmentally acceptable polymer alternatives that are employed in medical, agriculture, environmental, and medical industries due to their particularly renewable, nontoxic, and sustainable features as compared to hydrocarbon polymer [10, 111]. In the last few years, researchers have been interested in biopolymer/CuO nanocomposite research areas such as guar gum, tamarind gum, starch, cellulose, alginate, pectin, polysaccharide, chitosan dextran, polyacrylic acid (PAA), gelatin, etc. [11 - 21].

The biopolymer/CuO nanocomposite has been created utilizing a variety of techniques including the solution casting method [22], thermal method [23], co-precipitation method [24], sol-gel method [25], microwave irradiation method [26], also green synthesis [27] and one-pot synthesis [28]. Natural biopolymer is mixed into NPs to enhance their application in areas like adsorbent activity [29], antifungal activity [30], anti-cancer activity [31], antioxidant activity [32], drug delivery carrier [33], and antibacterial activity [110].

This review is based on the preparation of CuO nanocomposite with different biopolymers such as chitosan, guar - gum, carboxymethyl cellulose, alginate, graphene oxide, carboxymethyl starch, etc. by traditional methods and their applications in various fields.

Table 1. Literature data of biopolymers/CuO nanocomposites.

Biopolymer	**NP**	**Method**	**Size**	**Applications**	**Reference**
Chitosan	CuO	Precipitation method	20 - 100 nm	Cytotoxic, antibacterial and antioxidant activity	[34]
Chitosan	CuO	Sodium tripolyphosphate as a cross linker	10 - 25 nm	Antibacterial activity	[35]
Chitosan	CuO	Co-precipitation method	35 - 40 nm	Drug delivery	[24]
Chitosan	CuO	Facile synthesis	40 nm	Antibacterial activity	[35]
Chitosan	CuO	Green synthesis	51 - 62 nm	Antibacterial activity	[27]
Alginate	CuO	Tugachi method	--	Antibacterial activity	[36]
Guar Gum	CuO	Sol-gel method	20 - 50 nm	Organic pollutant removal	[25]
Cellulose	CuO	*In situ* method	50 - 100 nm	Food packaging	[37]
Cellulose	CuO	Green synthesis	300 nm	--	[26]
Cellulose	CuO	*In situ* method	50 - 200 nm	Antibacterial activity	[38]

Starch	CuO	Solution casting method	30 - 50 nm	Antibacterial, antioxidants and wound healing activity	[32]
Starch	CuO	*In situ* method	30 - 40 nm	Antibacterial and colon-specific naproxen delivery	[39]
Starch and Polyurethane	CuO	Thermal degradation method	50 - 200 nm	Antibacterial activity	[40]
Starch	CuO	Solution casting method	--	Humidity sensor	[22]
Starch	CuO+ZnO	Solution casing method	--	Food-packaging applications	[41]
Carboxymethyl cellulose	CuO	*In situ* method	40 - 75 nm	Antibacterial activity	[28]
Graphene Oxide	CuO	Hydrothermal method	25 nm	Biosensors	[42]
PVA	CuO	Solution casting method	80 - 120 nm	Electric application	[43]
Dextran	CuO	Green synthesis	12 nm	--	[44]

Table 1 shows different biopolymers such as chitosan, alginate, guar gum, starch, dextran, carboxymethyl cellulose, etc. that have been mixed with CuO NPs using diverse synthetic techniques. Advanced techniques such as green synthesis, in situ, co-precipitation, microwave-assisted, aerothermal, solution casting, and thermal degradation methods have been used to develop the form and size of biopolymer/CuO-based nanocomposites. In this article, we go through the various synthetic approaches that can be utilized to create biopolymer/CuO using a variety of methods. Some synthetic methods of biopolymer/CuO nanocomposite are discussed in detail below.

The biopolymer/CuO nanocomposite exhibits significant quality due to its enhanced properties. Figure 1 demonstrates the thermal stability and mechanical strength of this composite material indicating its potential use in various industrial applications.

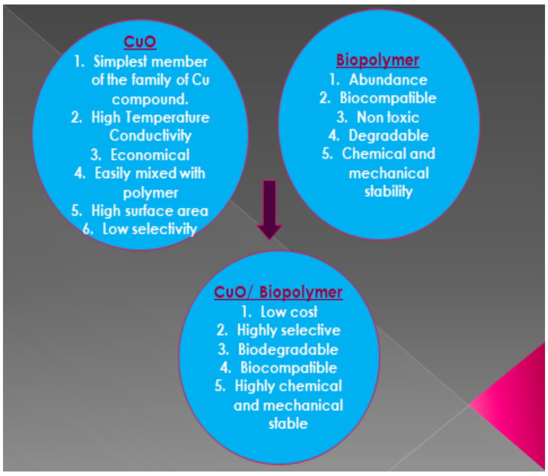
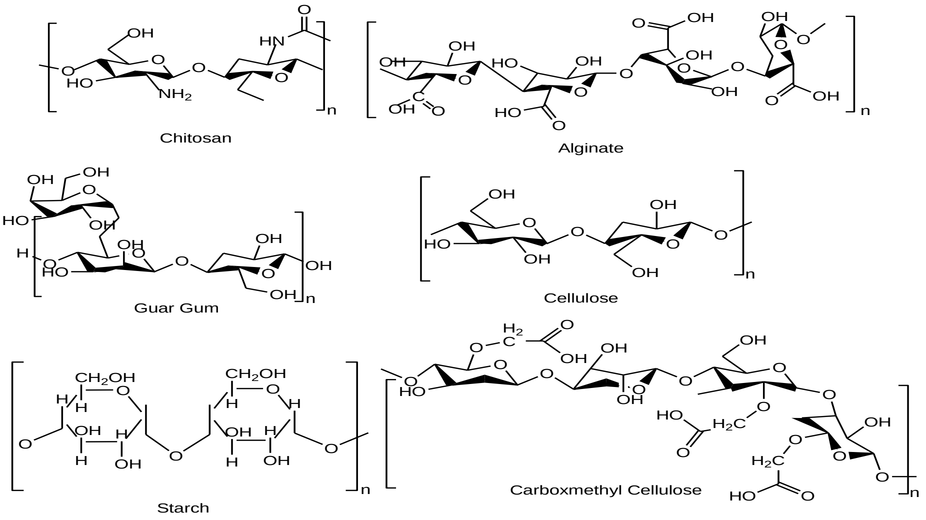


Figure 1. Properties of copper oxide/biopolymer nanocomposites.

The biopolymer structure used in this review is detailed in Scheme 1. This schematic representation helps to understand the molecular configuration and functional groups available for interaction.



Scheme 1. Structure of biopolymers used in this literature review.

2. SYNTHESIS OF BIOPOLYMERS/CuO NANOCOMPOSITES

For the production and stability of biopolymers/CuO composites, researchers have used friendly, non-toxic synthetic materials.

Figure 2 shows some common methods for the synthesis of biopolymer/CuO nanocomposites including *in-situ,* co-precipitation, sonochemical method, etc.

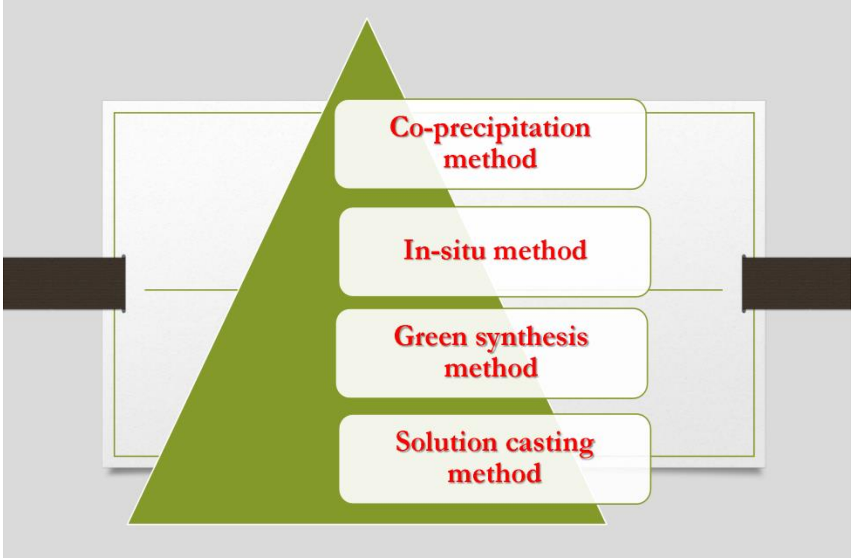


Figure 2. Some common methods for the synthesis of biopolymer/CuO nanocomposites.

2.1. Co-precipitation method

Co-precipitation is a very useful method for synthesizing biopolymer/CuO nanocomposites [102]. Copper acetate monohydrate (0.2 M, 600 mL) and sodium hydroxide (6 M, 30 mL) solutions were prepared separately in distilled water for the synthesis of CuO nanoparticles. At 100 ^{o}C with constant stirring, glacial acetic acid (2 mL) was dissolved in copper acetate monohydrate solution. At 100 ^{o}C, sodium hydroxide solution was then gradually added to the previously created solution in a dropwise fashion until a clear black colour was obtained. The precipitate was gathered, washed three times with ethanol and distilled water, dried in an oven at 100 ^{o}C, then ground into a fine powder. CuO NPs were obtained by calcining the powder at 500 ^{o}C for 4 hours. NPs of different sizes have been prepared with a notable speed employing organic compounds as stabilizing and reducing agents. These organic compounds include polyvinyl alcohol (PVA), polyethene glycol, and citric acid which effectively control the growth and prevent agglomeration of NPs. Other biopolymers that have stabilized CuO NPs include chitosan, starch, guar gum, alginate, etc. demonstrating the versatility and effectiveness of these organic compounds in nanoparticle synthesis [1, 34, 45].

2.2. Green synthesis method

The green synthesis method is an economical, environmentally beneficial, and energy-efficient way to create nanoparticles. The term green synthesis of nanomaterials refers to the formation of NPs using natural sources such as microorganisms, plant residue, crop residue, etc. Researchers are looking at using microbes, plant extracts, and other biomaterials as synthesis processes for metal NPs since there is an increasing demand to create "green" and cost-effective processes. The probability of pollutants is significantly reduced when natural bioactive substances are used to create metal nanoparticles. Different sizes of NPs were obtained when different biopolymers were mixed with CuO. Sysame *et al*. [27] prepared CuO/chitosan with an average size of 51 - 62 nm by green synthesis method. Crystals of CuO/biopolymers of different sizes and forms can be produced depending on the process parameters and the materials utilized [46 - 47].

2.3. *in situ* method

The enormous variety of functionalized biopolymers currently available and the various categories of NPs that may be created have combined to enhance the number of biopolymers that can now be made. Functional polymers, origins, interactions, the reaction that creates nanoparticles, and the structure of CuO NPs are the variables that influence how biopolymers behave. Biopolymers operate as a nonreactor in the process and offer a constrained intermediate for the synthesis of nanocomposite. They also isolate and stabilize the generated NPs to prevent their accumulation. Numerous biopolymer and CuO NPs have been synthesized and stabilized using *in situ* techniques such as the usage of chitosan, starch, and sodium tripolyphosphate as cross-linking agents [37, 39, 48].

2.4 Solution casting method

The most common process for creating composites remains solution casting, especially in small-scale lab settings. In the solvent casting method, prepolymer and polymer are combined and dissolved in an appropriate solution. The NPs dispersed in the same solution or a separate solution, but the polymer, which was the matrix phase, is completely soluble in the solution. NPs of variable size have been synthesized using different polymers. Starch-based CuO (20 - 30 nm), and carboxymethyl CuO (30 - 50 nm) sized NPs were obtained using solution casting method [32, 41].

3. COPPER OXIDE/BIOPOLYMER NANOCOMPOSITE APPLICATIONS

Generally, CuO is used in the medical field due to its antimicrobial, antifungal, and anticancer activity. Because of their remarkable chemical, physical and biological properties, biopolymer-based CuO NPs have been extensively applied in several technical fields instead of other ions. On combining CuO nanoparticles with biopolymer, biopolymer/CuO composite offers a distinct advantage over simple CuO nanoparticles. These polymer matrices not only enhance the dispersion of CuO nanoparticles but also contribute to their biocompatibility and biodegradability which makes the composite suitable for biomedical applications such as drug delivery systems and biosensors where control of release and toxicity is crucial. Many biopolymers such as chitosan/CuO, starch/CuO, alginate/CuO, etc. are widely used in various applications such as antibacterial agents [103], antimicrobial agents [104 - 105], food packaging [106], metal removal from wastewater [107], etc. Figure 3 differentiates the applications of biopolymer/CuO nanocomposites.

Figure 3. Various applications of copper oxide/biopolymer nanocomposites.

3.1. Applications of biopolymer/CuO nanocomposite to remove heavy metals from wastewater

Human depends on water resources for their health, cleanliness, food, energy, and economies among other necessities. Water resources are also essential for the survival and existence of the human population. Chemicals, detergents, fertilizers, pesticides, heavy metals, textile dyes, etc. are constantly released into the environment, contaminating the water. The popularity of biopolymer-based composites has increased, and they offer numerous benefits over conventional adsorbents due to their affordability, environmental-friendliness, and ease of availability [49 - 52]. Generally, for the adsorption and removal of metals, a large number of biopolymers such as chitosan, alginate, cellulose, etc. play a significant role [53, 57, 61]. Table 2 shows the removal of metals by different biopolymers/CuO nanocomposites with different adsorption capacities.

Table 2. Literature data on removing metal from wastewater by biopolymer/CuO nanocomposites.

Biopolymer/CuO	Removing metal	Maximum adsorption capacity (Qmax) mg/g	Reference
Chitosan/PVA/CuO	Pb (II)	6.8 mg/g	[53]
Hydroxyethyl cellulose/CuO	Cr (VI)	--	[54]
Chitosan/$Cu(OH)_2$	As (V)	39.0 mg/g	[55]
Chitosan /$Cu(OH)_2$	Cr (VI)	1.42 m mol/g	[56]
Hydroxyethyl cellulose/CuO	Pb (II)	--	[54]
Chitosan/CuO	As (V)	28.1 mg/g	[55]
Chitosan/CuO	Cr (VI)	2.62 mg/g	[54]
Alginate/CuO	Pb (II)	118.40 mg/g	[57]
Calcium alginate/CuO	Cr (VI)	--	[58]
Sodium alginate/CuO	Zr (IV)	28.73 mg/g	[59]
Sodium alginate/CuO	Co (II)	3.70 mg/g	[59]
Sodium alginate/CuO	Pb (II)	55.24 mg/g	[59]
Sodium alginate/CuO	U (VI)	24.44 mg/g	[59]
FeOOH/Water bamboo cellulose (WBC)/CuO	As (III)	76.1 mg/g	[60]
Cellulose/CuO	Pb (II)	150.14 mg/g	[61]

Chitosan-based CuO and $Cu(OH)_2$ sorbents were prepared by co-precipitation method in an alkaline solution of copper chloride ($CuCl_2$). The alkalization regulates the kind of CuO deposited in the polymer particle framework. These sorbents were effective for the adsorption of As(V). The effective adsorption of As(V) was calculated at equilibrium at pH around 6. Anions and the anionic charge of the sorbents are involved in the sorption mechanism, which is related to an anion transfer mechanism (which is confirmed by pH_{pzc} of the chitosan-based CuO biocomposite). At 20 ^{o}C and an equilibrium pH between 5 and 6, the highest capacities for chitosan/$Cu(OH)_2$ and chitosan/CuO were obtained at 39.0 and 28.1 mg g^{-1}, respectively. The process of sorption was endothermic [55]. An easy and efficient approach for the creation of a highly porous adsorbent is to encapsulate CuO NPs in the sodium alginate matrix and then perform high-temperature thermal oxidation. The conclusion of the experiment shows that nanostructured CuO granules may be utilized for water and wastewater treatment because they are a powerful adsorbent for the removal of Pb(II), Zr(IV), U(VI), and Co(II) from aqueous solutions [59]. The synthetic FeOOH/CuO @WBC exhibited strong As(III) removal capabilities, and the highest adsorption capacity was achieved when the pH was raised to 3.5 at room temperature. The utility of the materials in the experimental application is improved by the renewability of FeOOH/CuO @WBC for the adsorption of As(III) and the percentage removal can still be as high as 50 % after the recycling [60].

3.2. Biopolymer/CuO nanocomposites for organic impurities/dye removal

In today’s material removal industries and technologies, organic impurities and dyes have received substantial consideration and utilization. As a result of the development of robust, poisonous, cancer-causing, non-biodegradable, and mutagenic species, they contribute to several environmental issues. Because of their complicated aromatic structures, organic dyes are highly stable and can appear cationic, anionic, or non-ionic. Recently, developed economical, nontoxic, cost-effective, and productive tiny materials have attracted interest in many scientific fields including water treatment. Pollutants in wastewater can be removed very effectively using adsorbent-based nano-scale materials. Due to their special properties such as increased adsorption efficiency, biocompatibility, cost-effectiveness and promising outcomes in wastewater treatment, eco-friendly polymeric materials have been developed quickly for various applications [62 - 65].

Table 3 displays the applications of CuO-incorporated biopolymer nanocomposite with maximum adsorption capacity (Qmax) in mg g^{-1}.

Table 3. Applications of biopolymer/CuO nanocomposites for organic impurity removal.

Biopolymer/ Metal	Organic impurity/dye removal	Maximum adsorption capacity (Qmax) mg g^{-1}	Reference
Chitosan/carboxymethyl cellulose/CuO	Methyl orange dye	--	[64]
Carboxymethyl cellulose/guar gum/CuO	Malachite green	18.5 mg/g	[29]
Chitosan/CMC/CuO	Eosin yellowish dye	--	[64]
Chitosan/CuO	Congo red	119.70 mg/g	[66]
Chitosan/CuO	Erichrome black t	235.70 mg/g	[66]
Chitosan/PVA/CuO	Acid blue 25	171.4 mg/g	[67]
Chitosan/CuO	Indigo carmine	--	[68]
Chitosan/CuO	Congo red	--	[68]
Chitosan/CuO	Methyl orange	--	[68]
Poly AMPA/chitosan/CuO	Doxycycline	203.94 mg/g	[69]
Alginate/Fe_3O_4/CuO	Oxytetracycline	--	[70]
CMC/NiO_2/CuO	Eosin yellowish	--	[71]
Cellulose/CuO	4- Nitro phenol	--	[72]

CMC - Carboxy methylcellulose; PVA - Polyvinyl alcohol; Poly AMPA - Poly(2-acrylamide-2-methyl-1-propane sulfonic acid).

For the effective removal of acid blue 25 (AB 25) from the aqueous system an easy, economical, and safe chitosan-PVA@CuO composite was created. In the synthesized chitosan-PVA@CuO composite, the CuO nanocomposite was significantly dispersed throughout the organic matrix. With a high adsorption capacity of 171.4 mg/g, the chitosan-PVA@CuO has proven to be a successful adsorbent for the quick removal of AB 25. The elimination capacity of the chitosan-PVA@CuO composite also shows a significant temperature-dependent and spontaneous rise, according to the thermodynamic constants $\Delta G°$, $\Delta H°$, and $\Delta S°$ [67]. CuO@poly(AMPA)/chitosan, a novel adsorbent, was created to remove doxycycline (DXN) from an aqueous solution. The optimal conditions (at 203 K) for DXN removal utilizing CuO@poly(AMPA)/chitosan were evaluated via response surface methodology (RSM). The maximum removal efficiency and maximum adsorption capacity for DXN were determined to be 98.89 % and 203.94 gm/g, respectively. The kinetic and isotherm studies showed that the adsorption of DXN from aqueous solution was best characterized by the pseudo-second-order kinetic model with $R^2 > 0.9875$ and the Langmuir adsorption isotherm model with $R^2 > 0.99$ [69]. Alginate beads often contain Ba^{2+} or Ca^{2+} ions as cross-linkers to provide structural stability. Over repeated use, these cross-linking ions can be released into the solution, leading to an increase in the pore size within the alginate matrix. After employing the alginate beads multiple times and releasing Ba^{2+} into the solution, CuO-Fe_3O_4-Fe^0/alginate reactivity was improved. The addition of Fe^0 to the alginate, which was then coated with CuO-Fe_3O_4, improved the cycling performance. After the third recycling, the deterioration efficiency reached nearly 100 %. The efficiency of the degrading process was significantly increased by the use of photo-fenton [70].

3.3. Antibacterial, antioxidant, and anticancer applications of biopolymer/CuO nanocomposites

Public health worldwide is seriously threatened by the spread of infectious illnesses in general, particularly by the rise of bacterial strains that are resistant to antibiotics. In general, it is believed that both Gram-positive and Gram-negative bacterial strains pose a serious threat to public health [73]. It is commonly known that copper is very cytotoxic to bacteria (*P. aeruginosa*, *E.coli*, and *S. aureus*) making it a useful antibacterial agent that can be utilized in water treatment and food packaging [27]. CuO shows great antibacterial and antimicrobial properties against both gram-negative and gram-positive bacterial strains. When CuO NPs were incorporated with a biopolymer matrix, both their antibacterial and antimicrobial activities against gram-negative and gram-positive bacteria were enhanced.

Table 4 shows the antibacterial and antimicrobial applications of CuO incorporated with different biopolymers.

Table 4. Antibacterial, antimicrobial, and anti-cancerous applications of biopolymer/CuO nanocomposites.

Biopolymer/metal	Function of activity	Reference
Chitosan/carboxy methyl/CuO	Antibacterial activity against *S. aureus* and *E. coli*	[74]
Chitosan/CuO	Antibacterial activity against Gram-positive: (i) *streptococcus pneumonia* (ii) *staphylococcus epidermidis* Gram-negative: (i) *E. coli* (ii) *proteus mirabilis*	[75]
Alginate/CuO	Antibacterial activity against (i) *pseudomonas auriginosa* (ii) *staphylococcus aureus* (iii) *streptococcus pyogenes* (iv) *staphylococcus epidermidis*	[76]
Polyethyleneterepthalate/alginate/CuO	Antibacterial activity against Gram-positive: (i) *S. aureus* (ii) *C. calbicans* Gram-negative*: E. coli*	[77]
Starch/CuO	Antibacterial activity against (i) *Bacillus aureus* (ii) *Shigella sonnei* (iii) *Straptophylococcus epidermidis* (iv) *Enterococcus* (v) *pseudomonas aeruginosa* POA_1 (vi) *E. coli*	[78]

Polyurethane/starch/CuO	Antibacterial activity against *S. aureus*	[79]
Cellulose/CuO	Antibacterial activity against Gram-positive: *pneumonia* Gram-negative: *pseudomonas*	[80]
Cellulose/graphene oxide/CuO	Antibacterial activity against	[81]
Peroxidase/CuO	Antibacterial activity against *E. coli*	[82]
Gum acacia/Ni/CuO	Antibacterial activity (i) *Enterobacter* (ii) *Klebsiella* (iii) *pneumonia* (iv) *pseudomonas aeruginosa* (v) *staphylococcus aureus*	[83]
Polyvinyl alcohol/gelatin/CuO	Antimicrobial activity	[84]
Chitosan/CuO	Antibacterial activity Gram-positive i) *S.aureus* ii) *S. pyogenes* Gram-negative i) *E.coli* ii) *K.aerogenes* anti-cancerous activity against human breast cancer (MCF-7) cell line	[34]
Starch/CuO	Anti-cancerous activity against MCF-7 cells	[78]

Using the colony farming unit (CFU) technique, the in-vitro antibacterial properties of both carboxymethyl chitosan/CuO nanocomposite biopolymers and pure carboxymethyl chitosan biopolymers against gram-negative and gram-positive *E. coli* and *S. aureus* were investigated, respectively. Pure carboxymethyl chitosan biopolymer showed poor antibacterial effect against both types of bacteria, while good antibacterial activity was demonstrated by biopolymer incorporating CuO nanoparticles [74]. Chitosan is not as thermally stable as chitosan-CuO-neem seed (NS) nanocomposite. The chitosan-CuO-NS showed cytotoxicity against the MCF-7 cell line and good antibacterial activity against gram-negative and gram-positive bacterial pathogens. It also showed antioxidant activity utilizing DPPH and 2,2-azino-bis-3ethylbenzothiazoline-6-sulphonic acid (ABTS) radical scavenging tests [34].

3.4. Biomedical applications of biopolymer/CuO nanocomposites

Due to their useful applications, nanomaterials have recently received significant attention in the field of biomedicine. Nanoparticle production has important applications in the medical field, including cell imaging, drug delivery, and antibacterial and biosensing [7]. Drugs can be targeted to specific cells fixed to specially designed carriers. Nanoparticles, whose structures are less than 100 nm in one dimension, have recently demonstrated a significant capability as drug carriers. The NPs are advantageous for biomedical use because of their tiny sizes and distinctive physiochemical and biological characteristics (such as an improved reactive area and the capacity to pass cell and tissue barriers) [85 - 86].

Biopolymer/CuO nanocomposites have tremendous promising prospects in biomedical applications, and Table 5 provides an overview of recent advancements.

Table 5. Applications of biopolymer/CuO nanocomposites in the biomedical field.

Biopolymer/Metal	Application	Reference
Chitosan/CuO	Drug delivery (curcumin)	[88]
Carboxymethyl - chitosan - starch/CuO	Drug delivery (amoxicillin)	[89]
Chitosan - PVA - graphene oxide/CuO	Wound healing	[87]
PVA/CuO	Drug delivery (ibuprofen)	[90]
Starch/CuO	Drug delivery	[33]
Oxidized starch/CuO	Colon specific naproxen (npx) delivery	[39]
Carboxymethyl/starch / CuO	Wound healing	[32]
Chitosan/CuO	Anti-proliferative activity against human lung cancer cells A549	[92]
Starch/CuO	Treatment of gastrointestinal system	[92]

Bio-nanocomposites incorporating oxidized starch/CuO, designed to be pH-sensitive and antibacterial, were prepared and investigated for their potential as a drug delivery system targeting bacterial infections in the colon. Drug release was examined at pH 7.4 and total naproxen (NPX) release as a ratio of time was calculated to determine the prepared system capacity to transport NPX to the colon. Zone inhibition and NPX loading capabilities for the developed system were equivalent, superior, compatible, and suitable. It implies that synthetic oxidized starch/CuO bio-nanocomposite may be promising medication delivery technology with built-in antibacterial activity [39]. In comparison to nanocomposites and nanoparticles, the chitosan/PVA/CuO/graphene oxide patch demonstrated strong antibacterial activity against the test bacterium, which is frequently seen in wounds. According to the results of the cell viability experiments, the nanocomposite and CS/PVA/CuO/GO patch exhibited good cell viability and boosted NIH_3t_3 cell proliferation at a concentration of 5 g mL^{-1}. The maximum inhibition control (MIC50) value of the nanocomposite is close to 10 g mL^{-1}. It has stronger antibacterial action at this dose. The increased cell migration supports the possible use of CS/PVA/GO/CuO patch combined with GO/CuO nanocomposite for wound healing applications [87]. By depositing reduced CuO NPs on starch in an alkaline medium, a green method of creating CuO/starch nanocomposite has been developed. The cytotoxic and anticancer effects of the starch/CuO nanocomposite against pancreatic cancer (MIA, AsPC-1, and PaCa-2), gastric cancer (KATO III and AGS), and colon cancer (HCT-8 and HCT-116) were evaluated for biological applications. Cancer line viability decreased in the presence of the starch/CuO nanocomposite depending on the dose. The strongest antioxidant effects against 2,2-diphenyl-1-picrylhydrazyl (DPPH) were demonstrated by the starch/CuO nanocomposite [92]. By using the 3-(4,5-dimethyl thiazolyl-2)-2,5-diphenyltetrazolium bromide (MTT) test, the synthetic chitosan-CuO nanocomposite and rutin were assessed for their ability to inhibit the proliferation of A549 human lung cancer cells.

The antiproliferative effect of rutin and synthesized nanocomposite against a human lung cancer cell line was concentration-dependent [93]. The study demonstrated that as the concentration of CS-CuO nanocomposite increased from 3.1 to 200 g mL^{-1}, there was a significant reduction in the viability of A549 lung cancer cells.

4. CATALYTIC ACTIVITY OF COPPER OXIDE /BIOPOLYMER NANOCOMPOSITES

Since NPs have a high specific surface area ratio, which enhances their selectivity and activity while keeping the fundamental characteristics of a heterogeneous catalyst, nano-catalysis has recently emerged as a viable and affordable alternative to conventional catalysis [94]. Biopolymers support the synthesis of transition metal NPs because they serve as both stabilizing and reducing agents in an alkaline medium [95]. Due to the biodegradability and biocompatibility of biopolymers such as chitosan, guar gum, alginate, cellulose, PVA, etc. the catalytic activity of synthetic metal oxide NPs (such as CuO, Fe_3O_4, TiO_2, etc.) is enhanced. CuO is decorated on the surface of the biopolymer to increase the catalytic activity leading to the creation of an efficient catalyst for a range of chemical processes.

Table 6 shows the overview of the catalytic activity of CuO embedded with various biopolymers.

Table 6. Catalytic activity of biopolymer/CuO nanocomposites.

Biopolymer/Metal	Catalytic species	Reference
Chitosan/CuO	4-nitrophenol to 4-aminophenol	[96]
Tantalum Ta/chitosan/CuO	Methylene blue in the presence of $NaBH_4$	[97]
Chitosan/CuO	1,3,4 hydrazonyl chloride to 1,3,4 trisubstituted pyrazole	[98]
Na-Alginate/CuO	Carboxylic acid to amide	[76]
Agar/CuO	Nitrophenol to aminophenol	[99]
Cellulose/CuO	Catalysis of 4- nitrophenol	[72]
Cellulose acetate/CuO-	Catalysis of 4- nitrophenol	[100]
Chitosan/PVA/CuO	A catalyst for the synthesis of 1,2,3 triazole	[105]

The catalytic activity of tantalum Ta/chitosan/CuO [97] was observed in all media at 4 % Ta/chitosan/CuO. Greater surface areas were associated with the highest catalytic efficiency because they offered a more active site. In an acidic environment, the catalytic efficiency increased due to enhanced adsorption of H^+ions onto the nanorods (NRs) surface. Conversely, under basic conditions, the greater presence of -OH groups promotes the oxidation of reduced products, leading to a reduction in catalytic effectiveness. Biopolymer/CuO exhibits good catalytic activity as compared to single CuO NPs.

5. TOXICITY OF BIOPOLYMER/CuO NANOCOMPOSITE

Chitosan/CuO and alginate/CuO nanocomposites have been investigated for their toxicity effect, particularly concerning their biomedical applications. Chitosan, known for its biocompatibility, can mitigate some of the cytotoxic effects of CuO nanoparticles. However, studies have shown that higher concentrations of CuO in chitosan-based nanocomposites can lead to increased cytotoxicity due to nanoparticle-induced oxidative stress. In contrast, alginate, another biocompatible polymer, has been explored for its ability to stabilize CuO nanoparticles and reduce their cytotoxic potential. Alginate/CuO nanocomposites have shown promise in maintaining low cytotoxicity while retaining antimicrobial efficacy, making them suitable candidates for biomedical applications requiring controlled release and biocompatibility assessments [108 - 109].

6. RESEARCH DIRECTION IN THE COMING TIME

Future aspects of bio-nanocomposites such as chitosan/CuO, alginate/CuO, starch/CuO, cellulose/CuO, graphene oxide/CuO, etc. synthesized by different methods, such as green synthesis, alco-thermal, co-precipitation, in situ methods, hold significant promise across various fields. In the realm of antibacterial applications, these composites can be further optimized for enhanced efficacy and specificity, particularly in targeting drug-resistant bacterial strains. This is crucial for developing next-generation antibiotics and reducing the global burden of infectious diseases. Additionally, the heavy metal removal capabilities of these bio-nanocomposites present an eco-friendly solution for water purification, addressing critical environmental issues related to industrial pollution. Their catalytic activity, especially in organic reactions, can be leveraged to create more efficient and sustainable chemical processes. Advancements in these areas could lead to widespread adoption in environmental remediation, healthcare, and industrial applications, ultimately contributing to improved public health and environmental sustainability. Further research should focus on refining synthesis techniques for better control over particle size and distribution, enhancing the biocompatibility of these composites, and exploring their multifunctional roles in complex real-world scenarios.

7. CONCLUSIONS

In summary, CuO NPs have been extensively explored and are attracting a great deal of interest from material researchers and technologists today, due to their unique features and possible usage in a variety of industries. The incorporation of CuO NPs into natural biopolymers such as chitosan, guar gum, tamarind, alginate, starch, and cellulose, has led to the development of biopolymer/CuO nanocomposite with enhanced biological and antimicrobial properties. These nanocomposites have shown great potential in diverse applications including antimicrobial, wound dressing, organic impurity removal, and heavy metal removal from wastewater. Various synthesis methods, including co-precipitation, green synthesis, solvent casting method, and *in situ* methods have been employed to create nanocomposite. Over the past decade, research has demonstrated the significant potential of biopolymer/CuO nanocomposite in medical, environmental, and industrial applications. This review provides a comprehensive overview of the synthesis methods and applications of biopolymer/CuO nanocomposite highlighting their advantages and potential features developments. Researchers interested in the usage of CuO NPs supported by biopolymers will find this review to be helpful.

List of abbreviation

CuO - Copper oxide
NPs - Nanoparticles
PAA - Polyacrylic acid
Qmax - Maximum adsorption capacity
CMC - Carboxymethyl cellulose
Poly AMPA - Poly(2-acrylamide-2-1-methyl-1-propane sulfuric acid)
DXN - Doxycycline
RSM - Response surface methodology
CFU - Colony farming unit
DPPH - 2,2 diphenyl-1-picrylhydrazyl
ABTS - 2,2 azino-bis 3-ethyl benzoline-6-sulfonic acid
NPX - Naproxen

Acknowledgements. We would like to thank the Department of Chemistry, Gurukula Kangri (deemed to be University) Haridwar for providing us research facilities.

Credit authorship contribution statement. **Rajdeep Malik**: Formal analysis and Supervision. **Nazreen**: Writing - Original Draft, Formal analysis, Correspondence, Writing and Editing. **Jagram Meena**: Investigation, Review and Editing, Correspondence.

Declaration of competing interest. The authors declare that there are no conflicts of interest related to the work presented in this manuscript. None of the authors have financial, personal, or other relationships with other people or organizations that could inappropriately influence or bias the work.

REFERENCES

1. Ahamed M., Alhadlaq H. A., Khan M. M., Karuppiah P., and Al-Dhabi N. A. - Synthesis, characterization, and antimicrobial activity of copper oxide nanoparticles, Journal of Nanomaterials. **1** (2014) 637858. https://doi.org/10.1155/2014/637858
2. Tran T. H. and Nguyen V. T. - Copper oxide nanomaterials prepared by solution methods, some properties, and potential applications: a brief review, International scholarly research notices **1** (2014) 856592.https://doi.org/10.1155/2014/856592
3. Das D., Nath B. C., Phukon P. and Dolui S. K. - Synthesis and evaluation of antioxidant and antibacterial behaviour of CuO nanoparticles, Colloids and Surfaces B: Biointerfaces **101** (2013) 430-433.https://doi.org/10.1016/j.colsurfb.2012.07.002
4. Badetti E., Calgaro L., Falchi L., Bonetto A., Bettiol C., Leonetti B., Ambrosi E., Zendri E. and Marcomini A. - Interaction between copper oxide nanoparticles and amino acids: influence on the antibacterial activity, Nanomaterials **9** (5) (2019) 792. https://doi.org/10.3390/nano9050792
5. Ren G., Hu D., Cheng E.W., Vargas-Reus M. A., Reip P., and Allaker R. P. - Characterisation of copper oxide nanoparticles for antimicrobial

applications, International journal of antimicrobial agents **33** (6) (2009) 587-590. https://doi.org/10.1016/j.ijantimicag.2008.12.004

6. Rehana D., Mahendiran D., Kumar R. S., and Rahiman A. K. - Evaluation of antioxidant and anticancer activity of copper oxide nanoparticles synthesized using medicinally important plant extracts, Biomedicine & Pharmacotherapy **89** ((2017) 1067-1077. https://doi.org/10.1016/j.biopha.2017.02.101
7. Jawad M., Khan A., and Shah S. A. A. - Examination of couple stress hybrid nanoparticles (CuO-Cu/blood) as a targeted drug carrier with magnetic effects through porous sheet, Brazilian Journal of Physics **51** (4) (2021) 1096-1107. https://doi.org/10.1007/s13538-021-00930-7
8. Chen S., Wang H., Jian Z., Fei G., Qian W., Luo G., Wang Z., and Xia H. - Novel poly (vinyl alcohol)/chitosan/modified graphene oxide biocomposite for wound dressing application, Macromolecular Bioscience **20** (3) (2020) 1900385. https://doi.org/10.1002/mabi.201900385
9. Ren G., Hu D., Cheng E. W., Vargas-Reus M. A., Reip P., and Allaker R. P. - Characterisation of copper oxide nanoparticles for antimicrobial applications, International journal of antimicrobial agents **33** (6) (2009) 587-590. https://doi.org/10.1016/j.ijantimicag.2008.12.004
10. Verma D. K., Malik R., Meena J., and Rameshwari R. - Synthesis, characterization and applications of chitosan based metallic nanoparticles: A review, Journal of Applied and Natural Science **13** (2) (2021) 544-551. https://doi.org/10.31018/jans.v13i2.2635
11. Saya L., Malik V., Singh A., Singh S., Gambhir G., Singh W. R., Chandra R., and Hooda S. - Guar gum based nanocomposites: Role in water purification through efficient removal of dyes and metal ions, Carbohydrate polymers **261** (2021) 117851. https://doi.org/10.1016/j.carbpol.2021.117851
12. Ebnalwaled A. A. and Ismaiel A. M. - Developing novel UV shielding films based on PVA/Gelatin/0.01 CuO nanocomposite: On the properties optimization using γ-irradiation, Measurement **134** (2019) 89-100. https://doi.org/10.1016/j.measurement.2018.10.062
13. Meena J., Verma S. K., Rameshwari R., and Verma D. K. - polyaniline/carboxymethyl guar gum nanocomposites: as biodegradable, conductive film, Rasayan Journal of Chemistry **15** (2) (2022). http://doi.org/10.31788/RJC.2022.1526820
14. Abdollahi Z., Zare E.N., Salimi F., Goudarzi I., Tay F. R., and Makvandi P. - Bioactive carboxymethyl starch-based hydrogels decorated with CuO nanoparticles: antioxidant and antimicrobial properties and accelerated wound healing in vivo, International Journal of Molecular Sciences **22** (5) (2021) 2531. https://doi.org/10.3390/ijms22052531
15. Sharma N. and Rana V. S. - A review on polysaccharide based nanocomposite hydrogel systems fabrication using diverse reinforcing materials, J. Polym. Compos **8** (1) (2020) 6-17.
16. Mesgari M., Aalami A. H., Sathyapalan T., and Sahebkar A. - A comprehensive review of the development of carbohydrate macromolecules and copper oxide nanocomposite films in food nanopackaging, Bioinorganic Chemistry and Applications **1** (2022) 7557825.
17. Buk V., Emregul E. and Emregul K. C. - Alginate copper oxide nano-biocomposite as a novel material for amperometric glucose biosensing, Materials Science and Engineering: C. **74** (2017) 307-314.https://doi.org/10.1016/j.msec.2016.12.003

18. Shabahang Z., Nouri L., and Nafchi A. M. - Composite film based on whey protein isolate/pectin/CuO nanoparticles/betanin pigments; investigation of physicochemical properties, Journal of Polymers and the Environment **30** (9) (2022) 3985-3998. https://doi.org/10.1007/s10924-022-02481-7
19. Quignard F., Cot D., Di Renzo F., and Gérardin C. - Core-shell copper hydroxide-polysaccharide composites with hierarchical macroporosity, Progress in solid state chemistry **34** (2-4) (2006) 161-169. https://doi.org/10.1016/j.progsolidstchem.2005.11.016
20. Gouda M. and Hebeish A. - Preparation and evaluation of CuO/chitosan nanocomposite for antibacterial finishing cotton fabric, Journal of Industrial Textiles **39** (3) (2010) 203-214. https://doi.org/10.1177/1528083709103142
21. Balasubramanian S. and Kamaraj P. K. - Fabrication of natural polymer assisted mesoporous Co3O4/carbon composites for supercapacitors, Electrochimica Acta **168** (2015) 50-58.https://doi.org/10.1016/j.electacta.2015.04.019
22. Hashim A., Habeeb, M.A. and Hadi A. - Synthesis of novel polyvinyl alcohol–starch-copper oxide nanocomposites for humidity sensors applications with different temperatures. Sensor Letters. **15** (9) (2017) 758-761. https://doi.org/10.1166/sl.2017.3876
23. El-Trass A., ElShamy H., El-Mehasseb I., and El-Kemary M. - CuO nanoparticles: synthesis, characterization, optical properties and interaction with amino acids, Applied Surface Science **258** (7) (2012) 2997-3001. https://doi.org/10.1016/j.apsusc.2011.11.025
24. Javed R., Rais F., Kaleem M., Jamil B., Ahmad M. A., Yu T., Qureshi S. W., and Ao Q., - Chitosan capping of CuO nanoparticles: Facile chemical preparation, biological analysis, and applications in dentistry, International Journal of Biological Macromolecules **167** (2021) 1452-1467. https://doi.org/10.1016/j.ijbiomac.2020.11.099
25. Sharma G., Katwal R., and Sharma G. - Fabrication, characterization and cytotoxicity of guar gum/copper oxide nanocomposite: efficient removal of organic pollutant, In Materials Science Forum **842** (2016) 88-102. https://doi.org/10.4028/www.scientific.net/MSF.842.88
26. Ma M. G., Qing S. J., Li S. M., Zhu J. F., Fu L. H., and Sun R. C. - Microwave synthesis of cellulose/CuO nanocomposites in ionic liquid and its thermal transformation to CuO, Carbohydrate polymers **91** (1) (2013) 162-168. https://doi.org/10.1016/j.carbpol.2012.08.025
27. Syame S. M., Mohamed W. S., Mahmoud R. K., and Omara S. T. - Synthesis of copper-chitosan nanocomposites and their applications in treatment of local pathogenic isolates bacteria, Orient J. Chem. **33** (6) (2017) 2959-2969. http://dx.doi.org/10.13005/ojc/330632
28. Yadollahi M., Gholamali I., Namazi H., and Aghazadeh M. - Synthesis and characterization of antibacterial carboxymethylcellulose/CuO bio-nanocomposite hydrogels, International journal of biological macromolecules **73** (2015) 109-114. https://doi.org/10.1016/j.ijbiomac.2014.10.063
29. Naeini A. H., Kalaee M., Moradi O., Khajavi R., and Abdouss M. - Eco-friendly inorganic-organic bionanocomposite (Copper oxide-Carboxyl methyl cellulose-Guar gum): Preparation and effective removal of dye from aqueous solution, Korean Journal of Chemical Engineering **39** (8) (2022) 2138-2147. https://doi.org/10.1007/s11814-022-1074-7

30. Roopan S. M., Priya D. D., Shanavas S., Acevedo R., Al-Dhabi N. A., and Arasu M. V. - CuO/C nanocomposite: Synthesis and optimization using sucrose as carbon source and its antifungal activity, Materials Science and Engineering C. **101** (2019) 404-414. https://doi.org/10.1016/j.msec.2019.03.105
31. Biswas K., Mohanta Y. K., Mishra A. K., Al-Sehemi A. G., Pannipara M., Sett A., Bratovcic A., De D., Prasad Panda B., Kumar Avula S., and Mohanta T. K. - Wet chemical development of CuO/GO nanocomposites: its augmented antimicrobial, antioxidant, and anticancerous activity, Journal of Materials Science: Materials in Medicine **32** (2021) 1-11.https://doi.org/10.1007/s10856-021-06612-9
32. Abdollahi Z., Zare E. N., Salimi F., Goudarzi I., Tay F. R., and Makvandi P. - Bioactive carboxymethyl starch-based hydrogels decorated with CuO nanoparticles: antioxidant and antimicrobial properties and accelerated wound healing in vivo, International journal of molecular sciences **22** (5) (2021) 2531. https://doi.org/10.3390/ijms22052531
33. Gholamali I., Hosseini S. N., Alipour E., and Yadollahi M. - Preparation and characterization of oxidized starch/CuO nanocomposite hydrogels applicable in a drug delivery system, Starch-Stärke **71** (3-4) (2019) 1800118. https://doi.org/10.1002/star.201800118
34. Revathi T. and Thambidurai S. - Cytotoxic, antioxidant and antibacterial activities of copper oxide incorporated chitosan-neem seed biocomposites, International journal of biological macromolecules **139** (2019) 867-878. https://doi.org/10.1016/j.ijbiomac.2019.07.214
35. Siriphannon P. and Iamphaojeen Y. - Facile synthesis of chitosan/CuO nanocomposites for potential use as biocontrol agents, Bulletin of the Polish Academy of Sciences. Technical Sciences **66** (3) (2018) 311-316.
36. Safaei M. and Taran M. - Optimized synthesis, characterization, and antibacterial activity of an alginate–cupric oxide bionanocomposite, Journal of Applied Polymer Science **135** (2) (2018) 45682. https://doi.org/10.1002/app.45682
37. Zhang X., Guo H., Xiao N., Ma X., Liu C., Zhong L., and Xiao G. - Preparation and properties of epichlorohydrin-cross-linked chitosan/hydroxyethyl cellulose based CuO nanocomposite films, Cellulose. **29** (8) (2022) 4413-4426. https://doi.org/10.1007/s10570-022-04511-y
38. Xie Y. Y., Hu X. H., Zhang Y. W., Wahid F., Chu L. Q., Jia S. R., and Zhong C. - Development and antibacterial activities of bacterial cellulose/graphene oxide-CuO nanocomposite films, Carbohydrate Polymers **229** (2020) 115456. https://doi.org/10.1016/j.carbpol.2019.115456
39. Namazi H., Pooresmaeil M., and Hasani M. - Oxidized starch/CuO bio-nanocomposite hydrogels as an antibacterial and stimuli-responsive agent with potential colon-specific naproxen delivery, International Journal of Polymeric Materials and Polymeric Biomaterials **70** (18) (2021) 1296-1305. https://doi.org/10.1080/00914037.2020.1798431
40. Ashjari H. R., Dorraji M. S. S., Fakhrzadeh V., Eslami H., Rasoulifard M. H., Rastgouy-Houjaghan M., Gholizadeh P., and Kafil H. S. - Starch-based polyurethane/CuO nanocomposite foam: Antibacterial effects for infection control, International journal of biological macromolecules **111** (2018) 1076-1082. https://doi.org/10.1016/j.ijbiomac.2018.01.137
41. Peighambardoust S. J., Peighambardoust S. H., Pournasir N., and Pakdel P. M. - Properties of active starch-based films incorporating a combination of Ag, ZnO and CuO

nanoparticles for potential use in food packaging applications, Food Packaging and Shelf Life **22** (2019) 100420. https://doi.org/10.1016/j.fpsl.2019.100420

42. Song J., Xu L., Zhou C., Xing R., Dai Q., Liu D., and Song H. - Synthesis of graphene oxide based CuO nanoparticles composite electrode for highly enhanced nonenzymatic glucose detection, ACS applied materials & interfaces **5** (24) (2013) 12928-12934. https://doi.org/10.1021/am403508f
43. Rao J. K., Raizada A., Ganguly D., Mankad M. M., Satayanarayana S. V., and Madhu G. M. - Investigation of structural and electrical properties of novel CuO–PVA nanocomposite films, Journal of materials science **50** (2015) 7064-7074. https://doi.org/10.1007/s10853-015-9261-0
44. Kim Y. Y., Neudeck C., and Walsh D. - Biopolymer templating as synthetic route to functional metal oxide nanoparticles and porous sponges, Polymer Chemistry **1** (3) (2010) 272-275.DOI: 10.1039/B9PY00366E
45. Guesmi Y., Agougui H., Lafi R., Jabli M., and Hafiane A. - Synthesis of hydroxyapatite-sodium alginate via a co-precipitation technique for efficient adsorption of Methylene Blue dye, Journal of Molecular Liquids **249** (2018) 912-920. https://doi.org/10.1016/j.molliq.2017.11.113
46. Kumari S. C., Dhand V., and Padma P. N. - Green synthesis of metallic nanoparticles: A review, Nanomaterials (2021) 259-281. https://doi.org/10.1016/B978-0-12-822401-4.00022-2
47. Padil V. V. T. and Černík M. - Green synthesis of copper oxide nanoparticles using gum karaya as a biotemplate and their antibacterial application, International journal of nanomedicine (2013) 889-898.
48. Verma D. K., Malik R., Meena J., and Rameshwari R. - Synthesis, characterization and applications of chitosan based metallic nanoparticles: A review, Journal of Applied and Natural Science **13** (2) (2021) 544-551.https://doi.org/10.31018/jans.v13i2.2635
49. Meena J., Chandra H., and Warkar S. G. - Carboxymethyl Tamarind Kernel Gum/ZnO-Biocomposite: As an Antifungal and Hazardous Metal Removal Agent, Journal of New Materials for Electrochemical Systems **25** (3) (2022). doi 10.14447/jnmes.v25i3.a08
50. Kumar V. D., Jagram M., and Kumar V. S. - Synthesis of nickel nanorods and their conversion into nanoparticles, Research Journal of Chemistry and Environment **26** (2022) 12.
51. Shukla S. K., Pandey S., Saha S., Singh H. R., Mishra P. K., Kumar S., and Jha S. K. - Removal of crystal violet by Cu-chitosan nano-biocomposite particles using Box–Behnken design, Journal of Environmental Chemical Engineering **9** (5) (2021) 105847. https://doi.org/10.1016/j.jece.2021.105847
52. Sahithya K., Das D., and Das N. - Adsorptive removal of monocrotophos from aqueous solution using biopolymer modified montmorillonite–CuO composites: equilibrium, kinetic and thermodynamic studies, Process Safety and Environmental Protection **99** (2016) 43-54.https://doi.org/10.1016/j.psep.2015.10.009
53. Jiao X., Gutha Y., and Zhang W. - Application of chitosan/poly (vinyl alcohol)/CuO (CS/PVA/CuO) beads as an adsorbent material for the removal of Pb (II) from aqueous environment, Colloids and Surfaces B: Biointerfaces **149** (2017) 184-195. https://doi.org/10.1016/j.colsurfb.2016.10.024
54. Choudhury P. R., Majumdar S., Sahoo G. C., Saha S., and Mondal P. - High-pressure ultrafiltration CuO/hydroxyethyl cellulose composite ceramic membrane for separation

of Cr (VI) and Pb (II) from contaminated water, Chemical Engineering Journal **336** (2018) 570-578. https://doi.org/10.1016/j.cej.2017.12.062

55. Elwakeel K. Z. and Guibal E. - Arsenic (V) sorption using chitosan/Cu (OH) 2 and chitosan/CuO composite sorbents, Carbohydrate polymers **134** (2015) 190-204. https://doi.org/10.1016/j.carbpol.2015.07.012
56. Almughamisi M. S., Khan Z. A., Alshitari W., and Elwakeel K. Z. - Recovery of chromium (VI) oxyanions from aqueous solution using Cu (OH) 2 and CuO embedded chitosan adsorbents, Journal of Polymers and the Environment **28** (1) (2020) 47-60. https://doi.org/10.1007/s10924-019-01575-z
57. Ansari A., Siddiqui V. U., Akram M. K., Siddiqi W. A., and Sajid S. - Removal of Pb (II) from industrial wastewater using of CuO/Alg nanocomposite, In Smart Cities—Opportunities and Challenges: Select Proceedings of ICSC 2019 (2020) 167-175). https://doi.org/10.1007/978-981-15-2545-2_16
58. Mallakpour S., Azadi E., and Dinari M. - Mesoporous Ca-alginate/melamine-rich covalent organic polymer/cupric oxide-based microgel beads as heterogeneous catalyst for efficient catalytic reduction of hazardous water pollutants, Journal of Environmental Chemical Engineering **11** (2) (2023) 109294.https://doi.org/10.1016/j.jece.2023.109294
59. Ahmadi S. J., Sadjadi S., and Hosseinpour M. - Adsorption behavior of toxic metal ions on nano-structured CuO granules, Separation Science and Technology **47** (7) (2012) 1063-1069. https://doi.org/10.1080/01496395.2011.631675
60. Liu H., Li P., Qiu F., Zhang T., and Xu J. - Controllable preparation of FeOOH/CuO@ WBC composite based on water bamboo cellulose applied for enhanced arsenic removal, Food and Bioproducts Processing **123** (2020) 177-187. https://doi.org/10.1016/j.fbp.2020.06.018
61. Almasi H., Mehryar L., and Ghadertaj A. - Photocatalytic activity and water purification performance of in situ and ex situ synthesized bacterial cellulose-CuO nanohybrids, Water Environment Research **92** (9) (2020) 1334-1349. https://doi.org/10.1002/wer.1331
62. Naeini A. H., Moradi O., Khajavi R., and Abdouss M. - Carboxyl methyl cellulose@ guar gum@ cuo nanoparticle as effective adsorbent for the removal of dye from aqueous solution (2021). https://doi.org/10.21203/rs.3.rs-862550/v1
63. Meena J. and Jassal P. S. - Cresol and it derivative Organic pollutant removal from waste water by adsorption the magneto chitosan nanoparticle, International Journal of Chemical Studies **5** (2017) 850-854.
64. Maslamani N., Bakhsh E. M., Khan S. B., Danish E. Y., Akhtar K., Fagieh T. M., Su X., and Asiri A. M. - Chitosan@ carboxymethylcellulose/CuO-Co2O3 nanoadsorbent as a super catalyst for the removal of water pollutants, Gels **8** (2) (2022) 91. https://doi.org/10.3390/gels8020091
65. Meena J. and Jassal P. S. - Phenol Organic Impurity Remove from pollutants Water By Batch Adsorption Studies with using Magneto Chitosan Nanoparticle. Aijreas. **2** (2017) 2455-6300.
66. Srivastava V. and Choubey A. K. - Investigation of adsorption of organic dyes present in wastewater using chitosan beads immobilized with biofabricated CuO nanoparticles, Journal of Molecular Structure **1242** (2021) 130749. https://doi.org/10.1016/j.molstruc.2021.130749
67. Lakkaboyana S. K., Soontarapa K., Marella R. K. and Kannan K. - Preparation of novel chitosan polymeric nanocomposite as an efficient material for the removal of Acid Blue

25 from aqueous environment, International Journal of Biological Macromolecules **168** (2021) 760-768. https://doi.org/10.1016/j.ijbiomac.2020.11.133

68. Khan S. B., Ali F., Kamal T., Anwar Y., Asiri A. M., and Seo J. - CuO embedded chitosan spheres as antibacterial adsorbent for dyes, International journal of biological macromolecules **88** (2016) 113-119.https://doi.org/10.1016/j.ijbiomac.2016.03.026
69. Rahman N. and Varshney P. - Effective removal of doxycycline from aqueous solution using CuO nanoparticles decorated poly (2-acrylamido-2-methyl-1-propanesulfonic acid)/chitosan, Environmental Science and Pollution Research **28** (32) (2021) 43599-43617. https://doi.org/10.1007/s11356-021-13584-4
70. Alrebaki M. A., Ba-Abbad M. M., and Abdullah A. Z. - Novel Fe0 Embedded Alginate Beads and Coated with CuO-Fe3O4 as a Sustainable Catalyst for Photo-Fenton Degradation of Oxytetracycline in Wastewater, Arabian Journal for Science and Engineering **48** (7) (2023) 8957-8969. https://doi.org/10.1007/s13369-022-07577-9
71. Maslamani N., Khan S. B., Danish E. Y., Bakhsh E. M., Zakeeruddin S. M., and Asiri A. M. - Super adsorption performance of carboxymethyl cellulose/copper oxide-nickel oxide nanocomposite toward the removal of organic and inorganic pollutants, Environmental Science and Pollution Research **28** (2021) 38476-38496. https://doi.org/10.1007/s11356-021-13304-y
72. Zhou Z., Lu C., Wu X., and Zhang X. - Cellulose nanocrystals as a novel support for CuO nanoparticles catalysts: facile synthesis and their application to 4-nitrophenol reduction, RSC advances **3** (48) (2013) 26066-26073. https://doi.org/10.1039/C3RA43006E
73. Azam A., Ahmed A. S., Oves M., Khan M. S., Habib S. S., and Memic A. - Antimicrobial activity of metal oxide nanoparticles against Gram-positive and Gram-negative bacteria: a comparative study, International journal of nanomedicine (2012) 6003-6009.
74. Wahid F., Wang H. S., Lu Y. S., Zhong C., and Chu L. Q. - Preparation, characterization and antibacterial applications of carboxymethyl chitosan/CuO nanocomposite hydrogels, International journal of biological macromolecules **101** (2017) 690-695. https://doi.org/10.1016/j.ijbiomac.2017.03.132
75. Sathiyavimal S., Vasantharaj S., Kaliannan T., and Pugazhendhi A. - Eco-biocompatibility of chitosan coated biosynthesized copper oxide nanocomposite for enhanced industrial (Azo) dye removal from aqueous solution and antibacterial properties, Carbohydrate polymers **241** (2020) 116243. https://doi.org/10.1016/j.carbpol.2020.116243
76. Saberi D., Mansourinejhad S., Shadi A., and Habibi H. - One-pot synthesis of a highly disperse core–shell CuO–alginate nanocomposite and the investigation of its antibacterial and catalytic properties, New Journal of Chemistry **46** (1) (2022) 199-211. 10.1039/D1NJ02770K
77. Marković D., Radoičić M., Barudžija T., and Radetić M. - Modification of PET and PA fabrics with alginate and copper oxides nanoparticles, Composite Interfaces **28** (12) (2021) 1171-1187. https://doi.org/10.1080/09276440.2020.1868267
78. Alishah H., Pourseyedi S., Ebrahimipour S. Y., Mahani S. E., and Rafiei N. - Green synthesis of starch-mediated CuO nanoparticles: preparation, characterization, antimicrobial activities and in vitro MTT assay against MCF-7 cell line, Rendiconti Lincei **28** (2017) 65-71. https://doi.org/10.1007/s12210-016-0574-y

79. Ashjari H. R., Dorraji M. S. S., Fakhrzadeh V., Eslami H., Rasoulifard M. H., Rastgouy-Houjaghan M., Gholizadeh P., and Kafil H. S. - Starch-based polyurethane/CuO nanocomposite foam: Antibacterial effects for infection control, International journal of biological macromolecules **111** (2018) 1076-1082. https://doi.org/10.1016/j.ijbiomac.2018.01.137

80. Hussain R., Aziz W. and Abbas Ibrahim I. - Antibacterial activity of CuO-cellulose nano rods depends on a new green synthesis (cotton), Journal of Nanostructures **9** (4) (2019) 761-767. 10.22052/JNS.2019.04.017

81. Xie Y. Y., Hu X. H., Zhang Y. W., Wahid F., Chu L.Q., Jia S.R., and Zhong C. - Development and antibacterial activities of bacterial cellulose/graphene oxide-CuO nanocomposite films, Carbohydrate Polymers **229** (2020) 115456. https://doi.org/10.1016/j.carbpol.2019.115456

82. Karim M. N., Singh M., Weerathunge P., Bian P., Zheng R., Dekiwadia C., Ahmed T., Walia S., Della Gaspera E., Singh S., and Ramanathan R. - Visible-light-triggered reactive-oxygen-species-mediated antibacterial activity of peroxidase-mimic CuO nanorods, ACS Applied Nano Materials **1** (4) (2018) 1694-1704. https://doi.org/10.1021/acsanm.8b00153

83. Dwivedi L. M., Shukla N., Baranwal K., Gupta S., Siddique S., and Singh V. - Gum Acacia modified Ni doped CuO nanoparticles: an excellent antibacterial material, Journal of Cluster Science **32** (2021) 209-219. https://doi.org/10.1007/s10876-020-01779-7

84. Ismaiel M., Salem W., Sayed Abd El-sadek M., Mohamed Salman H., and Mohamed Said H. - Synthesis and Characterization of Polyvinyl Alcohol/Gelatin/CuO Nanocomposite Film Via γ-Irradiation for Antimicrobial Application, International Journal of Artificial Intelligence and Emerging Technology **1** (2) (2018) 49-62. 10.21608/ijaiet.2018.181644

85. Patel P. K., Prajapati N. K., and Dubey B. K. - Madhuca indica: a review of its medicinal property, International Journal of Pharmaceutical Sciences and Research **3** (5) (2018) 1285.

86. Wilczewska A. Z., Niemirowicz K., Markiewicz K. H., and Car H. - Nanoparticles as drug delivery systems, Pharmacological reports **64** (5) (2012) 1020-1037. https://doi.org/10.1016/S1734-1140(12)70901-5

87. Venkataprasanna K.S., Prakash J., Vignesh S., Bharath G., Venkatesan M., Banat F., Sahabudeen S., Ramachandran S., and Venkatasubbu G. D. - Fabrication of Chitosan/PVA/GO/CuO patch for potential wound healing application, International journal of biological macromolecules **143** (2020) 744-762. https://doi.org/10.1016/j.ijbiomac.2019.10.029

88. Sriram K., Maheswari P. U., Ezhilarasu A., Begum K. M. M. S., and Arthanareeswaran G.- CuO-loaded hydrophobically modified chitosan as hybrid carrier for curcumin delivery and anticancer activity, Asia-Pacific Journal of Chemical Engineering **12** (6) (2017) 858-871. https://doi.org/10.1002/apj.2124

89. Gholamali I. and Alipour E. - Carboxymethyl chitosan/starch/CuO nanocomposite hydrogels for controlled release of amoxicillin, Regenerative Engineering and Translational Medicine **6** (4) (2020) 398-406.https://doi.org/10.1007/s40883-020-00173-z

90. Ahmadian Y., Bakravi A., Hashemi H., and Namazi H. - Synthesis of polyvinyl alcohol/CuO nanocomposite hydrogel and its application as drug delivery agent, Polymer Bulletin **76** (2019) 1967-1983. https://doi.org/10.1007/s00289-018-2477-9
91. Dharmalingam K., Bordoloi D., Kunnumakkara A.B. and Anandalakshmi R. - Preparation and characterization of cellulose-based nanocomposite hydrogel films containing CuO/Cu2O/Cu with antibacterial activity, Journal of Applied Polymer Science **137** (40) (2020) 49216. https://doi.org/10.1002/app.49216
92. Chen J., Karmakar B., Salem M.A., Alzahrani A.Y., Bani-Fwaz M.Z., Abdel-Daim M.M. and El-kott A.F. - CuO NPs@ Starch as a novel chemotherapeutic drug for the treatment of several types of gastrointestinal system cancers including gastric, pancreatic, and colon cancers, Arabian Journal of Chemistry **15** (4) (2022) 103681. https://doi.org/10.1016/j.arabjc.2021.103681
93. Bharathi D., Ranjithkumar R., Chandarshekar B., and Bhuvaneshwari V. - Bio-inspired synthesis of chitosan/copper oxide nanocomposite using rutin and their anti-proliferative activity in human lung cancer cells, International Journal of Biological Macromolecules **141** (2019) 476-483. https://doi.org/10.1016/j.ijbiomac.2019.08.235
94. Konar S., Kalita H., Puvvada N., Tantubay S., Mahto M. K., Biswas S., and Pathak A. - Shape-dependent catalytic activity of CuO nanostructures, Journal of catalysis **336** (2016) 11-22. https://doi.org/10.1016/j.jcat.2015.12.017
95. Nasrollahzadeh M., Bidgoli N. S. S., Nezafat Z., and Shafiei N. - Catalytic applications of biopolymer-based metal nanoparticles, Biopolymer-based metal nanoparticle chemistry for sustainable applications, Elsevier, 2021, pp. 423-516.
96. Raghavendra G. M., Jung J., Kim D., and Seo J. - Chitosan-mediated synthesis of flowery-CuO, and its antibacterial and catalytic properties, Carbohydrate polymers **172** (2017) 78-84. https://doi.org/10.1016/j.carbpol.2017.04.070
97. Ikram M., Shahzadi A., Hayat S., Nabgan W., Ul-Hamid A., Haider A., Noor M., Goumri-Said S., Kanoun M. B., and Ali S. - Novel Ta/chitosan-doped CuO nanorods for catalytic purification of industrial wastewater and antimicrobial applications, RSC advances **12** (27) (2022) 16991-17004.DOI: 10.1039/D2RA03006C
98. Aljuhani A., Riyadh S. M., and Khalil K. D. - Chitosan/CuO nanocomposite films mediated regioselective synthesis of 1, 3, 4-trisubstituted pyrazoles under microwave irradiation, Journal of Saudi Chemical Society **25** (8) (2021) 101276. https://doi.org/10.1016/j.jscs.2021.101276
99. Kamal T. - Aminophenols formation from nitrophenols using agar biopolymer hydrogel supported CuO nanoparticles catalyst, Polymer Testing **77** (2019) 105896. https://doi.org/10.1016/j.polymertesting.2019.105896
100. Khan F. U., Khan S. B., Kamal T., Asiri A. M., Khan I. U., and Akhtar K. - Novel combination of zero-valent Cu and Ag nanoparticles@ cellulose acetate nanocomposite for the reduction of 4-nitro phenol, International journal of biological macromolecules **102** (2017) 868-877.https://doi.org/10.1016/j.ijbiomac.2017.04.062
101. Souza J. F., Costa G. P., Luque R., Alves D., and Fajardo A. R. - Polysaccharide-based superporous hydrogel embedded with copper nanoparticles: a green and versatile catalyst for the synthesis of 1, 2, 3-triazoles, Catalysis Science & Technology **9** (1) (2019) 136-145. DOI:10.1039/C8CY01796D

102. Warkara S. G. and Meena J. - Synthesis and applications of biopolymer/FeO nanocomposites: A review, Journal of New Materials for Electrochemical Systems **25** (1) (2022). https://doi.org/10.14447/jnmes.v25i1.a02
103. Bilal M., Ikram M., Shujah T., Haider A., Naz S., Ul-Hamid A., Naz M., Haider J., Shahzadi I., and Nabgan W. - Chitosan-grafted polyacrylic acid-doped copper oxide nanoflakes used as a potential dye degrader and antibacterial agent: in silico molecular docking analysis. ACS omega **7** (45) (2022) 41614-41626. https://doi.org/10.1021/acsomega.2c05625
104. Logpriya S., Bhuvaneshwari V., Vaidehi D., SenthilKumar R. P., Nithya Malar R.S., Pavithra Sheetal B., Amsaveni R., and Kalaiselvi M. - Preparation and characterization of ascorbic acid-mediated chitosan–copper oxide nanocomposite for anti-microbial, sporicidal and biofilm-inhibitory activity,Journal of Nanostructure in Chemistry **8** (2018) 301-309.https://doi.org/10.1007/s40097-018-0273-6
105. Ginjupalli K., Alla R., Shaw T., Tellapragada C., Gupta L. K., and Upadhya P. N. - Comparative evaluation of efficacy of Zinc oxide and Copper oxide nanoparticles as antimicrobial additives in alginate impression materials, Materials Today: Proceedings **5** (8) (2018) 16258-16266. https://doi.org/10.1016/j.matpr.2018.05.117
106. López O. V., Villanueva M. E., Copello G. J., and Villar M. A. - Flexible thermoplastic starch films functionalized with copper particles for packaging of food products, Functional Composite Materials **1** (2020) 1-10. https://doi.org/10.1186/s42252-020-00009-7
107. Chadijah S. and Nurhuda S. - Synthesis of chitosan-CuO composite and it's application as heavy metal adsorbent, Journal of Physics: Conference Series **1** (1899) (2021) 012029. DOI 10.1088/1742-6596/1899/1/012029
108. Sharma J. K., Akhtar M. S., Ameen S., Srivastava P., and Sing G. - Green synthesis of CuO nanoparticles with leaf extract of Calotropis gigantea and its dye-sensitized solar cells applications, Journal of Alloys and Compounds **632** (2015) 321-325. https://doi.org/10.1016/j.jallcom.2015.01.172
109. Kaur P., Thakur R., Barnela M., Chopra M., Manuja A. and Chaudhury A. - Synthesis, characterization and in vitro evaluation of cytotoxicity and antimicrobial activity of chitosan–metal nanocomposites, Journal of Chemical Technology & Biotechnology **90** (5) (2015) 867-873. https://doi.org/10.1002/jctb.4383
110. Meena J., Kumar M., Rasool A., and Krismastuti F. S. H. - Optimizing Antimicrobial Efficacy and Ammonia Sensing in a Novel Carboxymethyl Tamarind Kernel Gum/Fe Nanocomposite, Sustainable Chemistry One World, 2024, pp. 100010. https://doi.org/10.1016/j.scowo.2024.100010
111. Meena J., Warkar S. G., and Verma D. K. - Carboxymethyl Tamarind Kernel Gum Nanoparticles; As an Antioxidant Activity, Journal of New Materials for Electrochemical Systems **26** (3) (2023).10.14447/jnmes.v26i3.a01