

Moringa oleifera–Chitosan Composites for Sustainable Wastewater Treatment: A Review of Coagulation, Adsorption and Antimicrobial Performance

Vipin Bansal¹, Ankit Agrawal²

¹Research Scholar, Department of Biotechnology, Rabindranath Tagore University, Bhopal (M.P.), vipinbansal.in@gmail.com
India

²Supervisor, Department of Biotechnology, Rabindranath Tagore University, Bhopal (M.P.), India

Abstract – Conventional wastewater treatment relies on chemical coagulants such as alum and ferric salts, which generate bulky sludge, leave residual metals in treated water and raise treatment costs. Natural coagulants are biodegradable, renewable and low in toxicity, and among them the seed proteins of *Moringa oleifera* and the biopolymer chitosan are the most studied. This paper reviews the limitations of conventional coagulants, the properties and mechanisms of *Moringa oleifera* and chitosan, and recent work on their composites for the removal of turbidity, organic matter, heavy metals and pathogens. Reported removal efficiencies are compared, and the main research gaps are identified: limited work on stable bead-form *Moringa*–chitosan composites, scarce testing on real wastewater, insufficient statistical optimization, and little economic or scale-up assessment. Directions for future work are proposed.

Keywords: *Moringa oleifera*, chitosan, natural coagulant, composite beads, wastewater treatment, antimicrobial activity

I. INTRODUCTION

Water scarcity and pollution are among the most serious environmental problems. Domestic, industrial and agricultural wastewater carry organic matter, nutrients, heavy metals and pathogens, and their discharge without adequate treatment causes eutrophication, contaminates groundwater and spreads waterborne disease. Coagulation–flocculation is a central step in wastewater treatment and has traditionally relied on aluminium sulfate and ferric salts. These chemicals are effective, but they produce large volumes of non-biodegradable sludge, may leave residual metals in treated water, depend on pH control and add to operating costs, which is a particular burden for small and rural systems [1, 2].

Natural coagulants from plant, animal and microbial sources have therefore attracted wide attention. They are biodegradable, produce less and safer sludge, and can often be sourced locally [1, 3, 4]. Seeds of *Moringa oleifera* contain water-soluble cationic proteins that neutralize and bridge colloidal particles, and also show antimicrobial activity [5, 6]. Chitosan, obtained by deacetylation of chitin, is a cationic polysaccharide with coagulating, adsorptive and antimicrobial properties [7, 8]. Combining the two in a composite, particularly in bead form, may add the rapid charge neutralization of *Moringa* proteins to the bridging, adsorption and antimicrobial action of chitosan [9].

This paper reviews the literature on *Moringa oleifera*, chitosan and their composites for wastewater treatment. Section II summarizes the limitations of conventional coagulants, Section III introduces natural coagulants, Sections IV and V discuss *Moringa oleifera* and chitosan, Section VI covers their composites, Section VII compares reported performance, and Section VIII identifies research gaps and future directions.

II. LIMITATIONS OF CONVENTIONAL COAGULANTS

Alum and iron salts destabilize colloids mainly by charge neutralization and sweep flocculation. Their efficiency depends strongly on pH, temperature and the initial water quality, and they do little against dissolved organics, pathogens and emerging contaminants, so a separate disinfection step is usually needed [1, 2]. Residual aluminium has been linked, although the relationship is still debated, to neurological disorders, and aluminium and iron residues can be toxic to aquatic life. The sludge is bulky and often contains metals and salts, so dewatering, transport and disposal add cost and can cause secondary pollution [1]. Alum and ferric salts are also non-renewable and carry the footprint of mining and chemical manufacture. These drawbacks motivate the search for renewable and biodegradable alternatives.

III. NATURAL COAGULANTS

Natural coagulants are mainly proteins, polysaccharides or mixtures of both that carry positive charges and bind negatively charged colloids, forming flocs through charge neutralization, bridging and adsorption [4, 10]. Their advantages include biodegradability, low toxicity, reduced sludge volume, local availability and sometimes additional antimicrobial or adsorptive functions [1, 11]. Examples that have been studied include condensed tannins for surface water, coloured effluents and municipal wastewater, including pilot-plant trials [12–15]; okra and fenugreek mucilage for textile and tannery effluents [16, 17]; *Opuntia* (cactus) mucilage and powder for turbidity and Pb(II) removal [18–20]; papaya seeds for potable water [21]; orange peel and neem leaf powder for dairy wastewater [22]; banana pith and peel [23, 24]; and guar gum and its derivatives [25, 26]. Reviews also point to constraints: performance varies with source and region, extraction methods are not standardized, and large-scale use is limited [1, 3, 11].

IV. MORINGA OLEIFERA

A. Botanical Background and Active Components

Moringa oleifera (family Moringaceae) is a fast-growing, drought-resistant tree native to the Indian subcontinent and now widely cultivated in the tropics and subtropics. Its seeds contain cationic proteins, with molecular weights of about 6–16 kDa, that act as natural polyelectrolytes [5, 6, 27]. The seed cake left after oil extraction retains coagulant activity, which makes it a low-cost by-product [27, 28].

B. Mechanism

Coagulation by *Moringa* proteins proceeds by charge neutralization of negatively charged colloids, bridging of particles into larger aggregates, and settling of the flocs. In addition, the seeds show antibacterial, antifungal and antiviral effects that help reduce microbial load [5].

C. Reported Performance

Oria-Usifo et al. [27] treated surface water of 64 NTU with shell-blended seed powder, de-oiled powder and purified protein, and obtained turbidity removal of 75.7, 83.3 and 92.3 %, respectively, with total coliforms reduced below the WHO limit; combining *Moringa* with alum or ferric chloride allowed inorganic salt use to be cut by about 60 %. Camacho et al. [28] found that defatted *Moringa* powder at 50 mg/L removed 97.4 % of chlorophyll-a and 84 % of turbidity. Rifi et al. [29] reported about 83 % turbidity and 57.6 % COD removal for olive mill wastewater by combined flotation and *Moringa* coagulation. For heavy metals, *Moringa* coagulation followed by bentonite adsorption removed 98.71 % Cd, 99.84 % Cr and 99.95 % Pb under optimized pH [30]. *Moringa* has also been studied as a biosorbent in raw, modified and composite forms [31–33], and its protein has been used against microplastics [34]. Desta and Bote [35] used response surface methodology to optimize wastewater treatment with *Moringa* seeds.

V. CHITOSAN

Chitosan is obtained by deacetylation of chitin from crustacean shells, fungi and insects, and its degree of deacetylation and molecular weight govern solubility, charge density and coagulation efficiency [7, 8]. Under acidic conditions its amino groups are protonated, giving a cationic polymer that neutralizes and bridges colloids and binds metals and dyes by electrostatic attraction, chelation and hydrogen bonding [36, 37]. Its antimicrobial action is attributed to interaction of the protonated amino groups with negatively charged microbial membranes, causing leakage and cell death [7]. Limited solubility at neutral and alkaline pH and relatively high cost are the main drawbacks, which has led to modified and composite forms such as chitosan-Fe₃O₄ nanocomposites, chitosan-mangosteen peel biocomposite and graphene oxide-chitosan-PVA beads [38–40]. Coleman et al. [7] concluded that chitosan is a strong coagulant, flocculant and adsorbent for microbial removal and that modification or combination with filtration can improve it further.

VI. MORINGA-CHITOSAN COMPOSITES

Vigneshwaran et al. [9] showed that acid-treated carbonized chitosan incorporated with *Moringa oleifera* gave enhanced coagulation of synthetic turbid water with

minimal leaching and improved adsorption capacity. Ruelas-Leyva et al. [41] compared chitosan and *Moringa* seed flour directly in jar tests on river and agricultural wastewater: optimum doses were 1 mg/L for chitosan and 5 mg/L for *Moringa* flour in river water, both removed up to 95 % of Pb, and *Moringa* flour removed nearly 90 % of Mn. Faye et al. [42] reviewed *Moringa* and chitosan conditioning of sludge and highlighted the role of extracellular polymeric substances in dewatering.

Embedding *Moringa* extract in a chitosan matrix that is ionically cross-linked, for example with sodium tripolyphosphate, gives beads that can limit leaching of organic matter, allow recovery, and combine coagulation, adsorption and antimicrobial action [40]. Bead formation by dripping into a cross-linking bath is simple and uses non-toxic reagents, and bead size, porosity and surface chemistry can be tuned through nozzle size, extract ratio and cross-linking time.

VII. COMPARATIVE PERFORMANCE

TABLE I. Selected studies on *Moringa oleifera* and chitosan based materials

Ref.	Material	Main reported result
[9]	Chitosan– <i>Moringa</i> (acid-treated, carbonized)	Superior coagulation of turbid water; minimal leaching
[41]	Chitosan; <i>Moringa</i> flour	Pb removal up to 95 %; Mn about 90 % (<i>Moringa</i>)
[27]	<i>Moringa</i> protein powder	92.3 % turbidity removal at 90 mg/L
[28]	Defatted <i>Moringa</i> powder	97.4 % chlorophyll-a, 84 % turbidity
[29]	Flotation + <i>Moringa</i>	83 % turbidity, 57.6 % COD
[30]	<i>Moringa</i> + bentonite	Cd 98.71 %, Cr 99.84 %, Pb 99.95 %
[33]	<i>Moringa</i> nanofibres	71.7–80.7 % Pb(II) in real wastewater
[38]	Chitosan–Fe ₃ O ₄	99 % methylene blue; heavy metals 100 % in 30 min
[39]	Chitosan–mangosteen peel	93.47 % dye removal; 398.7 mg/g
[18]	<i>Opuntia</i> powder	Pb 100 %; Zn 85.7 %; Cd 84.2 %

Table I shows that single natural materials can reach more than 90 % removal for individual pollutants, but conditions differ widely, and most studies address one pollutant class at a time. Direct comparison is therefore limited by differences in wastewater type, dosage and analytical methods.

VIII. RESEARCH GAPS AND FUTURE DIRECTIONS

The review shows the following gaps. (1) Most studies use *Moringa* or chitosan individually; stable, reusable *Moringa*–chitosan beads and the interaction between *Moringa* proteins and chitosan are little studied [9, 41]. (2) Many tests use synthetic or low-complexity water, with few on real wastewater [1, 3]. (3) Systematic optimization of dosage, pH, contact time and temperature is limited [5, 35]. (4) Microbial reduction is often secondary to turbidity removal and is rarely compared with conventional

treatment [7]. (5) Economic, life-cycle and scale-up assessments are scarce [2, 3].

Future work should prepare cross-linked Moringa–chitosan beads over a range of extract ratios, characterize them (FTIR, SEM, XRD, BET, TGA), evaluate pollutant and pathogen removal together on real wastewater, optimize conditions by response surface methodology, test regeneration and reuse, and carry out techno-economic and life-cycle analysis.

IX. CONCLUSION

Moringa oleifera proteins and chitosan are complementary natural coagulants, and their combination is a promising route to biodegradable, low-sludge, dual-function wastewater treatment materials. However, bead-form composites tested on real wastewater with systematic optimization and quantified antimicrobial performance remain underexplored. Addressing these gaps is the aim of the authors' ongoing experimental work.

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