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Sustainable wastewater treatment in the U. S: Bio-flocculation of laundry fibers using calcium ions

Oluwaseyi Emmanuel Olorunfemi [1] and Edward Oware [2,*]

[1] *Department of Environmental Engineering, University of North Dakota, USA.*
[2] *Department of Physiology, School of Medical Sciences, Kwame Nkrumah University of Science and Technology, Ghana.*

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Abstract

This research investigates calcium-enhanced bio-flocculation as a sustainable approach for removing synthetic and natural laundry fibers from wastewater streams. With conventional wastewater treatment systems removing only 65-99.9% of microfibers and an estimated 700,000-12,000,000 fibers released per 6 kg wash load, innovative methods are urgently needed to address this growing environmental concern. This review examines the fundamental mechanisms through which calcium ions promote bio-flocculation of textile fibers, particularly focusing on interactions between calcium and extracellular polymeric substances (EPS) in activated sludge systems. By exploring various literature studies, we compare the efficiency of calcium-enhanced bio-flocculation with traditional chemical coagulants, analyzing fiber removal rates, effluent quality, and sludge properties. Results indicate that calcium ions significantly improve flocculation efficiency through charge neutralization, bridging mechanisms, and cross-linking with biopolymers, achieving removal rates of 85-97% for various fiber types under optimized conditions. The optimal operational parameters include calcium concentrations of 50-75 mg/L, pH range of 6.5-8.0, and temperature between 20-35°C. This paper demonstrates that calcium-based bio-flocculation represents a cost-effective, environmentally friendly alternative to conventional chemical flocculants, offering a scalable solution that can be integrated into existing wastewater infrastructure while reducing energy consumption and chemical usage in treatment processes.

Keywords; Bio-flocculation; Calcium ions; Laundry microfibers; Sustainable wastewater treatment

1. Introduction

With over 16,000 publicly owned treatment works handling around 34 billion gallons of sewage every day, wastewater treatment in the US is an essential piece of infrastructure [1]. Emerging pollutants nonetheless provide a challenge to established treatment paradigms, even with significant investments in treatment technology over the past few decades [2]. Although the Clean Water Act of 1972 laid the legal groundwork for wastewater management in the United States, new pollutants are constantly being introduced by industrial processes and consumer goods that conventional treatment systems were not intended to handle [3].

Wastewater treatment methods have undergone a paradigm shift as a result of the increased awareness of sustainability imperatives. According to Gu et al. [4], conventional treatment methods usually use 0.3–0.6 kWh of energy per cubic meter of wastewater treated, which adds up to about 3-4% of all power used in the United States. The development of sustainable treatment alternatives has increased due to this significant energy footprint, as well as worries about chemical additions and residual pollutants in treated wastewater. Resource recovery, energy efficiency, and pollutant removal are the three pillars of 21st-century sustainable wastewater treatment systems [5]. Researchers and environmental authorities are paying more attention to synthetic and natural textile fibers generated during home and

* Corresponding author: Edward Oware

commercial laundry procedures as one of the rising wastewater pollutants [6]. Depending on the fabric type, washing conditions, and age of the garment, these fibers, which are usually 100-5000 µm in length and 10-50 µm in diameter, can shed 700,000 to 12,000,000 fibers every 6 kg wash load during washing cycles [7].

A large amount of microplastic contamination in aquatic ecosystems is caused by synthetic fibers, especially those made from polyester (polyethylene terephthalate), nylon (polyamide), and acrylic (polyacrylonitrile) [8]. Laundry fiber contamination has an impact on aquatic habitats and the environment. Synthetic fibers have been found in freshwater lakes, marine sediments, and even drinking water supplies [9]. These fibers act as carriers of hydrophobic organic pollutants and can linger in the environment for decades to centuries [10]. All trophic levels, from zooplankton to bigger vertebrates, have been shown to consume microfibers, which may lead to bioaccumulation and biomagnification [11]. Fiber consumption can physically obstruct marine species' digestive systems and may release harmful monomers and compounds [12]. Due to the sheer number of fibers entering treatment facilities, a considerable number of microfibers still make their way into receiving waters despite the fact that current wastewater treatment systems normally remove 65–99.9% of them, mostly through sedimentation processes [13]. Furthermore, when biosolids are applied to agricultural land, fibers that were caught in sewage sludge may rejoin the environment [14]. Innovative, sustainable methods are required to handle this pollutant class due to the limits of traditional treatment technology. The removal of laundry fibers from wastewater streams using bio-flocculation with calcium ions is the primary objective of this review. Using naturally existing mechanisms to aggregate and settle particulate matter with less of an impact on the environment, bio-flocculation is a possible substitute for chemical coagulants [15]. Given calcium's availability, relative safety, and proven efficacy in laboratory and pilot investigations, the precise function of calcium ions in improving flocculation efficiency for textile fibers has drawn special attention [16].

This review has three goals in consideration: 1. to investigate the basic processes via which calcium ions promote the bio-flocculation of laundry fibers, Zhang et al. [17] focused on the interactions between calcium and extracellular polymeric substances (EPS) generated by microorganisms in activated sludge systems. 2. to evaluate the efficiency of fiber removal, effluent quality, and sludge properties of calcium-enhanced bio-flocculation in comparison to traditional chemical coagulants such ferric chloride, aluminum sulfate, and synthetic polyelectrolytes [18]. 3. to assess whether calcium-based bio-flocculation technologies can be scaled up from lab tests to large-scale deployment, taking into account integration with current treatment infrastructure [19]. By tackling these goals, this review seeks to give researchers, policymakers, treatment plant operators, and water quality managers a thorough evaluation of calcium-enhanced bio-flocculation as a long-term approach to reducing laundry fiber pollution in wastewater systems across the United States.

2. Literature review and case studies

2.1. Characteristics of laundry-derived microfibers

With unique physical and chemical characteristics that affect their environmental fate and treatability, laundry-derived microfibers make up a sizable portion of microplastic contamination in aquatic habitats. The three main types of textile fibers that are discharged during washing procedures are synthetic, natural, and semi-synthetic [20]. About 60% of the world's textile manufacturing is made of synthetic fibers, such as polyester (polyethylene terephthalate, or PET). According to De Falco et al. [7], these fibers usually have a diameter of 10–30 µm and lengths that vary from 100 µm to several millimeters. High tensile strength (400–800 MPa), hydrophobicity (water contact angle >90°), and resistance to biodegradation are characteristics of polyester fibers. Under ideal circumstances, their predicted environmental persistence exceeds 100 years [21]. Other popular synthetic fibers with unique physical characteristics are polypropylene, nylon (polyamide), and acrylic (polyacrylonitrile). Compared to polyester, nylon fibers are more elastic and have a higher capacity to absorb moisture, whilst acrylic fibers are more UV resistant but have a lower tensile strength [22].

Cotton, wool, and silk are examples of natural fibers that contribute significantly to laundry effluent, although their effects on the environment are different from those of synthetic fibers. Cellular structures made mostly of cellulose define cotton fibers, which make up about 24% of the world's fiber production. According to Ladewig et al. [23], these fibers usually have a diameter of 10–25 µm and lengths that range from 500 µm to several millimeters. Natural fibers have significant biodegradability in contrast to their synthetic equivalents; under ideal environmental conditions, cotton decomposes 95–100% in 6–12 months [23]. However, leftover chemicals from manufacturing processes, such as dyes, flame retardants, and antimicrobial compounds, may be present in processed cotton and can seep into aquatic ecosystems [24]. The intermediate category of semi-synthetic fibers, which are made from natural cellulosic sources but undergo chemical processing to change their characteristics, includes rayon, viscose, and lyocell.

According to Miller et al. [6], these fibers usually have diameters between 10 and 20 μm and biodegrade at a rate that is between that of natural and totally synthetic fibers. In maritime conditions, rayon, for example, may disintegrate 60–80% in 6 months, which is slower than untreated cotton but much faster than polyester [25]. Laundry fibers' surface chemistry greatly influences how they behave in the environment and how amenable they are to treatment. In order to facilitate the adsorption of hydrophobic organic pollutants, synthetic fibers usually have hydrophobic surfaces with negative zeta potentials between -15 and -40 mV at neutral pH [26]. On the other hand, cotton and other cellulosic fibers have a lot of hydroxyl groups that can form hydrogen bonds and interact with surfaces, making them more hydrophilic [27]. This difference has a substantial impact on how they aggregate, with synthetic fibers showing more resistance to traditional flocculation processes than their natural counterparts [28].

2.2. Prevalence in Domestic and Industrial Effluents

Recent years have seen a considerable evolution in the quantification of microfibers in wastewater streams, as methodological advancements have made it possible to assess fiber concentrations across treatment systems with greater accuracy. With an estimated 700,000–12,000,000 fibers emitted each 6 kg wash load, depending on fabric type, age, and washing conditions, domestic laundry is the main source of fiber emissions to municipal wastewater [7]. Fiber shedding rates are also greatly influenced by water temperature and detergent formulation, with front-loading washing machines often releasing seven times fewer fibers than their top-loading counterparts [9]. Invasive fiber concentrations ranged from 1.0 to 18.0 fibers/mL, according to extensive sampling campaigns conducted across U.S. wastewater treatment plants. Higher concentrations were noted in densely populated urban regions and at periods of peak household water demand [29]. In order to analyze the fiber compositions in wastewater streams, Talvitie et al. [13] used a cascade filtration approach in conjunction with micro-Fourier Transform Infrared spectroscopy. They found that the most common fiber types were polyester (52%), cotton (32%), polyamide (12%), and acrylic (4%).

Fibers make up over 60% of all microplastic particles, according to Mason et al. [30], who also reported fiber concentrations of 15.1 ± 5.2 particles/L in WWTP effluent from 17 U.S. plants. Sector-specific industrial contributions to fiber loading differ significantly, with textile manufacturing facilities producing especially large inputs. Textile mill wastewater, which is mostly made up of production-specific fiber types, can have fiber concentrations of more than 100 fibers/mL [31]. Intermediate fiber concentrations, usually 5–25 fibers/mL, are produced by commercial laundry operations catering to healthcare facilities, hospitality establishments, and institutional clients; the fiber compositions vary depending on the particular textiles treated [32].

Traditional microscopy methods have given way to more advanced strategies that use spectroscopic identification in microfiber detection. Conventional techniques usually entail visual enumeration using stereomicroscopy after progressive filtration through filters with decreasing pore sizes (usually 300 μm to 5 μm) [33]. For fiber characterization, advanced methods such as Raman spectroscopy, μFTIR, and thermal extraction desorption gas chromatography-mass spectrometry each have unique benefits [34]. According to Jiang et al. [35], recent methodological advancements include automated image analysis systems that can differentiate between different fiber types based on morphological traits, greatly speeding up the enumeration procedure. Additionally, synthetic polymer fibers can be selectively seen against complicated environmental matrices utilizing fluorescent staining techniques that employ Nile Red dye [36]. Accurately measuring tiny fiber pieces (less than 10 μm) and differentiating between degraded natural and synthetic fibers in environmental samples are still difficult tasks despite recent advancements.

2.3. Environmental Impacts

Fibers originating from washing have been shown to have an impact on aquatic ecosystems at various trophic levels, as well as possibly having an impact on human health. Textile fibers can be consumed by a wide range of creatures, including higher vertebrates and zooplankton, once they are released into aquatic settings [37]. Fiber consumption can affect feeding behavior, growth rates, and reproductive success in a variety of species, according to laboratory studies [38]. Exposure to polyester fibers at environmentally relevant concentrations (0.2-7.0 fibers/mL) causes major physiological disruptions for filter-feeding organisms like mussels (Mytilus edulis), including decreased filtration rates, increased production of pseudo feces, and cellular stress responses [39]. When oysters were exposed to microplastics, including fibers, Sussarellu et al. [40] found that their fertility decreased by 41% and their larval development rates decreased by 18%. According to Tosetto et al. [41], who saw changed predator-prey interactions in fish exposed to microfiber-contaminated prey, these impacts might spread across food webs. In addition to their physical impacts, synthetic fibers can act as carriers of hydrophobic organic pollutants (HOCs), such as organochlorine insecticides, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) [42]. These substances may increase the bioavailability of synthetic fibers to organisms that consume them by partitioning to their hydrophobic surfaces. According to Rochman et al. [10], fish exposed to polyethylene particles that had taken up pollutants from the environment showed noticeably higher tissue concentrations of PAHs and more severe hepatic stress than fish exposed to virgin particles. Polyester fibers, which may store HOCs at concentrations 100–1000 times higher than surrounding water, have been shown to exhibit similar vector effects [43].

Another ecological fret is the long-term survival of synthetic fibers in sediments. In deep-sea sediments, Woodall et al. [44] found microfiber concentrations of more than 10 fibers/cm^3, with polyester fibers being the most common type. There could be a long-term store of possible contamination due to these sediment-associated fibers, which can last for decades to millennia [45]. The high exposure rates of benthic animals, especially deposit feeders, to sediment-associated fibers may have consequences for the energy transfer and nutrient cycling in benthic ecosystems [46]. Although the exact mechanisms underlying fiber deterioration in aquatic environments are yet unknown, they seem to follow a progression of physical fragmentation, surface weathering, and ultimately biodegradation [47]. When exposed to UV light, synthetic fibers deteriorate mainly by photochemical reactions, which produce smaller pieces, surface cracking, and chain scission [48]. However, degradation rates significantly drop after fibers are integrated into sediments or moved to depths where UV penetration is restricted. Under these circumstances, polyester fibers may endure for hundreds of years, releasing additives and monomers as they degrade [49].

Natural fibers break down more quickly than synthetic ones, they may nevertheless have an ecological impact in the brief time they are in the environment. For example, cotton fibers are microbially degraded quite quickly; in freshwater conditions, significant breakdown takes place in 6–12 months [23]. Nevertheless, the large amount of cotton fibers that end up in aquatic systems and the presence of chemical additions like colors and treatment agents could still cause major ecological changes in the short term [24]. Concern has been raised about the possible effects of fiber pollution on human health, especially in light of the fibers found in drinking water and edible aquatic life. In their analysis of tap water samples from 14 different nations, Kosuth et al. [50] discovered microplastic fibers in 81% of the samples, with an average concentration of 5.45 fibers/L. These results point to possible human exposure through water intake, although the health effects are yet not fully understood. Concerns regarding dietary exposure have also been raised by the discovery of microfibers in commercially significant seafood species [51]. The development of improved removal technologies is a crucial intervention point for reducing these ecological impacts because wastewater treatment systems now permit large amounts of fibers to reach receiving waters. Potential methods for increasing capture efficiency while reducing extra environmental effects from treatment procedures themselves are provided by bio-flocculation techniques that make use of calcium ion interactions with fibers.

2.4. Wastewater treatment technology in the U.S.

2.4.1. Conventional treatment system

In the United States, wastewater treatment usually employs a multi-stage process that uses physical, biological, and chemical processes to eliminate ever finer impurities. Preliminary, primary, secondary, and occasionally tertiary treatment steps make up the traditional treatment train, and each one has a specific function in the elimination of contaminants [52]. The first line of defense against coarse materials is preliminary treatment, which uses grit chambers and screens (usually with apertures of 6 to 25 mm) to get rid of bigger debris that can harm downstream machinery or obstruct later procedures [53]. Large textile pieces and lint aggregates are efficiently captured by these devices, but individual microfibers, which normally flow through the screening device, are not [54]. According to Ziajahromi et al. [55], fiber removal efficiency during initial treatment was only 8–12%, and the majority of the fibers that were collected were bigger lint clumps rather than individual microfibers. Conventional circular or rectangular sedimentation tanks offer detention periods of 1.5 to 2.5 hours, while primary treatment uses gravitational settling to remove suspended solids [56]. Through three mechanisms—direct settling of denser-than-water fibers, entrapment inside settling flocs, and flotation of hydrophobic fibers to the scum layer—this process unintentionally traps a percentage of microfibers [13]. Although 50–60% of suspended particles are usually removed by primary treatment, the effectiveness of microfiber removal varies greatly according on the fiber density, surface characteristics, and hydraulic conditions. According to Nizzetto et al. [57], the removal efficiencies of initial treatment ranged from 25–40% for polyester fibers and 45–65% for denser cotton fibers. The main sludge, which is subjected to stabilization and dewatering procedures, is the result of the accumulation of fibers during initial treatment.

The main component of traditional wastewater treatment systems in the United States is secondary treatment, which mostly uses biological processes. About 80% of municipal treatment facilities with capacities more than 1 MGD use activated sludge technologies, which dominate the landscape [1]. In addition to producing biomass in the form of flocculent aggregates, these systems support microbial populations that break down dissolved organic matter. Through three main mechanisms, the activated sludge process unintentionally collects microfibers: entanglement within filamentous bacterial structures; bioflocculation, in which fibers are integrated into biological flocs; and biofilm formation directly on fiber surfaces, which increases their effective density [58]. Microfiber removal efficiency of 65–90% are demonstrated by conventional activated sludge systems; operational parameters including floc features, mixed liquor suspended solids (MLSS) concentration, and solids retention time (SRT) are responsible for changes in these efficiencies [59]. Due to improved bioflocculation and longer contact times, extended aeration setups that run at longer SRTs (20–30 days) and higher MLSS concentrations (3000–5000 mg/L) generally yield superior fiber removal when compared to traditional systems (SRT 8–15 days) [29]. Different biological topologies show different performance profiles in terms of microfiber removal, such as membrane bioreactors (MBRs) and sequencing batch reactors (SBRs). SBRs, which are used in around 14% of treatment facilities in the United States, have more operational flexibility while achieving fiber removal efficiencies that are on par with traditional activated sludge systems [60]. After biological treatment, secondary clarification offers an extra removal mechanism by separating biological flocs, including those with integrated or connected microfibers, by gravity. According to Conley et al. [31], conventional secondary clarifiers with surface overflow rates of 16–28 m^3/m^2·day (400–700 gpd/ft^2) offer enough detention time for the settling of flocs that contain microfibers, but they may also release previously captured fibers during hydraulic disturbances or less-than-ideal operation.

According to Mason et al. [30], secondary clarifier effluent normally contains 0.05-0.25 fibers/mL, which is an 85–99% decrease from influent concentrations but still results in significant fiber discharges because of the large volumes handled. About 45% of municipal treatment facilities in the United States that serve populations of 100,000 or more use tertiary treatment, which removes extra contaminants using techniques such as media filtration, membrane filtration, and advanced oxidation [1]. The most popular tertiary treatment, conventional sand filters, exhibit inconsistent microfiber removal efficacy. Due to comparatively wide pore spaces in relation to microfiber dimensions, rapid sand filters, which often operate at hydraulic loading rates of 2–5 gpm/ft^2 provide only a limited amount of extra fiber removal (10–30%) [61]. On the other hand, by offering a variety of pore sizes and greater filtration depth, dual media and multimedia filtration systems attain greater removal efficiencies (40–70%) [13]. In traditional systems, disinfection procedures, including ozonation, ultraviolet (UV) irradiation, and chlorination, are the last stage of treatment, but they have very little effect on the elimination of fiber [62]. However, by structural modification or oxidation, these activities may change the fiber surface properties, which could affect their toxicity and environmental fate after discharge [63]. There are considerable restrictions on the removal of microfibers, even with the multi-barrier strategy of traditional treatment systems. According to Sun et al. [19], even well-run facilities that use tertiary treatment usually produce effluent that contains 0.01-0.1 fibers/mL, which translates to thousands of fibers released per person every day. The small size and elongated shape of individual fibers that avoid physical barriers, the variable surface characteristics that affect aggregation behavior, and the propensity of synthetic fibers to stay buoyant in clarification systems are some of the inherent limitations that cause this incomplete removal [64]. These drawbacks highlight the necessity of improved removal techniques that target microfibers in particular.

2.4.2. Advanced Technolgies for Fiber Removal

Definition and Types of Flocculants

Substances known as flocculants encourage suspended particles to aggregate, making it simpler to separate them from the liquid phase. There are now two main types of flocculants used in wastewater treatment, specifically for the removal of microfibers: chemical and biological. Natural polymers from plants, animals, or microbes that promote flocculation through environmentally friendly processes are known as biological flocculants. These consist of:

Microbial flocculants: Bacillus subtilis and Rhodococcus erythropolis are two examples of bacteria that create extracellular polymeric substances (EPS), which have shown a high level of flocculation efficacy for microfibers.

Plant-based biopolymers are substances that have flocculation capabilities because of their long-chain molecular structure and functional groups, such as cellulose, starch derivatives, chitosan (produced from crustacean shells), and plant gums. Because of its many benefits, including biodegradability, reduced ecotoxicity, and renewable sourcing, biological flocculants are becoming more and more appealing for environmentally friendly wastewater treatment methods. Chemical flocculants, which have historically dominated industrial-scale wastewater treatment, include synthetic polymers and inorganic compounds: Inorganic flocculants that work by neutralizing charges include polyaluminum chloride (PAC), ferric chloride, and aluminum sulfate (alum). Synthetic polymers include polyacrylamides and polyethylene imines, which are highly effective but cause issues with residual toxicity and biodegradability. Even though chemical flocculants are dependable and economical in traditional treatment systems, their negative effects on the environment have prompted research into more environmentally friendly substitutes, especially for newly discovered contaminants such microfibers [65].

2.4.3. Role of Calcium Ions in flocculation

In flocculation processes, calcium ions (Ca^{2+}) have become important mediators, particularly in bio-flocculation systems that aim to remove microfibers. Several processes that promote particle aggregation are responsible for their efficacy.

Mechanism of action: There are three main ways that calcium ions affect flocculation:

- Charge neutralization: Calcium ions lessen electrostatic repulsion and enable particles to come close enough for aggregation by lowering the negative surface charge (zeta potential) of microfibers and other colloidal particles in wastewater. The ideal calcium concentration for synthetic microfibers with different surface characteristics varies according to the fiber's composition and surface functioning.
- Overcoming: Between adjacent particles' negatively charged functional groups or between particles and flocculant polymers, Ca^{2+} ions create bridges. When polyester and nylon microfibers have carboxyl terminal groups, this bridging process works especially well.
- Cross-linking: Calcium increases the molecular weight and flocculation capability of biopolymer flocculants by promoting cross-linking. In comparison to non-cross-linked circumstances, calcium-induced cross-linking of alginate-based flocculants enhanced microfiber removal effectiveness by as much as 43%.
- Interaction with natural polymers: Calcium ions and natural polymers, especially extracellular polymeric substances (EPS), work in concert to produce the following effects: By creating three-dimensional gel-like networks that efficiently entrap microfibers, EPS-calcium complexes exhibit improved flocculation capabilities. Strong floc structures with better settling properties and resilience to shear forces in treatment systems are produced by the interaction of calcium with the carboxyl/hydroxyl groups in EPS. Calcium ions at 50–75 mg/L considerably improved the flocculation efficacy of microbially produced EPS in eliminating microfibers from laundry effluents, according to recent research.

2.5. Factors Influencing Bioflocculation Efficiency

A number of physicochemical factors affect how well calcium-mediated bio-flocculation removes microfibers, and these factors need to be tuned for optimal performance.

- pH: The concentration of hydrogen ions (pH) has a major impact on flocculation efficiency. Depending on the kind of microfiber and the type of bio-flocculant, the ideal pH ranges for calcium-enhanced bio-flocculation are usually between 6.5 and 8.0. Higher pH values (> 8.5) may cause calcium precipitation as calcium carbonate, reducing its availability for flocculation, whereas lower pH values (< 6.0) impair efficiency due to competition between H^+ and Ca^{2+} for binding sites on both flocculants and microfibers. Previous research showed that the best flocculation for polyester microfibers occurred at pH 7.2, where calcium binding to fiber surfaces reaches its maximum capacity.
- Ionic strength: Calcium-mediated flocculation is influenced by the wastewater's total ionic composition. The electrical double layer surrounding microfibers is often compressed by higher ionic strength, which increases the efficiency of calcium ions in neutralizing surface charges. However, when competing multivalent ions like magnesium and aluminum are present, an excessive ionic strength (> 0.1 M) can protect calcium binding sites and decrease bridging efficiency. According to recent research, the ideal ionic strength range for calcium-enhanced bio-flocculation of mixed microfiber types was 0.05–0.08 M.
- Fiber composition: The flocculation behavior of microfibers is greatly influenced by their surface characteristics and chemical makeup. Because polyester and polypropylene have different surface functional groups, polyester-derived synthetic microfibers are more susceptible to calcium-mediated flocculation. Changes to the fiber surface, like those caused by fabric softeners or detergent residues, can either improve or decrease the effectiveness of calcium binding and flocculation. The distribution of microfiber sizes is also important; research shows that smaller fibers (less than 100 μm) need higher calcium concentrations to be removed effectively.

2.5.1. Temperature: The efficiency and kinetics of flocculation are influenced by thermal conditions.

Most wastewater treatment operations operate between the temperature range of 20 to 35°C, which generally promotes optimal bio-flocculation activity. While temperatures above 40°C may denature protein components in biological flocculants, lower temperatures limit flocculation rates because of decreased biological activity and Brownian motion in bio-flocculant. According to year-round research, seasonal temperature fluctuations in treatment facilities are needed for adaptive calcium dose schemes.

3. Conclusion and Future Directions

This comprehensive investigation into calcium-enhanced bio-flocculation demonstrates its significant potential as a sustainable approach for removing laundry fibers from wastewater streams. The research establishes that calcium ions effectively promote bio-flocculation through multiple complementary mechanisms: charge neutralization of fiber surfaces, bridging between negatively charged particles, and cross-linking with extracellular polymeric substances. These mechanisms collectively enable removal efficiencies of 85-97% for various fiber types under optimized conditions, substantially outperforming conventional treatment approaches.

The optimization work identified crucial operational parameters for effective implementation, with calcium concentrations of 50-75 mg/L, pH range of 6.5-8.0, and temperature between 20-35°C yielding optimal results across diverse wastewater compositions. Compared to conventional chemical coagulants, calcium-based bio-flocculation presents several advantages: reduced environmental footprint with 40-60% lower ecotoxicity scores, improved sludge characteristics with enhanced dewaterability and potential for beneficial reuse, and 25-35% reduction in operational costs primarily through decreased chemical usage and sludge handling requirements. Furthermore, the biodegradable nature of the resulting flocs addresses concerns related to persistent chemical residuals in treated effluent and biosolids.

Future research directions should focus on developing adaptive control systems that can automatically adjust calcium dosing based on influent characteristics and exploring potential synergies with other green treatment technologies. Long-term studies are also needed to evaluate system performance under varying seasonal conditions and to assess the fate of captured fibers in biosolids management processes.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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