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Fibrous super-bridging agents simultaneously improve contaminants removal and sludge dewatering via a very compact three-in-one process

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A compact three-in-one water treatment process, combining a flocculant, a fibrous super-bridging agent, and a screen-based floc retention system, simultaneously improves water treatment and sludge dewatering. The presence of fibrous materials allows for the formation of very large flocs, efficient floc separation via screening (without settling), and sludge dewatering through a compact press-filter system. The implementation of this three-in-one process is possible due to the formation of very large fiber-based flocs. The sludge containing fibers was subsequently dewatered using a screen-based press filter without further chemical addition. The use of fibers also significantly improved the removal of total organic carbon, nanoplastics, and microplastics. This three-in-one process could be used for decentralized water treatment in drinking water and wastewater applications in small cities, marginalized communities, and developing countries. The compact process, which also performs sludge dewatering, would reduce the risks associated with mismanaged sludge to the environment and human health.

Many populations around the globe still lack access to safe drinking water and proper infrastructure for wastewater treatment and management[1,2]. In industrialized countries, urban systems for water transit and sanitation are sewer-based and supported by advanced technologies involving chemistry, microbiology, physical and bioprocess engineering, as well as significant investments from high-income governments. The United Nations Sustainable Development Goals report that more than half of the global population cannot afford proper sanitation and drinking water systems[3]. This global issue is exacerbated in low- and middle-income countries, where infrastructure dedicated to water management (treatment and transit) is often prohibitively expensive[4]. Consequently, several developing countries and regions, as well as remote and marginalized communities would greatly benefit from a non-sewered sanitation system combined with decentralized, simple, robust, and inexpensive water treatment processes. Drinking water, wastewater, and sludge management applications must all be prioritized to ensure public health in these regions and to reduce endemic disease[5]. For many small and remote communities in Africa and North America, the high cost of centralized treatment infrastructure limits access to drinking water[6,7]. In Canada, drinking water primarily comes from treated surface water (>70%)[8], which generally requires extensive and costly treatment to sufficiently reduce the microbiological and toxicological risks. The issue of water access primarily affects remote and Indigenous communities. Conventional treatment for drinking water production via surface water involves coagulation-flocculation and chemicals such as metal salts, which require careful monitoring for proper operation. Studies on decentralized treatment emphasize the need for low-maintenance and low-cost technologies in remote communities[9]. However, many existing systems, including low-energy filtration and decentralized coagulation, often require multiple steps and sequential tanks, posing challenges for scalability[10]. In contrast, a three-in-one reactor integrating coagulation-flocculation, settling, and sludge dewatering in a single compact unit would minimize the operational complexity. This integrated system achieves high colloid removal and could provide a cost-effective, robust solution for safe water production in small and remote communities.

The performance of coagulation requires constant monitoring and qualified operators and is sensitive to pH, temperature, dose, and mixing time/intensity, among other factors. Consequently, metal-based coagulants cannot be easily implemented in decentralized systems for remote communities. Decentralized, simpler, smaller, more autonomous, and more robust processes could be cheaper than centralized water treatment plants in

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the long term and could be democratized for drinking water production[11] to be accepted and used by communities in need that are currently affected by water scarcity and untreated wastewater. However, practical considerations must be addressed for full-scale applications. In high-turbidity waters, the screen clogging and maintenance might increase the operation complexity. Periodic backwashing or cleaning would be necessary to maintain optimal performance.

This work proposes a new decentralized water treatment process that combines fibrous super-bridging agents, cationic flocculants, and screen-based press filters. The objective of this approach is to provide an efficient, compact, and affordable three-in-one solution for small, remote, or marginalized communities, as well as an alternative to conventional centralized plants that require three sequential tanks (coagulation-flocculation (1), settling (2), and sludge dewatering (3)) for the treatment of surface water. The same proposed three-in-one reactor was used for floc removal and sludge dewatering. The combination of super-bridging agents with cationic flocculants[12–14] can contribute to improving the removal of contaminants present in water through a simple separation process using coarse screens. The optimal flocculant and super-bridging agent concentrations were first determined, as well as the optimal screen mesh size for floc separation and sludge dewatering. The turbidity was measured for each condition tested. The results showed that the addition of fibers drastically improved the floc removal[15]. No metal-based coagulants such as alum were employed[16]; the flocculant was synergistically combined with fiber-based super-bridging agents to ensure an efficient floc formation and separation via settling and screening (up to 99% turbidity removal). The impact of fibers was also evaluated on the removal of i) total organic carbon, ii) nanoplastics, and iii) microplastics (polyethylene microbeads and polyester microfibers) all of which showed considerable improvement compared to the conventional treatment without fibers[17,18]. To evaluate the versatility and robustness of the fibrous treatment, two water samples from the Democratic Republic of the Congo (DRC) were also tested. It is crucial to note that these surface water samples exhibited significantly higher turbidity levels than those in Canada. Therefore, adapting the process to the African context is essential for effective treatment while maintaining a simplified and cost-effective approach.

Results and discussion

Impact of super-bridging agents on conventional and emerging contaminants

Conventional treatment required large amounts of both metal-based coagulants (e.g., alum) and synthetic flocculants (e.g., PAM) (Fig. 1a; a1), whereas, fiber-based treatment only required PAM (Fig. 1b; b1). In the context of decentralized water treatment, it is preferable to avoid the use of metal-based coagulants, which require monitoring, pH control, and precise dosage adjustment to maintain process performance. Herein, the separation process was designed to be more robust and simpler by using PAM without metal-based coagulant. Compared to conventional treatment (PAM, no fibers; Fig. 1a), the flocs formed by combining fibers and PAM (Fig. 1b) were approximately 7–10 times larger, depending on the concentration of PAM and fibers[19,20]. Fig. 1c, d show the impact of fiber-based superbridging agents on the removal of total organic carbon, turbidity, nanoplastics, and microplastics (after floc separation with a 500 µm screen mesh). When fibers were synergistically combined with a cationic flocculant (200 mg fibers/L and 1.2 mg c-PAM3/L), the removal of all contaminants was drastically improved. For turbidity, removal increased from 39% without fibers to 94% with fibers, while nanoplastic removal increased from 20% to 72%. As described elsewhere[21,22], microplastic and nanoplastics could be used to model and predict virus removal during filtration. Consequently, based on the nanoplastic and microplastic removals shown in Fig. 1d, the screen-based separation method could be used in combination with fibers for drinking water application to offer some protection against viruses and other pathogens[23–25]. For microplastics, the impact of fiber-based superbridging agents was also noticeable and statistically significant: removal increased from 49% to 91% for polyethylene and from 64% to 95% for polyester. Such improvements using fibers have also been observed elsewhere[26]. Cellulose fibers act as super-bridging agents due to their effective length, large surface area, high aspect ratio, and functional groups capable of interacting with both particles in suspension and flocculants (e.g., cationic PAM). When fibers are added, they serve as a structural framework within the solution, providing additional sites for particle attachment, which facilitates the formation of larger and more stable flocs. The cationic PAM is attached to the negatively charged sites on both the cellulose fibers and suspended particles, acting as a bridging structure. Such fiber-based bridging agent was also reported before for increasing the overall size and stability of the flocs[27]. Similar improvements in turbidity and microplastic removal were previously observed for settling treatment when fibers were used in the aggregation process[27,28].

Robustness of super-bridging agents for different water types

The impact of PAM concentration was tested during floc separation via settling (3 min) versus pressing (500 µm screen mesh) (Fig. 1b; b2). The screen-based pressing system replaced the settling unit and was also used as an alternative to membrane filters or granular filters for drinking water applications (objective <0.3 NTU, as required by regulations in North America; Fig. 1b; b5). The replacement of membrane or granular filters with a coarse screen mesh was possible due to the formation of very large fiber-based flocs. The drinking water minimal standard (<0.5 NTU) was not achieved when screens were used in combination with flocculant alone (conventional treatment; no fibers). When the PAM concentration was insufficient to initiate aggregation (<0.2 mg PAM/L), the impact of fibers was not noticeable, and both treatments provided low turbidity removal (<8%). However, at a concentration of 0.4 mg PAM/L, the presence of fibers significantly improved floc formation and turbidity removal up to 85%, compared to only 40% without fibers. This improvement with fibers was observed for both floc separation methods: settling (Fig. 2a) and pressing (Fig. 2b). When the concentration of PAM was increased to 0.8 mg/L, both treatments resulted in slightly lower turbidity removal of 78% and 33%, with and without fibers, respectively. This decrease was attributable to temporary charge reversal caused by the cationic PAM[29–31]. At concentrations of 1.2, 2.0, and 3.0 mg PAM/L used with fibers, the residual turbidity after settling was 0.39, 0.46, and 0.39 NTU, respectively (93–94% removal). For the same respective PAM concentrations without fibers, turbidity removal drastically dropped to 41–45%. Based on a paired *t*-test, there was no statistically significant difference between the settled and pressed turbidity values. For suboptimal PAM concentrations (<0.4 mg/L), contrary to settling, the pressing system captured more (smaller) flocs and partially compensated for the poor aggregation due to insufficient PAM concentration in the system. The concentration of 1.2 mg PAM/L was chosen as the optimal value under which all contaminant removal curves reached a plateau.

The same steps were conducted on Democratic Republic of the Congo B (DRC B) water (Africa) to investigate the impact of PAM concentration during floc separation after settling (3 min) and pressing (200 µm screen mesh). At a lower PAM concentration (0.2 mg/L), the presence of fibers showed no significant impact, reducing turbidity by only 30% after 3 min of settling, indicating poor floc formation. Pressing only achieved a 24% reduction, suggesting that small flocs passed through the mesh. A noticeable impact of fibers was observed at 0.8 mg PAM/L or higher (Fig. 2c, d). At 2 and 3 mg PAM/L, turbidity with fibers was 34 and 23 NTU after 3 min of settling, respectively, and 38 and 23 NTU after pressing. Differences between settling and screening were not statistically significant when fibers were used, as large flocs were effectively removed via both separation methods. Considerably higher turbidities were measured without fibers: 62 and 33 NTU after 3 min of settling, and 55 and 37 NTU after pressing, with 2 and 3 mg PAM/L, respectively. To reach the lowest residual turbidity, 3 mg PAM/L was selected for further investigations on DRC B water.

The difference in treatment effectiveness between DRC-B and synthetic water could be explained by the respective raw water turbidity (6 NTU vs. 589 NTU). With higher turbidity, aggregation systems usually required more coagulant and flocculant – hence forming large floc without the need of fibers of other promoting agents such as ballast media[27,28].

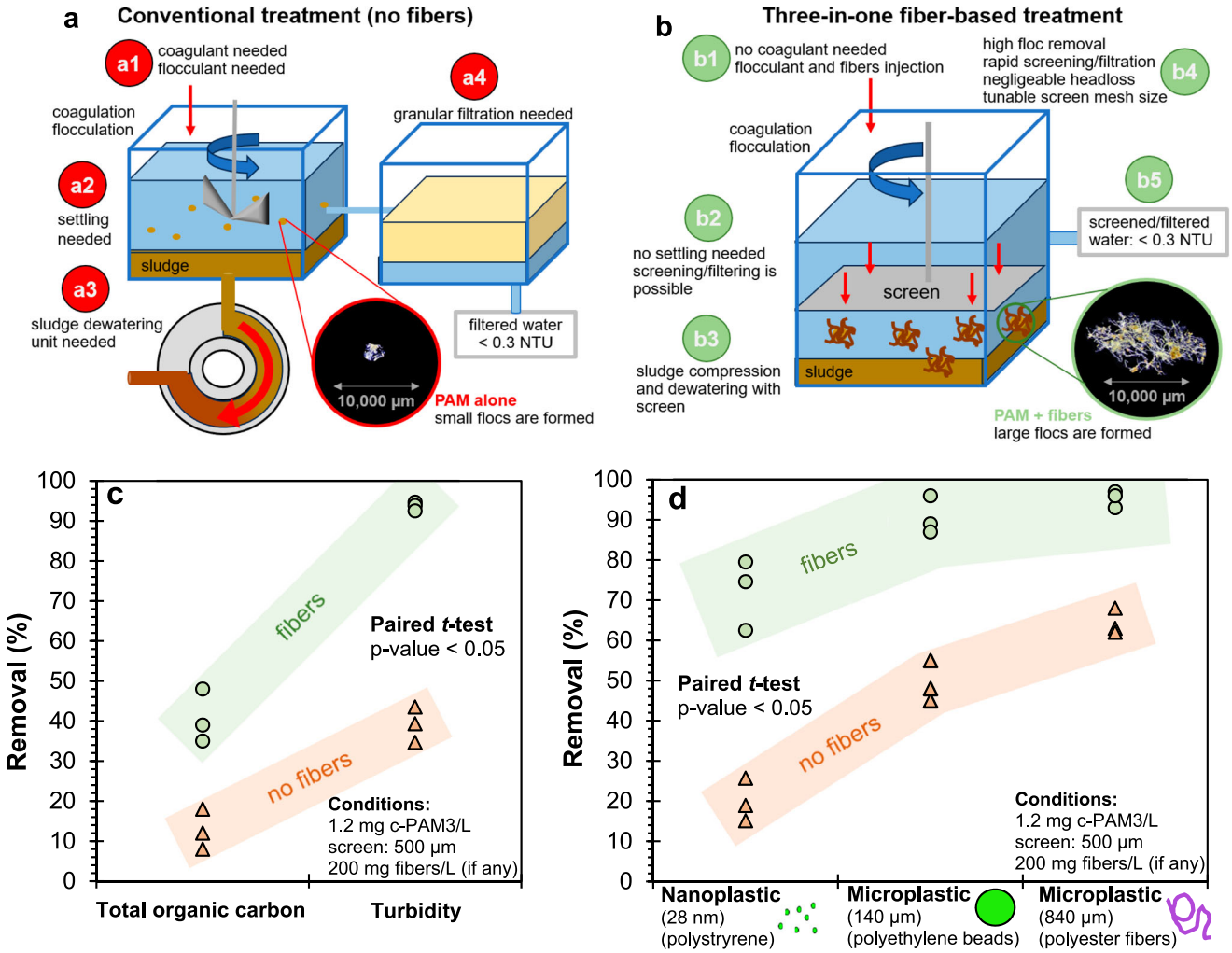


Fig. 1 | Contaminant removal improvement using fibers. a Conventional treatment combining polyacrylamide and screening: the flocs formed are too small to be screened and filter press can't be used to dewater the sludge. **b** Fiber-based treatment combining polyacrylamide, fibers, and screening (filter press): the flocs formed are very large and are screenable (filter presses; tested mesh sizes of 20–5000 µm), while filter press can be used to dewater the sludge. **c** Impact of fibers on the removal of total organic carbon and turbidity after screening. **d** Impact of fibers on the removal of nanoplastics, polyester fibers, and polyethylene beads after screening. Treatment conditions (c and d): 0.4–3.0 mg c-PAM 3/L, 200 mg fibers/L, 4 min of flocculation at pH 7.0 ± 0.3, temperature of 21 °C, flocs were removed during pressing with a 500 µm screen mesh (lab-scale press filter). Raw water turbidity: 6.0 ± 0.5 NTU. Colored areas (orange and green) are included as eye guides showing the minimal and maximal values (triplicate experiments). The difference between fibrous and conventional treatment (no fibers) was statistically significant (p-value < 0.05; **c** and **d**). Tested waters: St Lawrence River (**c**) and synthetic water (**d**).

Reducing the microbiological risk for decentralized applications

The optimal PAM concentration of 1.2 mg/L (synthetic water) was used to determine the optimal fiber concentration. The lowest turbidity (0.39 NTU) after settling and pressing was observed at 200 mg of fibers/L (Fig. 3a, b). This value complies with North American standards for drinking water and the design guide for drinking water production facilities, which requires post-filtration turbidity to be less than 0.5 NTU. This suggests that further improvements to the system or the use of smaller screen mesh sizes (e.g., 50 or 100 µm) could potentially achieve higher drinking water quality (e.g., <0.3 NTU for granular filtration, *Surface Water Treatment Rules* (SWTRs), USEPA) to reduce the microbiological risk for decentralized applications in marginalized communities and developing countries.

The mesh sizes were modified using the optimal concentrations of PAM and fibers (1.2 mg/L of PAM; 200 mg/L of fibers). The mesh size had minimal influence on turbidity (p-value: 0.37) (Fig. 3c). This could be explained by the large size of the flocs formed, allowing separation even with larger screen mesh sizes (0.45 NTU with a 2000 µm screen). For these tested conditions, screen mesh sizes of 50 and 20 µm reduced the turbidity to 0.32 NTU and 0.20 NTU respectively (Fig. 3d). It is hypothesized that smaller meshes were required to remove colloids that were not aggregated into the large fiber-based flocs. The 50 µm mesh in this study acts as a polishing filter to achieve turbidity levels below 0.3 NTU by capturing residual colloids. For such application with finer mesh size, as the turbidity is already low (0.39 NTU), minimal clogging is expected. For scalability, fine-mesh filtration in larger systems may face challenges related to maintenance and operational costs. However, in low-turbidity contexts, a low particle flux suggests less maintenance. Incorporating automated backwashing or using durable mesh materials could further support scalability, durability and performance. Future studies are needed to assess the mesh durability under continuous flow conditions. Optimization of mixing conditions (time and intensity) could also be performed to minimize shear stress on flocs and prevent floc breakage. According to the USEPA, the *RQEP* (Regulation on the Quality of Drinking Water in Canada), and the drinking water design guide (Ministry of the Environment, Quebec, Canada), after filtration, each filter should have a turbidity of less than 0.5 NTU, and water entering the distribution network should have a value below 1 NTU[32]. Although the results are compliant, they do not qualify for all the removal credits for *Giardia*, *Cryptosporidium*, and viruses[33]. For granular filtration, it is advised

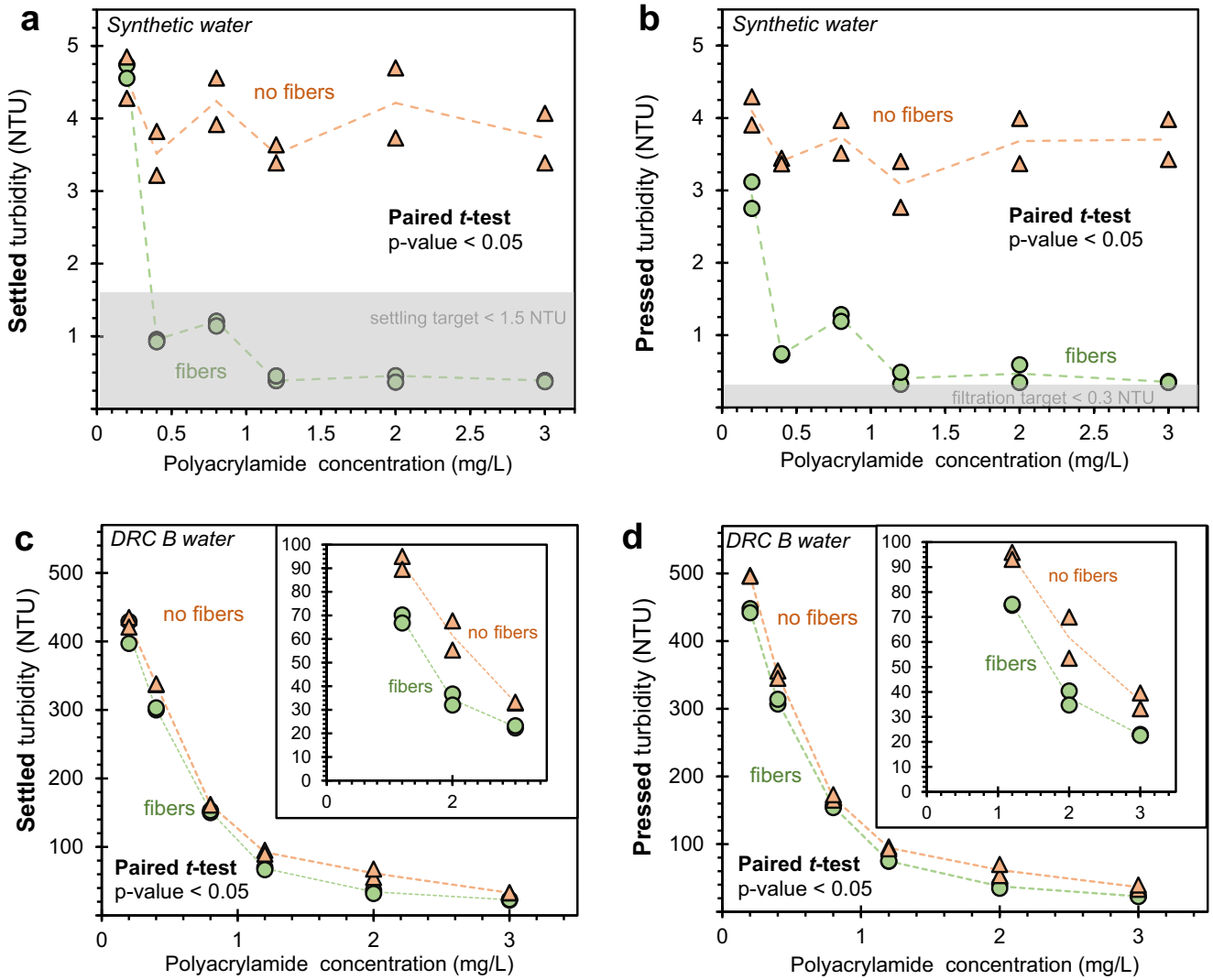


Fig. 2 | Performance of fibers on different water types. Impact of fibers on turbidity removal after 3 min of settling (synthetic water (**a**); DRC B water (**c**); *cf* Table 1). Impact of fibers on turbidity removal after pressing (synthetic water (**b**); DRC B water (**d**)). A 500 µm and a 200 µm screen mesh size were used for synthetic water and DRC B water, respectively. Aggregation conditions: 0.4–3.0 mg c-PAM 3/L, 200 mg fibers/L, 4 min of flocculation at pH 7.0 ± 0.3, temperature of 21 °C (**a**–**d**). Synthetic water turbidity: 6 NTU (**a**, **b**). DRC B water turbidity: 589 NTU (**c**, **d**). Dashed lines are included as eye guides connecting average values obtained from duplicate experiments. Grey areas show the industry standard after treatment: <1.5 NTU after settling and <0.3 UTN after pressing (screened-based press filter used as an alternative to membrane or granular filtration). The difference between fibrous and conventional treatment (no fibers) was statistically significant (p-value < 0.05; **a**–**d**).

to achieve a turbidity lower than 0.3 NTU for better removal credits from a safety standpoint, and ideally to achieve a turbidity below 0.15 NTU to obtain all removal credits[34]. For drinking water applications, the fiber and screen-based separation process presented in this study could be combined with disinfection to gain additional removal credits. Improving the PAM and fiber synergy and selecting the proper screen mesh size to achieve turbidity below 0.3 NTU would also be necessary to reduce the amount of chlorine needed for providing safer drinking water and reducing disinfection by-product formation[35,36] in marginalized communities and developing countries.

Performances of fibers with different physicochemical treatments

Different PAMs with varying charge densities and molecular weights were tested to determine the optimal flocculant properties for forming very large fiber-based flocs. After settling, the turbidity was 0.7, 0.4, 0.7, and 9.9 NTU for c-PAM 4, c-PAM 3, c-PAM 2, and c-PAM 1, respectively (Fig. 4a). No significant difference (p-value > 0.05, paired t-test) was observed between the settled (3 min) and pressed turbidities (mesh size of 200 µm), except for c-PAM 1, which showed lower final turbidity of 9.8 NTU and 7.3 NTU after settling and filter-pressing, respectively (Fig. 4b). In contrast to c-PAM 2, c-PAM 3, and c-PAM 4, which have higher charge densities (35% or 55%), the charge density of c-PAM 1 (only 7%) was not sufficient to destabilize and aggregate colloids via electrostatic affinities. Compared to c-PAM 3 without fibers, c-PAM 4 typically provides better floc formation and removal due to its higher molecular weight (*cf*. Fig. 7). However, when fibers are used as super-bridging agents—drastically promoting floc formation and size—the higher molecular weight provided by c-PAM 4 did not result in better turbidity removal compared to c-PAM 3. Based on the settled and pressed turbidities in Fig. 4b, a minimum charge density of 35% (c-PAM 2) was required to complete colloid destabilization and attachment onto the fiber structure.

Although fibers can be used in a very simple system combining only one flocculant with screen pressing (without settling and filtration), they can also be used in more advanced physicochemical treatments combining metal salts and PAM (both anionic and cationic) (Fig. 4c, d). The impact of alum concentration (0–100 mg dry alum/L) is shown in Fig. 4c, while the impact of more advanced physicochemical treatments on low, moderate,

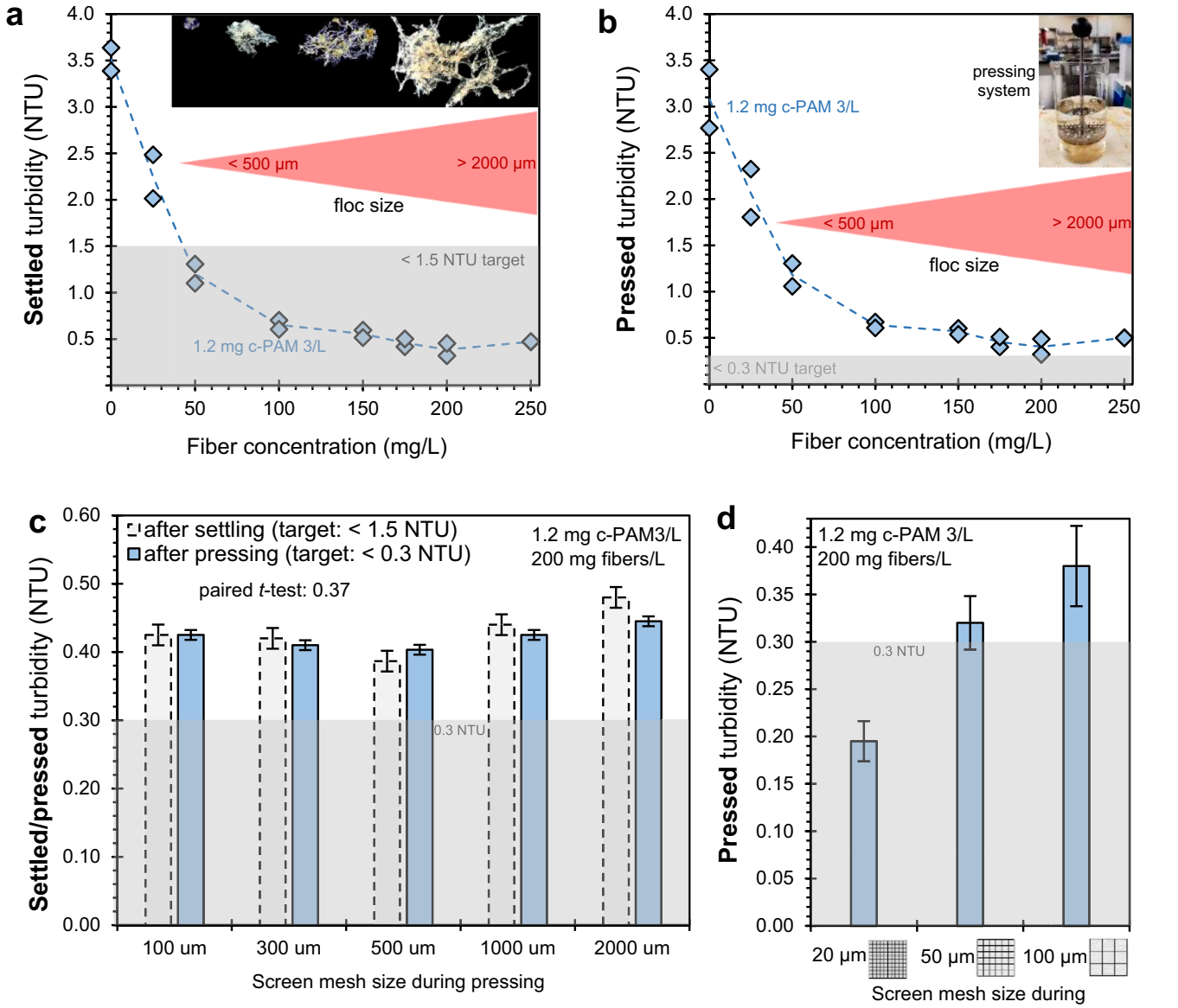
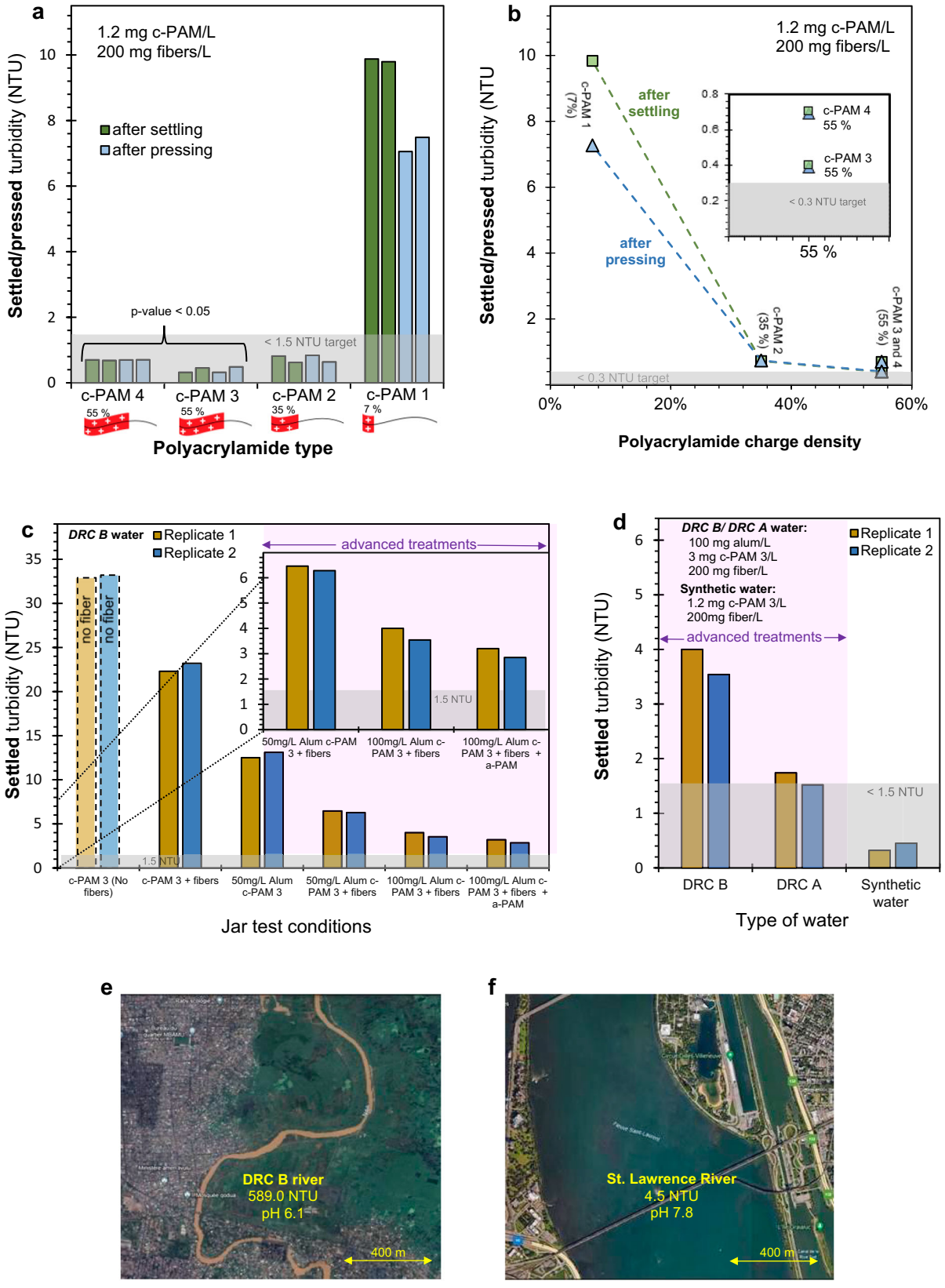


Fig. 3 | Process optimization to reduce the residual turbidity. Impact of fibers concentration on settled turbidity (**a**, 3 min of settling) and pressed turbidity (**b**, 500 µm screen mesh). **c** Impact of the screen mesh size (100, 300, 500, 1000, and 2000 µm) on pressed turbidity. Settled turbidites (no screen was used, grey bars) are shown as a reference. **d** Impact of smaller screen mesh size (20, 50, and 100 µm) on pressed turbidity. Aggregation conditions (**a**–**d**): 1.2 mg c-PAM3/L, 4 min of mixing, pH 7 ± 0.5, temperature of 21 °C. Turbidity of synthetic water (a–d): 6.0 ± 0.5 NTU. Dashed lines are included as eye guides connecting average values obtained from duplicate experiments (**a**, **b**). Grey areas show the industry standard after treatment: <1.5 NTU after settling and <0.3 UTN after press-filtering. Error bars represent the standard deviation (**c**, **d**).

and high turbidity water is shown in Fig. 4d. Such advanced physico-chemical treatment was required to improve aggregation and meet turbidity objectives after settling (<1.5 NTU) for African waters with very high turbidity (589 NTU). Settled turbidities of 3.75 NTU (99.4% removal, raw water: 589 NTU) and 1.63 NTU (98.0% removal, raw water: 78 NTU) were measured for DRC B and DRC A waters, respectively. The enhanced turbidity reduction observed with alum, c-PAM3, and fibers is due to their complementary roles in coagulation-flocculation. Alum neutralizes the negative charges on colloidal particles, allows precipitation of soluble compounds, and initiating aggregation, while c-PAM3 bridges these aggregates into larger flocs. Fibers further stabilize the flocs by providing additional surface area and structural support, forming a dense, resilient network with improved settling properties. This synergistic effect is evident when comparing results: using alum and c-PAM3 alone (50 mg/L alum and 3 mg/L c-PAM3) resulted in an average turbidity of 12.8 NTU. With the addition of fibers and an increased alum concentration (100 mg/L), turbidity further decreased to 3.75 NTU. These findings highlight the critical role of fibers as bridging agents, significantly enhancing floc formation, size and stability. As shown in Fig. 4d, further optimization efforts are needed to reach the target of 1.5 NTU for DRC B water; for example, pH adjustment, prehydrolyzed coagulants, optimal agitation intensity and/or aggregation time, optimal settling time, and smaller screen mesh sizes could be tested to achieve better water quality[37–39] Nonetheless, the fiber-based treatment considerably improved turbidity removal compared to conventional treatment, which resulted in a settled turbidity of 33 NTU.

Reducing polyacrylamide concentrations for drinking water application

Synthetic polymers, such as acrylamide-based polymers, are essential in clarification and remain necessary for the proposed fibrous treatment



herein. However, these synthetic polymers have faced criticism for their i) potential toxicity[40] (group 2A), ii) clogging effect in membrane/screen, and iii) cost[41–43]. For implementation in marginalized communities and developing countries, the process needs to be operated at low cost (low operational expenditures), and systemic/heavy process maintenance must be avoided. Consequently, the PAM concentration was reduced, and the inevitable formation of smaller flocs was compensated for by using a smaller screen mesh (Fig. 5).

The 500 µm mesh size was effective for a PAM concentration of 0.2 mg/L. Additional tests were conducted for different mesh sizes at both

Fig. 4 | Fibers used with physicochemical treatments. a Impact of polyacrylamide type (*cf* Fig. 7) on settled and pressed turbidity. Paired *t*-test between c-PAM 3 and c-PAM 4: *p*-value < 0.05. **b** Impact of polyacrylamide charge density on settled and pressed turbidity. Dashed lines are included as eye guides connecting average values obtained from duplicate experiments (**b**). **c**, **d** Different physicochemical treatments combining alum, c-PAM 3, and a high molecular weight anionic flocculant (a-PAM) for highly and moderately turbid water. Synthetic water: 6 NTU, at pH 7.0 (**a**, **b**). DRC B water: 589, at pH 6.1 (**c**, **d**). *DRC A* water: 78 NTU, at pH 6.7 (**d**). Aggregation conditions: 4 min of mixing at 21 °C. Floc separation: 3 min of settling or press filtering with a 200 µm screen mesh (**a**–**d**). Grey areas show the industry standard after treatment: <1.5 NTU after settling and <0.3 UTN after press-filtering (**a**–**d**). **e** Image of DRC B river (high turbidity and low pH and alkalinity). **f** Image of the St. Lawrence River (low turbidity and high pH and alkalinity).

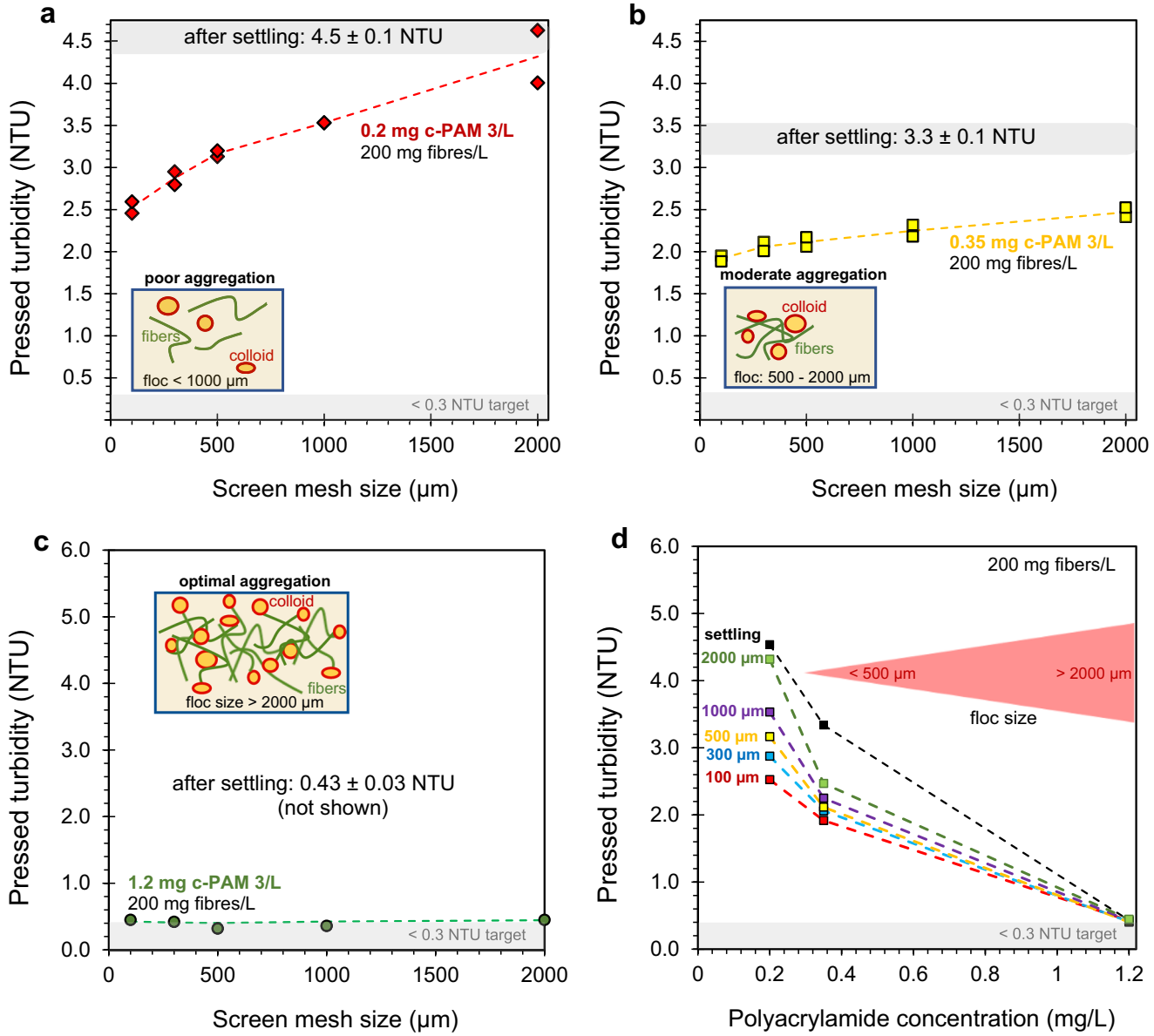


Fig. 5 | Limiting the use of synthetic flocculant for flocs separation via screening. Pressed turbidity with different screen mesh sizes with 0.2 mg c-PAM/L (**a**), 0.35 mg c-PAM/L (**b**), and 1.2 mg c-PAM/L (**c**). **d** Pressed turbidity obtained with different c-PAM concentrations and screen mesh sizes. Settled turbidities in **d** are shown as a reference (no pressing was performed). Conditions for **a**–**d**: 4 min of mixing, pH 7 ± 0.5, temperature of 21 °C, 3 min of settling (if any), tested screen mesh size: 100, 300, 500, 1000, and 2000 µm. Type of PAM: c-PAM 3. Fiber concentration: 200 mg/L. Turbidity of raw water: 6 ± 0.5 NTU. Dashed lines are included as eye guides connecting average values obtained from duplicate experiments.

0.2 mg/L and 0.35 mg/L PAM concentrations. At this concentration, the floc's size was visibly affected. Turbidity values measured after pressing decreased as the mesh size became finer (Fig. 6a, b). When the PAM concentration was low, the bridging effect between fibers was diminished, leading to smaller and more fragile flocs, a phenomenon also reported in a previous study[27,44]. However, at 1.2 mg PAM/L, turbidity removal was not noticeably impacted by the screen mesh size, as the flocs formed were very large and were intercepted by all the tested screen mesh sizes (100–2000 µm; Fig. 6c). The impact of the mesh size and PAM concentration on the turbidity is displayed in Fig. 6d. As the measured turbidities after pressing were still very low, the process could also be used for sludge dewatering. As shown in Fig. 6d, the pressed turbidities were <0.5 NTU, even though the sludge

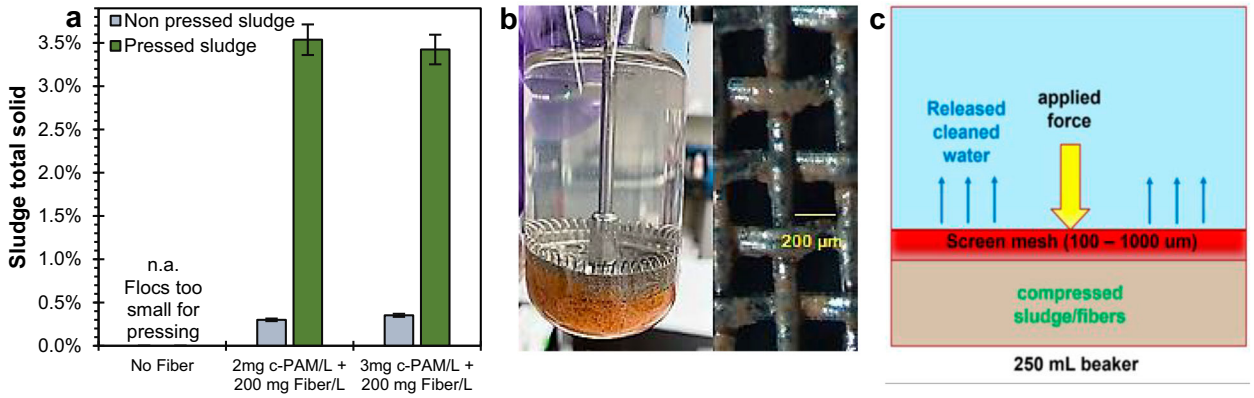


Fig. 6 | Improving sludge dewatering with fibrous agents. a Impact of fibers and treatment conditions on the sludge solid content (%) without pressing (grey) vs with pressing (green). **b** Pressed sludge after the fibrous aggregation treatment (left) and microscope image of the 200 µm screen mesh (right). **c** Schematic diagram showing the compression of the fibers-based. DRC B raw water conditions: 589 NTU, pH 7.0, temperature of 21 °C. Error bars correspond to the standard deviation calculated from triplicate experiments (**a**).

Fig. 7 | Properties of polyacrylamides.

Tested polyacrylamides	Charge	Charge Density (%)	Molecular weight
c-PAM 1	cationic	~ 7 %	High (> 10^6 g/mol)
c-PAM 2	cationic	~ 35 %	High (> 10^6 g/mol)
c-PAM 3	cationic	~ 55 %	High (> 10^6 g/mol)
c-PAM 4	cationic	~ 55 %	Very high (> 10^7 g/mol)
a-PAM	anionic	< 10 %	Very high (> 10^7 g/mol)

was manually pressed at the bottom of the 250 mL reactor (200 mg fibers/L, 500 µm screen mesh, *cf* Fig. 3b). The volume of sludge collected after pressing was <5 mL for all the jar tests performed. Consequently, this three-in-one reactor is a promising compact technology for contaminant aggregation, floc separation, and sludge dewatering (as shown in Fig. 1; b3).

Sludge dewatering and management, in situ

To evaluate the solid content in African (DRC B) water samples, two concentrations of c-PAM 3 (2 mg/L and 3 mg/L) were assessed under two conditions (with and without fiber addition) and using two dewatering methods (with and without pressing). The solid content was measured by drying the recovered solids at 103 °C for 1 h to determine the dryness. As illustrated in Fig. 6, the flocs obtained without fibers could not be effectively recovered due to their small size. In contrast, the addition of fibers resulted in more visible floc formation, although the percentage of solids remained relatively low. This can be attributed to the inherent characteristics of the sludge, which may contain extracellular polymeric substances with hydrophilic functional groups. These groups play a crucial role in making i) solid-liquid separation more challenging, ii) the thermal drying process less efficient, iii) the entire process more energy-consuming[45]. Comparing the two methods (with and without pressing), the differences are noticeable, with pressing yielding an 11-fold higher solid content in sludge: from 0.3% for the conventional treatment to 3.5% for the fibrous treatment (Fig. 7a). Increasing the solid content in sludge could considerably reduce the overall costs associated with sludge treatment, such as reducing the amount of sludge transported and the energy input during thermal drying, among others[46]. Such applications could benefit both centralized and decentralized wastewater systems by offering significant advantages in terms of public health, environmental sustainability, and operational efficiency[47].

Scaling up this approach would require several adaptations to accommodate operational demands in larger wastewater treatment plants. First, consistent fiber distribution throughout the sludge is crucial to maintaining uniform floc formation and maximizing dewatering efficiency. Transitioning from lab-scale systems to larger pressing systems, such as rotary press or belt press filters, would allow automated cycles that usually improve efficiency and maintain consistency in solid content across batches[45]. The increased solid content indicates a reduction in sludge volume, translating to lower transportation and thermal drying costs. In practical settings, this could result in significant energy savings and reduced operational costs[46]. In full-scale systems, regular maintenance and adjustments to fiber dosage and pressing parameters may be necessary to account for varying sludge characteristics. Monitoring systems could enhance scalability by optimizing fiber dispersion and sludge consistency in real time. These adaptations would be essential to replicate lab-scale efficiency at larger scales – and to reduce cost associated to sludge management.

Applications and future work

This compact unit using flocculants and fibrous super-bridging agents could serve as an alternative to complex and expensive conventional physico-chemical treatments, which involve a coagulant, a flocculant, a settling tank, and granular or membrane filtration. This compact unit is suitable for producing safer drinking water, wastewater applications, and sludge dewatering. When combined with super-bridging agents, coarse screen-based filters offer a cost-effective separation solution compared to granular

or membrane filters, which require qualified operators and more maintenance. Various lab-scale experiments were conducted to determine the optimal PAM concentrations, fiber concentrations, and screen mesh sizes for floc separation and sludge dewatering. The addition of fibers significantly improved the removal of regulated and emerging contaminants, such as nanoplastics and microplastics. The optimized treatment achieved treated water with turbidity levels below 0.2 NTU, thereby complying with drinking water regulations in North America. The treated African waters also demonstrated significant reductions in turbidity, achieving 3.77 NTU with a 99.4% reduction for DRC B raw water, and 1.6 NTU with a 98.0% reduction for DRC A raw water. Further experiments are needed to optimize floc removal, reduce residual turbidity, and minimize microbiological risks for remote, marginalized, and indigenous communities, as well as for developing countries. This three-in-one process could also reduce i) the environmental and health risks associated with mismanaged sludge—potentially at low cost—and ii) the energy required for sludge transport and subsequent processing.

Methods

Chemicals and materials

The jar tests were conducted to simulate a low-cost compact treatment process (e.g., without granular filtration) to assist isolated populations or those in developing countries that lack access to clean water. According to Health Canada, the USEPA, and the Ministry of the Environment (Environmental Quality Act; EQA)[32], the turbidity after filtration in conventional treatment systems must be below 0.3 NTU. The tested cationic polyacrylamides were supplied by Kemira Water Solution Canada Inc. and are listed in Fig. 7. The tested anionic polyacrylamide (a-PAM) was supplied by Hydrex. All solutions and suspensions were prepared using RO water. As described elsewhere[27,44], the fiber suspensions were prepared by blending 2.5 g of dried fibers in 500 mL of RO water (Ninja blender, for 7 s).

Waters characteristics

In this study, several waters were used during jar tests, including two surface waters from Kinshasa, Africa (water characteristics are listed in Table 1). Another surface water sample was taken from the St. Lawrence River in Montréal, Canada (3.2 ± 0.3 mg C/L; 4.5 ± 0.4 NTU; pH 7.8 ± 0.2). The water samples from the DRC and St. Lawrence River were selected to represent high-turbidity, particle-rich conditions and lower-turbidity surface water, respectively, showcasing the reactor's adaptability to diverse contexts. The synthetic water[28,48] was composed of 250 mL of tap water stabilized at stabilized at room temperature, 250 µL of a kaolin suspension (10 g/L), and 100 µL of a starch solution (500 mg/L). Starch was included to simulate organic matter commonly found in natural surface waters, creating a more representative model with both organic and inorganic particles for more realistic flocculation experiments. The kaolin suspension was made from fine white clay powder (Cattier), and the starch solution was made from cornstarch powder (Selection). To prepare the starch solution, 250 mg of corn starch was dissolved in 500 mL of water. For the kaolin suspension, 5 g of white clay powder was mixed with 500 mL of water. The turbidity and pH of the synthetic water were approximately 6 ± 0.5 NTU and 7 ± 0.5, respectively. The jar tests were performed using a 250 mL volume of samples in a glass beaker agitated at 200 rpm with a cross-shaped magnetic stir bar (3.5 cm×3.5 cm). The raw waters were all equilibrated at ~21 °C before each experiment.

Table 1 | Location and characteristics of the 4 tested waters

Type and source	Location	Turbidity (NTU)	pH
Surface water, St. Lawrence River	Montréal, Canada	4.5 ± 0.4	7.8 ± 0.2
Synthetic water	n.a.	6.0 ± 0.5	7.0 ± 0.5
Surface water, DRC A	Democratic Republic of the Congo	78.1 ± 0.5	6.7 ± 0.2
Surface water, DRC B	Democratic Republic of the Congo	589.0 ± 0.5	6.1 ± 0.2

Jar tests

Various concentrations of fibers, flocculant (PAM, 500 mg/L solution), and mesh sizes were tested during the jar tests. Four types of cationic PAM were used: c-PAM 1, c-PAM 2, c-PAM 3, and c-PAM 4 (see Fig. 7). The PAM solutions were prepared by dissolving 50 mg of dried PAM in 100 mL of water and mixing with a magnetic stirrer for 15 min. The turbidity objectives after settling and pressing were set to be below 1.5 NTU and 0.3 NTU, respectively (measurement range: 0.1–2000 NTU; turbidimeter Hach TL2350 model). Jar tests were performed using a Corning brand magnetic stirring plate. These objectives were used to determine the optimal doses of PAM and fiber, as well as other operational conditions under investigation (mixing time, mesh size, etc.).

The experiment began with the introduction of fibers into the synthetic water (fiber suspension dosed at 5 g/L). The cellulose fibers (eucalyptus hardwood, Sigma, NISTRM8496) were prepared by dispersing 2.5 g of cellulose in 500 mL of ultrapure water, which was blended for 10 s to achieve a homogeneous suspension. This blending process ensures the fibers dispersion, hence maximizing surface area for an effective interaction with colloids and PAM. Fibers (initial fibers suspension 5 g/L) were added at a concentration of 200 mg fibers/L to the beaker 10 s before the first half of the PAM dose was added into the system. The second half of the PAM was added after two minutes of mixing to reduce the PAM chain desorption and reconfiguration leading to floc fragmentation[43,49]. Subsequently, two minutes of mixing were followed by three minutes of settling. At this stage, an initial turbidity measurement was taken. A second turbidity measurement was performed after separating the flocs using a filter press, which kept the flocs at the bottom of the beaker (mesh size: approximately 200 µm). Different concentrations of PAM were tested: 0.2, 0.4, 0.8, 1.2, 2.0, and 3.0 mg/L. These concentrations were tested in the presence of 200 mg of fibers/L as well as in the absence of fibers (i.e., conventional treatment). Once the optimal PAM concentration was determined, additional fiber concentrations were tested to optimize the aggregation system and ultimately reduce the operational costs for full-scale applications: 0, 25, 50, 100, 150, 175, 200, and 250 mg of fibers/L.

The impact of mesh size was also tested once the optimal fiber dose was found. Pore sizes of 100, 300, 500, 1000, and 2000 µm were used. These different mesh sizes were also tested under suboptimal mixing conditions, with PAM doses of 0.2 mg PAM/L and 0.35 mg PAM/L. The quality of the treated water remained the same, except for meshes modified to compensate for aggregation affected by lower PAM doses. The measurements were conducted using a turbidimeter. An analysis vial was measured three times to minimize variability and device imprecision. For each tested treatment condition, replicates were performed in all jar tests. For the highly turbid DRC A (78.1 ± 0.5 NTU) and DRC B surface water (589.0 ± 0.5 NTU), to achieve adequate residual turbidity after treatment, 50–100 mg alum/L had to be added, along with the optimal dose of c-PAM 3 (3 mg/L) and 200 mg/L of fibers. Alum was added at the onset of the jar test, with agitation maintained for 2 min, followed by the addition of c-PAM 3 and fibers according to the previously mentioned protocol.

Total organic carbon, nanoplastics, and microplastics measurement

Fluorescent latex polystyrene nanoplastics were used in this study (28 nm, carboxylate modified, FluoSpheres, ex/em: 365/415 nm). Jar test experiments were spiked with 0.8 mg/L of nanoplastics. Polyester microfibers (PEST) were produced by blending a textile (SanMar Canada, ATC, ATC3600Y)[26,27]. The textile was blended for 5 min at room temperature using a Ninja blender (~1200 rpm)[50]. Polyethylene microspheres were obtained from Cospheric (140 µm, ex/em: 515/414 nm). Polyethylene microspheres and polyester microfibers were spiked at a concentration of 1000 microplastics/L. The properties of the tested plastics are listed

Table 2 | Properties of nanoplastics and microplastics

Type	Polymer	Shape	Mean size	Size range
Microplastic	Polyester	Fiber	840 µm (length)	460–1650 µm[27]
Microplastic	Polyethylene	Bead	140 µm (diameter)	125–150 µm
Nanoplastic	Polystyrene	Bead	28 nm (diameter)	20–35 nm

in Table 2. Turbidity measurements were performed using Standard Method 2130B (Hach 2100 N turbidimeter), and total organic carbon (TOC) measurements were performed using Standard Method 5310 C (Sievers 5310c total organic carbon analyzer, GE Water).

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Manel Mebarki: Conceptualization, Validation, Formal analysis, Investigation, Data Curation, Visualization, Writing - Original Draft. Gabriella Joge Ngale: Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft. Mathieu Lapointe: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing, Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

Competing interests

M.L. has applied for a patent on the use of fibre-based materials for water treatment. The remaining authors declare no competing interests.

Additional information

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