# Textile and industrial crops in constructed wetlands for aquaculture wastewater treatment: mechanistic roles, species performance, and research gaps

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**Abstract**. Constructed wetlands (CWs) are increasingly recognized as sustainable systems for the treatment of aquaculture wastewater, where nutrient removal is governed by complex interactions among plants, microbial communities, and substrate processes. This review critically evaluates the potential role of selected textile and industrial crops - *Chrysopogon zizanioides* (vetiver), *Phalaris arundinacea* (reed canary grass), *Cannabis sativa* (hemp), and *Hibiscus cannabinus* (kenaf) - within CWs designed for aquaculture effluent remediation. The analysis highlights that nutrient removal is predominantly microbially mediated, while plant contributions are largely indirect, influencing rhizosphere conditions, oxygen transfer, and biomass harvesting dynamics. Among the evaluated species, vetiver demonstrates the strongest evidence for direct application in aquaculture wastewater, including tolerance to mesohaline conditions and effective nitrogen and phosphorus removal. Reed canary grass shows robust performance in CW systems, particularly when biomass management strategies are optimized, although aquaculture-specific data remain limited. Hemp is primarily supported as a biochar-derived substrate for phosphorus adsorption rather than as a planted macrophyte, while kenaf lacks direct evidence in CW contexts, representing a significant research gap. The review further emphasizes the importance of hydraulic loading rates, salinity tolerance, and plant–microbe interactions in determining system performance. Future research should prioritize long-term, field-scale studies and a mechanistic understanding of trait-mediated plant effects to optimize the integration of industrial crops into aquaculture wastewater treatment systems.
**Keywords**: hemp biochar, kenaf, nitrogen cycling, nutrient removal, phosphorus adsorption, phytoremediation, reed canary grass, textile crops, vetiver.

**Introduction**. The increasing intensification of aquaculture systems has led to the generation of nutrient-rich effluents, characterized by elevated concentrations of nitrogen, phosphorus, and residual contaminants (Dequito et al., 2015; Pandey et al., 2026). If inadequately treated, these discharges contribute to eutrophication and ecological degradation of receiving water bodies (Chen et al., 2024; Li et al., 2025). In this context, constructed wetlands (CWs) have emerged as a sustainable and cost-effective treatment technology, integrating physical, chemical, and biological processes for efficient wastewater remediation.

Recent research has highlighted the potential role of plant species not only as structural components of CWs but also as active modulators of rhizosphere processes that enhance nutrient removal. In particular, textile and industrial crops have gained attention due to their high biomass production, economic value, and potential integration into circular bioeconomy frameworks. However, the extent to which these crops contribute directly to pollutant removal, as opposed to indirectly through interactions with microbial communities and substrate dynamics, remains insufficiently clarified.

**Aim of the Study**. The aim of this review is to critically assess the suitability and functional roles of selected textile and industrial crops in constructed wetlands used for the treatment of aquaculture wastewater. Specifically, the study seeks to:
1) Differentiate between direct and indirect plant contributions to nutrient removal processes within CW systems;
2) Evaluate the evidence supporting the performance of vetiver and reed canary grass as wetland macrophytes under aquaculture-relevant conditions;
3) Clarify the role of hemp as a substrate precursor (biochar) rather than a functional emergent plant species in CWs;
4) Identify and explicitly frame the absence of empirical data regarding kenaf as a priority research gap;
5) Analyze key design and operational parameters - such as hydraulic loading, salinity, and biomass harvesting - that influence the effectiveness of plant-based treatment systems;
6) Highlight mechanistic uncertainties, particularly regarding plant-microbe interactions and their implications for nutrient transformation and removal.

Through this framework, the review aims to provide a rigorous, evidence-based foundation for integrating industrial crops into sustainable aquaculture wastewater management strategies.

**Potential of Textile Crops in Aquaponic Systems**. Textile crops in aquaponic systems appear promising for nutrient recovery and sustainability, but direct crop-specific evidence remains strongest for hemp and largely indirect for kenaf and flax. Aquaponics reliably recycles fish-derived nitrogen to plants and can reduce water use, pollution, and some life-cycle impacts, yet nutrient imbalances, especially low P, K, Ca, Mg, Fe, and S relative to crop demand, remain the main constraint for high-value fiber production (Yep & Zheng, 2019; Nair et al., 2025) (Table 1).

Table 1

Textile crops and aquaponic performance: strength of evidence for textile crops in aquaponics

| *Evidence strength* | *Claim* |
|---|---|
| Moderate (7/10) | Hemp has direct experimental support in controlled-environment aquaponics: plant length was more than 42% higher than in hydroponics under both tested light intensities, and leaf area was 28.3% greater under low light, although slightly lower under high light (Subah et al., 2025). |
| Moderate (6/10) | Aquaponics can support substantial nutrient recovery, because fish-derived ammonia is nitrified to nitrate for plant uptake, while plants simultaneously purify recirculating water (Nair et al., 2025; Stoyanova et al., 2024; Lama et al., 2025). |
| Moderate (4/10) | For kenaf and flax, evidence is presently indirect: field fertilization studies show fiber yield and quality respond strongly to N, P, K, and S supply, implying aquaponic suitability will depend on whether fish effluent and supplementation can meet these crop-specific demands (Salih, 2022; Mazumdar et al., 2023; Zhu et al., 2025). |

The score was calculated based on the following information: the number of available studies, sample sizes, and the reproducibility of the results.

***Productivity and nutrient uptake***. The clearest crop-specific result is for hemp. In a controlled-environment comparison, aquaponic hemp outperformed hydroponic hemp in stem elongation by more than 42% under both light regimes, suggesting that fish-effluent cultivation can support vigorous early vegetative growth at least for leaf-type production systems (Subah et al., 2025). More broadly, aquaponic productivity can remain competitive even when dissolved nutrient concentrations are lower than in hydroponics, a pattern attributed in the literature to plant-growth-promoting microbes and efficient nutrient cycling rather than simply to high fertilizer concentration (Yep & Zheng, 2019).

Nitrogen recovery is central to this potential. Fish excrete ammonia, which biofilters convert first to nitrite and then nitrate, the main nitrogen form taken up by plants (Stoyanova et al., 2024). However, whole-system mass balance remains a limitation: less than 30% of feed nitrogen is retained in fish biomass, while only 9-17% is ultimately retained in plant biomass, with 59-70% of nitrogen inputs lost through denitrification, discharged effluent, and solids; phosphorus retention in plants is similarly limited to 11-25% despite potentially high recyclability from effluent (Lama et al., 2025).

***Fiber yield and quality***. Direct data on fiber yield and fiber quality of aquaponically grown hemp, flax, or kenaf are still scarce. The present aquaponic hemp study assessed vegetative growth and environmental performance rather than bast fiber yield, retting behavior, or tensile quality, so any claim that aquaponics improves textile-grade fiber would currently go beyond the evidence (Subah et al., 2025).

Indirectly, conventional studies on kenaf and flax show that nutrient management strongly controls both yield and fiber traits. In kenaf, optimized fertilization improved phenotypic performance, and some fertilizer regimes favored maximum biomass yield while others favored finer or stronger fiber, showing that yield and quality can diverge under different nutrient schedules (Zhu et al., 2025). Separate kenaf trials found that 150 kg $ha^{-1}$ NPK improved fresh and dry bast fiber yield and enhanced fiber morphology, while sulfur fertilization increased kenaf fiber yield by 37%, with 30 kg S $ha^{-1}$ identified as a practical rate for sustainable production (Salih, 2022; Mazumdar et al., 2023) (Table 2).

Table 2

Kenaf fiber responses to nutrient supply

| *Crop context* | *Main response* | *Relevance to aquaponics* |
|---|---|---|
| Kenaf, varied NPK fertilization | 150 kg $ha^{-1}$ NPK improved bast fiber yield and morphology (Salih, 2022) | Aquaponic systems may need supplementation if effluent nutrient ratios are insufficient |
| Kenaf, varied fertilization strategy | Highest-yield and best-quality treatments were not the same (Zhu et al., 2025) | Aquaponics should optimize separately for biomass versus textile quality |
| Kenaf, sulfur fertilization | 37% higher fiber yield at S45; 30 kg S $ha^{-1}$ recommended for practice (Mazumdar et al., 2023) | Sulfur deficiency could constrain aquaponic bast fiber performance. |

***Phytoremediation and sustainability***. The phytoremediation logic for textile crops in aquaponics is strong even where crop-specific trials are limited. Aquaponic plants reduce waste streams by absorbing $NH_4^+$ and $NO_3^-$, converting aquaculture effluent from an environmental liability into a productive input (Brahaita et al., 2015; Nair et al., 2025; Tumembouw et al., 2024). This fits the broader role of plant nutrient absorption in wastewater treatment systems, where ammonium-N removal efficiencies of 86-98% have been reported in wetland-like polishing systems receiving farm wastewater (Nair et al., 2025).

Textile-linked remediation studies also clarify the opportunity and the risk. In a biohybrid textile-based system, AlgalTextile removed up to 99% of phosphate and 76% of total bound nitrogen from a medium, showing that textile-associated biological materials can be highly effective nutrient sinks (Melnikova et al., 2022). But wastewater reuse is highly source-dependent: undiluted textile wastewater reduced red amaranth height by 37.03% and fresh weight by 44.83%, whereas 50% dilution minimized growth penalties, and tomato responded positively only to some lower-contaminant wastewater fractions, with mixed effluent reducing yield because salinity and heavy metals impaired nutrient use and plant physiology (Hassan et al., 2022; Sultana et al., 2025).

***Economic and system-level implications***. At system level, aquaponics offers a plausible economic case for textile crops when the crop can monetize both biomass and remediation functions. Integrated production can reduce infrastructure costs, conserve water, minimize pollution, and create dual revenue from fish plus crops (Stoyanova et al., 2024). Life-cycle evidence from hemp is encouraging: compared with hydroponics, aquaponics reduced midpoint impacts by 22% and endpoint impacts by 15% in controlled-environment leaf hemp production (Subah et al., 2025).

The main economic caveat is that biological promise does not automatically translate into profitability. Reviews consistently note high setup costs, energy demand, operational complexity, and nutrient balancing challenges as barriers to economic sustainability, especially for small-scale systems (Thaiparambil & Radhakrishnan, 2022;

Nair et al., 2025; Zamnuri et al., 2024). For textile crops specifically, the strongest near-term opportunity may be in decoupled or supplemented systems that use aquaculture water for partial fertilization and remediation while correcting known deficits in P, K, Ca, Mg, Fe, and S needed for reliable fiber yield and quality (Verma et al., 2023; Nair et al., 2025).

A balanced reading of the literature is that aquaponic cultivation of textile crops is scientifically plausible and environmentally attractive, but it is not yet equally evidenced across species. Hemp already has direct positive aquaponic growth data, whereas kenaf and flax are supported mainly by agronomic nutrient-response studies and general aquaponic nutrient-cycling evidence, so the next research priority is crop-specific trials measuring fiber yield, fiber chemistry, and textile quality under real aquaculture-effluent regimes (Lama et al., 2025; Subah et al., 2025; Zhu et al., 2025).

**Reuse of Aquaculture Wastewater in Fiber Production Systems**. This chapter examines effluent composition, agronomic and soil effects, safety constraints, and circular-economy implications for using aquaculture wastewater in textile crop production. Direct evidence for fiber crops is still limited, but the broader irrigation literature and wastewater-based cotton studies provide a strong comparative framework for assessing its potential (De Araújo et al., 2022; Liu et al., 2024).

***Effluent composition***. Aquaculture wastewater is consistently described as a nutrient-rich effluent containing nitrogenous compounds, phosphorus, and organic matter, which explains its agronomic interest as a partial substitute for mineral fertilization (Kimera et al., 2021; Kurniawan et al., 2021; Kurniawan et al., 2025). At the same time, its composition is not purely beneficial. Reviews of aquaculture discharges show that effluents can also contain conventional pollutants, organic contaminants, heavy metals, antibiotics, steroids, suspended solids, and biological contaminants, with composition depending on feed inputs, metabolic waste, chemicals, and system design (Petrescu-Mag et al., 2011; Li et al., 2023; Liu et al., 2024).

This variability is central for textile-crop reuse systems because irrigation performance depends on whether the wastewater behaves mainly as a nutrient source or as a salinity and contaminant load. In a multi-farm assessment, most aquaculture wastewaters showed no salinity, sodicity, or alkalinity hazards, but one farm reached Electrical Conductivity (EC) 3.31 dS $m^{-1}$, showing that source-specific screening is necessary before field reuse (Al-Wabel et al., 2024). Experimental work on greenhouse production also found that nitrogen concentration in aquaculture wastewater can fluctuate over the growing cycle, so nutrient supply from irrigation water cannot be assumed constant (Guo et al., 2023).

Composition therefore has to be understood in operational rather than generic terms. For reuse in fiber systems, the most relevant constituents are available nitrogen, phosphorus, potassium, dissolved salts, suspended solids, and any trace contaminants that can accumulate in soil over repeated applications (Kundu et al., 2022; Al-Hazmi et al., 2023; Li et al., 2023).

***Soil effects***. The dominant short-term soil effect of aquaculture wastewater irrigation is higher nutrient availability. In date palm orchards, aquaculture wastewater increased soil available P by 49.31%, K by 21.11%, nitrate-N by 33.62%, and ammonium-N by 52.31% relative to source-water irrigation (Al-Wabel et al., 2024). In saline-tolerant rice irrigated with mariculture wastewater, soil organic carbon, available K, Olsen-P, and alkali-N also increased significantly (Chen et al., 2024). Fish effluent fertigation in urban soils increased pH and potassium, although crop effects were modest where baseline fertility was already high (Cerozi et al., 2022).

These findings suggest that aquaculture effluents can function as a soil fertility input, especially where soils are nutrient-poor or where repeated fertigation allows cumulative benefits. Greenhouse tomato experiments further indicate that aquaculture wastewater can deliver more available nutrients, especially organic nitrogen forms, while lowering residual soil nitrate under reduced fertilizer regimes (Guo et al., 2023). That pattern is relevant to textile crops because nitrogen management in cotton and other fiber crops strongly affects vegetative growth, lint formation, and input efficiency.

The main caveat is that positive nutrient effects do not eliminate longer-term soil risks. Wastewater reuse reviews consistently warn that poorly treated wastewater can contaminate soils with salts, toxic inorganic and organic chemicals, and microbial pollutants, and that long-term impacts require better monitoring (Al-Hazmi et al., 2023; Trotta et al., 2024).

***Agronomic performance***. Direct studies on aquaculture wastewater in textile crops are scarce in the provided literature, but the available evidence supports a plausible productivity benefit when nutrient loads are matched to crop demand. In non-fiber crops, aquaculture effluents increased plant growth and yield in several systems. Sweet marjoram irrigated with fish effluent alone had significantly higher first-cut fresh and dry yields, while the 50:50 effluent-plus-fertilizer treatment produced the highest second-cut herbage and essential oil yields (Kimera et al., 2021). In date palm, aquaculture wastewater increased fruit weight by 26%, length by 23%, and moisture by 43% compared with source water (Al-Wabel et al., 2024). In saline-tolerant rice, mariculture wastewater raised theoretical yield by 9.01% over freshwater irrigation (Chen et al., 2024).

For textile crops specifically, the strongest directly relevant evidence comes from cotton studies using treated wastewater rather than aquaculture effluent. Because cotton is a non-food fiber crop, it is often treated as a lower-risk entry point for wastewater reuse. Across field studies, wastewater irrigation improved cotton growth, yield, and fiber quality relative to conventional water controls (De Araújo et al., 2022; Gonçalo-Filho et al., 2023; Velmurugan et al., 2023). In one open-field study, 100% sewage effluent promoted more significant cotton growth, production, and fiber quality than the control (Gonçalo-Filho et al., 2023). In another, supplemental irrigation with treated wastewater increased cotton yield by about 29% under normal rainfall and by roughly 255% and 251% under drought and severe drought scenarios, respectively (De Araújo et al., 2022). Recycled greywater also improved lint yield, fiber strength, stable length, spinning consistency index, and uniformity ratio in cotton cultivars (Velmurugan et al., 2023).

Because these cotton studies are not aquaculture-based, they should not be read as direct proof of equivalent outcomes from aquaculture effluent. They do, however, show that fiber crops respond well to nutrient-bearing reclaimed water, and they strengthen the case for targeted trials in cotton, flax, hemp, and other industrial fibers using characterized aquaculture wastewater (Kurniawan et al., 2021; Cerozi et al., 2022) (Table 3).

Table 3

Comparative agronomic evidence relevant to reuse of aquaculture wastewater in fiber-oriented production systems

| *Water or nutrient regime* | *Crop/system* | *Main outcome* | *Implication for fiber systems* |
|---|---|---|---|
| Aquaculture wastewater vs source water | Date palm | Higher soil P, K, $NO_3$-N, $NH_4$-N and improved fruit quality | Demonstrates fertilizer value of aquaculture effluent (Al-Wabel et al., 2024) |
| Mariculture wastewater vs freshwater | Saline-tolerant rice | 9.01% yield increase and higher soil nutrients | Suggests productive reuse where salinity is manageable (Chen et al., 2024) |
| Aquaculture effluent only vs chemical fertigation vs mixed | Sweet marjoram | Mixed treatment gave highest later yield and oil content | Partial substitution can outperform either source alone (Kimera et al., 2021) |
| Aquaculture wastewater with fertilizer reduction | Greenhouse tomato | 62.63% freshwater saving, 37.50% fertilizer reduction, slight yield penalty | Highlights trade-off between maximum yield and input savings (Guo et al., 2023) |
| Treated wastewater vs conventional water in cotton | Cotton | Higher yield and better fiber quality | Supports reclaimed-water use in non-food textile crops (Gonçalo-Filho et al., 2023; Velmurugan et al., 2023) |

Compared with classical fertilization, aquaculture wastewater appears most competitive when the goal is not maximal short-term yield alone, but combined water savings, nutrient recovery, and lower fertilizer dependence. In marjoram, the mixed treatment outperformed both sole chemical fertilization and sole effluent in later harvests, suggesting complementarity rather than full substitution (Kimera et al., 2021). Tomato experiments similarly showed that reduced-fertilizer systems with aquaculture wastewater saved substantial freshwater and fertilizer while maintaining yields close to the conventional control, despite a modest decline relative to the highest-input treatment (Guo et al., 2023).

That comparison is especially relevant for fiber crops because economic thresholds differ from food crops. Cotton studies found that wastewater irrigation can improve profitability while reducing fertilizer costs, especially under water-limited conditions (De Araújo et al., 2022). Since non-food crops face fewer direct dietary exposure concerns, partial replacement of mineral fertilization with treated aquaculture effluent may be agronomically and economically attractive even where regulators remain cautious about edible crops (De Araújo et al., 2022).

***Heavy metals and safety***. Safety remains the major constraint on wider adoption. Broad reviews of wastewater reuse in agriculture warn that poorly treated wastewater can contaminate plant and soil systems with toxic metals, salts, organic pollutants, and microbial pathogens, with potential consequences for environmental and human health (Petrescu-Mag & Petrescu-Mag, 2010; Petrescu-Mag et al., 2010; Petrescu-Mag et al., 2013; Al-Hazmi et al., 2023; Trotta et al., 2024). Reviews specific to aquaculture wastewater likewise identify heavy metals among the pollutant classes present in discharges, alongside antibiotics and biological contaminants (Li et al., 2023; Liu et al., 2024).

Heavy metals are a particularly important concern because they persist, bioaccumulate, and move through aquatic and terrestrial food chains (Sonone et al., 2021). The current evidence base does not show that aquaculture wastewater is uniformly high in heavy metals; rather, it shows that contamination risk is source-dependent and must be monitored. Recent reviews explicitly state that reliable long-term assessment of heavy-metal risks in wastewater reuse remains insufficient and should be strengthened in future work (Al-Hazmi et al., 2023; Liu et al., 2024).

For textile crops, risk framing is somewhat different than for edible crops. Cotton and other fiber crops reduce direct food-chain exposure from the harvested product, and one cotton study noted that contaminant concerns are less critical for cotton than for consumable products (De Araújo et al., 2022). That does not remove environmental risk, because metals and salts can still accumulate in soils, leach to water, or affect workers and surrounding ecosystems over time (Trotta et al., 2024). Safe reuse therefore depends on prior treatment, routine water and soil analysis, and control of contaminants at the farm source (Li et al., 2023; Liu et al., 2024).

***Circular-economy context***. The circular-economy rationale for reusing aquaculture wastewater is strong (Ulfah & Dewi, 2025; Setijaningsih et al., 2025; Lesmana et al., 2024; Castro-Gonzales et al., 2023; Aguirre et al., 2023). Aquaculture wastewater is increasingly framed not as a disposal problem but as a recoverable resource containing water, nutrients, organic matter, algae, and other value-bearing side streams (Kurniawan et al., 2025; Kundu et al., 2022; Kurniawan et al., 2021). Reviews on aquaculture circularity argue that nutrient recovery and reuse can shift wastewater management from a linear model to a more sustainable loop in which effluents are re-engaged in production systems such as agriculture, aquaponics, hydroponics, algae cultivation, and biofertilizer production (Kurniawan et al., 2025; Deswati et al., 2023; Utomo et al., 2023; Torres-Mesa et al., 2023; Petrescu-Mag et al., 2024).

This logic maps well onto textile crops because fiber production can absorb reclaimed water and nutrients without the same market barriers that often constrain wastewater use in fresh food systems. More broadly, integrated systems can reduce freshwater demand, reduce discharge-related pollution, and recover value otherwise lost from the aquaculture sector (Cerozi et al., 2022; Chen et al., 2024). Composting and sludge recovery studies further show that aquaculture-derived wastes can be transformed into nutrient-rich composts capable of replacing chemical fertilizers in agriculture, extending circularity beyond liquid effluent reuse alone (Kurniawan et al., 2025; Lopes et al., 2021) (Table 4).

Table 4
Main circular-economy pathways through which aquaculture wastewater can be integrated into fiber production systems and related value chains

| *Circular pathway* | *Recovered value* | *Evidence for relevance* |
|---|---|---|
| Direct irrigation reuse | Water plus dissolved nutrients | Reduces freshwater demand and recycles nutrients into crops (Kurniawan et al., 2025; Guo et al., 2023) |
| Partial fertilizer substitution | Lower mineral fertilizer input | Effluent can replace part of chemical fertilization in crop systems (Kimera et al., 2021; Guo et al., 2023) |
| Sludge to biofertilizer or compost | Stabilized nutrient product | Composting and digestion can convert waste into agricultural inputs (Kurniawan et al., 2025; Lopes et al., 2021) |
| Algae or biomass recovery | Additional high-value co-products | Wastewater nutrients can support algae cultivation and valorization (Kurniawan et al., 2025; Kurniawan et al., 2021; Spennati et al., 2022) |
| Integrated multi-trophic systems | Internal nutrient recirculation | Nutrient upcycling can improve resource-use efficiency (Campanati et al., 2022) |

The literature therefore supports a cautious but favorable interpretation of aquaculture wastewater reuse for fiber production systems. The strongest evidence supports its role as a variable but often valuable nutrient-water source, its capacity to improve soil fertility and crop performance, and its compatibility with circular resource recovery strategies. The main unresolved issue is not whether reuse is conceptually promising, but how to manage source variability, salinity, heavy metals, and biological safety under long-term field conditions in actual textile crops (Al-Wabel et al., 2024; Li et al., 2023; Kurniawan et al., 2021).

**Industrial Hemp in RAS Biofiltration**. Industrial hemp as a biofilter and phytoremediation crop in recirculating aquaculture systems is best supported as a forward-looking integrated systems concept rather than a mature RAS practice, because the literature is strong on hemp phytoremediation, aquaponic integration, biomass valorization, carbon capture, and regulation, but still sparse on direct hemp-specific RAS trials for ammonia and nitrate polishing (Jurga et al., 2025; Subah et al., 2025).

***System rationale***. Recirculating aquaculture systems and aquaponic variants are designed around nutrient and water reuse, discharge mitigation, and circular production, which makes them a logical framework for testing hemp as a polishing crop for dissolved wastes (Verma et al., 2023; Goda et al., 2025). Aquaponics specifically couples fish waste, nitrifying bacteria, and plant cultivation in a closed-loop ecosystem, reducing dependence on synthetic fertilizers while co-producing fish and plant biomass (Subah et al., 2025).

Hemp is an attractive candidate for this role because it is a fast-growing, multi-use crop with substantial nutrient demand, broad agronomic plasticity, and recognized environmental functions including phytoremediation and bio-sequestration (Adesina et al., 2020; Jurga et al., 2025). Recent cross-media reviews explicitly place hemp in soil, water, and air remediation contexts, but they also note that aquatic applications remain comparatively underexplored and are still dominated by laboratory-scale demonstrations rather than standardized field deployment (Jurga et al., 2025).

***Nutrient uptake***. The strongest inference for nutrient absorption in RAS is indirect but coherent: hemp has substantial macro- and micro-nutrient requirements, and those requirements vary by production type, environment, and management, which implies a meaningful capacity to assimilate dissolved nitrogen and other nutrients when grown in soilless systems (Adesina et al., 2020; Basak et al., 2025). Controlled-environment work also shows that nutrient optimization is central to hemp performance in hydroponic and aquaponic cultivation (Subah et al., 2025).

Evidence closest to RAS comes from aquaponic cultivation. In controlled-environment comparison, aquaponics supported greater hemp growth than hydroponics under the tested conditions, with plant length more than 42% higher under both light intensities and leaf area 28.3% higher under low light (Subah et al., 2025). That result does not directly quantify ammonium or nitrate removal, but it indicates that hemp can effectively use fish-derived nutrient streams in coupled water systems (Subah et al., 2025).

Aquatic hemp applications described in the recent remediation literature include hydroponic phytoremediation of landfill leachate, wastewater irrigation, and biosorption by hemp-derived materials for removing nutrients and other dissolved contaminants from water (Jurga et al., 2025). Taken together, the literature supports hemp as a plausible nutrient sink in RAS side-loops or decoupled polishing units, but not yet as a quantitatively validated replacement for conventional biofilters dedicated to nitrification (Jurga et al., 2025).

***Nitrogen removal***. Direct evidence for ammonia and nitrate reduction by hemp inside RAS is limited. The available literature supports the broader mechanism of nutrient recycling in aquaponics, where fish waste is converted by nitrifying bacteria into plant-available forms and then assimilated by crops (Subah et al., 2025; Verma et al., 2023). On that basis, hemp can be framed as a candidate crop for nitrogen capture rather than as a proven stand-alone nitrification technology.

This distinction matters because hemp literature is much stronger for phytoremediation of metals and mixed contaminants than for nitrogen mass-balance accounting in recirculating aquaculture water (Jurga et al., 2025; Wu et al., 2021). Reviews of aquatic hemp use emphasize promise, but also identify lack of standardized protocols, limited field validation, and uncertainty around scale-up as major barriers (Jurga et al., 2025; Ansari & De Prato, 2026).

A practical interpretation is that hemp is most defensible in hybrid RAS configurations: decoupled aquaponic beds, hydroponic side-streams, or downstream polishing units where nitrate-rich water supports plant growth while conventional microbial biofiltration continues to handle primary ammonia oxidation (Verma et al., 2023) (Table 5).

Table 5

Summary of the evidence base relevant to using industrial hemp in RAS-linked biofiltration and phytoremediation

| *Theme* | *What the literature supports* | *Key limitation for RAS integration* |
|---|---|---|
| Nutrient uptake | Hemp has high nutrient demand and performs well in aquaponic or soilless cultivation (Adesina et al., 2020) | Few hemp-specific RAS nutrient mass-balance studies (Jurga et al., 2025) |
| Ammonia/nitrate reduction | Hemp can likely assimilate fish-derived nitrogen in coupled plant beds (Subah et al., 2025) | No strong direct evidence that hemp replaces nitrifying biofilters (Jurga et al., 2025) |
| Aquatic remediation | Hemp-based materials can remove nutrients and other contaminants from water (Jurga et al., 2025) | Aquatic applications remain underexplored and often laboratory-scale (Jurga et al., 2025) |
| Biomass valorization | Most hemp fractions can enter bioenergy, textile, or biorefinery chains (Moscariello et al., 2021) | Post-remediation biomass routing must avoid contaminant entry into markets (Rheay et al., 2021) |
| Carbon sequestration | Hemp captures substantial atmospheric $CO_2$ and stores carbon in biomass and products (Ismagilov & Rusakov, 2024) | Net climate benefit depends on end use and system design (Todde et al., 2022). |

***Biomass valorization***. A major advantage of hemp over many polishing crops is that its biomass is unusually versatile. Reviews consistently describe hemp as a multi-use crop in which essentially all main fractions can be valorized through fiber, seed, bioenergy, paper, packaging, biocomposites, biochar, and bioplastics pathways (Visković et al., 2023; Basak et al., 2025; Sieracka et al., 2023). In circular bioeconomy terms, hurds, leaves, and inflorescences are not merely residues but potentially valuable feedstocks for biorefineries (Moscariello et al., 2021).

This matters for RAS because nutrient recovery is more economically attractive when the polishing crop also generates marketable biomass. Hemp can support biodiesel, bioethanol, biomethane, polyhydroxybutyrate, and microbial protein pathways, with reported biomethane yields of 98-426 mL $g^{-1}$ volatile solids and biodiesel yields of 1.6 g $g^{-1}$ volatile solids in modeled biorefinery scenarios (Moscariello et al., 2021). Contaminated or remediation-grown biomass can also be routed toward energy recovery; life-cycle analysis identified anaerobic digestion and incineration scenarios as the most energy-efficient, saving 25.3 and 36.8 GJ $ha^{-1}$ and avoiding 579 and 641 kg $CO_2e$ $ha^{-1}$, respectively (Todde et al., 2022).

At the same time, valorization depends on what the biomass has accumulated. The central caution across remediation reviews is that contaminants removed by hemp must not be reintroduced into consumer markets through food, feed, or poorly controlled downstream processing (Rheay et al., 2021; Jurga et al., 2025). This is directly relevant to RAS if hemp is used not only for nutrient capture but also for broader water polishing, including metals or contaminants of emerging concern (Wu et al., 2021) (Table 6).

Table 6

Major biomass valorization routes for hemp used in remediation-oriented production systems and their principal constraints

| *Biomass pathway* | *Opportunity* | *Constraint* |
|---|---|---|
| Textile fiber | Fibers from contaminated sites can remain below textile toxicity thresholds (De Vos et al., 2023) | Yield can decline on contaminated land by 30-50% (De Vos et al., 2023) |
| Bioenergy | Anaerobic digestion and incineration can improve energy and climate performance (Todde et al., 2022) | Contaminant partitioning during processing remains insufficiently characterized (Rheay et al., 2021) |
| Biorefinery products | Hurds, leaves, and inflorescences can feed circular biorefineries (Moscariello et al., 2021) | Marketability depends on clean, well-segregated feedstock (Jurga et al., 2025) |
| Food/feed uses | Some seeds and tissues may remain usable in specific cases (Flajšman et al., 2023) | Remediation-grown biomass should not enter food chains without strict testing (Rheay et al., 2021). |

***Carbon sequestration***. Hemp has a credible climate rationale in RAS-linked plant integration because the crop converts substantial atmospheric $CO_2$ into harvestable biomass and, depending on the end use, can retain a large share of that carbon in durable products or soils (Visković et al., 2023; Adesina et al., 2020; Basak et al., 2025). Field quantification reported 7.87 t $ha^{-1}$ of aboveground biomass and 1.02 t $ha^{-1}$ of roots, corresponding to 14.78 t $ha^{-1}$ of $CO_2$ captured and 4.03 t $ha^{-1}$ of carbon fixed (Ismagilov & Rusakov, 2024). The same study estimated that 91% of accumulated carbon could be conserved long term in products and soil, which is the strongest explicit sequestration figure in the present corpus (Ismagilov & Rusakov, 2024).

The climate value of hemp is therefore not limited to crop growth itself. It also depends on whether biomass is directed into long-lived materials, soil carbon pathways, or lower-emission energy systems (Ismagilov & Rusakov, 2024; Lubis et al., 2025; Sitanggang et al., 2025; Thoha et al., 2024; Solang et al., 2024; Basak et al., 2025; Tahir et al., 2023; Oroian et al., 2024a, b, c; Bora, 2023). In integrated aquaponic production, life-cycle evidence further suggests that hemp cultivation in aquaponics can reduce environmental burdens relative to hydroponics, with a 22% reduction in midpoint and a 15% reduction in endpoint impacts for hemp leaf cultivation under the tested design (Subah et al., 2025).

***Legislative limits***. The legislative case for hemp in RAS is favorable in direction but restrictive in practice. Recent reviews agree that hemp expansion has been driven by changes in legal frameworks, including the 2018 U.S. Farm Bill and evolving European rules, yet cultivation still faces regulatory complexity and uneven implementation (Visković et al., 2023; Adesina et al., 2020; Kaminski et al., 2024). Europe in particular links hemp's revival to legislative change, cultivar rules, and cannabinoid thresholds, with practical implications for breeding, cultivation, and market access (Kaminski et al., 2024; Sieracka et al., 2023).

For remediation-oriented production, the more specific legal bottleneck is the unclear regulatory status of harvested biomass. Multiple reviews identify uncertainty over whether post-remediation hemp should be treated as a resource or a waste stream, and they note the lack of clear frameworks for safe alternative utilization after contaminant uptake (Flajšman et al., 2023; Jurga et al., 2025). This issue would be especially important in RAS applications if hemp is positioned not only as a nutrient sink but also as a phytoremediator for mixed aqueous pollutants.

Regulatory burden also interacts with adoption economics. Farmers report opportunities through diversified revenue streams and lower chemical input needs, but also barriers related to regulation, market uncertainty, and the need to distinguish industrial hemp from drug-type cannabis in public and administrative contexts (Michels et al., 2025). That combination suggests that hemp integration into RAS is most feasible where licensing, cultivar compliance, biomass testing, and end-use pathways are defined before system deployment (Basak et al., 2025; Jurga et al., 2025).

**Textile and Industrial Crops in Constructed Wetlands for Aquaculture Wastewater Treatment**. Constructed wetlands (CWs) using textile and industrial crops appear to be a credible low-cost strategy for polishing aquaculture wastewater, especially for nitrogen and phosphorus, but the evidence is uneven across species: vetiver and reed canary grass are supported by direct wetland studies, while hemp is supported mainly as a phosphorus-sorbing biochar substrate and kenaf is scarcely documented in the supplied aquaculture-wetland literature (Yang et al., 2024; Yang et al., 2024; Huang et al., 2019).

Within aquaculture contexts, the main design questions are species choice, wetland configuration, salinity tolerance, and whether nutrient removal is driven primarily by plant uptake or by plant-mediated microbial and substrate processes (Yang et al., 2024; Yang et al., 2024; Liang et al., 2017).

***Scope and treatment context***. Aquaculture wastewater is a particularly relevant target for constructed wetlands because land-based systems discharge nutrient-rich effluents that can promote eutrophication in receiving waters (Blandford et al., 2024). Pilot-scale horizontal subsurface-flow wetlands treating aquaculture wastewater have already shown that planted systems can remove total nitrogen and ammonium at substantial rates, with total nitrogen removal ranging from 73.24 to 91.46% and $NH_4^+$-N removal from 61.20 to 92.27% depending on planting pattern (Huang et al., 2019). More broadly, constructed wetlands are recognized as low-energy, low-maintenance, and relatively low-cost systems for nutrient-rich wastewater, including remote applications where centralized treatment is impractical (Kamilya et al., 2022; Dell'Osbel et al., 2020; Blandford et al., 2024).

For nutrient-focused treatment, wetland configuration matters as much as plant identity. A recent synthesis found that vertical-flow wetlands tend to perform better for total phosphorus, averaging 64.6±30% removal, whereas horizontal-flow wetlands tend to perform better for total nitrogen, averaging 67.6±20% removal (Kamilya et al., 2022). Hybrid systems can further raise nitrogen removal, with reported total nitrogen removal around 89% in review evidence and 93.8% in an 11-month operational hybrid system, although phosphorus gains from hybridization are less consistent across studies (Kamilya et al., 2022; Dell'Osbel et al., 2020). A separate review similarly reported that subsurface-flow wetlands generally outperform surface-flow systems for nitrogen and pathogen removal, with multi-stage systems being the most effective overall (Yang et al., 2024).

***Comparative evidence for the four target crops***. The evidence base differs sharply among hemp, kenaf, reed canary grass, and vetiver. Vetiver has the strongest direct support as a wetland macrophyte relevant to aquaculture and nutrient-rich effluents (Delis et al., 2015). In flow water-surface constructed wetlands treating vannamei shrimp wastewater, vetiver tolerated mesohaline conditions and removed $NH_4^+$, $NO_3^-$, and $PO_4^{3-}$, with no significant difference between emergent and hydroponic planting modes (Raharjo et al., 2015). In a plug-flow constructed wetland model, vetiver simultaneously removed 93% of nitrogen and 84% of phosphorus while also removing 93% ciprofloxacin and 97% tetracycline, which is relevant to aquaculture systems where antibiotic residues can co-occur with nutrients (Panja et al., 2021). A tertiary horizontal-flow wetland study also identified a vetiver-containing bed with 64.64% ammonia removal, although nitrate and phosphate maxima were achieved by other planted beds in the same experiment (Junio et al., 2024).

Reed canary grass is supported less by aquaculture-specific trials than by broader constructed-wetland management and process studies. In the Czech Republic, *Phalaris arundinacea* was among the most commonly co-used macrophytes with *Phragmites australis* in horizontal subsurface-flow wetlands, indicating practical operability at system scale (Vymazal, 2001). Seasonal biomass data show that its aboveground biomass is greater in inflow zones and peaks earlier there than in outflow zones, so zone-specific harvesting can raise nitrogen and phosphorus removal via biomass export by up to 42% and 43%, respectively, relative to a single whole-bed harvest (Březinová & Vymazal, 2015). In reciprocating subsurface-flow microcosms, the presence of *P. arundinacea* was associated with much lower nitrate accumulation, below 0.4 mg $L^{-1}$ versus 15-26 mg $L^{-1}$ in reciprocating unplanted treatments, suggesting a useful role in nitrogen polishing under alternating oxic-anoxic conditions (Behrends et al., 2022).

Hemp is represented in the literature primarily as a substrate precursor rather than as a standing wetland crop. An enriched hemp biochar incorporated into constructed wetland cells reduced $PO_4$-P in primary treated sewage from an average influent concentration of 15.5 mg $L^{-1}$ to below 2 mg $L^{-1}$ over seven months, outperforming gravel controls (Bolton et al., 2019). The phosphorus concentration of the substrate increased by 77% during operation, and spectroscopy indicated iron phosphate formation and association with Al-, Si-, Fe-, Mg-, and Ca-rich mineral phases, which supports a substrate-driven phosphorus-capture mechanism (Bolton et al., 2019). For aquaculture wastewater, this suggests that hemp may be most defensible in the review as a feedstock for replaceable sorptive media in hybrid plant-substrate systems rather than as the primary emergent macrophyte.

Kenaf is the weakest-supported target species in the available literature. None of the supplied papers reports a constructed wetland experiment using kenaf for aquaculture wastewater, and the available material doesn’t provide direct evidence of its nutrient removal performance in wetlands. In a strict literature-grounded review, kenaf therefore has to be treated as a research gap rather than presented as an evidence-backed option.

***Mechanisms of nutrient removal and the role of plants***. Across the literature, nutrient removal in constructed wetlands is consistently described as a composite physical, chemical, and biological process involving plants, microorganisms, and substrate or filler materials (Yang et al., 2024). Microorganisms play the primary role in nitrogen transformation through ammonification, nitrification, and denitrification, while plants influence these processes by releasing oxygen and root exudates, providing surfaces and habitat for microbial communities, and contributing carbon through decaying tissues (Yang et al., 2024). Phosphorus removal is more strongly tied to matrix adsorption, replacement, precipitation, and plant absorption than to microbial transformation alone (Yang et al., 2024; Bolton et al., 2019).

This mechanistic distinction matters when evaluating textile crops. Direct plant uptake is often a minority share of total nutrient removal under typical loading conditions. In one hybrid wetland, plant contribution to nitrogen removal was only 8.08% and to phosphorus removal 17.92% in the horizontal subsurface-flow compartment (Dell’Osbel et al., 2020). A broader analysis of plant harvesting in horizontal-flow wetlands found common standing stocks of only 30-80 g N $m^{-2}$ and 2-6 g P $m^{-2}$, usually less than 10% of incoming nitrogen load and less than 5% of phosphorus load under municipal loading conditions (Vymazal, 2020). However, under lower inflow loading and high biomass, plant uptake can become much more consequential, accounting for up to 62% of nitrogen and 58% of phosphorus removal (Vymazal, 2020). For aquaculture applications, where loading can vary sharply with stocking density, feed input, and recirculation regime, this means biomass-rich industrial crops are most valuable when coupled to loading control and harvest management rather than assumed to be sufficient on uptake alone (Yang et al., 2024; Blandford et al., 2024).

Trait-mediated effects also appear important. In aquaculture wastewater wetlands, mixed planting patterns altered microbial community structure by decreasing anaerobe abundance and increasing bacteria associated with nitrogen metabolism, which coincided with better removal of conventional pollutants than single-species plantings (Huang et al., 2019). This suggests that industrial crops should not be evaluated only by tissue uptake or growth rate, but also by how their root architecture, oxygen release, salinity tolerance, and phenology shape rhizosphere function (Yang et al., 2024; Yang et al., 2024).

***Species-specific performance and design implications***. The table below (Table 7) summarizes what the supplied literature can support for the four requested crops.

Table 7

Evidence-supported roles of the four requested textile and industrial crops in constructed wetlands relevant to aquaculture wastewater treatment

| *Crop* | *Wetland role in supplied evidence* | *Main supported performance* | *Main limitation for this review* |
|---|---|---|---|
| Vetiver (*Chrysopogon zizanioides*) | Direct wetland macrophyte in aquaculture and other nutrient-rich wastewaters | Removed $NH_4^+$, $NO^{3-}$, and $PO_4^{3-}$ from shrimp wastewater; in other CW studies achieved 93% N and 84% P removal and tolerated mesohaline conditions (Raharjo et al., 2015) | Evidence is promising but mostly mesocosm, greenhouse, or non-aquaculture municipal/tertiary contexts (Panja et al., 2021) |
| Reed canary grass (*Phalaris arundinacea*) | Direct wetland macrophyte and management model species | Harvest timing can increase biomass-exported N and P removal by 42-43%; associated with very low nitrate accumulation in reciprocating wetlands (Březinová & Vymazal, 2015) | Little direct aquaculture-specific evidence in literature |
| Hemp (*Cannabis sativa*) | Biochar substrate feedstock in CWs | Enriched hemp biochar lowered $PO_4$-P to below 2 mg $L^{-1}$ and accumulated phosphorus in the substrate (Bolton et al., 2019) | Evidence supports substrate use, not hemp as a planted emergent crop |
| Kenaf (*Hibiscus cannabinus*) | No direct CW evidence in supplied papers | No evidence for aquaculture CW nutrient removal | Must be framed as a research gap in this review. |

A second design issue is hydraulic loading and retention management. In vertical-flow wetlands planted with reed grass or vetiver, the highest nutrient removal occurred at the lowest tested loading rate of 500 mL $min^{-1}$ $m^{-2}$, and planted beds consistently outperformed unplanted controls by 20-30% across removal rates (Kỳ et al., 2020). Specifically, at that loading rate, reed grass achieved TP, $PO_4^{3-}$, TKN, and $NH_4^+$-N removals of 95.4±1.5%, 54.4±8.5%, 74±17%, and 68±21%, while vetiver achieved 95.0±0.7%, 50.1±11.5%, 68±16%, and 64±15%, with no statistically significant difference between the two species at equal loading (Kỳ et al., 2020). These data suggest that, where aquaculture flow is buffered or equalized, both species can function effectively, but loading control is essential.

Salinity is another practical constraint for aquaculture integration. Direct evidence shows vetiver can grow and function under mesohaline shrimp-wastewater conditions (Raharjo et al., 2015). More generally, constructed wetlands planted with selected species can remove nitrogen and phosphorus across electrical conductivities of 7, 10, and 15 mS cm$^{-1}$, and salinity can even enhance plant absorption under some concentration regimes (Liang et al., 2017). This broader saline-wetland evidence does not prove equivalent performance for every textile crop, but it supports the plausibility of using salt-tolerant industrial species in brackish aquaculture treatment trains.

***Research gaps and framing for an academic review***. The strongest gap is taxonomic. Among the four requested crops, only vetiver has direct evidence in aquaculture wastewater, and only reed canary grass has substantial evidence as a constructed-wetland species with management relevance; hemp is represented indirectly through biochar, and kenaf is not represented at all in literature (Raharjo et al., 2015; Březinová & Vymazal, 2015; Bolton et al., 2019). A careful review should therefore distinguish direct plant evidence, substrate-derived evidence, and hypothetical candidate species rather than treating all four crops as equally validated options.

The second gap concerns scaling and duration. Several of the strongest species-specific studies are pilot, mesocosm, greenhouse, or microcosm systems, and some explicitly call for field-scale optimization of hydraulic retention time and plant density (Panja et al., 2021). Even where performance is high, phosphorus dynamics can remain operationally sensitive; in aquaculture wetlands, elevated P can persist for several weeks under high loading before strong reduction is achieved (Blandford et al., 2024). Future work on textile crops for aquaculture should therefore prioritize long-duration field trials under realistic salinity, solids loading, feed-derived nutrient pulses, and harvest schedules.

The third gap is mechanistic resolution. Reviews note that the role of plants in pathogen removal and in the specific mechanisms of nitrogen transformation remains incompletely resolved, despite clear evidence that plant species alter rhizosphere microbial communities and treatment outcomes (Yang et al., 2024; Huang et al., 2019). For an academic treatment of textile and industrial crops, this opens a useful line of discussion around whether desirable crop traits are high biomass alone, or a broader package including oxygen release, root-zone redox effects, harvestability, salinity tolerance, and compatibility with reactive substrates such as hemp-derived biochar (Yang et al., 2024; Bolton et al., 2019).

***Representative studies***. For the topic analysed, the supplied literature supports a strong discussion of vetiver and reed canary grass, a more cautious substrate-centered discussion of hemp, and an explicit statement that kenaf remains insufficiently documented in the provided constructed-wetland aquaculture literature (Table 8).

Table 8

Representative studies supporting the treatment of aquaculture or nutrient-rich wastewaters with constructed wetlands relevant to textile and industrial crop selection

| *Study focus* | *System and wastewater* | *Key result* | *Relevance to review* |
|---|---|---|---|
| Aquaculture wastewater with mixed macrophytes | Horizontal subsurface-flow pilot CWs | TN 73.24-91.46% and $NH_4^+$-N 61.20-92.27%; mixed planting improved conventional pollutant removal (Huang et al., 2019) | Benchmarks aquaculture CW performance and supports plant-physiology effects |
| Vetiver in shrimp wastewater | Flow water-surface CW | Vetiver tolerated mesohaline water and removed NH4+, $NO^{3-}$, $PO_4^{3-}$ (Raharjo et al., 2015) | Direct aquaculture evidence for vetiver |
| Vetiver in plug-flow CW | Secondary effluent CW model | 93% N and 84% P removal, with simultaneous antibiotic removal (Panja et al., 2021) | Shows vetiver's multifunctionality for nutrient and contaminant polishing |
| Reed canary grass harvest management | Horizontal subsurface-flow CWs | Split harvest could raise exported N and P removal by 42-43% (Březinová & Vymazal, 2015) | Supports biomass-management strategy for industrial grasses |
| Hemp biochar in CW substrate | Experimental CW cells | $PO_4$-P reduced to below 2 mg L$^{-1}$; substrate P increased 77% (Bolton et al., 2019) | Supports hemp as reactive substrate rather than planted crop. |

**Conclusions**. This review demonstrates that the integration of textile and industrial crops into constructed wetlands for aquaculture wastewater treatment must be approached with careful attention to mechanistic understanding and evidence hierarchy. Nutrient removal in CWs is primarily driven by microbial processes, with plants exerting significant but largely indirect effects through rhizosphere modification, oxygen transfer, and structural support for microbial communities.

Among the species analyzed, *Chrysopogon zizanioides* (vetiver) emerges as the most substantiated candidate for direct application, supported by evidence of effective nutrient removal and salinity tolerance in aquaculture contexts. *Phalaris arundinacea* (reed canary grass) also shows strong potential, particularly when biomass harvesting strategies are optimized, although further validation in aquaculture systems is required. In contrast, *Cannabis sativa* (hemp) is best supported as a source of biochar for phosphorus adsorption rather than as a planted macrophyte, while *Hibiscus cannabinus* (kenaf) remains insufficiently studied, representing a clear and significant gap in the literature.

The performance of CWs incorporating these crops is highly dependent on operational parameters, especially hydraulic loading rates, retention time, and salinity conditions. Additionally, trait-mediated effects - such as root architecture, oxygen release capacity, and compatibility with microbial communities - are critical determinants of system efficiency and should be prioritized over simple biomass productivity.

Future research should focus on long-term, field-scale investigations under realistic aquaculture conditions, including fluctuating nutrient loads and salinity regimes. A deeper mechanistic understanding of plant-microbe interactions and substrate dynamics will be essential to optimize system design and to fully realize the potential of industrial crops within circular and sustainable aquaculture wastewater treatment frameworks.

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