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Impact of wastewater and reeling effluent irrigation on mulberry cultivation and silkworm rearing performance: A comprehensive review

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Abstract
The utilization of wastewater and reeling effluent in agriculture has gained attention as a sustainable solution to address water scarcity and environmental concerns. This review critically examines the impact of wastewater and cocoon reeling effluent irrigation on mulberry (*Morus* spp.) cultivation, soil health and silkworm (*Bombyx mori* L.) rearing performance. Wastewater, particularly from domestic and agro-industrial sources, often contains significant amounts of organic matter and nutrients that can enhance mulberry growth and leaf yield. Similarly, reeling effluent rich in proteins, fats and minerals can influence plant physiology and soil microbial activity. However, continuous application lead to soil salinization, heavy metal accumulation, altered pH and deterioration in soil physical properties. These changes can affect leaf biochemical composition, which in turn influences silkworm health, larval growth, cocoon yield and silk quality. The review consolidates findings from various studies to highlight both the beneficial and adverse effects of such irrigation practices. It underscores the need for standardized treatment protocols and safe irrigation guidelines to harness the potential of wastewater and reeling effluents without compromising soil integrity, crop productivity and sericulture sustainability.

Keywords: Wastewater irrigation, sewage, reeling effluent, mulberry, cocoon yield, soil fertility, nutrient recycling

1. Introduction
The increasing scarcity of freshwater resources has led to the exploration of alternative irrigation sources, among which wastewater and effluent from agro-industrial processes have gained significant importance. In sericulture, wastewater including domestic sewage, municipal waste and silk reeling effluent is being considered for irrigating mulberry crops due to its rich nutrient content. These water sources are often composed of organic matter, macro-and micronutrients (such as nitrogen, phosphorus, potassium, calcium, and magnesium), as well as trace elements, suspended solids and varying levels of biological oxygen demand (BOD) and chemical oxygen demand (COD).
Reeling effluent, a byproduct of the silk reeling process, contains degummed proteins (mainly sericin), fatty substances, and mineral residues, which can influence soil fertility and mulberry plant nutrition. While these effluents are rich in beneficial nutrients, they may also contain pollutants such as salts, detergents and heavy metals, which can pose risks to soil quality and plant health if not properly managed. Understanding the chemical composition and nutrient profile of these alternative water sources is essential for evaluating their suitability for agricultural use. Proper characterization enables the optimization of application rates, minimizes environmental risks and supports the development of sustainable irrigation practices in sericulture. This section explores the major components of wastewater and reeling effluent, their variability and their potential impacts on soil and mulberry crop productivity.

2. Wastewater effluent irrigation: Composition and nutrient profile
2.1 Nutrient enrichment through wastewater
Wastewater from various sources including domestic sewage, agro-industrial effluents, distillery spent wash and textile mill discharges is increasingly being utilized in agriculture

due to its rich nutrient composition. These effluents contain substantial amounts of macronutrients such as nitrogen (N), phosphorus (P) and potassium (K), as well as micronutrients including iron (Fe), manganese (Mn), zinc (Zn), boron (B) and sulfur (S), all of which are essential for plant growth and physiological development.

Scientific studies have consistently shown the positive impacts of wastewater irrigation on nutrient availability and plant nutrient uptake:

- Basiouny (1984) [3] demonstrated that peach trees irrigated with treated wastewater exhibited elevated concentrations of N, P, K, Fe, Mn and B in their leaves. These nutrients are critical for various plant physiological functions: nitrogen is a fundamental component of amino acids and proteins; phosphorus is vital for energy transfer via ATP; potassium plays a key role in stomatal regulation and enzyme activation.
- In mulberry (*Morus* spp.), Bongale and Krishna (2000) [6] reported that irrigation with raw sewage significantly increased leaf nitrogen, chlorophyll, soluble protein and mineral content compared to borewell water. Elevated nitrogen levels lead to enhanced chlorophyll biosynthesis, which directly improves the photosynthetic efficiency of plants. Chlorophyll is the key pigment that drives the conversion of solar energy into chemical energy.
- Subbarayappa *et al.* (1996) [19] found higher concentrations of sulfur (0.40%) and manganese (280.5 ppm) in mulberry leaves irrigated with sewage. Sulfur is essential for protein structure and function-as it forms part of the amino acids cysteine and methionine-while manganese is important for photosynthetic oxygen evolution, acting as a cofactor in the water-splitting complex of photosystem II.
- The enhanced uptake of nutrients through wastewater irrigation leads to increased protein synthesis, enzyme activity, and metabolic processes in mulberry, ultimately resulting in improved leaf quality. This is particularly significant in sericulture, where leaf quality directly influences silkworm growth, cocoon yield, and silk filament quality.
- Moreover, the organic matter present in wastewater improves soil fertility by enhancing microbial activity and improving nutrient retention capacity. The slow mineralization of organic-bound nutrients provides a sustained nutrient supply over time, supporting prolonged vegetative growth in crops like mulberry (Shree *et al.*, 2000) [18].

Thus, when managed properly and free from toxic contaminants or heavy metals, wastewater serves as a cost-effective and sustainable source of plant nutrients, reducing dependency on chemical fertilizers while promoting environmentally sound practices in mulberry cultivation and other agricultural systems.

3. Impact on mulberry growth and biochemical traits

3.1 Vegetative growth

Irrigation with wastewater and effluents has shown a consistent positive influence on the vegetative growth of mulberry, as documented by several studies. The nutrient-rich composition of these waters provides an additional source of essential elements that support vigorous plant development.

- Kumar *et al.* (2021) [2] demonstrated that both raw and treated sewage water significantly enhanced the growth performance of V1 mulberry under paired row planting systems. These improvements in plant height, shoot number, leaf area, and overall biomass are primarily attributed to the abundant supply of macronutrients (N, P, K) and micronutrients (Fe, Mn, Zn) in the wastewater, which are necessary for cell division, expansion, and elongation.
- Nitrogen promotes rapid vegetative growth by supporting protein and nucleic acid synthesis, leading to increased shoot proliferation. Phosphorus aids in energy metabolism (ATP synthesis) and root development, while potassium regulates stomatal function and water use efficiency, all contributing to improved plant vigor.
- Chandraju *et al.* (2012) [7] reported enhanced nutrient uptake and morphological characteristics such as plant height and leaf size in mulberry varieties S-30, S-36 and vishwa when irrigated with 33% diluted distillery spent wash. The spent wash, being rich in organic carbon, calcium, magnesium, and other micronutrients, not only nourishes the plant but also improves soil microbial activity, leading to better root-soil interactions and nutrient absorption.
- Chikkaswamy and Paramanik (2014) [8, 9] observed enhanced sprouting rate and biomass production in mulberry seedlings irrigated with 10% tannery effluent. The improved sprouting could be attributed to the available nitrogen and trace metals in the effluent, which stimulate enzymatic activities and hormonal balance involved in bud breaking and shoot emergence.
- However, their findings also emphasize the toxic threshold higher concentrations of tannery effluent negatively impacted plant health due to the accumulation of heavy metals like chromium and high Biological Oxygen Demand (BOD), which lead to oxidative stress, membrane damage, and enzyme inhibition in plants. This highlights the importance of dilution and monitoring when using effluent for irrigation.

3.2 Biochemical composition

Effluent irrigation not only enhances the physical traits of mulberry but also significantly improves its biochemical composition, which is crucial for silkworm nutrition and cocoon productivity.

- Studies by Shree *et al.* (2000) [18] and Ambika *et al.* (2011) [1] reported that mulberry leaves irrigated with polluted river water and sewage showed increased levels of proteins, sugars, phenols, and chlorophyll. These biochemical enhancements are directly linked to increased nutrient availability, especially nitrogen, which drives amino acid synthesis and protein accumulation, and magnesium, which is central to the chlorophyll molecule.
- Rao *et al.* (2011) [15] found elevated photosynthetic rates, chlorophyll content, and transpiration rates in V1 mulberry under sewage irrigation. These physiological responses are due to better leaf turgidity, enzyme function, and stomatal conductance, all enabled by improved nutrient status and water availability. Enhanced photosynthesis increases carbon assimilation, supporting higher energy availability for metabolic processes and growth.

- According to Paramanik (2015) [14], effluent irrigation improved moisture retention capacity, amino acid content, and energy value of mulberry leaves. These parameters directly influence the palatability and digestibility of leaves for silkworms. High moisture content prevents leaf wilting and prolongs freshness, while elevated amino acids and soluble sugars provide essential nutritional building blocks and metabolic fuel for larval development.
- Phenolic compounds, though typically associated with plant defense, can also play a role in enhancing silkworm immunity and reducing disease incidence when present in moderate levels. Therefore, their increase in effluent-irrigated leaves may have indirect benefits for larval health and survival.

4. Soil health and nutrient dynamics

4.1 Soil enrichment

Effluent irrigation can significantly improve soil fertility and structure by enriching the soil with a wide range of nutrients and organic matter. The organic and inorganic constituents present in wastewater-especially from agro-industrial sources like distilleries, sugar mills, and domestic sewage-serve as supplementary fertilizers, enhancing the nutrient profile of the soil.

- Baskar *et al.* (2003) [4] and Baskaran *et al.* (2009) [5] reported that irrigation with distillery spent wash and sugar mill effluents led to increased levels of organic carbon, available nitrogen (N), phosphorus (P), potassium (K) and several micronutrients (e.g., zinc, iron, manganese, and copper). Organic carbon enhances soil microbial biomass, improves soil aggregation, and increases water-holding capacity, all of which are critical for sustained mulberry growth.
- The high nutrient content in effluents reduces the dependence on synthetic fertilizers and enhances microbial activity, which promotes mineralization the biological conversion of organic nutrients into plant-available forms. For example, nitrogen from proteins and urea in effluents is converted into ammonium and nitrate, both easily absorbed by plant roots.
- Ghodpage *et al.* (2013) [13] showed improved soil physico-chemical properties, including increased CEC (Cation Exchange Capacity) and nutrient availability, as well as enhanced Rabi vegetable yields under treated sewage irrigation. This implies a similar yield-improvement potential in mulberry cultivation, as soil enriched with sewage effluent supports better root development, nutrient uptake and leaf production.
- The humic and fulvic acids present in wastewater contribute to chelating micronutrients, keeping them in soluble forms readily available for plant uptake. This enhances the physiological efficiency of nutrient use, particularly in long-term crops like mulberry.

Therefore, when properly treated and managed, effluent irrigation serves not just as an irrigation source but also as a soil conditioner and nutrient reservoir, fostering sustainable mulberry farming with reduced input costs.

4.2 Heavy metals and toxicity

While effluent irrigation presents multiple agronomic benefits, long-term and unregulated use-especially of untreated wastewater poses the risk of toxic element accumulation in the soil-plant system.

- Heavy metals such as cadmium (Cd), lead (Pb), nickel (Ni), chromium (Cr) and arsenic (As) may be present in untreated domestic and industrial effluents, particularly from textile, tannery and electroplating industries. These elements can accumulate in soil over time and may become available, eventually being absorbed by plants and entering the food chain.
- Ambika *et al.* (2011) [1] reported significantly higher concentrations of cadmium, lead, and nickel in mulberry leaves irrigated with untreated sewage, raising concerns over potential toxicity to silkworms and human health risks through occupational exposure. Heavy metals interfere with enzyme activity, cellular respiration and oxidative stress responses in both plants and animals.
- However, Chandraju *et al.* (2012) [7] found that using diluted distillery spent wash (up to 33%) did not result in heavy metal buildup in mulberry leaves, suggesting that dilution significantly lowers toxicity risk by reducing metal concentration and improving leaching through soil layers.
- The soil's buffering capacity, pH, organic matter content, and cation exchange capacity (CEC) also play critical roles in immobilizing or mobilizing heavy metals. For example, alkaline and organic matter-rich soils tend to adsorb heavy metals, reducing their mobility and uptake by plants.
- Over time, however, if effluents are applied continuously without proper treatment or dilution, the cumulative effect can lead to soil contamination, loss of microbial diversity and reduced fertility, undermining the long-term sustainability of mulberry cultivation.

5. Effect on silkworm rearing and cocoon production

5.1 Cocoon yield and quality

Wastewater and effluent irrigation in mulberry cultivation have shown a generally positive impact on cocoon yield and quality due to the enhanced nutrient profile of leaves, which plays a direct role in silkworm growth and silk production.

- Bongale and Krishna (2000) [6] found significantly higher cocoon yields when silkworms were fed mulberry leaves from sewage-irrigated gardens. This is attributed to the elevated nitrogen and chlorophyll content in the leaves, which enhances protein synthesis in silkworms-vital for silk gland development and cocoon spinning.
- Surendranath *et al.* (1997) [20] confirmed that no deterioration in cocoon quality occurred under sewage irrigation, indicating that nutrient-enriched leaves do not compromise fiber characteristics, provided the wastewater is free of harmful pollutants.
- Debashish Saha *et al.* (2003) [10] observed improved silkworm performance in terms of larval weight, effective rate of rearing (ERR), cocoon shell weight and shell ratio-key economic traits in sericulture. These improvements are likely due to the enhanced levels of soluble proteins, sugars and amino acids in sewage-fed leaves, which are directly assimilated into body tissues and silk fibers. However, they advised limiting the frequency and concentration of wastewater irrigation to avoid accumulation of noxious elements or osmotic

stress, which may cause digestive imbalance or oxidative stress in larvae.

- Chandraju *et al.* (2012) [7] demonstrated significant improvements in cocoon yield in silkworm breeds like Kolar Gold, CSR19 and CSR2 × CSR4 when fed on mulberry irrigated with 33% diluted distillery spent wash. Notably, Kolar Gold achieved a 26% yield increase over control. This can be scientifically explained by the rich organic content and micronutrient profile (e.g., calcium, iron, magnesium) of the spent wash, which enhance leaf metabolic quality, supporting faster larval growth and more efficient silk synthesis.

5.2 Physiological response of silkworm
Silkworm physiological responses are directly influenced by the biochemical composition of mulberry leaves, which is, in turn, modulated by the quality of irrigation water.
- Rao *et al.* (2010) [16] emphasized that sewage-irrigated leaves had significantly higher levels of essential amino acids such as methionine, histidine and threonine. These amino acids are crucial for the biosynthesis of silk proteins-fibroin and sericin-and also support tissue repair, immune function, and hormonal regulation in silkworms. As a result, larvae reared on such nutrient-enriched leaves show improved weight gain, feed conversion efficiency and silk output.
- Saad (2014) [17] reported a significant increase (18-24%) in cocoon and pupal weight during the spring season when silkworms were fed sewage-irrigated mulberry. This seasonal effect may be amplified by favorable climatic conditions (optimal temperature and humidity) in combination with improved leaf quality. Higher pupal weight also indicates better nutrient assimilation and energy storage, which is essential for successful cocoon formation and moth emergence.

5.3 Non-significant differences in some studies
While many studies have demonstrated clear benefits of wastewater irrigation, others have shown neutral or inconsistent results, emphasizing the context-dependent nature of wastewater use in sericulture. Chikkaswamy *et al.* (2014) [8, 9] found that although mulberry plants irrigated with sewage showed better vegetative and biochemical traits, there were no significant differences in cocoon yield, larval weight, or growth compared to borewell irrigation. This suggests that improved leaf quality alone may not always translate into higher cocoon performance, especially if:
- The mulberry variety used has low nutrient responsiveness.
- The silkworm breed has already achieved physiological saturation in nutrient uptake.
- The duration of exposure to wastewater-fed leaves is too short to influence larval metabolism significantly.
- Environmental conditions, such as temperature, humidity, or disease prevalence, counteract the nutritional advantages.

Additionally, it is important to consider that soil type, irrigation interval, wastewater composition and silkworm rearing practices can influence the overall efficacy of wastewater use in sericulture.

6. Reeling effluent and its potential
6.1 Nutrient recycling in sericulture
The concept of nutrient recycling in sericulture is gaining attention as an environmentally sound and economically viable practice. A key aspect involves the reuse of reeling effluent, a wastewater byproduct generated during the silk reeling process, which is typically discarded as waste. However, scientific studies reveal that this effluent contains organic matter, soluble proteins, sericin residues and trace levels of macro-and micronutrients (*e.g.*, N, P, K, Ca, Mg, Fe), making it a potential resource for agricultural and biotechnological applications.

6.1.1 Enhancing mulberry growth through reeling effluent irrigation
- Garcia *et al.* (2015) [12] demonstrated that reeling wastewater, when used for irrigating mulberry saplings, led to significantly improved root and shoot development across multiple varieties. This effect is due to the presence of organic nitrogen and amino acids in the effluent, primarily derived from degumming proteins such as sericin, which promote cell division, tissue expansion, and early root initiation.
- Sericin, being hydrophilic and rich in polar amino acids like serine, aspartic acid, and glycine, enhances water absorption capacity of the soil and improves nutrient solubility, making essential elements more bioavailable to plants. This biochemical profile fosters rhizogenesis (root formation) and vegetative vigor, which are critical for nursery-stage mulberry plants.
- The organic acids and low concentrations of dissolved nutrients in reeling water may also stimulate beneficial microbial activity in the rhizosphere, contributing to improved nutrient mineralization and soil structure-further supporting plant development.

6.1.2 Algal cultivation and wastewater bioremediation
- Gao *et al.* (2021) [11] explored the use of cocoon wastewater (RW) to cultivate microalgae, specifically *Chlorella sorokiniana*. Their findings showed that the algae were capable of removing up to 60% of nitrogen, 95% of phosphorus and 87% of Chemical Oxygen Demand (COD) from the effluent. This is a clear indication that algal systems can be harnessed for wastewater bioremediation, effectively reducing the environmental impact of reeling effluent discharge.
- Scientifically, microalgae utilize inorganic nitrogen (ammonium, nitrate) and phosphorus (phosphate) from wastewater as primary nutrients for photosynthetic growth. Their rapid biomass production is supported by the availability of light, CO_2, and dissolved organics, turning a pollutant stream into a productive cultivation medium.
- The resultant algal biomass is rich in proteins, lipids, chlorophyll, and minerals, and can be processed into biofertilizers, livestock or aquaculture feed, or even explored for biofuel production, thus creating a circular bioeconomy within sericulture systems.

7. Environmental and economic implications
7.1 Water conservation and sustainability
The strategic reuse of wastewater in mulberry cultivation is a scientifically grounded solution to address growing water scarcity, especially in semi-arid, drought-prone and peri-

urban regions where freshwater availability is limited or highly competitive among agricultural, industrial, and domestic sectors.

- Mulberry (*Morus* spp.), the sole food plant of the silkworm (*Bombyx mori*), is a highly water-dependent crop during its vegetative growth phase. In regions with erratic rainfall and declining groundwater levels, the use of treated or partially treated wastewater ensures a reliable, year-round water supply, thereby stabilizing leaf yield and quality essential for consistent silkworm rearing.
- Reusing wastewater helps reduce extraction pressure on aquifers, slowing the rate of groundwater depletion. Over-extraction has led to aquifer compaction and declining water tables in many sericulture-intensive areas, especially in parts of Karnataka, Tamil Nadu and Andhra Pradesh. Integrating wastewater into irrigation cycles allows for the recovery and reuse of water that would otherwise be lost to drains or surface runoff.
- From a climate resilience perspective, wastewater reuse supports adaptation strategies in agriculture by promoting resource circularity-a key pillar of sustainable farming systems. It enhances the water-use efficiency (WUE) of the sericulture system, aligning with global Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production).
- Additionally, wastewater often contains organic carbon, which can improve soil structure, water retention capacity, and microbial biodiversity, indirectly reducing the frequency and quantity of irrigation required for optimal mulberry growth.

Thus, wastewater irrigation offers a win-win approach by ensuring water security for sericulture while promoting environmentally sustainable practices.

7.2 Cost reduction

In addition to conserving water, wastewater reuse also delivers direct economic benefits to sericulture farmers by reducing input costs, particularly those related to fertilizers and irrigation energy.

- Wastewater typically contains substantial quantities of plant-available nutrients such as nitrate, ammonium, phosphate, potassium, and trace elements like zinc, boron, and iron. These nutrients, when delivered through irrigation, serve as liquid fertilizers, reducing or even eliminating the need for external chemical fertilizers.
- Scientific studies (e.g., Baskar *et al.*, 2003; Chandraju *et al.*, 2012) [5, 7] have shown that soils irrigated with effluents exhibit higher concentrations of available NPK, which correlates with improved mulberry leaf yield and better leaf biochemical quality two critical factors for efficient silkworm rearing.
- For smallholder sericulture practitioners, who often operate with limited financial resources, reduced expenditure on synthetic fertilizers can translate into significant savings per cultivation cycle, improving profit margins. Fertilizer costs can constitute 20-30% of total cultivation costs, and partial substitution through wastewater can lower this burden.
- Moreover, by utilizing local wastewater sources, farmers can reduce fuel and electricity costs associated with pumping groundwater or transporting water, especially in regions facing power shortages or erratic supply.
- The added benefit of improved soil fertility over time further reduces the need for external soil amendments, enhancing the long-term economic viability of sericulture.

In essence, wastewater irrigation not only serves ecological goals but also provides a financially feasible alternative for resource-limited farmers, making sericulture more inclusive, resilient, and profitable.

8. Challenges and future perspectives

Although the reuse of wastewater in mulberry cultivation has demonstrated significant agronomic and economic benefits, its long-term application poses several risks if not properly managed. The potential for soil contamination, crop toxicity, and silkworm health hazards necessitates a scientifically sound and regulatory framework to ensure safe and sustainable use.

8.1 Challenges

- **Heavy Metal and Organic Pollutant Accumulation:** Over time, repeated irrigation with untreated or poorly treated wastewater can lead to the accumulation of heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni) in the soil. These metals are non-biodegradable and can enter the plant system through root uptake, eventually accumulating in mulberry leaves. Feeding silkworms with such contaminated leaves poses serious risks to larval health, cocoon quality, and even the occupational health of sericulture workers.
  Organic pollutants such as detergents, hydrocarbons, phenols, and endocrine-disrupting chemicals (common in urban sewage and industrial effluents) may also impair soil microbial diversity, disrupt plant metabolism, and accumulate in the food chain.
- **Nutrient Imbalance and Salt Accumulation:** Wastewater often contains high levels of sodium (Na) and other salts, which can lead to soil sodicity, reducing infiltration rates, soil permeability, and eventually impairing root respiration and nutrient uptake. Excess nitrogen and phosphorus can also lead to luxury consumption by the plants, altering leaf biochemistry and potentially reducing silkworm digestibility.
- **Pathogen Load and Public Health Risks:** Raw domestic sewage may harbor pathogens, including bacteria, viruses, and protozoa (e.g., *E. coli*, *Salmonella*, *Giardia*), which pose health risks to farm workers and silkworms alike. These pathogens can survive in moist soils and foliage, especially when mulberry is consumed fresh by larvae.

8.2 Mitigation strategies

To address these challenges and ensure the sustainable use of wastewater, the following scientifically backed practices are essential:

1. **Regular Monitoring of Effluent Quality:** Periodic testing of chemical (pH, EC, COD, BOD, heavy metals) and microbial (coliforms, pathogens) parameters is critical to ensure that wastewater remains within safe

limits. Monitoring helps detect early signs of toxicity or imbalance, enabling timely interventions.

2. **Use of Treated or Diluted Wastewater:** Scientific studies show that secondary-treated effluents or diluted effluents (25-33%) drastically reduce pollutant loads while retaining beneficial nutrients. This dilution buffers against salt and heavy metal accumulation while providing adequate moisture and nutrition for mulberry.
3. **Alternating Wastewater with Freshwater Irrigation:** Alternating irrigation cycles with freshwater can help flush accumulated salts and prevent the concentration of toxic substances in the root zone. This also supports the microbial recovery of soil and maintains its physical structure.
4. **Crop-Specific Threshold Limit Studies:** Different mulberry varieties and silkworm breeds respond differently to effluent components. Therefore, crop-specific tolerance thresholds for nutrients, heavy metals, and salinity need to be established through controlled field experiments and dose-response studies**.**

8.3 Future perspectives
To further enhance the safe and efficient use of wastewater in sericulture, future research and innovation should focus on the following areas:

- **Phytoremediation strategies:** Use of hyperaccumulator plants or cover crops that can extract or immobilize heavy metals from wastewater-irrigated fields. Plants like *Vetiveria zizanioides*, *Brassica juncea*, and *Helianthus annuus* have shown potential in remediating contaminated soils.
- **Refinement of effluent treatment technologies:** Low-cost, decentralized technologies such as constructed wetlands**,** bio-sand filters**,** aerated lagoons**,** and algal ponds can improve effluent quality before use. Advanced treatments like membrane bioreactors or activated carbon filtration may be explored in high-risk areas.
- **Standardized irrigation protocols:** Development of region-specific and crop-specific guidelines for wastewater use, including frequency, dilution ratios, safe intervals before harvest, and soil management practices, will ensure farmer safety and crop productivity.
- **Integration into circular economy models:** Incorporating wastewater reuse into broader circular economy frameworks within sericulture can maximize resource efficiency-linking mulberry cultivation, wastewater treatment, algal biomass production, and nutrient recycling into a closed-loop sustainable system**.**

9. Conclusion
The reviewed literature collectively supports the use of treated or diluted wastewater-including sewage, industrial effluents, and reeling effluent-as an effective irrigation alternative in mulberry cultivation. When applied judiciously, such water sources enhance leaf nutrient content, boost mulberry growth, improve soil health, and positively influence silkworm productivity and cocoon quality. However, the balance between benefit and risk must be maintained. The ecological footprint, potential for soil contamination, and bioaccumulation of toxic elements must be mitigated through scientific management practices. As climate change and water scarcity intensify, wastewater reuse offers a resilient strategy to sustain sericulture productivity while promoting environmental conservation and circular resource use.

10. Disclaimer (Artificial intelligence)
Author(s) hereby declare that NO generative AI technologies such as Large Language Mode (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

11. Competing Interests
Authors have declared that no competing interests exist.

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