Agricultural Reuse of Treated Paper Mill Effluent: Implications for Soil Health, Nutrient Cycling and Sustainable Crop Production.

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ABSTRACT

The pulp and paper industry ranks among the largest users of freshwater and produces vast amounts of wastewater laden with organic matter, suspended solids, salts, nutrients, and a range of chemical pollutants. Traditional disposal of this effluent continues to create serious environmental problems, threatening soil quality, water bodies, and broader ecosystem health. At the same time, mounting pressure from freshwater shortages and the push for more sustainable farming practices has sparked growing interest in reusing properly treated paper mill wastewater on agricultural land. This review examines the typical characteristics of paper mill effluent, the treatment methods available, and the outcomes of its application to crops. Special attention is given to how it impacts soil properties, nutrient availability, microbial communities, crop development, and overall agricultural output. The study also addresses the potential downsides of using untreated or inadequately treated effluent—particularly regarding its salinity, sodicity, heavy metal buildup, and toxicity to plants. The literature demonstrates that when paper mill effluent is effectively treated and carefully managed, it can become a useful source of both irrigation water and plant nutrients. The organic matter and essential elements it contains often enhance soil fertility, improve nutrient uptake by plants, boost microbial activity, and support better crop growth and yields, provided application rates and dilution are appropriate. While applying raw effluent directly can damage soil structure, reduce crop performance, and harm local ecosystems, effective treatment technologies, ongoing monitoring of soil and water quality, and sound regulatory frameworks are essential if this reuse is to be done safely. Ultimately, moving away from simple waste disposal toward resource recovery and circular economy principles provides an opportunity to turn paper mill effluent from an environmental liability into a valuable asset for sustainable agriculture and water conservation.

Keywords: paper mill effluent; wastewater; agricultural reuse; irrigation; nutrients; fertility; pollutants; sludge.

INTRODUCTION

Water is a valuable asset that is becoming increasingly scarce and needs to be sustained, globally and locally. This compounding deficit has intensified the pursuit of alternative resources to mitigate the impact on agricultural productivity. Consequently, recycled effluent usage for irrigation is becoming an increasingly popular practice in many areas of the world, particularly in arid and semiarid regions, where supplies of good-quality water are limited or lacking. The main obstacle for extending the use of effluents for the irrigation of crops has resulted from their poor quality. Generally, the quality of discharged effluent differs from industry to industry, which may or may not be suitable for the irrigation of crop. Hence, the quality of effluent should be properly assessed prior to its application for irrigation purposes. However, indiscriminate use of industrial effluent may retard crop growth and contaminants present therein may interfere with natural characteristics of soil [1]. The paper industry is one of the major industries that utilize a large quantity of water, resulting in the generation of large amounts of wastewater. It is considered the sixth-largest polluting industry and discharges a variety of pollutants into the environment. Land application of wastewater is a preferred alternative for its disposal, since soil is believed to have a capacity for receiving and decomposing wastes and pollutants, where organic materials are stabilized through the activity of microbial flora in the soil. The application of wastewater from pulp and paper industry leads to the deterioration of soil physical, chemical and biological properties [2].

The pulp and paper industry uses a large quantity of freshwater and lignocellulosic materials in the process of producing paper and it generates a large quantity of effluent [3]. The generated effluent is characterized by dark colour, foul odour, high organic content and extreme quantities of chemical oxygen demand (COD), biochemical oxygen demand (BOD_5) and pH [4]. Pulp and paper industrial wastewaters usually contain halogenated organic materials because chlorine-containing compounds are commonly used as bleaching agents during pulp and paper manufacture [5]. Due to the severe toxic effects of pulp and paper mill effluents, reduction and/or removal of pollution loads prior to their discharge into the environment is crucial. The treated wastewater contains organic matter (OM) and nutrients that can improve soil and crop productivity. Furthermore, treated paper mill effluent or wastewater is considered a resource that can be applied for productive uses since it contains a higher amount of essential plant nutrients that have the potential for use in agriculture [6]. Recently, attention has been diverted to the use of treated wastewater for agricultural crops as a source of fertilizer as well as irrigation water. Similarly, the use of treated wastewater for both agricultural production and environmental protection has increased in recent years in several countries.

Paper mill wastewater has appreciable concentration of carbonate and bicarbonate alkalinity (HCO_3^-) and exhibits a tendency to precipitate calcium (Ca) in the soil as $CaCO_3$, thus increasing the resultant proportion of sodium (Na) to calcium and magnesium (Mg) and sodium adsorption ratio (SAR) of the soil. Irrigation with undiluted paper mill effluent might lead to increased pH, electrical conductivity (EC), organic carbon, and available nutrients. The concentration of Nitrogen (N), Phosphorus (P), Potassium (K) and Sodium (Na) increased in all soil after irrigation with effluents as compare to irrigation by well water. Therefore, wastewater from these industries can be subjected to physical, chemical and biological methods, before disposal on land or into various water bodies [2].

The aim of this paper is to critically review and evaluate the potential of treated paper mill effluent as an alternative source of irrigation water and plant nutrients for improving soil health and agricultural productivity, while examining the associated environmental risks, treatment requirements, and sustainable management strategies for its safe agricultural reuse.

The objective of this review seeks to synthesize current knowledge on the characteristics, treatment, and agricultural reuse of paper mill effluent; evaluate its effects on soil health, nutrient availability, and crop productivity; assess potential environmental risks associated with its application; and identify sustainable management strategies and future research priorities for promoting its safe utilization as a resource in sustainable agriculture.

Methodology of Literature Collection

Literature Search Strategy

Relevant literature used in this review was collected from major scientific databases including Scopus, Web of Science, Google Scholar, ScienceDirect, ResearchGate, PubMed, Multidisciplinary Digital Publishing Institute (MDPI) and SpringerLink. The literature search focused on peer-reviewed journal articles related to the agricultural reuse of paper mill effluent and its effects on soil health and crop productivity. The literature search was conducted using combinations of the following keywords: “paper mill effluent”, “pulp and paper wastewater”, “treated paper mill effluent”, “wastewater irrigation”, “agricultural reuse”, “soil health”, “soil fertility”, “crop productivity”, “nutrient uptake”, “organic matter”, “soil microbial activity”, “salinity”, “sodicity”, “phytotoxicity”, “heavy metal accumulation”, “effluent treatment”, “resource recovery”, “nutrient recycling”, and “sustainable agriculture”. Boolean operators such as AND, OR, and NOT were used to refine search results and improve relevance. Search strings included combinations such as “paper mill effluent AND soil fertility”, “treated wastewater AND crop productivity”, and “paper mill wastewater AND sustainable agriculture”.

Inclusion and Exclusion Criteria

Studies included in this review met the following criteria: Publications in peer-reviewed scientific journals, written in English language, focused on paper mill effluent irrigation and agricultural applications, reported impacts on soil physicochemical properties, soil biological properties, nutrient dynamics, or crop productivity, and treated or untreated paper mill effluent studies relevant to sustainable agriculture. The following studies were excluded: Conference abstracts without full text, non-peer-reviewed articles, studies unrelated to agricultural reuse, duplicate publications, and studies lacking sufficient scientific data or relevance to the review objectives.

Data Extraction and Synthesis

Relevant information from selected studies was carefully extracted and synthesized under the following thematic areas: Characteristics of paper mill effluent, classification, treatment methods, effects of treated and untreated effluent(s) on crop growth and yield performance, nutrient dynamics. The collected information was synthesized and critically evaluated to examine the agronomic benefits, environmental limitations, emerging resource recovery opportunities, and research gaps associated with the use of treated paper mill effluent in sustainable agriculture.

Classification of Paper Mills

Paper mills are classified based on the raw material used, plant size, and end products manufactured as follows: A. Wood or forest-based mills; in this type indigenous hardwood pulp from bamboo, eucalyptus and imported pulp etc. are used. B. Agro-residue-based mills; in this class agricultural residues such as rice straw, wheat, sarkanda grass, bagasse, jute, etc. used as raw materials. C. Wastepaper based mills; these mills use imported and indigenous wastepaper, corrugated wastepaper, kraft paper, and waste cuttings as raw materials [7].

Characteristics of Paper Mill Effluents

Physicochemical Characteristics

Pulp and paper wastewater is a high-concentration multicomponent pollutant. Its main constituents include suspended solids, carbohydrates, ammonia nitrogen, cyanide, sulfate, phosphate, heavy metals [8]. Among various stages of paper making, raw material processing, pulping, pulp washing, screening, washing, bleaching, paper machine and coating operations are the important pollution sources [9]. The effluent is characterized by dark color, foul odour, high organic content and extreme levels of COD, BOD_5, TS (Total solids), TSS (Total suspended solids), TDS (Total dissolved solids), and pH [10]. In general, high OM and suspended solid contents are considered major pollutants of pulp and paper industry effluents. Among the paper making processes, pulping especially by chemical pulping generates high strength wastewater which contains wood debris and soluble wood materials, organic material and suspended solid [11]. Also, Chlorine used for bleaching of pulp generates enormous toxic chemicals as it utilizes chlorine for brightening the pulp [12]. The wastewater generated from pulping process also consist various wooden compounds such as lignin, carbohydrate and extractives. Chlorination is generally the first stage in kraft bleaching and during this treatment chlorinated organic compounds are produced [13]. Chloro-organic compounds tend to persist in nature because of their inherent recalcitrance. They are often toxic to aquatic life; many are genotoxic and have the potential to migrate widely throughout the ecosystem. The colour in paper mill effluent is caused by organic ligands such as wood extractives, resins, synthetic dyes, tannins, lignin and their degradation products [14, 15]. Addition of toxic compounds such as resin acids, unsaturated fatty acids, diterpene alcohols, chlorinated resin acids and others can exist in the wastewaters subjecting to the process [16]. The different bleaching sequence adopted by pulp and paper industry are especially problematic due to the presence of adsorbable organic halides (AOX), total organic chlorides (TOCl) and wood extractives in the effluents. The most important reaction in the bleaching step is oxidation of chlorine and the main problem about the wastewater content is the generation of chlorinated organic compounds [17]. The wastewater generated from paper making process include large number of degraded organic and inorganic contaminants depending upon the type of raw materials, end product, high concentration

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of chemicals such as sodium carbonate, sodium sulphide, bisulfites elemental chlorine dioxide, calcium oxide, hydrochloric acid, etc. [18].

Heavy Metal Content

Heavy metals are mostly found in black liquor in the pulp and paper industries. In the paper-making process, black liquor is a liquid that contains 70 % solids and is added to the digester. Pulp and paper industry (PPI) effluent contains a lot of organic compounds such chlorinated phenols, chlorinated hydrocarbons, ligno-sulphonic acid, chlorinated resin acids, and biocides. The effluent containing dangerous contaminants is discharged into rivers and lakes at a rate of 20–100 cubic meters per metric ton of product, contributing to the toxicity of the aquatic environment [19]. Lead (Pb), mercury (Hg), barium (Ba), cadmium (Cd), arsenic (As), and chromium (Cr) are examples of heavy metals that harm the environment. Copper (Cu), cadmium (Cd), mercury (Hg), zinc (Zn), aluminum (Al), chromium (Cr), and lead (Pb) are some of the hazardous heavy metals that are considered priority contaminants [20,21]).

The term heavy metal(loid) in general includes elements (both metals and metalloids) with an atomic density greater than 6 g cm^{-3} [with the exception of arsenic (As), boron (B), and selenium (Se)]. This group includes both biologically essential [e.g., cobalt (Co), copper (Cu), chromium (Cr), manganese (Mn), and zinc (Zn)] and nonessential [e.g., cadmium (Cd), lead (Pb), and mercury (Hg)] elements. Heavy metal(loid)s reach the soil environment through both pedogenic (or geogenic) and anthropogenic processes. Anthropogenic activities, primarily associated with the disposal of industrial and domestic waste materials including wastewaters and biosolids, are the major sources of metal(loid) enrichment in soils [22].

Nutrient Composition

Nutrient concentrations of paper mill effluents vary according to the pulping method and the level of microbial decomposition that has occurred during secondary treatment. Effluent from pulp mills is a rich source of OM, N, P, Ca, Mg, and trace elements, and consequently the application of pulp mill effluents on land is becoming a common method for recycling nutrients [23].

Land application is frequently practiced for wastewater and sludge management. Sludge and wastewater improves soil properties and plant growth by increasing soil exposure to air, water-holding capacity, and water infiltration as well as lowering bulk density and surface crusting. Applications of industrial wastes like fertilizer and soil amendment have become popular in agriculture [24]. Pulp and paper mill by-products have been used for amending agricultural soils and producing crops [25]. Sludge and wastewater are rich in macro and micro-contaminants that are beneficial, making it suitable for agricultural use [26]. However, heavy metals, organic compounds, and human pathogens and other contaminants are also present, which should be considered when it is utilized in agricultural soils [27].

Biological Characteristics

Pulp and paper wastewater is a type of pollutant that contains a large amount of organic and inorganic matter and microorganisms. Microbial pollution characteristics refer to the polluting biological substances present in pulp and paper wastewater as well as the type, quantity, and activity of these biological substances [28]. Bacteria, fungi, and viruses are the most common microorganisms found in pulp and paper wastewater, with bacteria being the most abundant, followed by fungi, and viruses being the least abundant. Bacteria in pulp and paper wastewater primarily include Bacillus, Proteus, anaerobic bacteria, Escherichia aerogenes, Escherichia coli, Pseudomonas aeruginosa, Staphylococcus aureus, Klebsiella pneumoniae, and Vibrio cholerae et al. [29]. These bacteria are highly active and can decompose OM to produce pollutants. In addition to bacteria, pulp and paper wastewater contains several fungi, such as yeast. Yeast can generate a large amount of heat through reproduction, thereby affecting the temperature of the wastewater; it can also metabolize harmful toxins, causing pollution of the environment [30]. Further, the wastewater contains several other fungi, primarily including various molds and mold spores. These fungi can produce a large amount of organic acids, reduce the pH level of the wastewater, and produce various toxic substances, thereby polluting the environment [31]. Pulp and paper wastewater may

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contain many viruses, which can enter the human body through wastewater, causing infectious diseases and health hazards [32]. The microbial pollution characteristics of pulp and paper wastewater primarily refer to microorganisms such as bacteria, yeast, fungi, and viruses contained in it as well as their types, quantities, and activities. These microorganisms can produce several pollutants and cause infectious diseases, posing health hazards [33]. To minimize environmental impacts, treated paper mill effluents should comply with established discharge standards before release or agricultural reuse. Typical effluent quality criteria adapted from regulatory agencies and international guidelines, such as the US Environmental Protection Agency (EPA, 2002) guidelines for water reuse, are presented in the table below [67].

Table: Selected Effluent Quality Standards for Pulp and Paper Mill Wastewater Discharge and Reuse.

Parameters	Unit	Permissible limit (EPA, 2002)
pH	-	5-9
Colour	Co-Pt.	Dark Brown
Total solid (TS)		-
Total dissolved solid (TDS)		-
Total suspended solid (TSS)	mg/L	35
Chemical oxygen demand (COD)	mg/L	120
Biological oxygen demand (BOD_5)	mg/L	40
Electrical conductivity (EC)	$\mu mhoscm^{-1}$	1000
Sodium Adsorption Ratio (SAR)	meq/L	< 3
Total Phenols	mg/L	0.50
Total nitrogen	mg/L	143
Sulphate	mg/L	250
Phosphorus	mg/L	200
Cl^-	mg/L	1500
Na^+	mg/L	200
K^+		-
Lignin		-
Chlorophenol	mg/L	3.0
Heavy metals		
Iron (Fe)	mg/L	2.00
Zinc (Zn)	mg/L	2.00
Copper (Cu)	mg/L	0.50
Cadmium (Cd)	mg/L	0.01
Manganese (Mn)	mg/L	0.20
Nickel (Ni)	mg/L	0.10
Chromium (Cr)		-
Lead (Pb)		-

EPA: United States Environmental Protection Agency.

BOD_5: Five-day Biochemical Oxygen Demand.

COD: Chemical Oxygen Demand; **TS:** Total Solids;

TDS: Total Dissolved Solids; **TSS:** Total Suspended Solids

EC: Electrical Conductivity in µmhos/cm

Co-Pt.: Cobalt-Platinum Color Scale

Cl^-: Chloride ion; **Na^+:** Sodium ion; **K^+:** Potassium ion **—:** Limit not specified.

Common Treatment Methods for Pulp and Paper Wastewater

Physical Treatment

The complex composition of pulp and paper mill wastewater requires treatment strategies capable of addressing high concentrations of suspended solids, organic matter, color, lignin derivatives, chlorinated compounds, and, in some cases, heavy metals. No single treatment process is capable of efficiently removing all contaminants; therefore, treatment systems often combine several physical, chemical, and biological operations to achieve the desired effluent quality before discharge or reuse in agriculture. Physical treatment technologies are generally employed as preliminary or primary treatment steps to remove coarse materials, suspended particles, and a portion of the organic load from pulp and paper wastewater. Common approaches include sedimentation, filtration, centrifugation, flotation, and membrane-based separation processes [34]. Sedimentation remains one of the simplest and most economical methods for reducing suspended solids, relying on gravitational settling to separate particulate matter from the liquid phase. The efficiency of this process can be improved through the addition of coagulants or flocculants that promote aggregation of fine particles into larger settleable flocs [35]. Coagulation-flocculation has become increasingly important as a pretreatment option for pulp and paper wastewater. During this process, chemicals destabilize colloidal particles and facilitate their removal through settling or filtration. For example, the use of polyaluminium chloride (PAC) together with cationic polyacrylamide (c-PAM) has been shown to significantly improve pollutant removal efficiencies under optimized conditions [36]. Filtration systems employing sand, gravel, activated carbon, or other porous media are widely used to further reduce suspended materials and residual organic contaminants [37]. Centrifugation and dissolved air flotation provide additional options for separating solids by exploiting differences in particle density and buoyancy. Membrane technologies such as ultrafiltration, nanofiltration, and reverse osmosis have attracted considerable attention because of their ability to produce high-quality treated water suitable for reuse applications. Studies have demonstrated substantial removal of silica and dissolved contaminants using these systems, with reverse osmosis achieving near-complete removal of target pollutants under optimized operating conditions [38,39]. Although physical treatment methods offer rapid operation and effective removal of particulate matter, they generally exhibit limited effectiveness for dissolved toxic compounds and may generate secondary waste streams requiring further management [40].

Chemical Treatment

Chemical treatment refers to the use of chemicals to remove pollutants from wastewater. Chemical treatment processes aim to transform, destabilize, or remove contaminants through chemical reactions and are particularly useful for the removal of color, lignin derivatives, phenolic compounds, and recalcitrant organic pollutants [41]. Coagulation remains one of the most widely applied chemical approaches in pulp and paper wastewater treatment. Metal salts such as ferric chloride and aluminum sulfate, together with polymeric coagulants such as polyacrylamide, are frequently used to aggregate colloidal particles and facilitate their removal [42]. Chemical precipitation techniques are commonly employed to remove selected inorganic contaminants and suspended materials through the addition of reagents such as lime or soda ash [43]. Oxidation processes constitute another important treatment category, particularly for wastewater containing persistent organic compounds. Oxidizing agents including chlorine and ozone can degrade complex organic molecules and reduce effluent color and toxicity. Advanced oxidation processes (AOPs) have received growing interest because they generate highly reactive hydroxyl radicals capable of mineralizing otherwise resistant pollutants into simpler and less harmful compounds. Such systems have demonstrated considerable potential for treating heavily polluted pulp and paper effluents [28]. Adsorption processes represent an additional chemical treatment option and rely on the affinity

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between contaminants and the surface of adsorbent materials such as activated carbon and zeolites [44,45]. The large surface area and porous structure of these materials provide numerous active sites for pollutant retention, making adsorption particularly effective for trace contaminants and color removal. Despite their high treatment efficiencies, chemical methods often involve substantial reagent consumption, sludge generation, and relatively high operational costs, which may limit their use as stand-alone treatment systems.

Biological Treatment

Biological treatment is classified into aerobic sludge and anaerobic biological methods based on the characteristics of the microorganisms used for the treatment.

Aerobic Sludge Method

The Aerobic sludge method is commonly used for treating pulp and paper wastewater. It primarily includes biofilm, biofilter, bioprecipitation, and activated sludge methods [46, 47]. Further, it uses the degradation mechanism of aerobic microorganisms to degrade organic matter in wastewater into carbon dioxide, water, and inorganic salts, thereby achieving the purpose of purifying wastewater [48]. The activated sludge and biofilm methods also use microorganisms to biodegrade OM in wastewater [49, 50]. Biological treatment offers the advantages of low investment and operating costs, and effective treatment. However, there are some disadvantages, such as lengthy treatment processes and difficulty in degrading heavy metals and antibiotics in wastewater [51].

Anaerobic Biological Method

The anaerobic biological method is suitable for treating pulp and paper wastewater with medium to high levels of pollutant concentrations. A wastewater treatment reaction device—upflow anaerobic sludge blanket (UASB reactor)—is employed, which is widely used in wastewater treatment in the pulp and paper industry around the world. Wastewater is introduced into the UASB reactor's bottom as evenly as possible. As the wastewater ascends through a sludge bed comprising granular or flocculent sludge, anaerobic reactions occur upon contact with sludge particles. The biogases produced in the anaerobic state (mainly methane and carbon dioxide) promote internal circulation, which is beneficial for the formation and maintenance of granular sludge. Some of the gases produced in the sludge layer adhere to the sludge particles. These gases, both attached and unattached, rise to the top of the reactor. When the sludge rises to the surface, it encounters the bottom of the gas emitter in the three-phase reactor. This interaction leads to the degassing of the sludge floc attached to the bubbles. Once the bubbles are released, the sludge particles settle back onto the sludge bed. Meanwhile, the attached and unattached gases are collected in the gas collecting chamber located within the three-phase separator situated at the top of the reactor. In current engineering practice, the methods of choosing an upflow anaerobic filter and anaerobic biofilter anaerobic baffle reactor are the most frequently employed [52].

Advanced Integrated Processing Technology

In addition to the above technologies, other technologies for the treatment and application of pulp and paper wastewater, such as electrochemical and ultrasonic treatment, have emerged in recent years [53]. Electrochemical and sonication treatments are the processes of removing pollutants from wastewater using electricity and ultrasonic waves, respectively [54]; these methods are gradually being employed in the industry.

Comprehensive treatment is the most commonly used method in the treatment of pulp and paper wastewater [55]. It primarily uses biological, chemical, and physical treatments as well as other technologies to separate harmful substances such as organic matter and heavy metals from wastewater [56]. The ozone biological method involves directing water, after undergoing ozone treatment, into a biological filter from the bottom, where aeration is provided as needed. This biological filter is equipped with an activated carbon filler as a biological carrier, allowing for the further removal of residual COD through biological contact oxidation. Cui et al. assessed the suitability of the ozone biological method for treating wastewater with low COD concentrations, such as raw water with a COD of only 50 mg/L. This method can achieve a COD level of <30 mg/L. In cases where raw water has a high COD concentration and strict discharge standards apply, a two-stage ozone biological series

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treatment can be performed. This approach eliminates the need for additional chemicals, ensures safety, and minimizes labor requirements. Melchiors et al. evaluated the efficiency of a physicochemical pretreatment combination, combining the coagulation–flocculation–sedimentation (CFS) process with the Fenton advanced oxidation process for treating wastewater generated from industrial chemithermal–mechanical pulp (CTMP) in Brazil. When the CFS and Fenton processes were combined for CTMP wastewater treatment, the total organic carbon removal rate reached 95%, the COD removal rate reached 61%, and the lignin removal rate reached 76% [28]. The advantages of comprehensive treatment include good treatment effects and high treatment efficiency; however, there are some disadvantages, such as high treatment costs [57].

Effects of Untreated Effluent on Agriculture

Effect of Untreated Effluent on Soil Quality

Elements such as magnesium, sodium chloride, and sulphur, which are also common in pulp mill wastewater, can cause nutrient imbalances in crops, increase soil salinity, deteriorate soil structure, and ultimately lower crop productivity in the long run. Higher values of organic carbon, available K, exchangeable cations (Ca^{2+}, Mg^{2+}), exchangeable anion (Cl^-, HCO_3^-), and micronutrient cation (Cu^{2+}) have been reported in soils being irrigated by paper and pulp industry effluents. The high alkalinity and chemical load alter soil pH and increase EC, creating a hostile environment for beneficial soil microorganisms [58].

Effect of Untreated Effluent on Crops

Pulp and paper mill effluent is also responsible for affecting the quality of crops due to irrigation with polluted water, which damages the soil, growth, quality, and yield of the crop. Toxic elements—such as cadmium and mercury often found in industrial pulp discharges—interfere with photosynthesis, causing a dramatic depletion in plant pigments [59].

Effect of Untreated Effluent on Water Bodies

The dark color and high turbidity due to suspended solids can cause problems with both water opacity and blanketing of river or lakebeds and can reduce photosynthetic activity in aquatic plants [60,61]. Severe blanketing may result in anaerobic decomposition under the blanket, releasing hydrogen sulphide into aquatic ecosystems. Therefore, it becomes necessary to remove color and toxicity before they can be accepted into surface waters.

Effects of Treated Effluent on Agricultural Productivity

The reuse of treated paper mill effluent for irrigation has gained considerable attention as a sustainable strategy for addressing water scarcity and reducing the environmental burden associated with industrial wastewater disposal. Treated paper mill effluent contains appreciable amounts of nutrients, organic matter, and dissolved minerals that can contribute to crop growth and productivity when applied under controlled conditions. Several studies have demonstrated that appropriately treated and diluted effluent can serve as both an irrigation source and a supplementary nutrient input, thereby reducing dependence on freshwater resources and synthetic fertilizers [62].

Improvement in Crop Growth and Yield

Numerous investigations have reported positive responses of agricultural crops to irrigation with treated paper mill effluent. The presence of essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium in the effluent can stimulate plant growth, enhance chlorophyll synthesis, and improve biomass production. Studies have shown increased germination percentage, plant height, root development, and yield components in crops irrigated with treated effluent at suitable dilution levels [62].

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Lysimeter studies revealed that irrigation with treated pulp and paper mill wastewater increased organic carbon, available nitrogen, phosphorus, and potassium in soils, resulting in improved grain and straw yields of wheat, jowar, and moong without causing significant soil deterioration [63].

Similarly, diluted paper mill effluent improved yield attributes of blackgram, maize, greengram, rice, and sunflower grown on acidic lateritic soils [64]. The authors observed that dilution levels between 60% and 80% were optimal for certain crops, indicating that crop response depends largely on effluent concentration and soil characteristics. In another studies, when effluent undergoes strict secondary biological treatment and is diluted with fresh water—typically at concentrations between 25% - 50% —the residual nitrogen, phosphorus, and potassium can safely fertilize crops like mustard, pea, and rice. However, using the effluent raw or undiluted remains destructive [65].

Enhancement of Nutrient Uptake

Treated paper mill effluent can improve nutrient availability and uptake by supplying both macro- and micronutrients required for plant growth. Wastewater irrigation has been shown to increase the availability of nitrogen, phosphorus, potassium, and organic matter in soils, thereby enhancing nutrient cycling and plant nutrient acquisition. In addition, treated wastewater often contains trace elements such as zinc, iron, manganese, and copper that support various physiological processes in plants [66].

Improved nutrient uptake contributes to increased photosynthetic activity, protein synthesis, and biomass accumulation. However, nutrient loading must be carefully managed because excessive nutrient application may lead to nutrient imbalance, leaching, or reduced crop quality [66].

Impact on Soil Fertility and Productivity

The use of industrial effluents for agricultural purposes involves two main principles: the use of soil as a treatment system to reduce pollution of surface water and the use of wastewater as a supplementary source of irrigation. One of the major benefits of treated effluent irrigation is the enhancement of soil fertility. Long-term application of treated wastewater can increase soil organic carbon and improve nutrient reserves, thereby contributing to higher agricultural productivity. Studies have reported significant increases in total nitrogen, available phosphorus, and exchangeable potassium in soils receiving treated wastewater irrigation compared with freshwater-irrigated soils [66].

The addition of OM through effluent irrigation may also improve soil structure, water-holding capacity, and microbial activity, creating favorable conditions for crop growth. These improvements can be particularly valuable in nutrient-deficient or degraded soils where fertility restoration is required [66].

Sustainable Use for Agricultural Production

The successful utilization of treated paper mill effluent in agriculture depends on proper treatment, periodic monitoring of soil and water quality, appropriate dilution ratios, and crop selection. When managed effectively, treated effluent can function as a valuable alternative source of irrigation water and plant nutrients, supporting sustainable agricultural production while promoting resource recovery within a circular economy framework [62].

Recommendations and Future Perspectives

The findings synthesized in this review demonstrate that treated paper mill effluent possesses significant potential as an alternative source of irrigation water and plant nutrients. Its beneficial effects on soil organic matter, nutrient availability, microbial activity, and crop productivity support the growing transition from conventional waste disposal approaches toward resource recovery and circular economy practices. However, the sustainability of this approach depends largely on treatment efficiency, application rate, soil characteristics, and long-term environmental management.

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RECOMMENDATIONS

To ensure safe and sustainable agricultural reuse, paper mill effluent should undergo adequate treatment before application to agricultural land. Advanced treatment technologies such as coagulation–flocculation, electrocoagulation, membrane filtration, adsorption, biological treatment, and advanced oxidation processes have demonstrated considerable effectiveness in reducing pollutant loads and improving effluent quality. The selection of treatment systems should be guided by effluent characteristics, economic feasibility, and intended agricultural applications.

Regular monitoring of soil and irrigation water quality is essential to prevent salinity buildup, sodicity, nutrient imbalances, and contaminant accumulation. Key indicators including pH, electrical conductivity (EC), sodium adsorption ratio (SAR), organic carbon, nutrient concentrations, and heavy metal levels should be routinely assessed to ensure long-term soil productivity and environmental protection.

The nutrient contribution of treated paper mill effluent should be integrated into site-specific nutrient management programs. Such an approach would reduce dependence on synthetic fertilizers, improve nutrient-use efficiency, and promote sustainable nutrient cycling within agricultural systems. Similarly, the beneficial reuse of paper mill sludge as compost, biofertilizer, or soil amendment should be encouraged to enhance soil fertility while minimizing waste disposal challenges.

Governments, environmental agencies, and industry stakeholders should establish comprehensive regulatory frameworks governing wastewater reuse in agriculture. These frameworks should include effluent quality standards, monitoring protocols, irrigation guidelines, and risk assessment procedures to support sustainable and environmentally responsible reuse practices.

Future Perspectives

Although substantial progress has been made in understanding the agricultural benefits and environmental implications of paper mill effluent reuse, several critical knowledge gaps remain. Most existing studies have focused on short-term greenhouse and field experiments. Long-term investigations are required to evaluate cumulative effects on soil physicochemical properties, microbial diversity, nutrient dynamics, groundwater quality, crop productivity, and ecosystem health under continuous effluent irrigation. Such studies would provide stronger scientific evidence for the development of sustainable irrigation guidelines.

Future research should also focus on heavy metal speciation, mobility, and bioavailability rather than solely determining total metal concentrations. Understanding the chemical forms and transformation pathways of metals in soil environments will improve risk assessment and support the development of effective mitigation strategies. The role of soil microorganisms in nutrient cycling, contaminant degradation, and plant growth promotion under effluent irrigation remains insufficiently explored. Emerging molecular tools, metagenomics, and microbial ecology approaches can provide valuable insights into soil–plant–microbe interactions and facilitate the development of biologically based remediation strategies.

Future technological advancements should also focus on cleaner production strategies within the pulp and paper industry. Process optimization, enzyme-assisted pulping, biological treatment systems, and environmentally friendly manufacturing practices may substantially reduce wastewater generation and pollutant loads at the source. Furthermore, the development of integrated treatment systems combining physical, chemical, and biological processes could improve contaminant removal efficiency while facilitating safe water reuse. Given increasing freshwater scarcity and climate change pressures, treated paper mill effluent is expected to play an increasingly important role in sustainable water resource management. Future studies should therefore incorporate economic feasibility analyses, life-cycle assessments, and sustainability indicators to evaluate the practicality of large-scale effluent reuse programs under diverse environmental and socioeconomic conditions. Overall, future research should prioritize long-term sustainability assessments, nutrient recovery technologies, circular bioeconomy approaches, integrated treatment systems, and evidence-based regulatory frameworks to fully realize the transformation of paper mill effluent from an environmental liability into a valuable agricultural resource.

CONCLUSIONS

Paper mill effluent has traditionally been regarded as an environmental pollutant due to its high organic load, suspended solids, salinity, and potential toxic constituents. However, findings from the literature reviewed in this study demonstrate that, when adequately treated and properly managed, paper mill effluent can be transformed from a waste product into a valuable resource for sustainable agriculture. Several studies have reported that treated paper mill effluent contains appreciable quantities of essential plant nutrients and OM capable of improving soil fertility, enhancing nutrient availability, and supporting crop growth and productivity.

Evidence from numerous investigations indicates that the controlled application of treated paper mill effluent can improve soil organic carbon, stimulate microbial activity, enhance nutrient uptake, and increase crop growth, biomass accumulation, and yield. These benefits are particularly important in the context of increasing freshwater scarcity and the growing need to optimize the use of available land, water, and fertilizer resources for sustainable food production. Consequently, treated wastewater is increasingly being recognized as a potential source of both irrigation water and plant nutrients that can contribute to improved agricultural productivity while reducing pressure on conventional freshwater resources.

Nevertheless, the agronomic benefits of paper mill effluent are highly dependent on effluent quality, treatment efficiency, application rate, crop type, and site-specific soil conditions. While raw or inadequately treated paper mill effluent may adversely affect soil properties, crop growth, and environmental quality, numerous studies have demonstrated that properly treated and appropriately diluted effluent can be utilized safely for agricultural purposes without causing significant toxicity to crops or soils. Therefore, the sustainable use of treated paper mill effluent requires effective treatment processes, regular monitoring of soil and water quality, and adherence to recommended dilution and application practices. When these measures are implemented, treated paper mill effluent can serve as a viable alternative irrigation and nutrient source capable of enhancing soil health and agricultural productivity while supporting sustainable resource management.

Conflict of Interest

The authors declare no conflict of interest.

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