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MUNICIPAL WASTEWATER IN AGRICULTURE: A COMPREHENSIVE REVIEW OF RISKS AND ENVIRONMENTAL IMPACTS

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ABSTRACT

Population expansion, urbanization, industrialization, and increased household water use are all contributing to a significant increase in wastewater production. The most prevalent type of effluent is sewage or municipal wastewater, which includes home and industrial wastewater, sewer line inflows and infiltrations, and storm water runoff. Whether treated or untreated, municipal wastewater serves as the second-largest water source for irrigation in agriculture. Wastewater used for agricultural irrigation is becoming increasingly prevalent worldwide as freshwater resources become scarcer. This approach offers a cost-effective solution for irrigation while also providing fresh produce to urban populations. Additionally, farmers benefit from this method, as wastewater is readily available and possesses fertilizing properties, further enhancing crop yields. However, despite its benefits, wastewater irrigation poses significant health risks to people and animals by exposing them to a diverse range of pathogenic microorganisms. These incorporate viruses, bacteria, protozoa, and helminths, which can cause severe and debilitating infections such as cholera, dysentery, dengue fever, and malaria. Moreover, prolonged use of contaminated water can have harmful consequences for soil health and biodiversity, leading to long-term environmental degradation. The review addresses the critical problem of using untreated municipal wastewater for agricultural irrigation, which poses significant risks to public health, environmental

sustainability, and food safety. The review also emphasizes the urgent need for proper wastewater treatment to mitigate these adverse effects and promote safe and sustainable agricultural practices.

Keywords: Wastewater, Agriculture, Impact, Pathogens, Health

1. INTRODUCTION

Municipal wastewater, the most abundant form of wastewater, includes domestic and industrial wastewater, sewer line inflows and infiltrations, and storm water runoff [1]. It is composed of 99.9% water and small concentrations of suspended or dissolved organic and inorganic particulates, pathogenic organisms, and various gases [2]. The organic components include volatile organic substances such as synthetic detergents, soaps, pesticides, phenols, chlorobenzene, and hydrocarbons. Non-volatile organic compounds include biological oxygen

demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), and total organic compounds (TOC) like carbohydrates, lignin, fats, proteins, and starch (Figure 1). These substances contribute to the organic load of wastewater, which is further augmented by a diverse array of natural and synthetic chemicals from process industries. Disintegration of these chemicals also has significant implications, as their breakdown products can persist in their surroundings and pose additional risks [3].

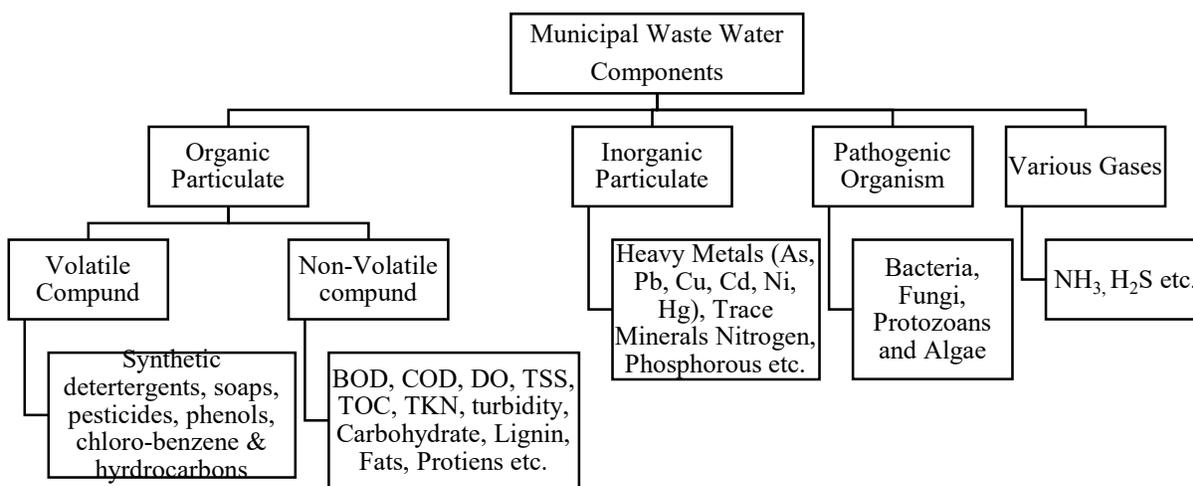


Figure 1: Different constituents of municipal waste water

The inorganic content of wastewater includes toxic heavy metals such as mercury, lead, cadmium, zinc, copper, arsenic, and chromium, along with trace minerals such as nitrogen, phosphorus, sulfur, and chlorides. Dissolved gases, resulting from the decomposition of organic matter, commonly found in wastewater include oxygen, nitrogen, carbon dioxide, ammonia, methane, and hydrogen sulfide [4]. Pathogenic organisms

present in wastewater mainly include bacteria, fungi, protozoans, and algae [3]. Wastewater is typically gray, has a musty and pungent odor due to H₂S and NH₃ gases, and contains about 0.1% dissolved and undissolved suspended solids. The characteristics of municipal wastewater vary depending on the area, sources of discharge, types of industrial effluents, and storm water and sanitary waste discharge [5] (Figure 2).

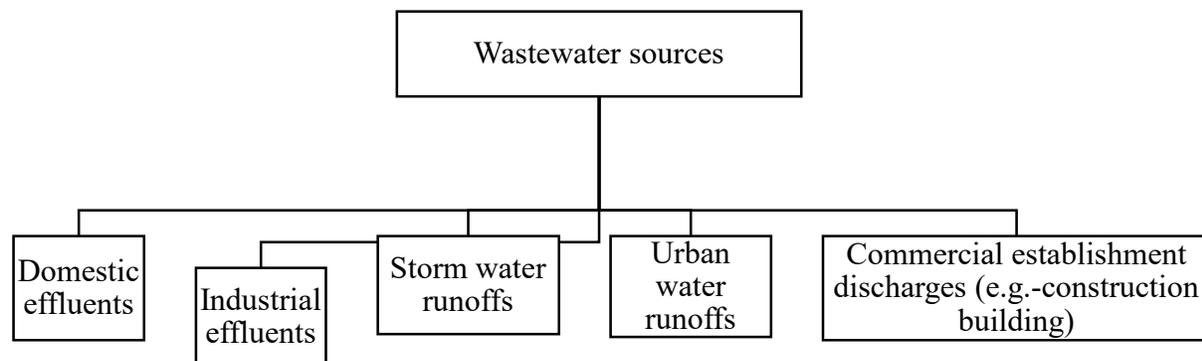


Figure 2: Different constituents of municipal wastewater

The population of humans is anticipated to increase gradually from 7.6 billion in 2017 to 9.8 billion in 2050 [6], [7]. The increase in population, industrialization, and urbanization has significantly increased wastewater production [4], [7]. India faces a critical water security crisis, ironically, despite being surrounded by an abundance of water—70% of the Earth's surface. The large volume of freshwater is frozen in glaciers, making only 1% of it suitable for life [8]. This small amount of freshwater is essential to life. Despite arguments to the contrary,

groundwater is still the world's principal supply of freshwater, and it is essential for human needs and agriculture [9]. According to CWC [10] predictions, 11 of India's 15 major river basins would face water shortages by 2025, with a yearly sustainable water supply of fewer than 1,700 cubic meters per person. Therefore, exploring alternate water sources is critical for closing the demand-supply imbalance. Worldwide, approximately 380 billion cubic meters of wastewater is produced annually, with only 56% treated before discharge. India processes just 28% of the

entire sewage generated daily in urban areas [11]. India generates around 72,368 million liters per day (MLD) of wastewater from urban areas, but only 26,869 MLD (37%) is treated, leaving more than 45,000 MLD of untreated wastewater flowing into the environment [12]. According to CPCB [13], Class I cities (above 1,000,000) and Class II cities (50,000–99,999) account for 72% of the population of urban regions and generate an estimated 38,254 MLD of sewage, with just 30% being treated. Untreated wastewater is then released into freshwater bodies like rivers. In many developing countries, municipalities discharge untreated wastewater into lakes and rivers, leading to water body contamination. Conventional wastewater processing techniques use three levels of treatment: primary, secondary, and tertiary. Primary and secondary stages of treatment are used by most of the municipal wastewater treatment plants, while some facilities additionally utilize tertiary treatments. Nevertheless, these methods are not fully effective in removing many contaminants, such as pharmaceuticals, antibiotic residues, and antimicrobial-resistant bacteria [13]. Based on the United Nations Water Development Report [14], approximately 80% of wastewater worldwide is dumped into the environment untreated or inadequately

treated. In India, around 12,000 million liters of sewage wastewater are treated daily out of 38,000 million liters, highlighting a substantial gap between wastewater creation and treatment. With freshwater resources depleting, wastewater is increasingly being used for agricultural irrigation across the world, notably in metropolitan and peri-urban areas known as "urban agriculture." Untreated or treated municipal effluent offers an additional, endless supply of water for agriculture [15]. This custom originated with ancient civilizations like the Egyptians, Mesopotamians, Minoans, and Indus Valley societies. The ancient Minoans, around 3500 BC, utilized wastewater as irrigation for their fields. In Crete, Greece's largest island, wastewater irrigation was reported for farming crops and fruit trees around 1700 BC. It is estimated that approximately 73,000 hectares of agricultural land in India are irrigated using untreated wastewater. Globally, about 29 million hectares (12% of all irrigated land) are irrigated using wastewater, either treated or untreated, with significant portions in developing countries like Mexico, China, and India [16].

Wastewater irrigation presents a mixed picture, offering several advantages alongside significant disadvantages (**Figure 3**). Utilizing wastewater as irrigation for crops

not only replenishes the soil with nutrients (N, P, and K), but it also offsets the cost and use of artificial fertilizers [17], [18]. It has been shown that crop production may be increased by introducing additional organic matter [19], better soil physical qualities [20], and microbial activity [21], While unconventional wastewater offers benefits, its prolonged use raises substantial environmental concerns, particularly regarding food safety and soil fitness. Continuous application can result in the buildup of harmful substances,

jeopardizing crop quality and soil productivity. Vegetables cultivated on polluted ground may acquire hazardous metals [22]. Prolonged use of contaminated food may also result in the accumulation of heavy metals in humans' livers and kidneys, disrupting biochemical processes such as hepatic, renal, cardiovascular, neurological, and bone issues. Long-term wastewater irrigation also reduces the soil's structure, microbial biodiversity, and porosity, which has an impact on soil health [23].

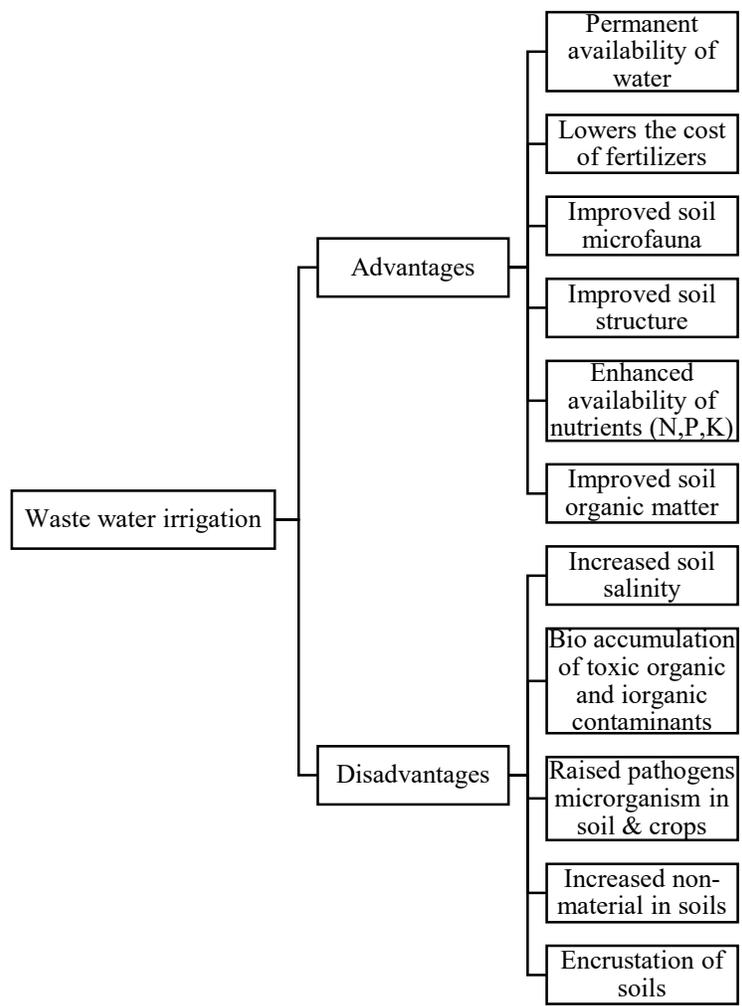


Figure 3: Advantages and disadvantages of wastewater irrigation

Despite the growing body of research on municipal wastewater irrigation, several limitations hinder a comprehensive understanding and application of wastewater reuse in agriculture. Most studies focus on short-term impacts, examining immediate changes in soil properties, crop yield, and water quality over a few growing seasons or years. This emphasis on short-term results creates a critical gap in understanding the cumulative effects of continuous wastewater irrigation on soil health, crop productivity, and ecological balance. Long-term studies are essential to assess the sustainability of wastewater reuse over decades and investigate potential long-term issues, such as soil degradation, reduced fertility, and persistent contamination. Additionally, while many studies concentrate on heavy metals and nutrient content, there is insufficient data on the prevalence and fate of pathogens (viruses and bacteria) and emerging contaminants (pharmaceuticals, personal care products, microplastics, and endocrine disruptors) in wastewater, which is vital for understanding health risks and designing effective treatment methods.

The impacts of wastewater irrigation can vary significantly based on regional soil types, crop varieties, climate, and farming practices; however, many studies do not account for these regional differences, limiting the generalizability of findings across diverse agricultural settings. Existing research often emphasizes technical and environmental aspects while neglecting socioeconomic and policy challenges, such as farmer awareness, access to technology, cost constraints, and government regulations that are crucial for promoting safe wastewater use in irrigation. Moreover, although various treatment technologies (e.g., constructed wetlands, biochar, membrane filtration) have been studied, there is limited research on integrated or hybrid solutions that combine multiple techniques for enhanced efficacy, particularly at the community or farm scale. Much of the existing literature is based on laboratory-scale experiments, creating a notable gap in studies that evaluate the effectiveness of proposed treatment technologies, like biochar-assisted methods, at larger field-scale levels or through pilot programs in real-world agricultural systems. Finally, in many regions, there are few

comprehensive monitoring frameworks for wastewater quality over time, as well as a lack of established standards or guidelines for safe irrigation practices using treated or untreated wastewater. Addressing these gaps necessitates interdisciplinary research efforts that combine environmental science, agriculture, public health, economics, and policy studies to develop practical, scalable, and sustainable wastewater treatment and irrigation systems, ultimately enhancing the safe reuse of municipal wastewater in agriculture.

2. Review Methodology

This review was conducted through an extensive survey of literature published between 2010 and 2024, focusing on the impacts of municipal wastewater irrigation on crops, soil, livestock, and human health. Sources included peer-reviewed articles, books, government reports, and reputable websites, accessed via databases such as Google Scholar, PubMed, Science Direct, Scopus, and Web of Science. Keywords used for the search included wastewater irrigation, soil health, crop contamination, heavy metals, and public health risks. The inclusion criteria emphasized studies that investigated the

use of raw or treated municipal wastewater in agricultural irrigation, focusing on impacts related to soil health, crop yield, and public health risks from pathogens and heavy metals. Articles on sustainable wastewater management were also considered. However, studies solely addressing industrial wastewater or lacking empirical evidence were excluded. The literature was categorized into five key sections: effects on human health, soil, crops, livestock, and groundwater and surface water. The data were synthesized by comparing findings across different regions and case studies, noting variations based on geography, climate, soil types, and wastewater treatment methods. Patterns of contamination, including heavy metal accumulation and pathogen persistence, were closely examined to assess the broader influence of wastewater on soil and crop health. By focusing on high-impact, peer-reviewed research published within the last five years (2018-2024) for better relevance, the review ensured robust, evidence-based conclusions. Studies published before 2010, conference papers, dissertations, and articles not specifically addressing

wastewater's impact on agriculture and the environment were excluded.

3. Impact of raw municipal wastewater

3.1. On Human Health

In terms of human health, irrigation with wastewater presents both advantages and disadvantages. On the positive side, it can raise revenue in underdeveloped communities and promote food security, enhancing nutrition and quality of life. However, the negative health impacts are significant. In regions using untreated wastewater for irrigation, 50–70% of farmers report experiencing skin and respiratory infections. Microbial contamination is responsible for 80–90% of wastewater-related health risks in developing areas, leading to widespread diseases such as cholera, dysentery, and typhoid [17]. Approximately 2.2 million deaths annually are linked to unsafe water, sanitation, and hygiene practices, including wastewater irrigation [24]. The use of urban wastewater poses risks to four primary groups: farm communities, crop handlers, crop consumers (including those consuming milk and meat), and residents—particularly the elderly and children—living in areas where wastewater is utilized for irrigation [25].

The consumption of raw vegetables such as radishes, carrots, onions, and lettuce increases health risks. Additionally, areas irrigated with wastewater for rice cultivation have reported higher populations of malaria vectors compared to neighboring regions [26]. Diseases can persist in soil and crops long enough to spread to humans or animals. Highly resistant helminth eggs are particularly concerning in underdeveloped nations, where their concentrations in wastewater are significantly higher than in affluent countries [27]. The prevalence of poverty and inadequate sanitation in these areas is alarmingly high, with 90% of the overall population affected, making the problem even more severe and challenging to address [27]. Ascariasis, a common helminth infection, impacts 1.3 billion people globally, primarily children under the age of 15, leading to growth and fitness problems even after treatment. Effluent usage is also associated with various waterborne diseases, including typhoid fever, cholera, shigellosis, and gastrointestinal infections, posing a substantial public health threat [28]. Heavy metals in wastewater also pose serious health risks. While these metals are biologically necessary in small

amounts, they become hazardous at higher concentrations [29]. Cadmium is particularly dangerous due to its accumulation in the kidneys and liver, remaining toxic even at low levels [30]. Additionally, wastewater often contains hazardous chemicals, including endocrine disruptors from pesticides, detergents, and pharmaceuticals, which can persist in the environment and potentially lead to cancer and reproductive issues [27]. Although the health consequences of wastewater irrigation are not yet definitively proven, research has indicated negative effects in various animal species, underscoring the need for ongoing research and monitoring to assess these risks comprehensively [28].

3.2. Impact on Soils

Soil is an intricate and dynamic matrix, comprising varying proportions of organic and mineral components that differ by temperature and location, making it challenging to ascertain whether wastewater chemicals have beneficial or detrimental effects [29], [30]. The physical properties of soil, such as hydraulic conductivity, pH, and leaching efficiency, are negatively impacted, further impeding the leaching

of harmful salts through the root zone [31], [32], and an increase in P and N in the soil profile occurs over time [33]. Wastewater irrigation increases sodium (Na), which results in a decline in soil structure. This, in turn, negatively affects soil porosity and microbial diversity.

Organic nitrogen, ammoniacal nitrogen, nitrates, and nitrites are among the several chemical types of nitrogen. According to Oliveira *et al.* [33] and Mishra *et al.* [24], soils convert several forms of nitrites into nitrates, while most crops only absorb nitrates. To prevent nitrate pollution in aquifers and surface water, the quantity of nitrogen present in wastewater used for irrigation must be adjusted, as it can easily dissolve in water and harm the environment [34]. Domestic wastewater has a higher nitrogen content than soil (0.05–2%) and is required by crops (50–350 kg/ha) [35]. Prasad *et al.* [36] examined the effects of irrigation using municipal water on soil samples in Kanpur, Bhopal, and Varanasi. They observed higher organic carbon levels in municipal-irrigated soils (0.41% in Varanasi, 0.34% in Kanpur, and 0.60% in Bhopal). Elevated quantities of heavy metal were observed (Cd: 0.50–1.33 ppm, Cr: 27.57–49.43 ppm, Pb: 10.75–24.37

ppm) in soils that had considerable amounts of organic matter and pH levels (6.5–8.5). Fortunately, municipal water has an alkaline pH of 7.2–7.6, which helps preserve the soil's natural pH when combined with the soil's alkalinity [32]. Studies conducted in India have revealed that heavy metal concentrations in soils irrigated with untreated wastewater are significantly elevated compared to those in soils irrigated with clean water. For instance, lead (Pb) concentrations in wastewater-irrigated soils range from 50 to 200 mg/kg, exceeding the safe limits of 10 to 50 mg/kg. Similarly, copper (Cu) levels can reach 200 to 300 mg/kg, far surpassing the acceptable range of 30 to 100 mg/kg. Zinc (Zn) can accumulate at levels as high as 400 to 600 mg/kg, which is well above the safe limit of 150 mg/kg. Furthermore, chromium (Cr) concentrations in wastewater-irrigated soils have been reported at 60 to 150 mg/kg, exceeding the permissible limit of 20 mg/kg. These findings highlight the significant environmental and health risks associated with the use of untreated wastewater for irrigation [24]. Irrigation with untreated wastewater has significant implications for soil quality, particularly in terms of

salinity and organic carbon accumulation. Studies show that wastewater irrigation contributes to increased soil salinity, with electrical conductivity (EC) levels reaching 3-6 dS/m, well above the ideal range of less than 2 dS/m recommended for most crops. Elevated salinity adversely affects crop growth, yield, and overall soil health [37]. Salinization is influenced by various factors, including groundwater depth, irrigation rate, organic matter content, the soil's capacity to transfer water, and water quality. Salinity issues include soil conductivities higher than 3 dS/m, dissolved solids exceeding 500 mg/L (severe if above 2,000 mg/L), chlorine levels below 140 mg/L, and a sodium absorption ratio (SAR) greater than 3-9, all of which depend on soil type and drainage conditions [21].

In addition to salinity concerns, soils irrigated with untreated wastewater often have 2-3 times higher organic carbon content compared to non-irrigated soils. While this increase can initially enhance soil fertility, it can lead to long-term degradation and imbalance in soil properties, ultimately undermining agricultural productivity. Therefore, managing these effects is crucial for

sustainable agricultural practices in regions that rely on wastewater for irrigation [36].

3.3. Effects on crops

Crop impacts can be classified into two categories: those that alter crop quality (taste, appearance, or presence of pollutants) and those that alter yields [38]. When nitrogen is given to plants in excess of what is needed, it might encourage vegetative growth instead of fruit development and postpone ripening. This has also been seen with regard to beets, rice, and cane [21]. Heavy metals move from soil to plants via the root system, resulting in heavy metal accumulation in plants. When ingested, it may be detrimental to the health of both humans and animals [39], [40]. Apart from decreasing soil productivity, salinity also causes crops to have a higher salt content [41]. Chlorides in soil (below 140 mg/L in susceptible crops or over 350 mg/L in resistant crops) and carbonates (above 500 mg/L of calcium carbonate) are impacted by crop morphology. Depending on the kind of plant and the environment, crops can get contaminated by microbes, heavy metals, and other hazardous compounds via immediate contact with irrigation water or, in the

instance of metals, by soil absorption [42]. Mussarat *et al.* [43] found elevated quantities of hazardous metals such as Pb, Ni, Cd, Mn, and Zn in edible parts of the wheat crops when they were watered with wastewater. This pattern was constant across several crops that were watered with wastewater, such as onions, wheat, and beans. This suggests a possible danger to food safety. According to a study, compared to other crops, Courgette spray-watering with low-quality wastewater had higher surface-level cryptosporidium oocyst acquisition (160–20,000 oocysts/kg) [44]. Courgette grows near the ground and has sticky, hairy coverings that can concentrate various infections on its exterior. In many studies, protozoan parasites such as amoeboid, giardia, and cryptosporidium have been identified in various vegetable samples. Some poisonous organic chemical compounds found in wastewater can persist in fruits and foliage through direct contact [45]. Crops irrigated with untreated wastewater present significant health risks due to heavy metal uptake and microbial contamination. Studies have shown alarming concentrations of heavy metals in edible parts of vegetables, with lead (Pb) detected at

levels of 5–10 mg/kg, far exceeding the safe limit of 0.3 mg/kg for human consumption. Similarly, cadmium (Cd) has been found at levels of 0.5-1.5 mg/kg, surpassing the acceptable threshold of 0.1 mg/kg, and chromium (Cr) levels in crops like spinach range from 2-6 mg/kg, which is well above the permissible limit of 1 mg/kg. These heavy metals pose serious health risks, including neurological damage from lead exposure, kidney damage from cadmium, and potential carcinogenic effects from chromium. Furthermore, microbial contamination is a major concern, with *E. coli* levels in vegetables reported at 100-1,000 CFU/g, exceeding the permissible level of 100 CFU/g in many regions. This contamination has been linked to a 30% increase in intestinal infections among populations consuming vegetables irrigated with untreated wastewater compared to those consuming produce irrigated with clean water, highlighting the public health threat associated with contaminated crops [46].

3.4. Effects on Cattle

Cattle may experience growth or health issues if they uptake wastewater-contaminated pasture [3]. In some underdeveloped countries with limited

water resources, cattle are permitted to consume the wastewater in addition to being fed wastewater-cultivated grass. According to reports, these cattle have *Taenia* infection, which causes cysticercosis. A nitrogen, potassium, and magnesium imbalance in pasture grasses can result in grass tetany in cattle that consume high-nitrogen wastewater-irrigated fodder [36].

Cattle grazing on lands irrigated with wastewater poses significant concerns regarding heavy metal accumulation in livestock tissues, which can have serious implications for food safety [3]. For instance, lead (Pb) levels in livestock organs can reach up to 1.5 mg/kg, exceeding the safe limit of 0.5 mg/kg. Additionally, chromium (Cr) and cadmium (Cd) have been detected in dairy products from these regions at concentrations 2-3 times higher than the allowable limits for human consumption. Crops containing up to five milligrams of molybdenum per kilogram of feed are hazardous to livestock, especially ruminants. Consumption of sulfates and copper also causes toxicity [24]. This elevated presence of heavy metals raises substantial public health concerns, as the consumption of contaminated animal

products can lead to toxic effects in both livestock and humans. The risks associated with heavy metal exposure may result in organ damage and long-term health issues, highlighting the urgent need for stringent monitoring and regulation of wastewater irrigation practices, particularly in areas where livestock are grazed. Overall, the accumulation of heavy metals in cattle on wastewater-irrigated lands necessitates immediate action to protect animal health and ensure the safety of food products for consumers.

3.5. Effects on Groundwater and Surface Water

Aquifer recharge is an unintended result of crop irrigation, and it happens in porous soils, whether accomplished with clean, reclaimed, or recycled wastewater. The excess water used for irrigation causes water infiltration, as does irrigation water infiltration during storage and transit [47]. A study investigated recharging from wastewater used to irrigate in a variety of areas (Lima's peri-urban area; Wagi Dhuleil, Miraflores, Mexico; Leon, Jordan; Mezquital Valley, Mexico; and Hat Yai, Thailand) and determined that at least 1,000 millimeters of water is recharged each year, a figure

that frequently surpasses regional pluvial rainfall. It is estimated that 50–70% of the water used in agriculture is attributed to infiltration. As a result, it is critical to acknowledge that reusing agricultural water will replenish the aquifer and make the best possible plans for it [25].

Several studies [43] have demonstrated the presence of heavy metals, including Cr, Cu, Cd, Co, As, Ni, P, and Zn, in groundwater affected by irrigation with wastewater. In wastewater used for irrigation, volatile and semi-volatile organic materials volatilize; nevertheless, the majority of these materials are hydrophilic, difficult-to-degrade substances that have the potential to penetrate aquifers and contaminate groundwater [48]. There is great concern over the rising nitrate concentration in groundwater, as it may cause methemoglobinemia in babies [42]. When wastewater is applied to extremely porous or fractured soils, some microorganisms, such as viruses, may be present in high numbers in the recycled water and might potentially infiltrate aquifers. Some of them may result in the creation of organo-chlorides when groundwater becomes available for human utilization and treated using

chlorine (the prevalent approach). The potential for trihalomethane (THM) generation in aquifers replenished with wastewater varies from 20 to 45 micrograms per milligram of TOC (toxic organic compounds) and can yield sterilized water with concentrations of as high as 100 micrograms per liter. Wastewater infiltration into aquifers will cause the long-term salt content to continuously grow [49].

Surface-level water is also impacted by the water drainage system of municipal wastewater used in agriculture [50]. The magnitude of the influence is determined by the type of soil, the kind of water body (river, dam, lake, or irrigation canal), its usage, and the fluid retention time [6]. Consuming surface water increases the risk of ingesting germs and viruses (protozoans and helminths). Microorganisms are the main cause for worry even in situations where treatment facilities for drinking water are accessible, since they are not usually equipped to handle high microbe levels and are unable to destroy bacteria that are resilient to common disinfection techniques (viruses or protozoa). The greatest impact on surface-level water sources is caused by residual nitrogen

present in wastewater, which causes the eutrophication of reservoirs, lakes, and slow-flowing rivers. Eutrophication not only affects the quality of water but also reduces the lives of fish and birds, resulting in the loss of biodiversity, aquaculture, and leisure activities [51].

4. Recommendations-

The economic implications of untreated wastewater irrigation present a complex cost-benefit landscape. In regions like Jodhpur, farmers using untreated wastewater can save 30–40% on water costs compared to clean water irrigation. However, these short-term savings are outweighed by the long-term economic costs related to health treatments, soil remediation, and reduced agricultural productivity due to soil contamination, which are estimated to be 3-5 times higher than the immediate financial benefits. Conversely, implementing basic wastewater treatment can yield significant economic advantages. Studies indicate that such initiatives could reduce the health burden on communities by up to 50% and increase agricultural productivity by 10–15% through improvements in soil and water quality [52]. This highlights the importance of investing in sustainable wastewater

treatment solutions, as they not only enhance public health and environmental quality but also contribute to the long-term economic viability of agricultural practices. With a focus on low-cost, decentralized wastewater treatment technologies such as biochar-assisted treatment and nature-based solutions, the review provides innovative recommendations for sustainable and economical treatment solutions. These proposed technologies are particularly relevant for resource-constrained regions, as they are designed for scalability and community-level implementation, unlike large-scale industrial solutions that may be economically unfeasible. Phytoremediation and bioremediation are sustainable, cost-effective techniques for treating municipal wastewater by leveraging natural processes to remove contaminants. Phytoremediation uses plants such as *Typha* and *Phragmites* to absorb, accumulate, and detoxify pollutants through mechanisms like phytoextraction, phytostabilization, and rhizofiltration, making it effective for heavy metals, nutrients, and organic pollutants [53]. It is commonly applied in constructed wetlands and green spaces, offering a low-cost and energy-efficient

solution. Bioremediation, on the other hand, employs microorganisms (bacteria, fungi, or algae) to break down organic contaminants and detoxify heavy metals through processes like bioaugmentation, biostimulation, and anaerobic digestion, transforming pollutants into harmless byproducts [54]. Emerging technologies like microbial fuel cells combine treatment with renewable energy generation. Both methods are advantageous for their environmental friendliness, low operational costs, and applicability in decentralized systems, but challenges include optimizing conditions for maximum contaminant removal and ensuring scalability for larger applications. Another unique aspect of the review is its focus on farmer education and policy recommendations. It advocates for collaborative approaches involving farmers, policymakers, scientists, and health professionals to mitigate risks and promote safer irrigation practices. Additionally, the review highlights the need for legislative frameworks and incentives to support sustainable wastewater reuse in agriculture. Overall, this review stands out by providing an integrated, region-specific, and long-term analysis of

untreated municipal wastewater irrigation, filling gaps in existing research while proposing practical, low-cost solutions to improve irrigation practices in developing regions.

5. CONCLUSION

The proposed review offers novel insights into the complexities of municipal wastewater irrigation by integrating the impacts on human health, soil quality, crop contamination, livestock health, and water resources into a unified framework. It emphasizes the risks associated with untreated municipal wastewater, particularly in developing countries with inadequate treatment infrastructure, and provides tailored solutions to address specific challenges in these regions. Additionally, the review introduces an updated risk assessment framework that evaluates the combined threats posed by pathogens and heavy metals, integrating both microbiological and chemical hazards. It highlights the urgent need for long-term studies to better understand contamination and health impacts, thereby filling critical gaps in existing research. While recognizing potential benefits like improved food availability and increased crop yields in low-income areas, the review also details

the harmful effects of using untreated municipal wastewater for irrigation. This practice poses significant health risks, as untreated wastewater often contains heavy metals, chemical pollutants, and microorganisms that can cause serious health issues for agricultural workers, consumers, and nearby residents, including urinary tract infections, cancer, and other long-term ailments. Although wastewater irrigation may enhance soil fertility, it can lead to soil salinization, heavy metal contamination, and a decline in microbial diversity, jeopardizing agricultural sustainability. Crops exposed to contaminated water may accumulate heavy metals and pathogens, affecting consumer health, while nutrient imbalances and increased salinity have a negative impact on crop quality and yield. Furthermore, contaminated fodder can harm cattle's health and compromise the safety of meat and dairy products. The pollution of surface and groundwater from wastewater irrigation threatens human health, ecosystem integrity, and aquatic habitats. As a result, the review emphasizes the need for effective wastewater treatment and stringent regulations to ensure the safe and sustainable use of wastewater in

agriculture. Overall, it provides a comprehensive analysis that bridges critical gaps in the literature and proposes practical strategies for enhancing agricultural practices in developing regions.

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