Practice of wastewater irrigation and its impacts on human health and environment: a state of the art

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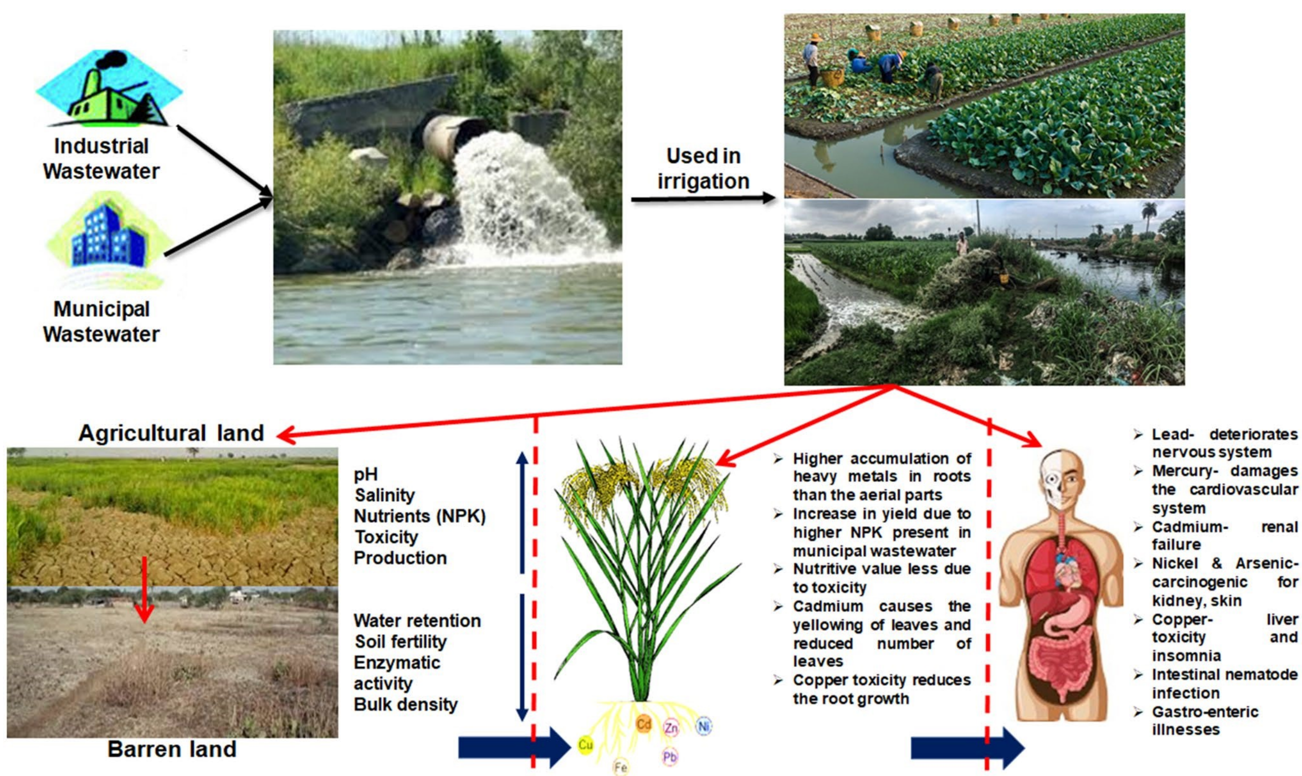
Graphic abstract



Abstract

The practice of wastewater irrigation lessens the pressure on the aquatic environment by minimizing the use of freshwater resources. However, this may lead to significant damage to the human health and environments. Recycled wastewater possesses a substantial amount of nutrients that act as fertilizers for crops and facilitate the metabolic action of microorganisms. The major advantages of wastewater irrigation are increased agricultural production, nutrient recycling, reduced stress on freshwater, economical support and provision of livelihoods for farmers. However, several harmful impacts of wastewater irrigation are also prominent due to inappropriate wastewater management and irrigation practices. These include severe hazards to farmer's health, contamination of agricultural land and crops with toxic metals, chemical compounds, salts and microbial pathogens. In addition, long-term irrigation using wastewater can significantly affect the groundwater through leakage of salty and toxic metal-rich wastewater making it unfit for human consumption. Wastewater irrigation may also alter the physicochemical properties and microbiota of soil, which in turn can disturb land fertility and crop productivity. Several factors need to be considered while using treated or partially treated wastewater for irrigation such as diversity and type of pollutants, available nutrients, pathogenic microorganisms and soil salinity. In this review paper, we assess the impact of wastewater irrigation on humans as well as on the environment based on available case studies globally, outline current use of wastewater for irrigation of agricultural crops such as cereals, vegetables, fodder crops, including agroforestry and discuss suitable management practices of wastewater reuse for irrigation.

Keywords Wastewater reuse · Water quality · Agricultural crops · Heavy metals · Bioaccumulation · Management practices

Introduction

Due to scarcity of available freshwater resources and lack of optimum wastewater management practices, around 3.5-million-hectare land is irrigated with untreated or partially treated wastewater worldwide (Van Rooijen et al. 2010; Thebo et al. 2017; Zhang and Shen 2019). It is estimated that about 200 million farmers are using partially treated or untreated wastewater for the irrigation of 20 million hectares of their agricultural land globally (Raschid-Sally and Jayakody 2009; Raja et al. 2015; Jaramillo and Restrepo 2017). In terms of percentage, about 8% of the total land area is irrigated by wastewater worldwide, out of which two-third of the land area belongs to Asia only (Miller-Robbie et al. 2017). A worldwide survey revealed that vegetables (32%) and cereals (27%) are the main crops produced via wastewater irrigation throughout the world (Raschid-Sally and Jayakody 2007; Qadir et al. 2010). There are millions of small and marginal farmers in developing countries that depend on wastewater to irrigate their crops directly via wastewater canals. Such wastewater contains several undesirable substances such as toxic metals (Cr, Cd, Cu, Ni, Zn, Fe, Mn, Pb and Co), organic/chemical compounds, salts and microbial pathogens that could impact human wellbeing as well as the environment (Libutti et al. 2017). Therefore, irrigation by wastewater has become a primary health concern for many regulatory agencies that are accountable to maintain ecological integrity and human health (Qadir et al. 2010). Agricultural crop production through wastewater represents approximately 15% of livelihood for farmers around the world, although the percentage of rural and urban farmers is not always equal. The majority of rural farmers depend upon wastewater for irrigation (FAOSTAT 2009).

There are numerous benefits as well as hazards of irrigating agricultural land with wastewater. The principal advantages include groundwater conservation (Pedrero et al. 2010), reduced fertilizer requirements (Corominas et al. 2013) and nutrient recycling (Libutti et al. 2017). The harmful impacts of irrigation with wastewater include severe hazards to human health and gradual pollution of groundwater, land and crops with noxious metals and microbial pathogens (Ensink et al. 2008; Miller-Robbie et al. 2017). Pathogenic microorganisms such as viruses, bacteria, fungi, protozoans and nematodes are the source of several diseases (Ensink et al. 2008; Cisneros and Rose 2009; Evans and Mara 2011; Jaramillo and Restrepo 2017). Most of the agricultural land and aquatic water bodies in developing countries are contaminated with toxic metals and chemicals, due to discharge of both industrial and sewage wastewater without their proper treatment (Tiwari et al. 2011). The wastewater treatment and their reuse for crop production are a good example of the recycling of wastewater throughout the world (Qadir et al. 2010). However, management of wastewater irrigation requires several considerations such as crop yield, crop-specific nutrient content, nutrient content and other fertility parameters of soil, energy consumption in wastewater treatment plant (WWTP) and the quality of wastewater after treatment (Rusan et al. 2007). The core concern towards conducting this study is to provide and disseminate evidence-based scientific information between scientists, government agencies, researchers, policymakers and institutions involved in agriculture to draft policies and action plans for the management of wastewater and its safe use for crop production, agroforestry and greenbelt systems.

Nature/characteristics of wastewater

Around the world, several industrial activities such as tannery for leather production, paper and pulp industries, food-processing and beverage industries produce a large volume of wastewater that are dark brown in color, with objectionable odor and high pH. The wastewater contains high chemical oxygen demand (COD), high biochemical oxygen demand (BOD), total dissolved solids (TDS) and several other highly toxic heavy metals (HMs) such as Cr, Pb, Cd, Cu, Zn, Fe, Ni, Mn, and Co and organic chemicals (Chandra et al. 2011; Suganthi et al. 2013; Bharagava et al. 2018). The main HM associated with tannery wastewater is Cr because it is used in the tanning process of leather. Besides this, the huge amount of domestic wastewater is generated from urban areas, which is also black in color, having objectionable odor, high BOD, phosphorus, nitrate, sulfate and dissolved and particulate organic matter and several infectious pathogenic microorganisms (Henze and Comeau 2008; Barreto et al. 2013). Domestic wastewater is the major source of macronutrients (N, P and K) that also leads to eutrophication of the aquatic ecosystem (Liu and Haynes 2011; Jaramillo and Restrepo 2017).

Global wastewater irrigation

Around the world, about 200 million farmers produce market-oriented crops using wastewater as main source of irrigation (Qadir et al. 2010). In West African countries, around 60–100% of green vegetables are grown under wastewater irrigation (Drechsel et al. 2006; Qadir et al. 2010). In Vadodara, Gujarat, India, small and marginal farmers enhance their yearly farm production by Rs. 266 million with wastewater irrigation (Kaur et al. 2012). In Vientiane, the capital of Laos, aquatic wetlands are used as a traditional facility for wastewater treatment and reuse in agriculture (Angelakis and Gikas 2014; Marsalek et al. 2014). Several other countries are also using their majority of wastewater for the production of fodder crops, recharging groundwater and other ecological functions including improving water supply to wetlands, urban lakes, ponds and natural wildlife habitats. It is believed by the local farmers that financial profits from the agricultural sector somehow depend on the usage of wastewater as an irrigation source for their crops. Therefore, further investigations are required to understand the use of wastewater in terms of livelihood enhancements. (Jimenez et al. 2010; Keraita et al. 2014).

The practice of irrigation with wastewater engages a large number of agricultural labors in the cultivation of vegetables, cereals, fodders and woody plants that are bought in nearby marketplaces or used by their livestock (Kaur et al. 2012). Wastewater irrigation is able to generate around 130 million employments and add about 1 million tons of nutritive elements into the soil annually (Minhas and Samra 2004; Kaur et al. 2012). In India, around 1 to 1.5 million hectares of agricultural land is irrigated with wastewater annually, which is generated from various sources (Kaur et al. 2012). Worldwide, major agricultural crops, fruit orchards and greenbelts irrigated with wastewater (Fig. 1) are summarized as follows: -

Cereals

Al Hayer wastewater treatment plant in South Riyadh discharges their effluents in a canal that is used by farmers to irrigate their barley crop (Pico et al. 2019). Around southwest Isfahan Province, central Iran, Zayandeh Rood River wastewater from the communities is broadly utilized to irrigate rice fields (Rahimi et al. 2017). In Hyderabad, India, almost all of the untreated wastewater is discharged into the Musi River, through which several farmers take out wastewater with the help of irrigation canals for production of cereals (Ensink et al. 2010). There are thousands of hectares of land that are irrigated with partially treated or untreated wastewater for the production of paddy crops and the area under wastewater irrigation is constantly increasing since 2005 (Van Rooijen et al. 2005). Wastewater irrigation is extensively used to produce crops such as wheat and rice in Ahmedabad, Gujarat and adjoining areas of Unnao and Kanpur in Uttar Pradesh (Buechler and Devi 2003; Sekhar et al. 2005; Chandra et al. 2009; Kaur et al. 2012).

Fig. 1. Irrigation with untreated sewage wastewater discharges around Kali River (A, B, C) in Meerut city and partially treated wastewater discharges from a canal (D, E, F) through Common Effluent Treatment Plant (CETP) at Jajmau, Kanpur, Uttar Pradesh, India.

Vegetables

Along the Akaki River in Addis Ababa (Ethiopia), farmers are producing vegetable crops at several stretches. Presently, more than 800-hectares of land are used for the production of vegetables such as beetroot, mustard and lettuce using water from the Akaki River (Woldetsadik et al. 2017). Around Melbourne, Australia, vegetables such as broccoli, cabbage, cauliflower and lettuce are produced by irrigation with treated wastewater from household activities (Barker, 2014). A vast number of green vegetables are grown on 1700-hectare land irrigated with sewage adjoining the Okhla and Keshopur STPs (sewage treatment plants) in New Delhi, India. Green vegetables such as coriander, cucurbits and eggplants are grown in the summer season, whereas cabbage, spinach, cauliflower and mustard are grown in the winter season (Kaur et al. 2012). In Hyderabad, along the Musi River, vegetables such as coriander, spinach, mint and amaranths are grown throughout the year (Buechler and Devi 2003; Sekhar et al. 2005; Kaur et al. 2012).

Fodder crops

The Egyptian clover (berseem clover) is irrigated with canal wastewater around the El-Saff area of Giza governorate, on the bank of Nile River. Clover is broadly cultivated as a fodder crop for livestock in Egypt (Farrag et al. 2016). Alongside Musi River near Hyderabad, approximately 10,000-hectares of agricultural land is used for the cultivation of Para grass, a fodder crop through wastewater irrigation (Buechler and Devi 2003; Sekhar et al. 2005; Kaur et al. 2012).

Agroforestry

In Apulia Region of Southern Italy, the majority of municipal wastewater is used for the irrigation of nectarine orchards (Moretti et al. 2019). Agriculture farms in several villages close to Hubli, Karnataka, India, use wastewater as an irrigation source for growing fruit plants such as sapota (chiku), guava, banana, mango, pomegranate, coconut, areca nut and medicinal/woody plants such as neem, curry leaf, teak, lemon and flowering plants such as mulberry, galimara and many other local varieties (Bradford et al. 2003; Kaur et al. 2012).

Greenbelts

Development of the greenbelts (a system of green parks, courtyards, squares, tree-lined streets/roadside trees) around the cities, along the streets/roadsides and at open barren land by native trees via irrigating with wastewater can minimize the wastewater treatment cost (Zinia and McShame 2018). Through these practices, the economic/ecological stability and environmental quality can be maintained by ensuring fuel wood, improving air quality, noise abatement, environmental sanitation, eco-restoration, wildlife habitat/corridor, microclimate regulation, urban flood prevention and for creating shield against extreme heat incidents (Kazmierczak and Carter 2010; de Oliveira, et al. 2014; Ranta et al. 2015; Zinia and McShane 2018). The impact of greenbelts on the urban environment in many ways depends on the topography, dimensions, design and type of the vegetation (Zinia and McShane 2018). Treated wastewater is reused in the forestry to develop greenbelts alongside the Tensift River over an area of about 10-hectares in the city of Marrakesh, Morocco (El Moussaoui et al. 2019). After secondary treatment, wastewater is used to irrigate public gardens and roadside plants in Hyderabad, India (Yadav et al. 2016). In tropical semi-arid environments of Northwest India, Eucalyptus, pine, poplar, bamboo, etc., are the best-suited trees grown via wastewater irrigation because of their high-transpiration rate (Minhas et al. 2015; Yadav et al. 2016).

Impacts of wastewater irrigation

Several human and environmental hazards are linked to the wastewater irrigation practices. Some of the contaminants stay in the environment for a short-time duration and differ in their toxicity depending on the capability of living beings or interaction with the environment (e.g., pathogenic microorganisms). Some contaminants may have long-time impacts, for instance, the salinity of soil increases with the continuous wastewater irrigation (Qadir et al. 2010; Jaramillo and Restrepo 2017). Several research outcomes highlighted the impact of wastewater on vegetables, cereals, fruit crops and agricultural land of Mediterranean countries (Palese et al. 2009; Disciglio et al. 2014; Lonigro et al. 2015; Gatta et al. 2016). Excessive contamination of toxic metals in agricultural land through wastewater irrigation generates noteworthy complications for crop yield and overall production (Libutti et al. 2017).

Environment (air, water and soil)

Wastewater irrigation results in serious hazards for the environment such as toxic metal pollution of the soil and groundwater (Amiri et al. 2008). Long-term wastewater irrigation may significantly affect the groundwater through leakage of salty and toxic metal-rich wastewater making them unfit for human consumption (Jaramillo and Restrepo 2017). The potential consequences of poisonous compounds (polycyclic aromatic hydrocarbons, polychlorinated biphenyls and phenols) and pollutants are the contamination of groundwater via percolation into the aquifers through the porous shallow water table (Zheng et al. 2013; Akpor et al. 2014). They can cause serious threats to human beings if used for domestic purposes (WHO 2006b; Chen et al. 2011, 2013). These organic/chemical compounds and contaminants could also enter into freshwater bodies through runoff and potentially affect aquatic ecosystems (Bolong et al. 2009; Munoz et al. 2009; Qadir and Scott 2010; Chen et al. 2011). Wastewater irrigation may also alter physicochemical properties and microbiota of soil, which in turn can disturb land fertility and crop productivity due to their long-term application (Becerra-Castro et al. 2015; Jaramillo and Restrepo 2017). Several other findings reported the threats of wastewater irrigation and their impacts on soil affecting pH, salinity, nutrients availability, organic matter content and microbial diversity (Jaramillo and Restrepo 2017) (Table 1).

Agricultural crops

The yield of several crops in terms of grain and straw is increased significantly by wastewater irrigation as compared to irrigation with groundwater (Jaramillo and Restrepo 2017). This is due to the occurrence of elevated levels of nutrients (NPK) and carbon-based materials in wastewater (Singh et al. 2012). Leafy green vegetables that accumulate higher metal concentrations are more susceptible to toxic metals like cadmium as compared to non-leafy vegetables (Qureshi et al. 2016; Naser et al. 2018). Usually, the toxicity of metals increases in plant tissues due to wastewater irrigation, and the maximum accumulation is found in roots as compared to leaves (Balkhair et al. 2016; Kchaou et al. 2018). The long-term impacts of wastewater irrigation on agricultural crops, as reported through various case studies around major parts of the world are represented in Table 2.

Human and animal health

The main problem associated with wastewater irrigation is the entry of pathogenic microorganisms in the food chain. They can cause severe health hazards to farmers and consumers (Petterson et al. 2001; Toze 2006; Rubino and Lonigro 2008). It is reported that the farmers and consumers are increasingly exposed to the intestinal nematode, Ascaris/ hookworm infections and the possibility of enteric diseases due to wastewater irrigation (Ensink et al. 2008). Microbial pathogens and toxic elements that are carried with wastewater may differ by location because of the level of hygiene and socio-economic environments. These microorganisms are considered as potent disease-causing agents for all living creatures, and their impacts are long lasting. The harmful impacts of these microorganisms are often cited as cause of significant premature mortality particularly in developing countries (Gerba and Rose 2003; Jimenez et al. 2010). World Health Organization (WHO 2006a) prescribed a guiding principle for safe use of treated wastewater as irrigation source in developing countries where the proper treatment of wastewater is not feasible due to lack of cost-effective wastewater treatment technologies (Table 3).

Wastewaters originating from tanneries and domestic sources are laden with several toxic elements. Use of these wastewaters for irrigation of agricultural crops leads to significant impacts on soil health. The transfer of HMs from wastewater to soil proceeds primarily via the absorption system. The absorption of HMs within soil depends upon pH, temperature, organic matter, nutrient availability and moisture content. However, occurrence of sufficient organic matter is able to enhance the uptake of numerous HMs such as Cr, Pb, Zn and Cu. (Wang et al. 2017). Transfer of HMs from soil to crops occurs mainly through the accumulation into vegetative parts. Soil–plant allocation of toxic HMs is also influenced by pH, texture and cation exchange capacity of soil and physiology of crops such as type of crops, root secretions, surface area of roots and transpiration (Santos and Rodriguez 2012; Shahid et al. 2017). It is reported that the high pH of soil can smooth both the precipitation and adsorption of HM ions; however, the acidic nature of soil can raise the mobilization, consequently enhancing their uptake by crops (Komarek et al. 2013; Wang et al. 2017). Availability of organic matter within the soil is also able to reduce the mobility of HMs through combination with HM ions by developing organic complexes (Guo et al. 2012; Wang et al. 2017). It is reported that vegetables accumulate higher proportion of HMs such as Cr, Pb, Zn and Cu in their vegetative parts as compared to grain or tuber crops. Continuous irrigation with partially treated or untreated wastewater imposes serious threats on quality and productivity of the crops by accumulation of several hazardous metals into their tissues that are edible (Khan et al. 2015; Shahid et al. 2017). However, growth and development of crops require macro- (N, P, K, Ca, S, and Mg) and micronutrients (Fe, Zn, Mn, Ni, Cu and Mo) both at desirable levels. They may possess toxic effects at higher concentrations; therefore, crops have evolved with specific ability to uptake, translocate and store them within their vegetative parts (Khan et al. 2015; Shahid et al. 2017). Finally, the exposure of HMs from crops to human beings takes place directly by dietary intake of contaminated crops, especially green vegetables (Muchuweti et al. 2006). There are numerous exposure pathways that mainly depend upon contamination sources, but the route of exposure through the food chain is the main source (Fig. 2). The vegetarian population relies primarily on several leafy vegetables that are consumed by the local residents or are sold to the nearby markets for the consumption of dispersed population (Chaoua et al. 2019). These populations are exposed to several toxic contaminants due to consumption of crops that are grown with partially treated or untreated wastewater and induce severe health hazards for humans and animals (Ahmed et al. 2016; Shahid et al. 2017).

Table 1 Wastewater irrigation and its impact on physicochemical, biochemical and microbiological parameters of soil

Parameters	Effects on the soil and the ecosystem		References
	Physicochemical and biochemical properties	Microbiological Properties	
pH	Increases the accessibility of nutrients and trace elements due to the long-term application, mineralization of organics and advances the CEC (cation-exchange capacity)	Intensifications of the microbial community	White et al. (2013), Jaramillo
Salinity	Increases soil salinization, decreases the steadiness of soil aggregates and structure, permeability of soil and water retention, impacted soil fertility, altered dynamics of inorganic and organic compounds, leaching of heavy metals	Alteration of the soil microhabitats including richness, diversity and activity of the microbial populationy	Ke et al. (2013), Jaramillo and
Nutrients (N, P, K)	Elevated soil organics and water retention, increases nutrient content, risk of eutrophication and algal bloom, leaching to groundwater	Disturbance of the metabolic activity of soil microbial communities	de Oliveira Marinho et al. (20 et al. (2016), Jaramillo and
Organic matter	Stabilizes soil and development of aggregates, improves nutrient availability (NPK), water retention, CEC, enzymatic activity, TOC and the contaminants	Choice of specific microbial populations and soil microenvironments	Perez et al. (2015), Jaramillo
Contaminants	Increases toxicity, accumulation and leaching in soil, negatively impacts soil fertility, contaminates the food chain directly or indirectly, mineralization of organics, alteration in enzymatic activity	Improved microbial tolerance to contaminants, antimicrobial resistance, decrease in microbial biomass and changes in their structure/composition	Becerra-Castro et al. (2015), et al. (2015), Jaramillo and

Table 2 Long-term impact of wastewater irrigation on agricultural crops

Study area	Wastewater types and their toxicity/chemical composition	Crop studied	Effects on crops	R
Khyber Pukhtoon Khaw, Pakistan	Canal and River wastewater (rich in heavy metals, inorganic and organic compounds)	Wheat	Accumulation of metals in root, aerial parts and grains	Al
Central zone of Tigray, Adwa town, Ethiopia (Almeda Textile Factory)	Industrial wastewater (very high concentration of noxious metals such as Cr, Cd, Cu, Co, Mn, Zn Ni, and Pb)	Cabbage, garlic, gesho and tomato	Accumulation of metals in food crops in order: Mn > Zn > Cu > Pb > Ni > Co > Cr > Cd Cd and Pb were found above the maximum permissible limit set by FAO/WHO	G
Ramtha Wastewater Treatment Plant, Jordan	Municipal wastewater (nitrate, phosphate and organic matter)	Wheat and barley	Wheat crop formed taller plants, additional heads per unit area, heavier seeds and higher grain yields because of the presence of nutrients (NPK). However, the biomass of barley crops increased with added nutrients with wastewater application. Concentration of phosphorus in barley shoot significantly higher	R
National Environmental Engineering Research Institute (NEERI), Nagpur, Maharashtra, India	Domestic wastewater (containing organic matter, nitrate and phosphate)	Gram, wheat, Palak, methi and berseem	Attains higher biomass when irrigated with sewage as compared to water from wells	Si
Dinapur, Varanasi Uttar Pradesh, India	Wastewater from Sewage Treatment Plant (organic matter, nitrate and phosphate)	Vegetables and cereals (Amaranthus, cabbage, cauliflower, lady finger, bitter gourd, bottle gourd, pumpkin, spinach and wheat)	Accumulation of toxic metals was lesser in the cereals (rice and wheat) in comparison to the vegetables crop Higher accumulation of Zn and lower accumulation of Cd was found in all the vegetables and cereals	Si
Vadodara, Gujarat, India	Industrial wastewater (high amount of toxic metal and metalloids As, Cr, Cd, Ni and Pb)	Spinach, tomato, coriander, chili, cabbage, radish and brinjal	Accumulation of metals in soil with maximum accumulation in shoot as compared to root of selected crops	Ti
Jajmau, Kanpur, Uttar Pradesh, India	Tannery effluents (toxic metals such as Cu, Cr Fe, Zn, Mn, and Ni)	Amaranthus, bitter gourd, black mustard, bottle gourd, cauliflower, chili, coriander, garlic hemp, maize, potato, spinach, Sudan grass, sugarcane, turmeric, wheat and yellow mustard	Higher accumulation of Fe and lesser of Cu was found in all the crops In majority of the crops, the concentration of metals was found minimum in the edible parts Maximum accumulation of toxic metals was observed in the leafy vegetables as compared to non-leafy vegetables/crops	Si
Adjoining vicinity of Unnao and Kanpur Uttar Pradesh, India	Distillery and tannery effluents (very high concentration of toxic metals such as Cu, Cr, Cd, Zn, Mn, Fe and Ni)	Wheat and mustard	Extreme concentration of Fe accompanied with Cr and Mn in roots and Mn and Zn in seeds of the crops. Mustard crop has elevated concentration of Fe followed by Mn and Zn in root and seed	Ch

Table 3 Report of infections and diseases from wastewater irrigation

Study area	Type of wastewater	Health Risk (infections and diseases)	Observations	Referen
Kampala, Uganda	Sewage and industrial effluents, leakage from Fecal sludge	Intestinal pathogenic infections	Health risk of hookworm, such as *Ascaris lumbricoides* and *Trichuris trichiura*), intestinal protozoa cysts and oocysts (e.g., *Entamoeba histolytica* and *Giardia intestinalis*)	Fuhrima
Hyderabad, India	Sewage	Intestinal nematode infections	Increased risk of hookworm, *Ascaris lumbricoides* and *Trichuris trichiura*, elevated concentrations of metals in cow's milk	Ensink e
Sobantu, South Africa	River water (mixed with sewage)	Gastroenteric illnesses via oral /fecal route	Increased risk of fecal coliforms, total coliformsto and *Escherichia coli*, spread of waterborne diseases	Gemmel
Beijing and Tianjin, China	River water (mixed with sewage)	Increased incidences of cancer	Health risk to humans and animals through long-term perseverance of toxic metals in the ecosystem, increased incidences of cancerous and skin diseases	Wang et
Marrakesh	Sewage	Enteric pathogenic infections	Transmission of *Giardia cysts* and *Ascaris eggs* to human beings through crops, risk to giardiasis and diarrhea	Amahmi

Previous investigations highlighted the disadvantages of wastewater irrigation due to metal toxicity with other pollutants and their potential bioaccumulation in the food chain. These toxic HMs can cause severe health hazards to humans and animals when their concentrations are beyond the permissible limits (Martin and Griswold 2009; Raja et al. 2015). A study carried out on wastewater irrigation through the polluted water of Musi River at Hyderabad, Telangana, India, showed the translocation of toxic HMs at different trophic levels. For example, accumulation of toxic metals through food chain in cow's milk has been observed by Para grass (a fodder crop) irrigated with wastewater. Results showed that the cow's milk had several toxic metals such as Cd, Cr, Pb, Fe and Ni whose concentration was about 12 to 40 times higher than the acceptable limits (Qadir et al. 2010; Kaur et al. 2012). In spite of the harmful impacts, several regions of the world prominently use treated wastewater for the production of their crops. For examples in Chile, Maipo, Maipocho, Antofagasta and Santiago de Chile, many settlements use treated wastewater for the irrigation of crops (Jimenez 2005). The arid or semi-arid northern and central part of the Mexico use reclaimed water to irrigate their crops. Moreover, the Tula Valley, one of the largest areas of the world covering more than 90,000 ha land, is using treated wastewater for the agricultural activity (Navarro et al. 2015). In Peru (South America), an area with lower rainfall, where minor irrigation projects have been established, farmers often augment the irrigation with wastewater (Jimenez and Asano 2008). In Mendoza (Argentina), an area identified as Campo Espejo used treated wastewater from stabilization ponds to irrigate their crops (Navarro et al. 2015). In India, several regions use treated or partially treated wastewater for the irrigation of several crops. However, the impact of wastewater irrigation has not been fully understood.

Wastewater irrigation management approaches for risk reduction

A series of four volumes about the safe reuse of treated wastewater in agriculture has been published by the World Health Organization (WHO). It also provides clear guidelines for decision-makers on the use of treated wastewater in local environments. The purpose of such guiding principles is to provide setting standards and regulations about the best use of wastewaters (WHO 2006b; Mara et al. 2007; Navarro et al. 2015; Jaramillo and Restrepo 2017). Similarly, several guidelines for the best use of treated wastewater in crop production have been formulated by the Food and Agriculture Organization (FAO 1992). In 2012, the United States Environmental Protection Agency (USEPA) and the United States Agency for International Development (USAID) restructured the guiding principle for the best reuse of wastewater. The major concern of the amended guidelines was to simplify the wastewater reuse on the basis of compilation of global practices. Theyalso explained about the regional differences in wastewater reuse, advancement in the wastewater treatment technologies, practices to include societies in developmental projects and aspects that sustain the extension of safe wastewater reuse (EPA and USAID 2012; Navarro et al. 2015; Jaramillo and Restrepo 2017). However, the existing guidelines/suggestions for wastewater generation and their treatment in India are dependent on the environmental acts and legal provisions. Some of them are Hazardous Waste (Management and Handling) Rules, 1989, National Environment Policy, 2006, Constitutional Provisions on Sanitation and Water Pollution, National Sanitation Policy, 2008 and Municipalities Act, etc. (Chakraborty and Mukhopadhyay 2014). In urban areas, the development of sewerage substructures for sewage disposal is vested with the Municipal Corporations as well as the State Governments. However, ample efforts are being made by the various Central Government schemes such as NRCP (National River Conservation Plan), the NLCP (National Lake Conservation Plan), the JNNURM (Jawaharlal Nehru National Urban Renewal Mission) and the UIDSSMT (Urban Infrastructure Development Scheme for Small and Medium Towns). Operation and maintenance of STPs come under the State Governments/Municipal Corporations as well as their other local agencies (Kaur et al. 2012;). According to the Water (Prevention and Control of Pollution) Act, 1974, the State Pollution Control Boards (SPCBs) can take legal action against defaulting agencies. Indian Government started technological and economical provisions to encourage the remediation of wastewater discharged from the small-scale industries (SSI Units) by considering them a single unit (Kathuria 2007).

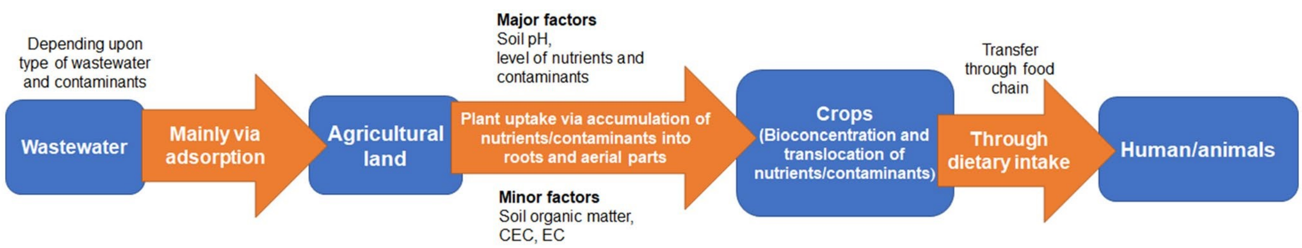


Fig. 2. Transfer of nutrients/contaminants through wastewater to humans and animals

Sustainable wastewater treatment mechanisms

A number of technologies have been described in several studies worldwide for the treatment of domestic and industrial wastewater prior to its safe reuse or discharge into freshwater streams. Such technologies include physicochemical, biological and combined treatment methods. These can be utilized separately or in combination with others to advance the treatment efficiency of different wastewaters. Some advanced, cost-effective and eco-friendly technologies are outlined below.

Physicochemical treatment approaches

The physicochemical processes mainly include adsorption, membrane filtration, advanced oxidation, coagulation and flocculation, etc. These processes are reported effective for the removal of color and several other wastewater contaminants from tannery industry effluent as well as from domestic wastewater (Pavithra and Jaikumar 2019; Siyal et al. 2020; Kishor et al. 2021). However, the application of these processes is expensive and requires time and some of them produce sludge as secondary pollutant (Pavithra and Jaikumar 2019; Ceretta et al. 2020; Kang et al. 2020; Kishor et al. 2021).

Biological wastewater treatment approaches

Biological methods are considered as eco-friendly and cost-effective wastewater treatment methods. These are the most effective and alternative methods for the degradation of wastewater pollutants by transforming them into less harmful or harmless substances using microorganisms and aquatic macrophytes (Saxena et al. 2016; Tian et al. 2019; Ceretta et al. 2020; Kishor et al. 2021). The microbial populations such as bacteria, algae and fungi have been widely used by various researchers in several continents for the treatment of almost all types of wastewater. These microbial populations are capable of degrading, detoxifying and decolorizing a range of wastewater contaminants including heavy metals through their metabolic actions and biosorption (Cao et al. 2019; Kang et al. 2020; Kumar et al. 2020; Kishor et al. 2021).

Constructed wetlands

Constructed wetlands (CWs) are engineered ecosystems that mimic the function of natural ecosystem to eliminate the wastewater contaminants. They employ natural forces, vegetation, substrate materials and microbial populations for the treatment of almost all types of wastewater. The removal efficacy of CWs for several wastewater contaminants including HMs reached upto 98% as reported in several studies (Pazdzior et al. 2019; Kumar et al. 2020; Kishor et al. 2021) The effectiveness of CWs for the removal of wastewater contaminants depends upon several environmental and working parameters, in which pH, DO and temperature are crucial (Kadam et al. 2018; Kumar and Dutta 2019). However, selection of suitable substrate materials and macrophytes is also vital. Different macrophytes like *Phragmites spp.*, *Typha spp.*, *Scirpus, Juncus, Canna* and *Myriophyllum* *spicatum,* etc., are extensively used in CW before applying as irrigation water (Hussain et al. 2019; Kishor et al. 2021).

Combined treatment methods

Combined use of several physicochemical and biological processes gives accelerated removal capacity upto 99% for majority of the toxic chemicals/ pollutants (Pazdzior et al. 2019; Sun et al. 2020; Kishor et al. 2021). For better efficiency, integration of CW technology with effluent treatment plants (ETPs) and sewage treatment plants (STPs) as a polishing unit have emerged as highly cost-effective and sustainable wastewater treatment facilities. Incorporation of CWs as a green infrastructure into urban development also provides an excellent opportunity for the treated wastewater reuse in crop production, to generate a circular economy and numerous other environmental benefits. Integration of advanced oxidation processes (AOPs) and biological processes is also considered as an efficient approach to treat wastewater contaminants originating from several industrial and household activities (Waghmode et al. 2019). In this system, AOPs transform the complex structure of contaminants and generate biodegradable products, and then, biological processes convert them into the simple harmless substances by the action of oxidoreductive enzymes. The effectiveness of this system reached upto 99% as described in various studies (Waghmode et al. 2019; Ceretta et al. 2020; Kishor et al. 2021).

Prevention of human exposure to pathogens and contaminants

Primary protective equipment (PPE) such as wearing gloves, boots and full coverage of body with cloths can reduce farmer's exposure to many diseases associated with wastewater irrigation. After the practice of wastewater irrigation, farmers are required to clean their hands and legs with running water to avoid the spread of infectious diseases. Many agencies throughout the world actively engage in public awareness programs to decrease the enormity of diseases transmitted by exposure of wastewater contaminants (Yadav et al. 2016).

Wastewater management at farm-level

Sustainable management of wastewater for irrigation requires the implementation of appropriate wastewater management practices. This can be accomplished by selecting suitable crops according to irrigation requirements, irrigation methods and water quality and soil-based interventions that are dependent on soil composition, farming practices and uses of fertilizers. Several aspects such as the existence of pathogenic microorganisms, hazardous compounds, salinity and the structure of the soil require serious consideration. Many of these factors can be managed by appropriate treatment of wastewater as described earlier and suitable farm handling practices (Raschid-Sally and Jayakody 2007; Yadav et al. 2016).

Crop limitations and diversification

Crop selection is the most important factor to minimize the health hazards of wastewater irrigation on human beings, as the rate of accumulation of metals is higher in vegetable crops. However, there are certain limitations due to the high demand of vegetables for meeting the daily requirements (Qadir et al. 2010). An alternative approach of crop production with agroforestry for fuel and timber production by farmers has been adopted to improve the overall benefits. Several oil and timber-producing species such as *Jatropha sp*., *Eucalyptus sp., Olive sp.* and *Populus sp*. can be grown with crops (Bedbabis et al. 2015; Keraita et al. 2016). The structure of agroforestry called HRTS (high-rate transpiration system) is designed based on the transpiration ability of green plantation (Yadav et al. 2016).

Managing irrigation systems

Furrow irrigation is well suited for row crops where water is a limiting factor that needs favorable topography and land smoothing which offers higher levels of health safety from recycled wastewater (Goswami et al. 2015). Drip irrigation is found to be the most environment-friendly approach, whereas sub-surface drip irrigation can mitigate health and ecological risks and can reduce nitrate leakage by 70% (Zhang and Shen 2019). Drip irrigation can minimize the impact on crops and humans effectively by using sub-surface drippers (Minhas and Samra 2004; Qadir et al. 2010). Watering cans and sprinklers are not suggested because in this technique, most of the water is spread on the surface of the crops (Qadir et al. 2010).

Conclusion and future prospects

Around the world, about 200 million farmers produce market-oriented crops such as cereals, oilseeds, pulses and vegetables using untreated wastewater. In many regions, treated wastewater is also used for improving water supply to wetlands, urban lakes, ponds and other natural wildlife habitats. The practice of wastewater irrigation engages a large number of agricultural laborers. There are several benefits as well as hazards associated with wastewater irrigation. Even though elevated levels of nutrients, organic matter and other carbon-based materials in wastewater can increase the crop yields, their long-term application as irrigation source may alter physicochemical properties and microbiota of soil, which in turn can disturb land fertility and crop productivity. Transfer of heavy metals from soil to crops occurs mainly through the accumulation into vegetative parts. Soil–

plant allocation of toxic metals is also influenced by pH, texture and cation-exchange capacity of soil and physiology of crops such as type of crops, root secretions, surface area of roots and transpiration. Usually, the toxicity of metals increases in plant tissues due to wastewater irrigation, and the maximum accumulation is found in roots as compared to leaves.

Recycled wastewater possesses a significant amount of nutrients (NPK) that act as fertilizers for crops and facilitate the metabolic action of microorganisms within the soil. A considerably higher yield of grain and straw has been recorded through irrigation via untreated or partially treated wastewater as compared to groundwater. The principal advantages include increase agricultural production, conservation of freshwater resources, reduced fertilizer requirement, nutrient recycling, ecological balance, economical support and livelihoods of millions of farmers. The harmful impacts of wastewater irrigation include severe health hazards and gradual contamination of groundwater, agricultural land and crops with toxic metals and microbial pathogens. One of the severe problems linked with wastewater irrigation is the pathogenic microorganism. They can cause severe hazards to farmers' health.

Recycling wastewater through improved treatment technologies can reduce the many harmful impacts and has the potential to augment continuous and dependable supply for irrigation in water-stressed areas (Qadir et al. 2010). Reusing recycled wastewater after proper treatment could have a substantial impact on lowering the effect of run-offs on receiving surroundings. Furthermore, reusing wastewater for irrigation purpose has several benefits such as increasing agricultural production, reduced pressure on freshwater resources, maintenance of ecological balance, economical support, reduction of fertilizers, protection of natural water sources and the livelihoods of millions of farmers around the world (Pedrero et al. 2010; Libutti et al. 2017; Hong et. al., 2018). Recycled wastewater possesses a significant amount of nutrients which can act as fertilizers for agricultural production and facilitate the metabolic action of microorganisms within the soil (Meli et al. 2002; Ramirez-Fuentes et al. 2002; Drangert et. al., 2018). In the present scenario, the long-term risks of wastewater irrigation to human beings and the environment are largely unknown, especially for small and marginal farmers (Pico et al. 2019). Long-term irrigation with wastewater is replete with several significantly known concerns about the gradual deposition of toxic metals in agricultural land and food crops which make dependent population vulnerable to exposure to contaminants and pathogenic microorganisms (Nabulo et al. 2010; Qureshi et al. 2016; Zhang and Shen 2019).

Primary protective equipment (PPE) such as gloves, boots and full coverage of body with cloths can reduce farmer's exposure to various diseases. Wastewater irrigation may also alter the physicochemical properties and microbiota of the soil that in turn can disturb land fertility and crop productivity. Sustainable management of wastewater irrigation depends on the execution of appropriate practices such as the selection of suitable crops according to the irrigation requirements and irrigation methods. Therefore, the main aim towards conducting this study is to disseminate the scientific information among scientists, researchers, policymakers and government agencies to draft and enforce appropriate action plans and policies for the management of wastewater and its safe reuse in agriculture, agroforestry and greenbelt systems.

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