

# Heavy metals and pathogenic contamination in vegetable crops through wastewater irrigation and risk reduction in developing countries

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## ABSTRACT

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Over the past few decades, the demerits of wastewater (WW) irrigation have been well understood, yet the percussion and given attention appear to be inadequate in most parts of the world, especially in developing countries, where sustainable agriculture has become more questionable. As part of a diet, vegetables are inevitable in almost all communities in the world. This paper reviewed two key challenges; heavy metal and pathogenic contamination in vegetable crops through WW irrigation and possible mitigation strategies with regard to developing countries. Yet, there are not enough studies conducted in majority of the developing countries to support planners and policy-makers in this regard. According to the available literature, it is clear that WW should never be used for irrigation without adequate pre-treatment and the treatment method should be fitted-for-purpose. Implementation of farm-level filtration systems, sedimentation ponds and drip irrigation systems like methods will further help to minimize these impacts. Under these circumstances, reuse of adequately treated WW for irrigation will be a sensible solution to address the challenges of water scarcity and the rising demand for food.

**Keywords:** wastewater; water scarcity; pre-treatment; sustainable agriculture

## 1. INTRODUCTION

Water shortage is a growing issue worldwide (Pedrero et al., 2010; Kummur et al., 2016; Falkenmark, 2013), and around 1.2 million people in the developing countries are faced with water scarcity. It is also projected that the number may reach 1.8 million by the year 2025 (Balkhair, 2016). The ever-increasing human population, economic

development and dietary shift (towards more animal products) have all contributed to the increase in water demand (Liu et al., 2017; Yue et al., 2017; Busari et al., 2019). In addition, climatic changes have exacerbated the water crisis (Abedin et al., 2019).

Being the largest consumer of water, today agriculture accounts for an average of 70% of all water use, and by 2030, food production will have to increase by 50% to feed

the growing world population, thus the demand for water is becoming far higher (World Economic Forum, 2015). Given the rising prevalence of water shortage, there is an essential need to manage water used for agriculture. In order to cope with water scarcity, in recent decades, there has been renewed interest in the reuse of wastewater (WW), especially for crop irrigation. The Food and Agriculture Organization (FAO) of the United Nations stated that WW irrigation would be the best option to meet future agricultural water needs in the long term (FAO, 2012). According to FAO, WW is defined as the combination of liquid wastes discharged from domestic households, farms, institutions, commercial and industrial operations mixed with ground, surface, and stormwater. FAO closely collaborated with many government bodies to promote sustainable agriculture employing WW. There are three basic ways to irrigate the WW in the cropping system; direct use of raw/untreated WW, direct use of treated WW and indirect use of WW (Hoek, 2004). In the developing countries, direct use of untreated WW is the most widespread practice (Keraita et al., 2008b; Qishlaqi et al., 2008) and may economically sound than the freshwater application. The method has also been questioned, as some contaminants can survive and bioaccumulate in the food chain and eventually create health effects on consumers (Ramos et al., 2019). While direct use of treated WW is common practice in developed countries due to regulations and safety concerns. The indirect application of WW takes place with the discharge of municipal, industrial or domestic WW without subsequent treatment. Ultimately, farmers could be used such a water resource, which composition is unknown (Hoek, 2004).

### 1.1 Brief history of WW irrigation

The use of WW for irrigation has a long history. The first historical evidence of the reuse of WW for irrigation comes from the Minoan period (ca. 3200-1100 BC), in Crete, Hellas and to Mohenjo-Daro (ca. 2600-1900 BC), in Indus valley (Angelakis and Gikas, 2014). Thereafter, according to the historical records, WW utilized for irrigation (also as fertilizers) by Hellenic civilizations as well by Romans in areas surrounding cities such as Athens and Rome (Angelakis and Snyder, 2015). Between 1550 and 1700, farms in Germany, Scotland, and England began using WW directly on their crops. In the early 1800s, fast-growing cities in Europe and the US such as London, Paris and Boston started to practice soil WW irrigation (Jaramillo and Restrepo, 2017). It is not clear when exactly WW irrigation started in China, Mexico, Peru, Egypt, Lebanon, Morocco, India and Vietnam, although the practice is believed to have started many decades or perhaps centuries ago (Raschid-Sally, 2010). In 1897, a large "sewage farm" was established in Melbourne and started to irrigate the WW (Angelakis and Snyder, 2015). In the early 1900s, the Parisians used partially treated WW for irrigation (Raschid-Sally, 2010). The first official use of treated WW began in Melbourne in 1981 and, because of its pathogenic effect, only peeled, cooked, or commercially processed vegetables were allowed to be irrigated (Barker et al., 2011). With the increasing knowledge of diseases and technologies, irrigation of untreated WW is now becoming the least practice in developed countries, while it is common practice in developing countries for several reasons, which will be described later.

### 1.2 WW as a primary resource for the agriculture in many developing countries

Today, 10% of the global population utilize the food from crops that have been irrigated with the WW (Ungureanu et al., 2020). Yet, the exact figure for global WW (both treated and untreated) irrigation is fragmentary (Hamilton et al., 2007), it is more likely to range between 5 and 20 million hectares (Drechsel and Evans, 2010) in 50 countries (Qishlaqi et al., 2008).

Mexico, Israel, Egypt, Cyprus and Argentina are the leading countries using treated WW to irrigate approximately 250,000, 66,000, 42,000, 39,000, and 24,000 hectares, respectively (Jiménez, 2006; Scott et al., 2010). Mezquital Valley in Mexico uses untreated WW to irrigate more than 90,000 hectares of arable land. This could be one of the largest cropping areas in the world that is irrigated with raw WW (Jayawardena et al., 2006). In Vietnam and Pakistan alone 10,000 and 30,000 hectares are grown with undiluted WW (WW not mixed with stream/stormwater) (Hajjami et al., 2013). According to Drechsel et al. (2014a), Ghana also irrigated more than 40,000 hectares of croplands with polluted WW. In Morocco, 7,000 hectares of agricultural lands are irrigated with the WW (Hajjami et al., 2013). Global estimates for raw and diluted WW irrigation could be ranged from about 3-3.5 million hectares and China shares the largest (Jayawardena et al., 2006). Over 1,330,000 hectares of lands in China are irrigated directly and indirectly with WW (Jiménez, 2006). According to the statistics by Jayawardena et al. (2006), Pakistan and most parts of Sub-Saharan Africa, WW irrigation contributes to the cultivation of perishable vegetables, which cover 60-100 % of the daily requirement in most cities and similar conditions are observed worldwide. Figure 1. shows further details on WW irrigation in some developed and developing countries.

### 1.3 Heavy metal and pathogenic contamination in WW as a great risk on human

A number of threats have been recorded due to the use of untreated/poorly treated WW such as the potential accumulation of trace metals, toxic organic and pathogenic contaminants, along with consequences of the public health (Batarseh et al., 2011; Wu et al., 2014). It is also identified several risks on soil properties such as significant changes in soil pH, electric conductivity, infiltration rate, and organic matter (Bedbabis et al., 2014; Albalasmeh et al., 2020).

Worldwide, many studies have been conducted to examine the impact of WW irrigation, yet mitigation measurements seem to be not matured adequately in many countries. Heavy metals are described as metallic non-degradable elements with a density that is higher than that of water (Tchounwou et al., 2012; Mateo-Sagasta et al., 2013). Some heavy metals are important for the growth of plants and act as micro nutrients (e.g., cobalt-Co, iron-Fe, copper-Cu, nickel-Ni, chromium-Cr, manganese-Mn, and molybdenum-Mo). While the elements such as mercury (Hg), cadmium (Cd), lead (Pb), silver (Ag), arsenic (As), and zinc (Zn) are considered as highly toxic. Despite the essentiality of heavy metals to crop growth and development, excessive accumulation poses a threat to the crops and consumers (Selvi et al., 2019). Exposure to such heavy metals can lead to cause serious health issues, including cancer formation (Tchounwou et al., 2012), neurological and reproductive

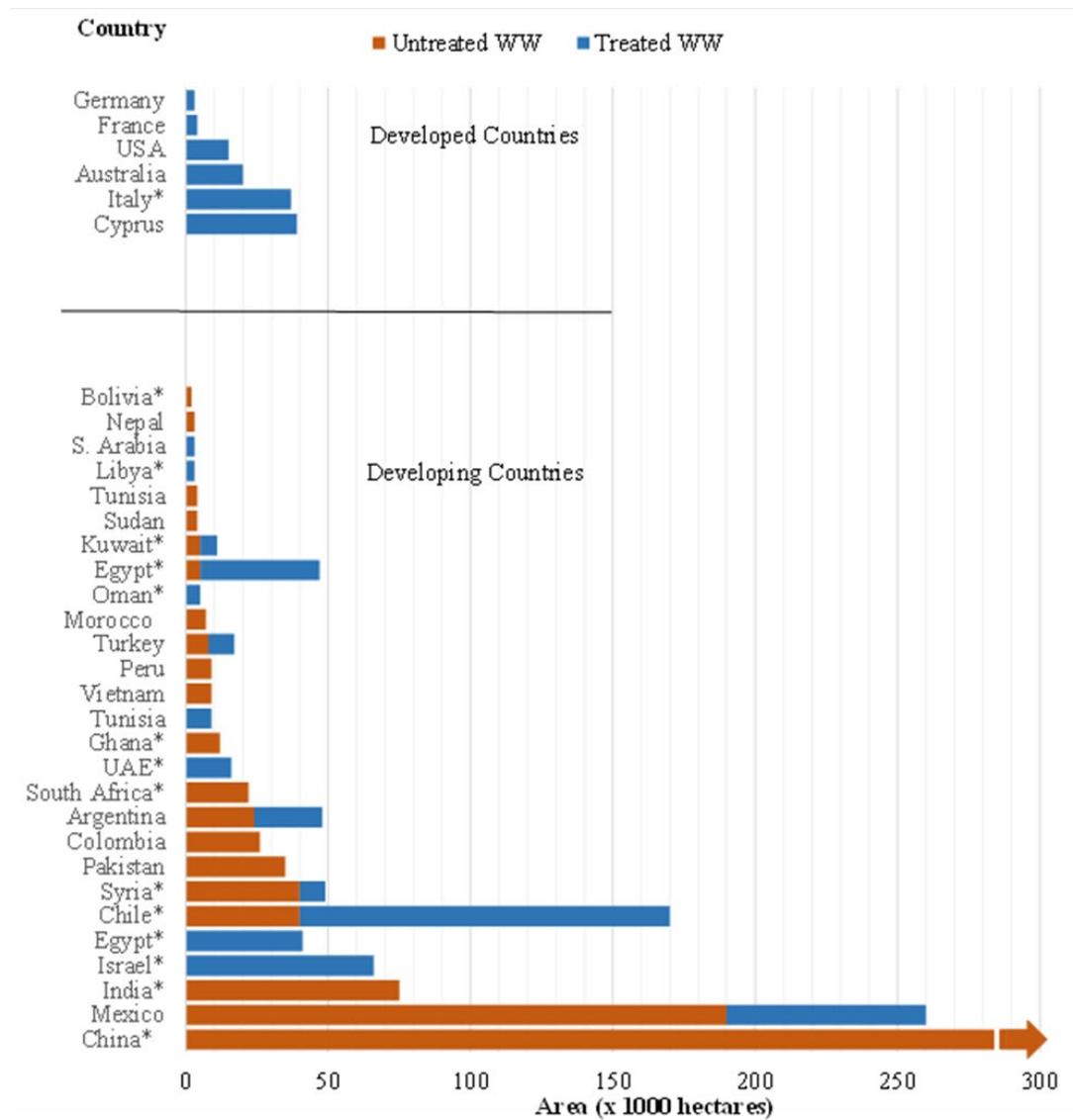
disorders, integumentary dysfunction (Gwaltney-Brant, 2013), enzymic malfunctioning, destruction of membranes, and many more (Sobukola et al., 2010). However, the effect on human health also depends on the degree of accumulation, prolonged consumption, quantity of vegetables consumed, age and weight of the individual (Ametepey et al., 2018).

Heavy metal contamination and other chemical pollutants in WW is a major public concern in higher-income countries, where pathogenic risks are sufficiently under control. However, in developing countries, risks from heavy metals and other chemical pollutants are a setback, as microbial contamination has received the greatest attention (Mateo-Sagasta et al., 2013).

The presence of pathogenic contaminants, including bacteria, viruses, helminths, protozoa, and schistosomes, is another problem associated with the use of WW, and

consumption of contaminated vegetables can cause diarrhea, nausea, dehydration, headache, fever, malaise, anorexia, cough, vomiting, and cramps. More serious conditions, such as arthritis and paralysis can also happen due to the infection of pathogens such as campylobacter and poliovirus, respectively (Abaidoo et al., 2010).

This review paper has been devoted to highlighting the adverse effects of the aforementioned heavy metals and pathogenic contamination of WW irrigation on vegetable fields, as the most attention in the world is for those in nowadays. This paper also aimed to highlight the mandatory changes required to mitigate the disadvantages of WW irrigation for its sustainable use, particularly to provide opinions/options to developing countries (Figure 2).



**Figure 1.** Top-ranked countries using untreated or treated WW for irrigation (Jiménez, 2006; Scott et al., 2010)  
 Note: \*unclear/underestimated/missing data; USA: United States of America; S. Arabia: Saudi Arabia; UAE: United Arab Emirates

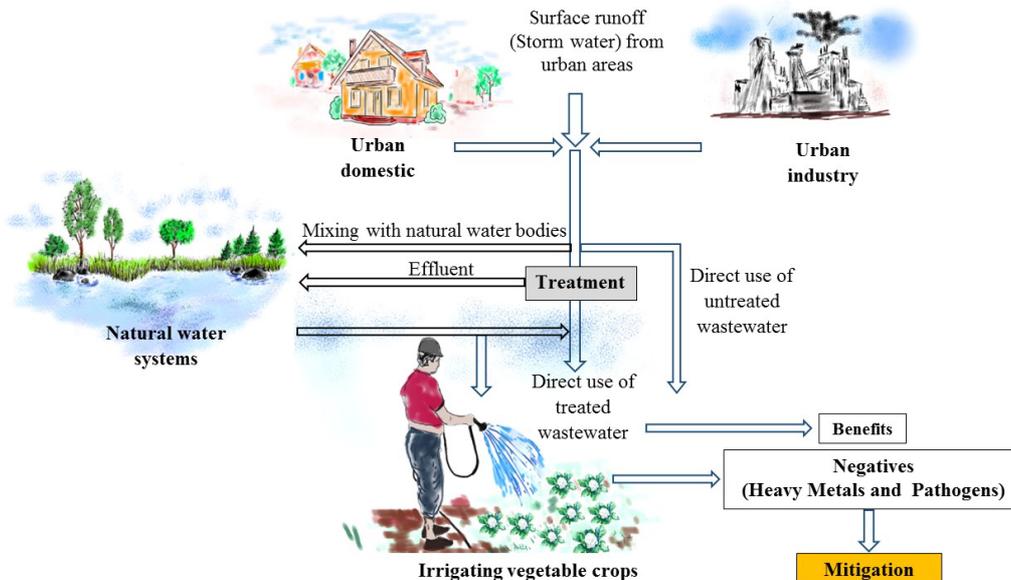


Figure 2. Overview of the present review paper

## 2. CONSTITUENTS PRESENT IN WW

Generally, WW consists of 99% water and suspended colloidal and dissolved solids make up about the rest of 1% (Ungureanu et al., 2020). The constituents in WW can be divided into several main categories (Table 1). The overall composition of the WW is purely dependent on its sources. Not all anthropogenic activities can produce the same amount and composition of waste. Several factors determine the composition of WW, including technical and legal frameworks in the region, behavior, lifestyle and standard of living of its residents and so on (Henze and Comeau, 2008). Therefore, there are enormous possibilities for changing the amount and composition of different waste streams that arise.

Constituents present in the WW can be removed to varying degrees based on the following treatment; preliminary, primary, secondary, tertiary and/or advanced. The primary treatment removes larger solid particles from WW, including fecal, wood, rags, and other heavier grit particles, also removes more floating substances and suspended solids. The secondary treatment further reduces the suspended solids and floating materials that could not be removed from the primary treatment. The process is also important in bringing the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) to acceptable levels. Tertiary and/or advanced treatment removes heavy metals and the other nutrients that could not be removed by the previous treatments. The disinfection operations (e.g., chlorination, ultraviolet radiation, and ozonation) decrease microbial contamination (Hashem and Qi, 2021).

## 3. USE OF WW IN VEGETABLE FIELDS AND ITS ADVANTAGES

Due to the year-round availability and lower or no costs, vegetable farmers have been driven to use the WW (Emenyonu et al., 2010). In Sri Lanka, domestic WW has

traditionally been used to irrigate the vegetables that grow in the backyard of most villagers (Figure 3) (Udagedara and Najim, 2010).

WW, generated from kitchens, bathrooms and washrooms, directed to supply the necessary water for the plant. The locals use young leaves, petioles and rhizomes as vegetables. These household cultivated vegetables are generally used to fulfil the household food requirements shared with the neighbours and sold in the market.

In addition, reliable WW flows motivate the farmers to grow the higher quality and more water-intensive vegetables (Thebo et al., 2017). Compared to conventional irrigation, the use of WW has further advantages to the farmers by increasing their income and saving expenses, reducing the high cost to have clean water (Jayawardena et al., 2006). For example, farmers in Pakistan earn 30-40% more income per year by irrigating the WW and while in Ghana, it is about 40-50% (Jayawardena et al., 2006). Like many other developing countries, Thailand also uses WW for growing vegetables and has become famous with the rapid progressive urbanization, and a considerable amount of nutrients are being loaded annually to the vegetable fields (Honda et al., 2010). Nutrients presented in the WW such as organic carbon, nitrogen, phosphorus, potassium, and magnesium are higher than the groundwater and thus enhance crop growth and productivity through continuous irrigation (Kfle et al., 2020). A comparative study by Kausar et al. (2017) found that the content of nitrate nitrogen in the WW is about 117% higher than in the groundwater. Peverill and Premier (2006) recognized that 35% of the cost allocated for the fertilizers can be saved by WW irrigation, as it saved 60%, 33% and 40% of inorganic nitrogen, phosphorus and potassium fertilizers, respectively.

Today, WW irrigation is also considered as a solution to reduce soil degradation, restore nutrient levels, and improve chemical and biological properties of the soil (Angin et al., 2005; Emenyonu et al., 2010; Nazário et al., 2019). Li et al. (2019) found the increase in the growth and

yield of vegetables such as eggplant, tomato and cucumber with the application of WW. Kausar et al. (2017) also recorded the notable growth (fresh and dry weight, length) of fenugreek (*Trigonella foenum-graecum*), spinach (*Spinacia oleracea*), radish (*Raphanus sativus*) and carrot (*Daucus carota*) after irrigation with WW compared to vegetables irrigated with groundwater. They highlighted that WW irrigation can improve plant growth by up to 50% compared to groundwater treated vegetables.

Noteworthy that treated WW has the potentiality to provide an appreciable amount of necessary nutrients for plants and thereby can reduce the application of fertilizers

(Tran et al., 2016). However, the amount of nutrition in the WW could also be varied according to the treatment (Truu et al., 2009). In contrast, Disciglio et al. (2015) documented that the application of WW has the ability to alter the local soil microflora communities in a way that favorable to the crops by increasing the population of saprophytic fungi, some of them (e.g., *Trichoderma* spp., *Penicillium* spp. and *Aspergillus* spp.) can act as antagonists of soil-borne plant pathogens. The application of secondary treated agro-industrial WW for irrigation increases the population of saprophytic species and gradually decreases phytopathogens such as *Fusarium oxysporum*.

**Table 1.** Constituents present in WW and associated risks

Waste water constituents	Examples	Associate risk/impact on humans and environment
Microorganisms	Pathogenic bacteria, virus and worms eggs	Risk when bathing and eating shellfish
Biodegradable organic materials	Oxygen depletion in rivers, lakes and fjords	Fish death, odors
Other organic materials	Detergents, pesticides, fat, oil and grease, colouring or dyes, solvents, phenols, cyanide	Toxic effect, aesthetic inconveniences, bio accumulation in the food chain
Nutrients	Nitrogen, phosphorus, ammonium	Eutrophication, oxygen depletion, toxic effect
Metals	Cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), zinc (Zn)	Toxic effect, bioaccumulation in food chain, accumulate in irrigated soils and the environment
Other inorganic materials	Acids, for example hydrogen sulfide, bases	Corrosion, toxic effect, affect permeability and soil structure
Thermal effects	Hot water	Changing living conditions for flora and fauna
Odor (and taste)	Hydrogen sulfide	Aesthetic inconveniences, toxic effect
Radioactivity	-	Toxic effect, accumulation



**Figure 3.** Small-scale cultivation of *Lasia* (*Lasia spinose*) in the household in Sri Lanka

#### 4. WW IRRIGATION AND HEAVY METAL CONTAMINATION OF VEGETABLE CROPS

Municipal WW (MWW) defined as a combination of water and wastes that have been thrown away from residential, institutional and commercial premises along with infiltration, surface and stormwater runoff, generated

within urban areas (Al Enezi et al., 2004; Mateo-Sagasta and Salian, 2012). MWW is the main sources of heavy metals, particularly due to the industrial discharges (Abdel-Sabour, 2003; Luo et al., 2009; Müller et al., 2012; Shifaw, 2018; Tytla, 2020). Before using the MWW for agricultural irrigation, it is mostly treated by well-developed various processes and techniques in developed

countries. It has also been reported that due to the higher energy costs, technology requirements and frequent maintenance, most of the developing countries are not adequately practicing the recommended procedures. Therefore, untreated WW obtained from such polluted resources may elevate the problems associated with irrigation (Hussain et al., 2002).

Accumulation potential of heavy metal depends on the type of crop, where leafy and tuberous vegetables have the ability to accumulate higher levels of heavy metal concentrations than the other crops (e.g., grain) and fruits, thus more attention should be paid to these croplands when irrigating the WW (Kalavrouziotis and Drakatos, 2002; Castro et al., 2013; Galal et al., 2018). Rather than the crop species, type of heavy metal also decides the accumulation amount of heavy metal in the plant bodies (Gatta et al., 2018).

#### 4.1 Macro- and micronutrient elements

Hussain et al. (2017) found the accumulation of heavy metals (Ni, Cr, Mn, Cu, and Co) in WW treated vegetables; carrot, spinach, and radish. In addition, Hussain et al. (2017) have highlighted that the daily consumption of those vegetables may not create health-hazardous due to the amount of daily intake of toxic metals is not at a high level. Furthermore, Hussain et al. (2017) concluded that WW containing such heavy metal could be safe to irrigate the vegetable crops. However, Chaoua et al. (2019) states that the long-term intake of heavy metal contaminated such vegetables should be avoided. In contrast, Kausar et al. (2017) reported that the accumulation of heavy metals in edible parts of these plants are higher, compared with groundwater irrigation. Furthermore, they have found that the accumulation of Ni and Cr are above the standard given by FAO or World Health Organization (WHO) for all above vegetables. In another study, Galal et al. (2018) evidenced that the use of MWW for cultivating the cabbage (*Brassica oleracea*) may not be suitable. In their study they found that the heavy metals Cu, Ni and Mn in WW are exceeded the safe ranges and Co is just near to surpass the recommended level.

#### 4.2 Highly toxic elements

Ibrahim et al. (2019) have found that accumulation of Zn in different parts of the tomato plant (*Lycopersicon esculentum*), which are irrigated with MWW. They have found that the highest-level accumulation of Zn is along with the leaves (13.7 mg/kg), followed by roots (11.11 mg/kg), fruits (10.50 mg/kg) and stems (12.30 mg/kg). In their demonstration study, Bayat et al. (2018) found that heavy metal concentrations in selected vegetables were in the following order: Zn>Pb>Cd (Table 2) with the addition of 100% MWW.

Recent work by Gebeyehu and Bayissa (2020) also showed the exceeded accumulation of heavy metals; As, Pb,

and Hg in edible parts of the tomato and cabbage crops collected from Mojo area, Ethiopia. Chaoua et al. (2019) recently conducted a study investigating the effect of raw sewage application for vegetable fields, which is discharged from a WW treatment plant in Marrakech city, Morocco. They have found that heavy metal contamination in crops; broad bean (*Vicia faba*), nettle (*Urtica dioica*), broadleaf plantain (*Plantago major*), and mallow (*Malva sylvestris*) (Table 2).

Eissa and Negim (2018) recommended that sewage WW should not be used to irrigate the vegetable fields unless it is mandated, as they evidenced that Pb and Cd (also Ni) accumulation in lettuce and spinach plants exceed the permissible limit. Similarly, a study conducted by Singh et al. (2010) in Varanasi (India) also found that accumulation of Pb and Cd (also Ni) in vegetables; bitter gourd, okra, spinach, and mint are above the national and international permissible limits. Furthermore, Galal et al. (2018) have found elevated concentrations (exceeded the health risk index) of both Pb and Cd (Cr and Zn in critical level) in cabbage leaves, which irrigated with MWW. On the other hand, many studies have proved that adequate treated WW contains a low level of heavy metals. Lonigro et al. (2007) used a tertiary-membrane filtered MWW to irrigate the tomato, fennel and lettuce vegetable crops and found that the process can keep Cd, Hg, Pb and Zn (also Cr, Cu, Fe and Mn) impurities below the maximum permissible level. Moreover, the study revealed that the accumulation of heavy metals in the crops at the time of harvesting is also below the maximum recommended levels.

#### 4.3 Accumulation of heavy metals in WW irrigated farmland

Long-term irrigation of contaminated WW can also lead to accumulation of heavy metals in soil that can be absorbed by the vegetable plants and eventually can pose threats on human when consumed (Chaoua et al., 2019; Ibrahim et al., 2019; Priyashantha and Mahendranathan, 2019). Huong et al. (2010) have analyzed the soil samples that are irrigated by industrial WW in Hanoi, Vietnam. The researchers have evidenced the contamination of several macro- and micronutrient elements including, Cu (196 mg/kg), Cr (175 mg/kg) and Ni (60 mg/kg), and the highly toxic elements Zn (204 mg/kg), Pb (131 mg/kg) and Cd (4 mg/kg). They further noted that Cd, Cu, and Pb are above the permissible levels of the country standard. In another study, Kfle et al. (2020) analyzed the soil samples from WW irrigated vegetable fields around Asmara, Eritrea, and found that, out of many heavy metals presence (Mo<Cd<Co<Cu<Pb<V<Cr<Zn<Mn<Fe<Al) in the soil, Fe, Mn and Pb are generally exceeded the FAO/WHO permissible limit.

**Table 2.** Contamination of heavy metal of some vegetable crops reported in developing countries

Vegetable	Plant part	Irrigation method	Type of WW (untreated or treated)	Concentration of heavy metal (mg/kg)								
				Micronutrient elements						Highly toxic elements		
				Cr	Mn	Fe	Co	Ni	Cu	Zn	Pb	Cd
Bitter gourd ( <i>Momordica charantia</i> )	Leaf	NR	Untreated	-	76.9±17.53 <sup>1</sup>	-	0.035±0.015 <sup>1</sup>	-	-	-	-	0.058±0.002 <sup>1</sup>
	Fruit			-	8.25±2.64 <sup>1</sup>	-	0.040±0.021 <sup>1</sup>	-	-	-	-	0.071±0.008 <sup>1</sup>
Cabbage ( <i>Brassica oleracea</i> )	Leaf	NR	Untreated	4.17±0.58 <sup>8</sup>	106.67±16.07 <sup>8</sup>	3673.33±44.81 <sup>8</sup>	3.98±0.53 <sup>8</sup>	4.47±0.06 <sup>8</sup>	3.83±0.58 <sup>8</sup>	20.00±5.0 <sup>8</sup>	606.67±16.07 <sup>8</sup>	90.00±13.23 <sup>8</sup>
	Root			2.50±0.50 <sup>8</sup>	146.67±12.58 <sup>8</sup>	7191.67±15.28 <sup>8</sup>	4.15±0.74 <sup>8</sup>	4.17±0.29 <sup>8</sup>	0.77±0.23 <sup>8</sup>	35.00±5.0 <sup>8</sup>	423.33±44.81 <sup>8</sup>	111.67±16.07 <sup>8</sup>
Mustard green ( <i>Brassica campestris</i> )	Leaves and stalks	Watering cans	Secondary treated (biological)	ND <sup>6</sup>	ND <sup>6</sup>	0.005±0.00 <sup>6</sup>	ND <sup>6</sup>	0.004±0.00 <sup>6</sup>	ND <sup>6</sup>	0.03±0.00 <sup>6</sup>	ND <sup>6</sup>	ND <sup>6</sup>
Celery ( <i>Apium graveolens</i> )	NR	NR	Untreated	0.04±0.02 <sup>3</sup>	-	-	-	0.10±0.08 <sup>3</sup>	-	2.45±1.01 <sup>3</sup>	0.16±0.28 <sup>3</sup>	0.99±0.83 <sup>3</sup>
Cress ( <i>Lepidium sativum</i> )	Leaf	NR	Untreated	-	-	-	-	-	39.20 <sup>7</sup>	35.38 <sup>7</sup>	6.11 <sup>7</sup>	1.82 <sup>7</sup>
Lettuce ( <i>Lactuca sativa</i> )	NR	NR	Untreated	0.03±0.05 <sup>3</sup>	-	-	-	0.01±0.01 <sup>3</sup>	-	3.15±0.84 <sup>3</sup>	0.29±0.32 <sup>3</sup>	1.10±1.09 <sup>3</sup>
High mallow ( <i>Malva sylvestris</i> )	Root	NR	Untreated	-	-	-	-	-	10.53±2.42 <sup>9</sup>	79.695±9.36 <sup>9</sup>	38.17±3.73 <sup>9</sup>	6.095±0.63 <sup>9</sup>
	Leaves			-	-	-	-	-	7.085±0.62 <sup>9</sup>	58.08±1.80 <sup>9</sup>	39.98±6.68 <sup>9</sup>	4.69±0.55 <sup>9</sup>
Broad-leaved plantain ( <i>Plantago major</i> )	Root	NR	Untreated	-	-	-	-	-	8.705±0.29 <sup>9</sup>	68.23±4.48 <sup>9</sup>	75.365±13.04 <sup>9</sup>	12.37±2.56 <sup>9</sup>
	Leaves			-	-	-	-	-	4.505±0.54 <sup>9</sup>	57.545±13 <sup>9</sup>	37.965±6.48 <sup>9</sup>	8.355±1.06 <sup>9</sup>
Radish ( <i>Raphanus sativus</i> )	Tuber	NR	Untreated	-	-	-	-	-	42.46 <sup>7</sup>	37.30 <sup>7</sup>	7.14 <sup>7</sup>	1.88 <sup>7</sup>

Table 2. (Continued)

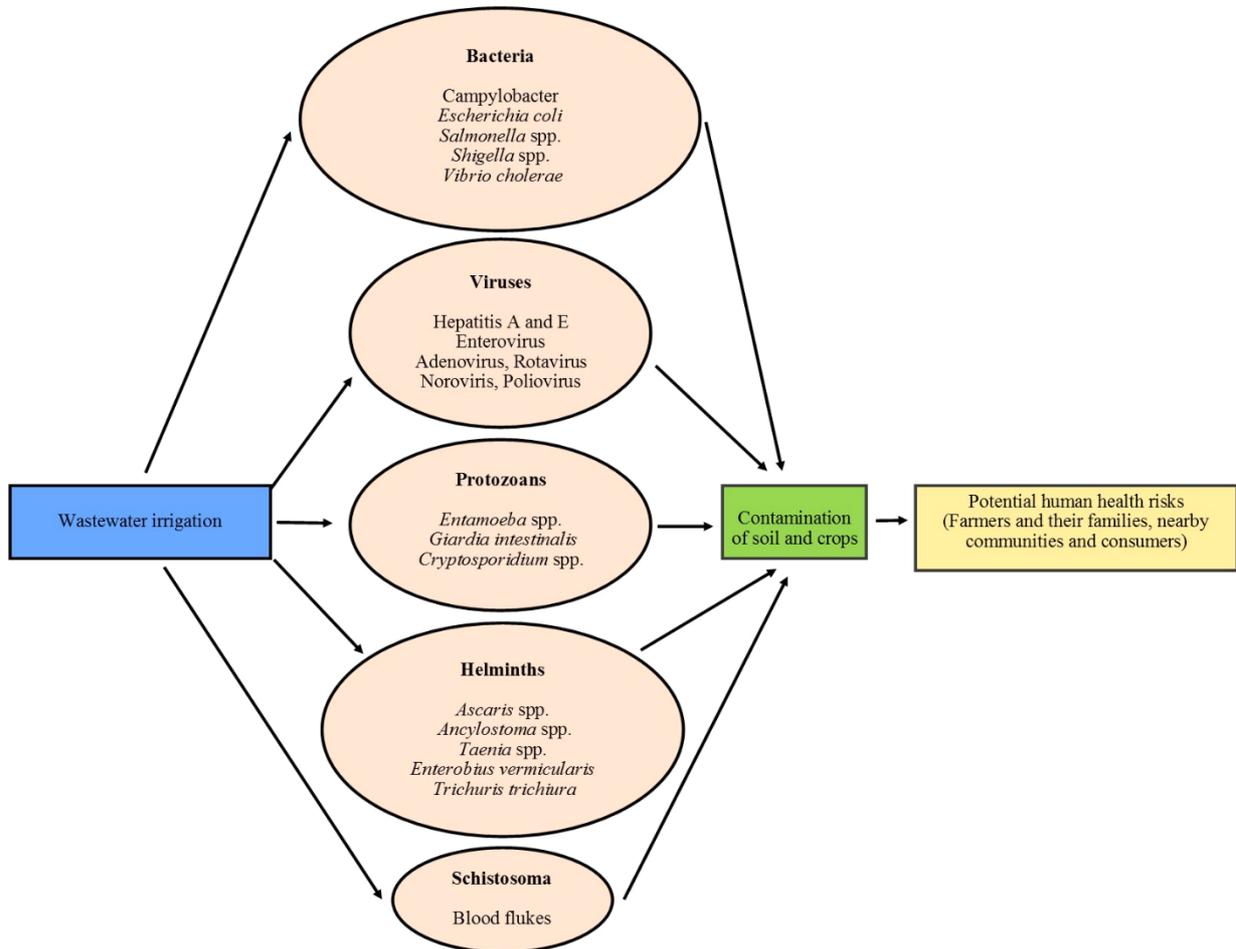
Vegetable	Plant part	Irrigation method	Type of WW (untreated or treated)	Concentration of heavy metal (mg/kg)								
Spinach ( <i>Spinacia oleracea</i> )	Leaf	NR	Untreated	-	102.2±54.66 <sup>1</sup>	-	0.035±0.015 <sup>1</sup>	-	73.08 <sup>3</sup>	60.74 <sup>3</sup>	13.82 <sup>3</sup>	3.27 <sup>3</sup> 0.073±0.028 <sup>1</sup>
		NR			0.01±0.02 <sup>3</sup>	-	-	0.05±0.05 <sup>3</sup>	-	2.02±0.74 <sup>3</sup>	0.97±1.03 <sup>3</sup>	1.82±1.81 <sup>3</sup>
Common nettle ( <i>Urtica dioica</i> )	Root	NR	Untreated	-	-	-	-	-	20.44±4.69 <sup>9</sup>	104.685±7.80 <sup>9</sup>	83.09±7.02 <sup>9</sup>	11.13±1 <sup>9</sup>
	Leaf			-	-	-	-	-	16.025±2.34 <sup>9</sup>	74.965±3.27 <sup>9</sup>	32.555±5.39 <sup>9</sup>	ND <sup>9</sup>
Broad bean ( <i>Vicia faba</i> )	Root	NR	Untreated	-	-	-	-	-	7.045±0.18 <sup>9</sup>	77.255±0.89 <sup>9</sup>	45.73±3.41 <sup>9</sup>	8.455±0.86 <sup>9</sup>
				-	-	-	-	-	5.825±2.38 <sup>9</sup>	73±34.35 <sup>9</sup>	18.35±2.08 <sup>9</sup>	6.01±2.62 <sup>9</sup>
	Leaf Pod			-	-	-	-	-	2.905±0.05 <sup>9</sup>	33.88±2.18 <sup>9</sup>	36.925±11.24 <sup>9</sup>	11.185±1.41 <sup>9</sup>
	Seed			-	-	-	-	-	5.39±1.15 <sup>9</sup>	58.585±11.12 <sup>9</sup>	30.775±6.95 <sup>9</sup>	12.03±0.80 <sup>9</sup>
Turnip ( <i>Brasica rapa rapa</i> )	Tuber	NR	Untreated	-	-	-	-	-	83.20 <sup>7</sup>	80.92 <sup>7</sup>	23.70 <sup>7</sup>	4.19 <sup>7</sup>
Tomato ( <i>Solanum lycopersicum</i> )	Fruit	Furrow irrigation	Treated	-	1.3 <sup>2</sup>	9.3 <sup>2</sup>	-	-	0.6 <sup>2</sup>	2 <sup>2</sup>	-	-
		Surface drip irrigation	Treated	-	1 <sup>2</sup>	6.2 <sup>2</sup>	-	-	0.6 <sup>2</sup>	2 <sup>2</sup>	-	-
Okra ( <i>Abelmoschus esculentus</i> )	Leaf	NR	Untreated	-	96.8±42.50 <sup>1</sup>	-	0.034±0.020 <sup>1</sup>	-	-	-	-	0.074±0.022 <sup>1</sup>
	Fruit			-	7.70±3.22 <sup>1</sup>	-	0.035±0.019 <sup>1</sup>	-	-	-	-	0.052±0.031 <sup>1</sup>
MPL				1 <sup>2</sup>	0.01 <sup>1</sup>	425.5 <sup>4</sup>	40 <sup>5</sup>	10 <sup>3</sup>	73.3 <sup>4</sup>	100 <sup>3</sup>	5.00 <sup>7</sup>	0.2 <sup>3</sup>

Note: NR: not recorded; ND: not detected; MPL: maximum permissible level (<sup>1</sup>Murtaza et al., 2003; <sup>2</sup>Najafi, 2006; <sup>3</sup>Qishlaqi et al., 2008; <sup>4</sup>Mensah et al., 2009; <sup>5</sup>Elbagermi et al., 2012; <sup>6</sup>Ali and Shakrani, 2013; <sup>7</sup>Bayat et al., 2018; <sup>8</sup>Galal et al., 2018; <sup>9</sup>Chaoua et al., 2019)

## 5. WW USAGE AND PATHOGENIC CONTAMINATION OF VEGETABLE CROPS

The use of WW in the cropping fields is mostly associated with pathogenic microbes, (Figure 4), where contaminations are mostly observed in elevated condition in developing

countries (Da Fonseca et al., 2007; Jang et al., 2013; Symonds and Breitbart, 2015). For example, Ferrer et al. (2012) have found that the consumption of morning glory (*Ipomoea aquatic*) is the main source of diarrhea infections (fourth cause of death in adults in developing countries) in Thailand.



**Figure 4.** Pathogen risks associated with the application of waste water in agriculture (WHO, 2006; Abaidoo et al., 2010; Jaramillo and Restrepo, 2017)

### 5.1 Bacteria

In a study, Hounmanou et al. (2016) noted the presence of *Vibrio cholerae* along with the WW irrigated vegetable, Chinese cabbage. While Abubakari (2018) found that the presence of the *Salmonella* spp. along with the lettuce cultivation. Ait et al. (2001) examined 16 samples of vegetable crops (lettuce, parsley, tomatoes, and pimento) in spreading areas of Marrakesh (El Azzouzia). Results showed the presence of serogroups *Salmonella* B and C in 68.75% of vegetable samples. They have further noticed that vegetables such as lettuce and parsley are at higher contamination than the pimento and tomatoes that grow higher above the soil surface. Further, they have concluded that WW irrigation was the main source of *Salmonella* contamination. Busgang et al. (2018) found that the occurrence of *Salmonella enterica* and *Shigella* spp. in raw greywater exceeded the maximum permissible level (50 cfu/100 mL and 1 cfu/100 mL). They have also warned that consuming vegetables that are irrigated with greywater, could pose some health issues relevant to microbial infections. The treated WW also can

contain a considerable amount of microbial pathogens, as evidenced by Ayni et al. (2011). Moreover, they have found that tertiary treated WW in Korba (Tunisia) is with the considerable contamination of *E.coli*. Further, they have strictly recommended not to use the treated WW to irrigate the vegetable fields, even it is super cheaper than the freshwater. Aiello et al. (2007) also recorded the presence of *E.coli* and fecal Streptococci in the tomato field, which irrigated with urban WW. Similarly, Rageh et al. (2017) found a higher concentration (up to  $78 \times 10^6$  CFU/100 mL) of coliforms in WW uses in Dhamar City, Yemen.

### 5.2 Viruses

Prez et al. (2018) found norovirus, rotavirus and astrovirus in vegetable samples of spinach, lettuce, arugula, and silverbeet. They have found the main source for this contamination is the farm-level irrigation of WW (treated waste discharges from the WW treatment plant). Ouardani et al. (2016) examined 271 WW samples associated with five sewage treatment plants to evaluate the

hepatitis A virus in the urban setup, Tunisia. They have detected the presence of viruses in 53.9% of the collected samples. They also noticed that the detection of viruses in treated water is greater than the presence in raw water. Based on the results, Ouardani et al. (2016) concluded that hepatitis may be resistant to the current WW treatment processes and the use of this treated WW may be responsible for the spread of viral diseases. Hassine et al. (2010) and Schlindwein et al. (2010) reached similar conclusions, emphasizing that current treatment methods for WW may need to be improved in order to eliminate/inactivate the viral pathogens. Nevertheless, Kitajima et al. (2014) found that not all viruses can be removed equally, with some viruses (e.g., Aichi virus) exhibiting many complications in removal by the WW treatment plants.

### 5.3 Protozoans

Shahnazi and Jafari-Sabet (2010) recognized the risk of protozoa contamination of vegetables due to the irrigation of untreated WW. They have observed the presence of one or more species of protozoa eggs; *Entamoeba coli*, *Entamoeba histolytica*, and *Giardia lamblia* with the unwashed vegetable samples of leeks (*Allium porrum*), spring onions (*Allium cepa*), cress (*Lepidium sativum*) and coriander (*Coriandrum sativum*). El Kettani et al. (2008) have analyzed the stool samples of 333 people residing in Dladla, Boukallou and Ouled Afif, Morocco. They had analyzed the stool samples from 214 people who consumed the untreated WW irrigated crops and used the adjacent groundwater. The rest of 119 people never had untreated WW irrigated crops and consumed water from various groundwater sources. They have found an elevated level of parasites in WW exposed group than the non-exposure group. Furthermore, they have observed the presence of *Entamoeba coli*, *Endolimax nana*, *Pseudolimax butschlii*, *Giardia intestinalis* and *Chilomastix mesnili* at 52.3%, 12.1%, 6.5%, 11.7% and 1.9% in exposed groups, respectively. While in non-exposed group, the sequence of pathogen presence is considerably minimum (except *C. mesnili*). In another study, Fonseca et al. (2016) recognized that treated WW also could have pathogenic contamination as similar to the untreated WW. In their study, they detected the presence of *Entamoeba* spp. (e.g., *E. histolytica*, *E. dispar*, *E. moshkovskii*) at significance level in both raw (70%) and treated (80%) WW samples.

### 5.4 Helminths

Hajjami et al. (2013) conducted a study to assess the contamination of helminth eggs in directly irrigated WW in Morocco farmlands. They have analyzed the WW samples used for irrigation, crop leaf samples, and farmland soil. They have found that helminth eggs (*Ascaris* spp. for nematodes, *Taenia* spp. and *Hymenolepis* spp. for cestodes and digestive *Strongyle* eggs) with an average concentration of 0.13 eggs/L in the treated WW samples. Further, they revealed that *Taenia* spp., *Cappilaria* spp., and *Habronema* spp. contamination with vegetable samples of mint, and *Ascaris* spp. and *Toxocara* spp. presence with the coriander. *Strongyle* eggs are found on both vegetable samples. As well, they found that the total helminth contaminations are higher in mint (4.33 eggs/100 g) than the coriander (2.17 eggs/100 g). Hajjami et al. (2013) also carried out a demonstration study by irrigating three different water sources into the vegetable grown in experimental plots and found that few pathogen

species, including *Moniezia* sp. contamination in some samples (Figure 5). Similarly, Kausar et al. (2017) found that treated WW (India) is having a significantly higher number of helminth eggs (9.5±11.4 eggs/L) concerning the WHO standard (<0.1 egg/L) for crops likely to be eaten raw. In another study, Amoah et al. (2016) reported the presence of *Ascaris* spp. and hookworm ova in WW and farmland soil (Kumasi, Ghana), above the WHO recommendation.

The presence of helminths in crop fields is generally higher than the other pathogenic groups once irrigated with the inadequately treated/untreated WW, due to their survival under the hazardous environment and familiar humid condition of the farmland. Helminth eggs can survive for several years, while other pathogenic groups are usually less than 10 to 70 days (Mateo-Sagasta et al., 2013; Hajjami et al., 2013).

## 6. MITIGATION OF NEGATIVE IMPACTS OF WW IRRIGATION

### 6.1 Policies

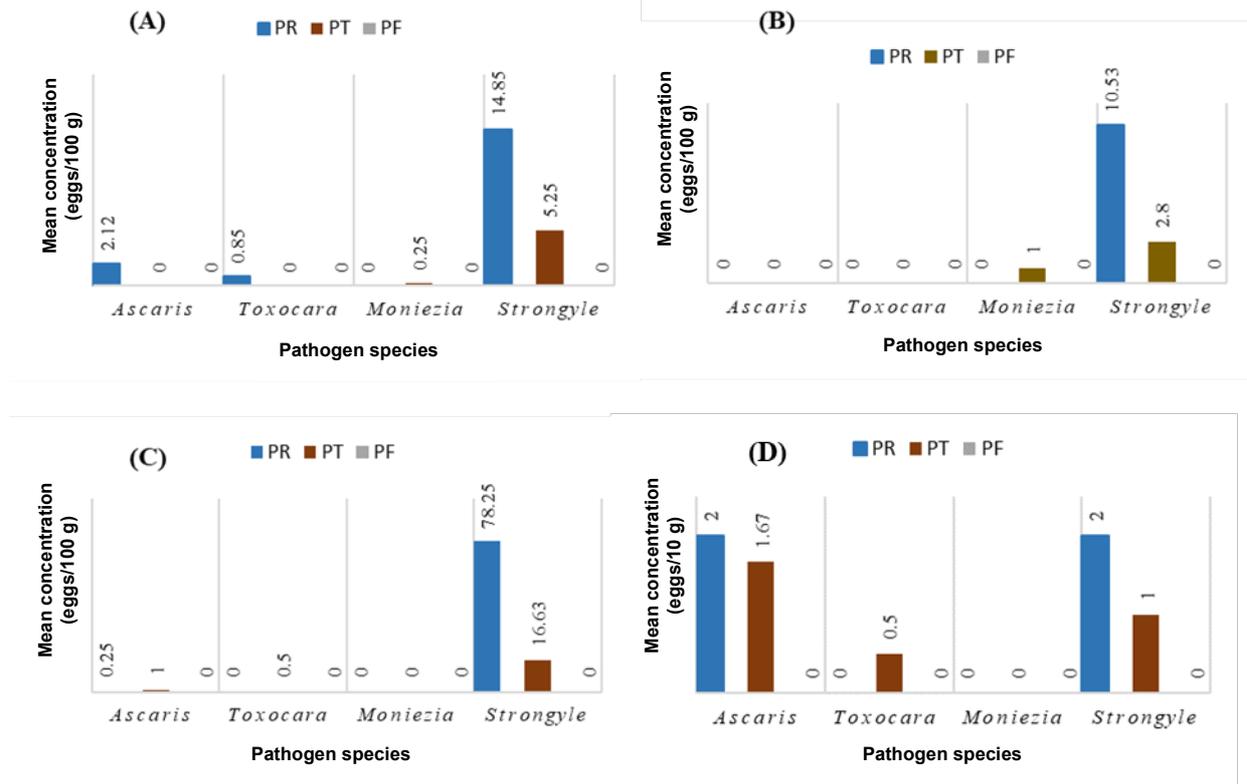
Development of adequate policies to manage the WW irrigation could be a mandatory action to follow. Nevertheless, many countries in the world are lacking policies or legal implementations (Mañas et al., 2009; Qadir et al., 2010) to use the WW. Mateo-Sagasta et al. (2013) reported that out of 51 developing countries (from Asia, Africa, and Latin America and the Caribbean) 10 nations have no regulation/guideline, while 21 countries have national guidelines and 9 are having WHO guidelines. Further, 11 countries follow both WHO guidelines and national guidelines. Nevertheless, it does not seem to be practiced the implemented safe guidelines mainly due to the poor human capacity and financial background; therefore, WW may not be treated adequately before discharge into the environment or reuse (Mateo-Sagasta et al., 2013).

Being an agricultural nation, Sri Lanka uses its water resources at the maximum. Along with industrial development, Sri Lanka also started to irrigate the WW for large-scale commercial cultivations (no sufficient/trustable data on the volume of WW generated and used the area for the whole island). The Central Environmental Authority (CEA) of Sri Lanka laid down standards for effluent discharge and by law, it is mandatory to use secondary treated WW for irrigation. However, along with the introduction of inexpensive treatment methods (e.g., combination of biogas plant and reed bed) via new projects, today primary and advanced primary treatments are being used to treat WW instead of secondary treatment (Jayalal and Niroshani, 2007). Countries like Jordan, where the pronounced water deficit occurred, developed a number of policies to maintain the qualities of the WW to reuse it for agriculture purposes and secure environmental and public health care (Al-Zboon and Al-Ananzeh, 2008). However, as the world's second most water-scarce country, Jordan still needs to adjust to effective policies to ensure a sustainable water supply via a waste management system (Mohammad et al., 2020).

According to our understanding, implemented policies may not always work well where the social background and education of people may influence its

actions. As well, once the household or small-scale WW irrigation practices are there, it could be very difficult to trace and regulate. Fragmented attempts also lead to

failure of the expectation; therefore, regulation measurements should be accompanied by technical solutions (Jayawardena et al., 2006).



**Figure 5.** Graphical representation of the data obtained from Hajjami et al. (2013) showing the occurrence of helminth eggs on vegetable and soil due to the WW irrigations; parsley (A), coriander (B), radish (C) and soil (D)  
 Note: PR: plots irrigated by raw WW; PT: plots irrigated by treated WW; PF: plots irrigated by freshwater

## 6.2 Farm operations

### 6.2.1 Implementation of on-farm WW storage and filtration systems

The options for on-farm treatment process are the same as those used in conventional WW treatment, such as sedimentation, flocculation, and filtration. The establishment of on-farm sedimentation ponds further limits contamination, particularly from larger pathogenic microorganisms in the WW. Farmers can set up a pond and store WW for several days before applying it to the cropping fields. During WW storage, worm eggs and harmful bacteria linked to silt and other particles settle down at the bottom (FAO, 2012). Therefore, water must be carefully collected from sedimentation ponds without disturbing the sediment.

According to Keraita et al. (2008a), it takes three days to deposit the helminth eggs to meet the WHO recommendation (less than 1 egg/L) and may take several more days to eliminate the thermotolerant coliforms. Though sedimentation pond practices are less expensive and easier to implement, viruses and other micro-pathogens may not be removed, and a significant reduction of such pathogens can be achieved via filtration systems (Stevik et al., 2004). Using on-farm filtration systems such as slow sand and fabric filters can effectively minimize the pathogenic contamination—including viruses, and likely to be more cost-effective, therefore

much suitable for low-income countries (FAO, 2012; Cescon and Jiang, 2020). A study conducted by Keraita et al. (2008a) have found that column-slow sand filters are effective in removing 71-96% of helminths and 2 log units (from 7 to 5 log units) of thermotolerant coliforms, while fabric filters remove only 12-62% for helminth eggs and 1 log unit of thermotolerant coliforms.

### 6.2.2 Irrigation methods

In order to minimize the health risks on consumers, it is necessary to reduce the contact between edible parts of vegetables and WW or contaminated soil (FAO, 2012). According to the FAO guidelines, this can be accomplished by selecting proper irrigation methods such as drip and furrow irrigation. Drip irrigation is especially important to prevent the closer contact between WW and the above-ground leafy vegetables (near soil line) like lettuce and cabbage (FAO, 2012; Libutti et al., 2018). Furrow irrigation reduces the contact between the WW and edible parts that grow in the ridges, such as green pepper. On the other hand, these methods are also important to reduce water losses. Watering cans and sprinkler irrigation are generally splashes the contaminant soils onto the plants and hence better not to use these methods or careful irrigation can be followed, not to splash the contaminant soils or the WW (FAO, 2012). Also, these methods enable farmers to get in to closer touch with polluted water.

Most pathogens could be killed by harsh environmental conditions such as heat, sunlight, and lack of water (FAO, 2012). Nevertheless, present-on-farm practices do not appear to provide enough time to die off the pathogens under natural conditions between the last irrigation to harvest (Drechsel et al., 2014b). Hence, discontinuing the WW irrigation to the crops a few days (e.g., 2-4 days) before the harvest could be a good practice to decrease the level of pathogen contamination (FAO, 2012). As an example, discontinuation of WW for 3 days is more than enough to eliminate *Salmonella* contamination (Ait et al., 2001). This method can be applied to vegetables that are less sensitive to water shortage, such as green pepper, spring onions, cabbage, etc. However, water-sensitive vegetables may need daily watering and this method could not be adaptable. The applicability of this method is also debatable to practice in outdoor farming since, the climatic conditions determine the success of this method (FAO, 2012).

### 6.3 Educating the public and farmers

It is important to give enough knowledge to the public and farmers about the associated risks of using municipal WW, water quality, and measures, which can be used to mitigate the associated risks (Jiménez, 2006). As well, consumers can also wash the vegetables with disinfectant solutions (also salt/vinegar), followed by rinsing with clean water or soaking in cold water for few seconds to minimize the pathogen contamination before consuming raw (Amoah et al., 2007; Mara and Sleight, 2010; Beyhan et al., 2016).

### 6.4 Adapting to emerging WW treatment technologies

Due to the limitation of traditional WW treatment technologies such as; high energy consumption, low selectivity, moderate efficiency, and generation of large amounts of secondary sludge, leads to find alternative strategies (Lucaci et al., 2019). In this concern, nowadays emerging technologies are becoming popular, especially in developed countries. It has been proven that the nanomaterials (e.g., carbon, silica, and metal oxide-based) can be used to remove heavy metals from WW (Yang et al., 2019). Today, the use of nanocomposites/nanomaterials (multi-phasic materials ranged 10-100 nm) has emerged as a prominent area of research and development. For example, application of polymer nanocomposite ion exchangers, magnetic chitosan nanocomposites (Pandey et al., 2017), superadsorbent composite hydrogels (Saber et al., 2019) have gained attention.

After the introduction of membrane bioreactors in recent years, there has been an improvement in adapting this technique in WW treatment plants. Most of these unit operations (except for disinfection) are primarily intended to remove, suspended solids, organic substances, and nutrients, but not for pathogens. However, during the process, it eliminates enteric viruses and coliform effectively along with suspended solids (Hai et al., 2014; Lonigro et al., 2015; Zhang et al., 2016). However, especially in developing countries, due to the capital and running cost, implementation is problematic, nevertheless, if the cost can afford it would be a great technology to eliminate microbial pathogens over other conventional activated sludge process (Hai et al., 2014; Curtis, 2003). Upflow anaerobic sludge blanket reactors is

another less bio-solids waste generated, relatively cheaper technique and shows effectiveness by removing the pathogens (Von Sperling et al., 2005; Dutta et al., 2018). The method has also been identified as one of the most effective WW treatment technologies among the anaerobic treatment methods (Daud et al., 2018). In addition to the above methods, decentralized WW management systems recently attracted because of their efficiency of removing microbes, smaller size, less energy consumption, more eco-friendly and sustainable nature (Zhang and Shen, 2017).

### 6.5 Other eco-friendly methods

Some other available techniques, such as *in situ* immobilization (change the physical and chemical properties of the heavy metals in the sediments and lower the bioavailability through different processes) and phytoremediation (use of plants to restore the polluted environments through phytostabilization, phytoextraction and phytovolatilization) techniques have been regarded as useful tools for remediate metals, yet the application of those are only reported in developed countries (Wuana and Okieimen, 2011; Zhang et al., 2019; Tiodar et al., 2021). Today, as heavy metal accumulation becomes a worldwide concern, application of those methods would be timely important. More specifically, hyperaccumulators (plants that accumulate heavy metals at 100 to 1000-fold in their tissues than the non-accumulators) would be a safe and simple strategy to reduce the impact of heavy metal (Suman et al., 2018). Treated WW can be further subjected to phytoremediation before use for irrigation. Under such circumstances, Babaeian et al. (2016) found that carrot has a higher ability to absorb the Pb from contaminated fields; hence, the crop can simply be introduced as a hyperaccumulator to phytoextract and phytostabilization Pb from contaminated agricultural fields. Sun et al. (2009) showed the chelator-enhanced phytoextraction of heavy metals from industrial WW irrigated soils with the hyperaccumulator plant, *Sedum alfredi*. They have used ethylenediaminetetraacetic acid and citric acid as chelators and found the significantly enhanced phytoaccumulation of Cd, Cu, Pb and Zn in the aerial parts of the *S. alfredi*.

## 7. CONCLUSION

Irrigation of WW has both pros and cons. Despite the negative impacts of WW, there has been a significant growing interest to utilize WW for agriculture. In the future, crop production will have to be accelerated more and more to feed the growing population and demand for the water never seems to be dropping. Irrigation of WW in many arid and semiarid areas are becoming mandatory to save the limited water resources. The use of WW has become common practice worldwide due to the consistent availability, cheaper than the conventional water resources, and minimize the requirement of fertilizers to the crops. Nevertheless, due to the irrigation of WW, a number of human health and environmental risks have been arisen, especially due to the sources for the heavy metals and pathogens. Therefore, with no doubts, more attention has to be paid once applying the WW for the vegetable fields, especially concerning developing countries.

Untreated WW should never be used to irrigate the vegetable fields and must always use the adequately treated WW. Though treated WW is considered as more environmentally sound and safe, many studies have revealed that most of the current WW treatment plants are not managed properly, outdated or inadequate with new technologies. Therefore, the threat has yet to be resolved by adjusting to the novel techniques, such as membrane reactors and nanomaterials, whenever possible. As well, it should try to replace the less effective techniques with available best techniques (e.g., upflow anaerobic sludge blanket). As well, continuous assessment of water quality (e.g., inlet and outlet) of WW treatment plants are mandatory to follow and it should always meet the recommended guidelines for microbial and heavy metal contaminations. Treatment plants should be managed by identifying the types of pollutants produced by nearby communities and making the necessary changes.

Moreover, farmers also have a responsibility not to use the WW directly to the farm. They can establish on-farm filtration systems, and sedimentation ponds to minimize the coming threats. Improper legislation would create the worst condition. Yet there is an urgent requirement to update the implemented legislation to mitigate the ill practice of WW irrigation in many developing countries. State and local government agencies should identify the prevailing gaps of the policies/legislation and should enact laws accordingly, and stringent standards must be enforced. Perhaps, instead of completely banning WW application, it can restrict the irrigation based on the types of crops/vegetables. In addition, more educational programs should be organized to increase the awareness of the public about these detrimental effects of WW irrigation and mitigation strategies. Future research should focus on identifying risk reduction techniques, addressing irrigation system improvements, and introducing low-cost, new WW treatment approaches to promote them in economically impoverished countries.

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