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Adverse Impacts of Water Pollution from Agriculture (Crops, Livestock, and Aquaculture) on Human Health, Environment, and Economic Activities

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ABSTRACT

At the time being, water is a restricted indispensable resource for sustainable development worldwide. In Egypt, water resources are fairly inadequate and the challenges for achieving the highest possible water use efficiency are not that easy. Now, it is imperative to save and conserve water while providing the necessary quantities to satisfy both social and economic needs sustainably. In association with the witnessed increases in population and rise in economic and social activities, the anxiety on the water is getting higher. Decision-makers in Egypt adopted several strategies to secure water allocation and distribution including the reuse of low-quality water particularly agricultural drainage water which is already used in farming on a large scale. Most of the agricultural drainage water in Egypt is apt to many types of pollutants coming from varied sources. Those pollutants are contentiously disposed of in agricultural drains and could be destroying the soil ecosystem when used in farming. The main adverse impacts of such pollutants are lowering the quality of water as a source for irrigation crops, as well as the suitability of harvests for consumption. In Egypt, climate change is expected to have some adverse impacts on the agro-environmental ecosystem. This, however, when linked to the low quality of irrigation water, would need urgent and fast actions. Therefore, the aim of this review is to throw light on the potential negative impacts on human health, environment and economic activities due to water pollution from agriculture (crops, livestock, and aquaculture) in Egypt.

INTRODUCTION

Globally, water is a restricted indispensable resource for agriculture, industry, and human existence. In arid and semi-arid regions, where water resources are fairly inadequate, challenges for achieving the highest possible water use efficiency are not that easy. Egypt has been suffering from severe water scarcity in recent years. Rising population, rapid economic development, pollution and environmental degradation decreased the water availability in the country. Nowadays Egypt is facing an annual water deficit of around 7 billion cubic meters. It is imperative to save and conserve water while providing necessary quantities to satisfy social and economic needs in a sustainable way (Table 1).

Table (1) Available water in Egypt

Water resources	Present (2004) (Milliyard m3 in a year)	Future (2017) (Milliyard m3 in a year)
Nile Water	55.5	57.5
Rainfall Harvesting	1.0	1.5
Deep groundwater	0.9	3.5
Shallow groundwater	5	7.6
Drainage reuse	4.9	8.4
Treated sewage	0.7	2.5
Desalination	0.1	0.2
Water-saving by IIP	1.0	4.0
Total water resources	69.1	85.2

Source: Updated from FAO, 2005

At the time being, the irrigation system in Egypt is tremendous both in size and complexity. It consists of Aswan High Dam, eight main barrages, approximately 300.000 km of public watercourses, 17.00 km of public drains, 80.000 km of private watercourses, mesas and farm drains, 450.000 km of private water-lifting devices, sakes or pumps), 22.000 km of public water control stretchers and 670 large public pumping stations for irrigation (**Icarda, 2011; Nile Basin Initiative, 2016**). Though out this system approximately 59 billion m^3 distributed annually not only for cultivated lands but also for municipal and industrial activities, generation of hydro-electricity as well as for navigation of freighters and tourist boats on the River Nile. It is worthy to mention that one of the Egyptian water strategies is the reuse of low water quality, e.g., agricultural drainage water and treated sewage effluent, in farming. It is expected that Egyptian farmers might receive very shortly less irrigation water both in quantity and quality. The low-quality irrigation water is always polluted with enteric pathogens, emerging pollutants as well as certain potential toxic elements that pose adverse environmental hazards to both human and biodiversity besides restricting water reuse. Fair sustainable management of farming through proper crop pattern, remediation of polluted irrigation water would maintain a good quantity and quality production. Most of the water sources in Egypt were apt to many types of pollutants coming from varied sources. Those pollutants are contentiously disposed of in agricultural watercourses and agricultural drains. This situation was adversely reflected on the quality of water as a source for irrigating crops, as well as on the suitability of harvest for consumption. Worthy, in Egypt, climate changes are expected to have serious adverse impacts on the agro-environmental ecosystem. This, however, when linked to the low quality of irrigation water, would need urgent and fast actions.

Adverse agro-environmental consequences of using agricultural drainage water in irrigation water in the different climatic regimes in Egypt should be periodically monitored. The follow up of these hazards would enable the researchers to reach proper remediation biotechnologies able to avoid such adverse impacts. Therefore, the aim of this review is to through light on the potential negative impacts on human health, environment and economic activities due to water pollution from agriculture (crops, livestock and aquaculture) in Egypt **(Hegazi *et al.*, 2005)**.

GLOBAL WATER POLLUTION

Nowadays, water pollution is a global challenge that has increased in both developed and developing countries, undermining economic growth as well as the socio-environmental sustainability and health of billions of human beings. Although global attention has focused primarily on water quantity, water-use efficiency, and allocation issues, the poor management of wastewater and agricultural drainage has created serious water quality problems in many parts of the world worsening the water crisis (**Biswas *et al.*, 2012**). Water scarcity is caused not only by the physical scarcity of the resource but also by the progressive deterioration of water quality everywhere as well as reducing the quantity of water that is safe to use (**FAO, 2014**).

Agricultural pressures on global water quality mainly arise from cropping, agroforestry, fishery, and livestock production as well as from aquaculture, all of which have been recently expanded and intensified to meet the escalating food demands related to population growth and mobility as well as to changes in dietary patterns **(FAO, 2014)**. Human settlements, industries and farming, i.e., crops, livestock production and aquaculture as well are the major sources of water pollution. Globally, 80 percent of municipal low-quality water is discharged into water bodies untreated, and the industry is responsible for dumping millions of tons of PTEs (Potential Toxic Elements), solvents, toxic sludge, and other wastes into water bodies each year (**WWAP, 2017).**

Farms discharge large quantities of agrochemicals, organic matter, drug residues, sediments and salts into water bodies. The resultant water pollution poses demonstrated risks to aquatic ecosystems, human health and productive activities (**UNEP, 2016**). The intensive farming of crops and livestock production often inserts intensive amounts of chemical fertilizers and pesticides in varied terrestrial and aquatic ecosystems. The total number of livestock has more than tripled from 7.3 billion units in 1970 to 24.2 billion units in 2011 **(FAO, 2016a)**. No doubt, livestock wastes have serious implications on water quality **(FAO, 2006)**. Aquaculture has grown more than twenty-fold since the 1980s, especially inland-fed aquaculture and particularly in Asia **(FAO, 2016b).** Fish excreta and uneaten feeds from fed aquaculture diminish water quality. Increased aquaculture production has combined with greater use of antibiotics, fungicides and anti-fouling agents that in turn contribute to polluting downstream ecosystems **(Li and Shen,**

2013). Moreover, a new class of agricultural pollutants has emerged during the last 20 years in the form of veterinary medicines, e.g., antibiotics, vaccines, growth promoters and hormones are moved from farms to aquatic ecosystems. Zoonotic waterborne pathogens are another major concern in this respect **(WHO, 2012)**.

Worldwide, 80 percent of the municipal wastewater generated in the human settlement is discharged untreated into aquatic water ecosystems. Human settlements are one of the major factors in the degradation of soil and aquatic coastal ecosystems through eutrophication. Furthermore, the industry is responsible for releasing millions of tons of liquid wastes impregnated with potentially toxic elements, solvents, sludge and other wastes into water bodies each year **(WWAP, 2017**). The resultant water pollution associated with these activities represents huge risks to aquatic ecosystems, human health and productive activities **(UNEP, 2016)**.

In the near past, adverse impacts associated with long-term reuse of drainage water received limited consideration. However, with increasing population coupled with the pressures of intensive human activities, protection of land and water resources acquired some priority thoughtfulness. Unfortunately, neither a reasonably clear understanding of these adverse impacts nor any accurate estimates on their cost on the national economy does exist. However, today, available estimates are already noteworthy, and if no drastic actions are taken, the existing trends illustrate that it is likely to become even senior during the third millennium as far as pollutants threaten the ecosystem quality, health and agricultural revenues. The World Health Organization (WHO) estimates that 40 % of the world's population is still suffering from insufficient sanitation and agricultural drainage water treatment systems that interrupt water supply quality **(WHO, 2012).**

POLLUTANTS IN AGRICULTURE DRAINAGE WATER

Egypt suffers from a sum of serious environmental problems, not the least of which is the incompetent water and wastewater systems. Moreover, the Nile River, which is the main source of water in Egypt, is being heavily polluted by discharges of untreated and/or partially treated domestic and industrial wastewater effluents and agricultural drainage water as well. In Egypt low-quality water is a byproduct composed mainly of domestic wastewater from households, municipal sewage effluent, industrial wastewater and agricultural drainage water, the characteristics of such water vary depending on their source. **Negm (2019)** stated that low-quality water might contain physical, chemical and biological pollutants. Egypt, an arid country situated at the end of the longest river worldwide, is now suffering from a harsh negative water balance.

The numerous types of drainage water pollutants and the relative contribution from different agricultural production systems and examples of potential negative impacts on human health, the environment and economic activities due to water pollution from agriculture are illustrated in Table 2 and Table 3 respectively.

Table (2): Categories of major water pollutants from agriculture and the relative contribution from different agricultural production systems

Pollutant category	Indicators/examples	Relative contribution by: Crops	Livestock	Aquaculture
Nutrients	Primarily nitrogen and phosphorus present in chemical and organic fertilizers as well as animal excreta and normally found in water as nitrate, ammonia or phosphate	***	***	*
Pesticides	Herbicides, insecticides, fungicides and bactericides, including organophosphates, carbamates, pyrethroids, organochlorine pesticides and others. Many, such as DDT, are banned in most countries but are still being used illegally and persistently	***	-----	----
Salts	Ions of sodium, chloride, potassium, magnesium, sulphate, calcium and bicarbonate. These are measured in water, either directly as total dissolved solids or indirectly as electric conductivity	***	*	*
Sediment	Measured in water as total suspended solids or nephelometric turbidity units – especially from pond drainage during harvesting	***	***	*
Organic matter	Chemical or biochemical oxygen-demanding substances (e.g. organic materials such as plant matter and livestock excreta), which use up dissolved oxygen in water when they degrade	***	***	*
Pathogens	Bacteria and pathogen indicators, e.g. Escherichia coli, total coliforms, fecal coliforms and *enterococci* sp.	*	***	*
Metals	E.g. selenium, lead, copper, mercury, arsenic and manganese	*	*	*
Emerging pollutants	E.g. drug residues, hormones and feed additive	----	***	***

Mateo-Sagasta *et al*. (2018)

Table (3) Examples of potential negative impacts on human health, the environment, and economic activities due to water pollution from agriculture (crops, livestock, and aquaculture)

Impacts on:	Examples of impacts
Health	Increased burden of disease due to reduced drinking water quality Increased burden of disease due to reduced bathing water quality Increased burden of disease due to unsafe food (polluted fish, vegetables, etc.)
Environment	Decreased biodiversity (e.g. as a result of pesticide toxicity) Eutrophication and dead zones Visual impacts such as landscape degradation Bad odors (e.g. from manure) Diminished recreational opportunities Increased greenhouse gas emissions
Productive activities	Reduced agricultural productivity (e.g. by the use of saline drainage water) Reduced market value of harvested crops if pollution acknowledged Reduced number of tourists in polluted areas Reduced fish and shellfish catches

Adapted from Hernandez-Sancho *et al.* (2015)

Inorganic Pollutants

There are varied types of inorganic pollutants that reach drainage waterways. The most important are PTEs, mineral fertilizer residues, nutrients, nitrate, phosphorus, and salts **(Mateo-Sagasta and Burke, 2010)**.

PTEs (Potential Toxic Elements): are the most serious inorganic pollutants in agricultural drainage water and are responsible for several ecosystem and agricultural problems as well as risks to human health. In most cases, the concentrations of PTEs in polluted agricultural drainage water are often hundreds of times greater than those required to exert a hazardous effect. A quality criterion gives numerical levels only for some PTEs such As, Cr, Mn, Zn, Pb, Cd, Hg, Se, Ni, and Cu that usually have concentrations above the guideline levels in agricultural drainage water. Control requirements for PTEs in agricultural drainage water are stringent and are usually prescribed in parts per million. However, the control of PTEs on water resources is complex and difficult as PTEs must be periodically assessed on a case-by-case basis (**Mateo-Sagasta and Burke, 2010)**.

From an environmental point of view, PTEs are of great interest due to their tendency to accumulate in the soil and water ecosystems and taken up by higher plants. They are not biologically degradable and persist in the ecosystem indefinitely. Once accumulated in agricultural drainage water, PTEs inversely affect the metabolism of biotas. Despite no single classification encompasses all nutrients and PTEs, yet those of major concern is the group which includes the transition elements Cd, Cr, Co, Cu, Mn. Hg, Mo, Ni, S, V, and Zn. PTEs of concern to agricultural drainage water include mainly

Ni, Zn, Cu, Cd, Pb, Hg, Cr, Se, Mo, As, V, and B, yet, As, B, Pb, and Se exerted special attention **(Mateo-Sagasta and Burke, 2010).** Cr is mainly found in an oxidation state, the trivalent form had a great tendency to coordinate with oxygen and nitrogen legends, and the hexavalent is the most toxic form of the oxidation states of Cr. The exchangeable soluble Cr could be easily absorbed by plants and metabolized by microorganisms. The toxicity of Cr depends upon its oxidation state. When Cr binds with calcium carbonate it is fixed in the surface while CrO_4 is less mobile and always combined with soluble divalent and trivalent cations or bounded with carboxylic or phenolic groups of organic matter, its content ranges between 1.82 to 63.53 ppm depending on the type of growing plants **(FAO, 2018)**.

Lead Pb had an oxidation status of II & IV, its salts might be slightly soluble in water (chlorides and bromides) or almost insoluble (carbonates and hydroxides). In the arid region, Pb exists in different forms i.e., exchangeable, sorbed, organic, carbonate, and sulfide fractions. Most of the Pb was found in the surface layer, the organic matter binds about 45-65% of total Pb which decreases by depth. Cd exists as a stable divalent ion i.e., Cd $(NH_3)_6$ and Cd (CN) or forms stable complex **(FAO, 2018)**. It forms insoluble compounds usually hydrated with carbonate, arsenate, phosphate, or oxalate. Cd exists in different forms, i.e., exchangeable, adsorbed on clay and organic matter, hydrous oxides of Fe, Mn, Al, reducible, hydrous oxides, co-precipitated with carbonate, phosphate, sulfate, organic binding, fixed with the crystalline lattices of mineral particles **(Li and Chen, 2013)**.

Hg is found in three stable oxidation statuses 0, I and II, as well as instable Hg sulfates or in the form of organic and inorganic complexes. It is very unstable and might volatilize and easily converted to an organic form or chelated with humic acid in a soluble form. Hg II inorganic complexes might be combined with chloride and hydroxides reaching 207 ppm in water. Hg mobility is mainly affected by pH, organic matter and type of minerals. Se naturally becomes concentrated when its leachates are accumulated to toxic levels. Cu is an essential element and enzyme co-factor for oxidases (cytochrome oxidase, superoxide dismutase) and tyrosinases, however, it could be accumulated to a toxic level. At super optimal levels, Cu is highly toxic to plants. Always, the level of PTEs in drainage water was found to be higher compared to irrigation water (**Mateo-Sagasta and Burke, 2010**).

Mineral fertilizers residues: All chemical fertilizers residues have major adverse impacts on soil, canals, drains and water supply sources. Mainly, the inefficient use of nitrogen fertilizers results in losses of nitrate through leaching out from the soil and polluting both surface and groundwater as well. The increase in the average concentrations of nitrogen compounds in drains (irrigation return flow) was found to be roughly corresponding to the increase of application rates of nitrogen fertilizers. Other types of mineral fertilizers, i.e., phosphate and potash fertilizers contain a significant portion of pollutants that lastly accumulate in drainage waterways.

Nutrients: Nutrients occur when fertilizers are applied at a greater rate than they are fixed by soil particles or exported from the soil profile, e.g. by plant uptake or when they are washed off the soil surface before plants could take them up. Excess nitrogen and phosphates could be leached into groundwater or move via surface runoff into waterways e.g., agricultural drainage water. Phosphate is not as soluble as nitrate and ammonia and tends to get adsorbed onto soil particles and enter agricultural drainage water through soil erosion. Together with other stressors, high nutrient loads could cause the eutrophication of lakes, reservoirs, ponds, agricultural drainage water and coastal waters, leading to algae blooms that suppress other aquatic plants and animals **(WRI, 2008)**. The excessive accumulation of nutrients in agricultural drainage water might also increase the adverse health impacts, such as blue-baby syndrome. Nutrient pollution and harmful algal blooms create toxins and compounds that are dangerous to human health. People, livestock, and pets could be exposed to these compounds, including contact with polluted agricultural drainage water or consumption of polluted water or foods **(US EPA, 2017).**

Nitrate pollution in drinking water originated from agricultural drainage is a serious health concern in many developing countries. Nitrate poses a serious threat to the health of infants less than six months of age, pregnant women, and people with low stomach acid, i.e., hypochlorhydria. **WHO, 2006** thus recommends limiting nitrate-nitrogen levels in drinking water to 10 mg/l. Infants less than six months of age who drink water too high in nitrates could develop methemoglobinemia, the so-called 'blue-baby' Syndrome. Infants have bacteria in their stomach that converts nitrate to nitrite **(Mateo-Sagasta and Burke, 2010).**

Phosphorus could promote the unwanted growth of algae in agricultural drainage water, leading to reduced water quality and low levels of oxygen in the water that could cause fish kills and pose a risk to human health and biotas. Species of algae that are common in algal blooms produce neurotoxins that affect the nervous system and heap-toxins that affect the liver, both are extremely dangerous when touched or consumed. Drinking, accidentally swallowing, or swimming in polluted water affected by a harmful algal bloom could cause serious health problems including rashes, stomach or liver illness, respiratory problems, and neurological effects (**US EPA, 2017).**

Salts: Salts could accumulate in soil ecosystems when irrigated with agricultural drainage water. Other adverse health effects include skin diseases, miscarriages, diarrhea and acute respiratory infection (**Khan *et al.*, 2014**). Salinization could affect agricultural drainage water causing changes within species and community composition and could ultimately lead to biodiversity loss and migration. Generally, when salinity increased, the biodiversity of microorganisms, algae, plants and animals declined (**Lorenz, 2014**).

Irrigation could mobilize salts accumulated in the soil ecosystem (leaching fractions), which are then transported by drainage water causing salinization. Human health may be affected by salinized drinking water. The maximum allowable intake of sodium is 2 g per day, equivalent to 5 g salt per day **(WHO, 2012).** For chloride in drinking water, the limit is 250 mg per liter **(WHO, 2006)**.

Organic Pollutants

Pesticides mainly include insecticides, herbicides, fungicides, which are nowadays applied so intensively within farming in many countries **(Schreinemachers and Tipraqsa, 2012).** When improperly selected and managed, they could pollute water resources with varied carcinogens and other toxic substances that could affect humans.

Pesticide polluted soil and water ecosystems hamper development efforts in rural communities that are suffering from acute and likely chronic health effects related to pesticide poisoning **(FAO, 2016).** The health effects of pesticides depend on the type of pesticide. Some, such as the organophosphates and carbamates, affect the nervous system. Others might irritate the skin or eyes, cause cancer, or affect the hormone system. In any case, exposure to a sufficient amount of almost any pesticide could make a person ill and the toxicity of some pesticides is so high that even very small quantities can kill a person.

Pesticides impact human and animal health through eating food products and/or drinking water polluted with them **(FAO, 2013).** For instance, polluted fruits and vegetables are believed to be responsible for about 10 percent of cancer cases in India **(Aktar *et al.*, 2009).** Furthermore, when pesticides come in contact with water ecosystems, they could invade the food chain. When some PTEs such as lead or copper enter water ecosystems through pesticides, fish take them up and concentrate them in their cells, and people eating these polluted fish are exposed to kidney damage **(FAO, 2016a)**. Acute pesticide poisoning causes significant human morbidity and mortality worldwide especially in developing countries, where poor farmers often use highly hazardous pesticide formulations. Pesticides might also affect biodiversity by killing weeds and insects with negative impacts up the food chain

According to WHO and UNEP, worldwide there were more than 26 million human pesticide poisonings and about 220,000 deaths per year **(Richter, 2002).** In the United States alone, there are 67 000 human pesticide poisonings per year, compared to 500 000 in China, where such incidents result in 100 000 deaths per year **(Zhang *et al.*, 2011).** The incidence of breast cancer was linearly correlated with the frequency of pesticide use and that the organochlorine pesticide DDT, and its derivative DDE, were likely responsible for breast cancer **(Zhang *et al.*, 2011).**

Organic matter pollution is growing because of increasing municipal and industrial wastewater discharge, the intensification of farming including livestock, and the reduction in river dilution capacity due to climate changes and water extractions. Water pollution by organic matter from intensive livestock farming is now significantly more widespread than organic pollution from urban areas, affecting a larger extent of water bodies (**Wen *et al.*, 2017**). Organic matter originating from animal excreta, uneaten animal feed, animal-processing industries, and mismanaged crop residues are all significant water pollutants. Livestock-related wastes have among the highest biological oxygen demand (BOD). For example, the BOD of pig slurry is in the range of 30 000–80 000 milligrams per liter, compared with the typical BOD of domestic sewage of 200–500 milligrams per liter (**FAO, 2006**). Locally, aquaculture could be a major contributor to organic loads in water. In Scotland, for example, the discharge of untreated organic waste from salmon production is equivalent to 75 percent of the pollution discharged by the human population. Shrimp aquaculture in Bangladesh generates 600 tons of waste per day (**SACEP, 2014**). Organic matter consumes dissolved oxygen in the water as it degrades, contributing strongly to hypoxia in water bodies. The discharge of organic matter also increases the risk of eutrophication and algal blooms in lakes, reservoirs and coastal areas.

In developed countries, although considerable use of older broad-spectrum pesticides persists, the trend is towards the use of newer pesticides that are more selective and less toxic to humans and ecosystem and which require lower quantities per unit area to be effective. Nevertheless, millions of tons of active pesticide ingredients are now used in farming (**FAO, 2016a**). The production of Organochlorinated Pesticides (OCPs) was officially banned in Egypt since late 1990,

Persistent organic pollutants (POPs) are classed as PBTs (Persistent Bio-accumulative and Toxic) or TOMPs (Toxic Organic Micro Pollutants). There are few natural sources of POCs and most of them are created by humans in industrial processes, either intentionally or as byproducts. They are the most difficult of the pollutants to assess because of their relatively recent appearance, consequent lack of surveys, and ever-increasing numbers. POCs are able to resistant ecosystem degradation by inorganic, biological, and photolytic processes. Because of this, they had been observed to persist in water ecosystems. The existence of organic toxins in drainage water collected from different sites in Egypt was monitored in voluminous literature**.** Their results indicated that all drainage water samples contained both natural and industrial pollutants (man-made). While industrial pollution was rather low, considerable natural pollution was present. Analyses of the aromatic fraction of water samples suggested that, most of the organic toxins are still from natural processes**. Mansour (2009)** reported that organic pollutants in drainage water might be arranged according to their magnitudes as residual=oxides (27%)>carbonate (21.35%)>exchangeable= organic (11%).

Enormous amounts of a diversity of pollutants always exist in the agricultural drains water in Egypt. Such agricultural drains regularly discharge their effluent to River Nile branches, wetlands, irrigation canals, and/or the Mediterranean Sea. These pollutants, in most cases, are either inorganic, emerging. i.e., Indigenous, water borne pathogens and parasites or biological, all are originating from domestic and/or industrial wastewater both raw, treated, or partially treated effluent.

Emerging pollutants

Emerging pollutants comprise a wide range of chemicals, substances and microbial pollutants that enter water bodies from various sources, including municipal wastewater treatment plants, agricultural runoff and industrial effluents. Emerging pollutants are also collectively referred to as ‘emerging pollutants’ or ‘pollutants of emerging concern'. New agricultural pollutants such as antibiotics, vaccines, growth promoters and hormones have emerged in the last two decades. These could reach water via leaching and runoff from livestock and aquaculture farms, as well as through the application of manure and slurries to agricultural land (**OECD, 2012**). Residues of PTEs in agricultural inputs such as pesticides and animal feed are also emerging threats. Farming is not only a source of emerging pollutants, it also contributes to the spread and introduction of these pollutants into aquatic ecosystems through wastewater re-use in irrigation and the application of municipal biosolids onto the land as fertilizers (**Bolong *et al.*, 2009)**. The Routes of pollutants discharged to surface waters and their importance illustrated in Table 4

Table (4) Routes of emerging pollutants to surface waters and their importance compared to other sources

Emerging pollutant class	Route of input from agricultural systems	Other sources and routes to the environment	Relative importance of agricultural sources in terms of water contamination
Natural toxins	Release from plants, algae and fungi	N/A	high
Veterinary medicine	Excretion to soils by animals at pasture; application of contaminated manure and slurry to land	Manufacturing releases; disposal of containers	high
Hormones	Excretion of natural and synthetic hormones by animals at pasture; application of manure and slurry to land	Discharge of sewage sludge, containing natural and synthetic hormones from the human population	High – hormonal substances arising from animals Low – hormonal substances arising from the human population
Transformation products (TPs)	Produced from human induced chemicals that are applied directly to agricultural systems or in activated sludge/irrigation water	Formed in wastewater treatment processes	Depends on the nature of the parent compound; High – TPs of veterinary medicines Low – TPs of pharmaceuticals, personal care products
Nanomaterial	Excretion of nanomedicines by livestock; application of sewage sludge to agricultural land as a	Emissions from wastewater treatment plants; disposal of waste to landfill;	Currently low, as nanomaterials are mainly used in personal care products and paints

	fertilizer; irrigation with wastewater or contaminated surface water	manufacturing release	and coatings Importance could increase in the future as nanopesticide and nanomedicine markets developed
Bioterrorism/ sabotage agents	Sabotage of crops and livestock	Chemical incidents in cities	Has the potential to be high (depending on the agent)
Human personal care products	Application of sewage sludge to agricultural land as a fertilizer; irrigation with wastewater or contaminated surface water	Emissions to surface waters from wastewater treatment plants	Low
Emerging persistent organic pollutants (e.g. flame retardants)	Application of sewage sludge to agricultural land as a fertilizer; irrigation with wastewater or contaminated surface water	Emissions to surface waters from wastewater treatment plants	Low
Human medicines	Application of sewage sludge to agricultural land as a fertilizer; irrigation with wastewater or contaminated surface water	Emissions from wastewater treatment plants; disposal of unused medicines to landfills; manufacturing releases	Low

Source: adapted from Boxall, 2012.

Emergent pollutants are broadly grouped into pharmaceuticals, personal care products, pesticides and industrial & household chemicals. Diverse types of emergent pollutants are present in highly variable concentrations in freshwater ecosystems such as rivers, streams lakes and groundwater. Currently, more than 700 emerging pollutants, their metabolites and transformation products, are listed as present in the European aquatic environment **(NORMAN, 2016)**. Nevertheless, they are rarely controlled or monitored, and further research is needed to assess their impacts on human health and the environment (**UNESCO, 2015**).

Manufactured nanomaterials by definition have a particle size of approximately 1–100 nm, and examples include amorphous silicon dioxide (SiO2), carbon nanotubes (CNTs), and titanium dioxide (TiO2) **(Kovacic and Somanathan, 2013 and Morimoto**

***et al*., 2010**); these materials are considered to be emerging contaminants **(Dreher, 2004)**. Manufactured nanomaterials are widely used in sunscreen products, agriculture, transport, healthcare materials, energy and information technologies **(Kovacic and Somanathan, 2013 and Nemeno *et al.*, 2014),** however, novel trace methods for examining the relevant residues and nanoscale pollutants have not been established because of their limited production and relatively immature detection techniques **(Kim, *et al.*, 2013)**. Nanoscale materials will generate physical and chemical properties, such as particular surface effects, small size effects, and quantum effects, which may produce uncertain biohazard effects **(Kovacic and Somanathan, 2013)**. The atomic interface of nanomaterials can cover 15 to 50% of the overall surface area, and this structure provides nanomaterials with strong adsorption capacity in the air, water, and soil, which can adsorb toxic gases (NO2, SO2, and others), toxic heavy metals (copper, lead, mercury, cadmium, and others), and biologically active substances (polycyclic aromatic hydrocarbons, pesticides, microorganisms, proteins, nucleotides, refractory organics, and others) **(Kroll *et al.*, 2013)** Other special properties of nanomaterials, such as their catalytic character and superior toughness and strength, make these materials resistant to degradation using chemical and biological methods **(Kovacic and Somanathan, 2013)**.

Manufactured nanomaterials undergo long-term migration, conversion processes, and complex chemical reactions in the environment while adsorbing various inorganic and organic molecules on their surfaces. As a result, new pollutants are formed. In animal tests and in vitro assays, manufactured nanomaterials have shown well-defined carcinogenic potentials, especially reproductive and developmental toxicity at high doses **(Ema *et al.*, 2010)**. Some scientists have suggested that nanomaterials may be carcinogenic, regardless of their chemical components **(Schillin *et al.*, 2010)**. Some epidemiological studies in different periods and regions estimated the association between the exposure levels of TiO2 and lung cancer in humans, but none have shown statistically significant results (**Boffetta *et al.*, 2004)**.

Nanomaterial biological safety issues have attracted worldwide interest **(Kovacic and Somanathan, 2013**). To date, the mechanisms underlying the toxicity to humans and animals remain unknown **(Morimoto *et al.*, 2010)**. Therefore, more attention should be paid to the environmental safety of manufactured nanomaterials and to strengthening research related to human health effects.

Biological Pollutants

Water pathogens

Pathogens in agricultural drainage water represent a major threat to the public health of humans and livestock, food safety and ecosystem quality. Drainage water had been implicated as a significant source of health risk for chronic, low-grade gastrointestinal disease as well as outbreaks of more acute diseases. The transmission of pathogens might occur through groundwater, surface run-off, aerosols as well as with direct contact between drainage water and raw edible harvests.

Livestock excreta contain many zoonotic microorganisms and multicellular parasites, which could be harmful to human health. Pathogenic microorganisms could be water-borne or food-borne especially if the food has been irrigated with polluted drainage water or with untreated or partially treated wastewater. Some pathogens could survive for days or weeks in animal feces that have been discharged onto a given soil ecosystem and they might later pollute water resources via runoff **(FAO 2006; WHO 2012)**. Pathogens from livestock that are detrimental to public health include bacteria such as *Campylobacter* spp., *Escherichia coli* O157:H7, *Salmonella* spp., *Clostridium botulinum* and some parasitic protozoa such as *Giardia lamblia*, *Cryptosporidium parvum, Microsporidia* spp., all of which cause hundreds of thousands of infections every year **(Christou, 2011)**.

Understanding and quantifying the loads, transport and fate of pathogens are challenging tasks because the agricultural drainage ecosystem pathways are complex and observational data is very scarce (**Atwill *et al.*, 2012)**. The risks associated with animal waste reaching drainage water are episodic, because of sporadic loads or transmissions (e.g. after rainy events). *Cryptosporidium* has been proposed as a good indicator for modeling at the global scale as it is a widespread water-borne livestock pathogen that has a relatively high incidence in childhood diarrhea. **Liu *et al*. (2015) and Vermeulen *et al.* (2017)** modeled the global loads of livestock *Cryptosporidium*, which they estimated to be 3.2 × 1023 oocysts per year. The study showed that cattle, especially calves, are the largest contributors to oocysts loads, followed by chickens and pigs. The human risks associated with pathogen pollution of water from livestock have not yet been well defined **(WHO, 2012)** but they are potentially high, given the number of outbreaks of infections with zoonotic pathogens that have been reported and documented among swimmers and other water users **(Dufour *et al.*, 2012)**. For example, in one outbreak in Swaziland, cattle manure was thought to have caused more than 40 000 cases of water-borne infections **(Effler *et al.*, 2001)**. A more recent example is the 2016 outbreak of gastroenteritis on the North Island of New Zealand, which was attributed to the ingestion of water polluted by livestock feces. Thousands of people were infected **(Reiff, 2016)**.

Giardia and *Microsporidia* are pathogenic parasites of humans and animals, producing asymptomatic to severe intestinal infections **(Fayer and Xiao, 2008)**. Detection of these pathogens in drainage water continues to be of great interest for public health, and direct detection monitoring is warranted given a poor correlation with standard fecal pollution indicators **(Harwood *et al.*, 2005)**. Currently, the U.S. and several European nations mandate the use of combined immunomagnetic and microscopy-based (IMS) procedures (i.e., IT rule; Method 1623) for monitoring drainage waters for *Cryptosporidium* and *Giardia*. These methods are hampered by their costs and require specific expertise to distinguish between human and animal pathogenic *Cryptosporidium* and *Giardia* species **(Allen *et al.*, 2000)**. Problems also arise with false positive and negative results and poor dissociation of oocysts from magnetic beads in the purification step **(Ware, 2003)**. These methods are specific only to *Cryptosporidium* and *Giardia*, and though Microsporidia and other waterborne pathogens are listed in various pollutants lists, no cost and time-effective method for their detection exist. It is well known that molecular techniques have been developed that are more effective than immunofluorescence microscopy in detecting specific pathogens **(Xiao *et al.*, 2006)**. Notably, drainage water impacted by sewage outfalls presents complex sample matrices known to contain numerous organic and inorganic dissolved and particulate substances that could affect sample collection and purification as well as having the potential to inhibit PCR reactions **(Jiang *et al.*, 2005).**

More than any other causes, parasitic diseases are contributing significantly to the burden of illnesses, leading sometimes to death, and affecting people in the developing and developed world, even in regions that include high-income countries **(Lozano *et al.*, 2012)**. Amoebiasis is a major cause of morbidity and mortality worldwide, mostly in tropical and sub-tropical countries characterized by inadequate health services and sanitation infrastructure **(Fotedar *et al.*, 2008)**. The majority of deaths are a consequence of severe complications associated with intestinal or extra-intestinal invasive disease. Approximately 4 to 10% of the carriers of this amoeba infection develop clinical symptoms within a year and amoebic dysentery is considered the third leading cause of death from the parasitic disease worldwide after Malaria and Schistosomiasis **(Ghasemi *et al.*, 2015)**.

Helminths are the main source of pathogenic germs in agricultural drainage water particularly eggs and cysts of Ascaris, ancylostoma, Tania and pathogenic protozoa as well as Ascaris that are the most common ones. Many widespread diseases are transmitted through helminths egg ingestion from vegetables irrigated with sewage effluent or drainage water. Helminths eggs are resistant to chlorine, ultraviolet light and ozone. Infective doses are very low (1–10 eggs/L) compared to those for bacteria. Helminths eggs size range between 20–80 mm, and have a specific density fluctuating between 1.238–1.036. They might be removed from settlers, lagoons by coagulation-flocculation and filtration. Soil-transmitted helminths (STHs) comprise several intestinal nematodes i.e. hookworms (*Ancylostoma duodenale*, *Necator americanus*), roundworm (*Ascaris lumbricoides*), whipworm (*Trichuris trichiura*), and *Strongyloides stercoralis* though WHO formally does not include *S. stercoralis* in the STH list. STH has been included in the WHO's list of 17 neglected tropical diseases (NTDs) because of the associated poverty, significant morbidity and DALY's (Disability Adjusted Life Years) loss **(Hotez *et al.*, 2016).** As there is no adequate gold standard for STH detection, this further makes the comparison and standardization of any new technique difficult **(Tarafder *et al.*, 2010).** Conventionally, the STHs are diagnosed by the examination of fecal or other GI specimens for the presence of helminthic eggs, larvae or sometimes adult worms or their segments. Due to intermittent shedding of eggs and/or larvae, several specimens (at least 3) collected for 10 days are required to detect parasites

(Amoah *et al.*, 2016). Floatation techniques (zinc sulfate floatation, saturated sodium chloride floatation, etc.) are not widely used because infertile eggs of *Ascaris* and larvae of *Strongyloides* do not float and thus cannot be easily recovered by this method **(Cheesbrough, 2006).** The use of indirect immunofluorescent antibody test (IFAT) or direct immunofluorescent antibody test, immunoblotting, and some rapid immunochromatographic tests (RDTs) are also indicative **(Ndao, 2009)**. The much better sense of molecular techniques makes them especially useful to monitor the effectiveness of treatment or control strategies. The molecular targets used mainly are ITS-1, ITS-2, 18S, etc., several different polymerase-chain-reaction (PCR) based methods are available, i.e., conventional PCR, quantitative PCR (qPCR), multiplex PCR reaction, etc. **(Gordon *et al.*, 2011; O'Connell and Nutman, 2016).**

Antimicrobial resistant bacteria

There is a direct link between water quality used for irrigation and antimicrobial-resistant bacteria on foods. Low water quality might contain antibacterial resistant genes (ARGs) and antimicrobial-resistant bacteria (**Christou *et al.*, 2017; Karkman *et al.*, 2017)** that pollute irrigation and drainage water. Water sources adjacent to manure-treated pilots might also be enriched within antimicrobial-resistant bacteria (**Pruden *et al.*, 2006; Coleman *et al*, 2013).**

Comparison of fresh produce and its agricultural environment indicates that the Enterobacteriaceae population found on fresh produce is a reflection of that present in the soil ecosystems in which it was grown (**Blaak *et al.*, 2015).** A high degree of genetic relatedness between *E. coli* from irrigation water and lettuce has indicated a possible common waterborne pathway of transmission (**Aijuka *et al.*, 2015).** In a Brazilian study, forages maize and tanner grass irrigated with treated low-quality water exhibited high levels of surface pollution with *E. coli* and *Salmonella spp*. (**Bevilacqua *et al.*, 2014).**

Antimicrobial-resistant strains of *E. co*li present in irrigation water and vegetables from 16 household farms were evaluated by **Araujo *et al.* (2017).** The same sequence types and indistinguishable clones as shown by repetitive sequence-based PCR typing were detected in water and vegetables, suggesting cross-pollution. Furthermore, a national soil survey in Northeast China detected a hot spot of ARGs, most likely due to long-term low-quality water irrigation (**Zhou *et al.*, 2017).** The *E. coli* isolates from low-quality irrigation water and leafy green vegetables in different food production systems at large commercial farms, small-scale farms and homestead gardens were investigated (**Jongman and Korsten, 2016**). Their results confirmed that the prevalence of multidrug-resistant *E. coli* was lower in isolates from farms certified as implementing specific good farming practices to prevent Global GAP-certified pollution compare to isolates from non-certified commercial and small-scale farms and homestead gardens. An *E. coli* transmission link between the irrigation water sources and leafy green vegetables was established using both phenotypic (AMR) and genotypic DNA fingerprinting analyses.

Constructed wetlands are used as biological treatment of animal, human and industrial waste. Their efficiency concerning the removal of antibiotics and ARGs varies according to the types of antibiotics and ARG (**Chen *et al.*, 2016**). In some locales, however, such wetlands are concomitantly used for food production, i.e. crops and/or food of aquatic origin. New evidence indicates that these integrated wetland food production systems might be implicated in AMR spread (**Krzeminski *et al.*, 2019**). As many fruits and vegetables are frequently eaten raw or with minimal processing, it could be stated that fresh fruits and vegetables serve as a source of dietary exposure to antimicrobial-resistant bacteria and ARGs. Other reports also confirm the role that many foods originated from a plant origin play a major role in the transmission of foodborne antimicrobial-resistant bacteria (**Hassan *et al.*, 2011; Walia *et al.*, 2013**). Therefore, reducing the pollution with antimicrobial-resistant bacteria and ARGs in foods and feeds originated from plant origin would reduce human and animal exposure to antimicrobial-resistant bacteria and ARGs. Crops grown for animal feeds might also be polluted with bacteria from the soil ecosystem that commonly harbor ARGs (**Wright, 2010**). If antimicrobials are administered to livestock production while the animals are consuming crops polluted with antimicrobial-resistant bacteria, a selection for this population in the animal gut might occur. This could be a route of introduction and amplification of ARGs of environmental origin into the food chain (**Witte, 2000; Marshall and Levy, 2011**) and should be taken into account when considering whether the animal feed and soil ecosystems should be a part of the surveillance.

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