

Human Health Risk Assessment Associated with Treated Wastewater Reuse in Arid Areas

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ABSTRACT

Highly treated wastewater is an important component of water budget in many countries. Qatar is a leading country in treating domestic wastewater using advanced technologies (granular media filtration (GMF), ultrafiltration (UF), chlorination, and ultraviolet (UV) oxidation). Such treated effluent can be used in several options including irrigation. The study is introducing comprehensive analyses of the effluent of the three central wastewater treatment plants (WWTPs) for chemical pollutants and the mostly used antibiotics. Additionally, the study assessed human health risks associated with the exposure to the treated wastewater (TWW) via dermal and ingestion routes. Although the origin of domestic wastewater is desalinated water (the only source of fresh water), the results show that TWW all parameters in general were within the international standards. However, among the anions of Cl, F, Br, NO₃, NO₂, SO₄ and PO₄, only Cl concentrations were slightly elevated of (average 389 mg/L). On the other hand, among all cations, metals and metalloids, only B was 2.1 mg/L which is higher than the Qatari guidelines for TWW reuse in irrigation of 1.5 mg/L. Additionally, Sr and Tl were detected with relatively high concentrations of 30 mg/L and 12.5 µg/L, respectively. The study found that the low concentrations of all tested metals and metalloids don't pose risks to human health. However, thallium (Tl) presents exposure levels above the 10% of oral reference dose ($HQ=0.4$) for accidental oral ingestion of TWW exposure scenarios. The results of antibiotics show that exposure for adults and children to TWW are far below the admissible daily intakes set using minimum therapeutic dose and considering uncertainty factors.

Keywords: Water scarcity; Treated wastewater; Water reuse; Human health risks.

1. Introduction

Water security is one of the global crisis (MacAlister et al., 2023). Its challenge extends to several critical sectors (Babuna et al., 2023). Water is linked to health security, food security, energy security, sustainability and social stability (MacAlister et al., 2023). It is not surprising that treated wastewater (TWW) has been considered in the water budget of many countries (Danboos et al., 2023). In addition, the United Nations (UN) World Water Day 2023 has been entitled "Accelerating Change to Solve the Water and Sanitation Crisis". This theme emphasizes the urgent need for collective action to address the global water and sanitation crisis and achieve Sustainable Development Goal 6, which is to ensure access to water and sanitation for all by 2030 (Zeitoun et al., 2023).

A simple search on the literature reveals that thousands of studies have been released on TWW reuse across the globe over the past 5 decades (Garduño-Jiménez et al., 2023; Hosney et al., 2023; Zhang et al., 2023). Several successful local and regional projects have benefited from TWW (del Villar and García-López, 2023; Hastie et al., 2023; Wagner et al., 2023). The principle emerged from the scientific fact where wastewater has 1% of pollutants and removing such percentage returns water to be usable (Grant et al., 2012). Among the many pioneering examples is the use of treated water in agricultural production (Zhao Y et al., 2023), whether related to direct food security (Wani et al., 2023) or through the food chain including fodder (Mayor et al., 2023), industrial crops and fibers (Gonçalo-Filho et al., 2023), or fertilizing poor areas in seas and oceans and enriching them with nutrients and organic matter (Lu et al., 2023). It is well-known practice to see TWW use in various industrial processes (Khan et al., 2023), as well as in district cooling systems (Asgari et al., 2023), recreation zones (Andrzejak et al., 2023), irrigation of parks and green spaces (Zhao F et al., 2023), sports facilities (Maréchal et al., 2023), especially golf courses (Candela et al., 2007), as well as natural and constructed wetlands (Wu et al., 2023), and protecting and enriching biodiversity and maintaining ecosystems (Stach et al., 2023). Finally, and perhaps the most difficult and mature option is the reuse of treated wastewater in the production of drinking water, as is known in Singapore (Jarin et al., 2023) and Japan (Jin et al., 2023).

However, there remain many known and emerging challenges for TWW reuse, most of which are anthropogenic related to the wastes of advanced industries and technologies (Deng et al., 2024). Examples of such industries include, medical (Yang et al., 2023) and electronics (Gulfam-E-Jannat et al., 2023). These technologies have led to a hidden, undeclared battle between wastes and removal (treatment/remediation) (An et al., 2023). The features of the global battle are summarized in answering the question: Are wastewater treatment technologies capable of dealing with emerging contaminants? (Cochran, 2022). Almost daily, we identify emerging contaminants and the list has no end (Li et al., 2024). The most advanced wastewater treatment systems including membranes, advanced oxidation and disinfection, etc. compatible with the appropriate removal of such new and ultra-trace cocktail of contaminants? (Meng et al., 2024; Zhu et al., 2024; Karić et al., 2022).

Since these contaminants are produced in many countries and they occur in the wastewater, do these countries have the treatment technology to remove them?. Do these countries or even international institutions able to rectify, renew and adapt guidelines, regulations, and standards for treated wastewater reuse?. Also, among the many challenges is the existence

of the infrastructure associated with the entire process from the moment of TWW discharge, then to the tools and instrumentation for advanced measurement and analysis of the emerging contaminants (Puri et al., 2023). Followed by investigation of the transport and fate of these contaminants in different environments and climate conditions (Shi et al., 2024). And finally, the extent of the potential risks associated with the presence of these contaminants for the short and long terms on the ecological and human health (Zhang et al., 2024; Agusiegbe, 2019).

Over the past few years, studies have been conducted on the potential ecological and human health risks of contaminants in treated wastewater (Compagni et al., 2020; Shivarajappa et al., 2023). Examples include the presence of heavy metals (Ahmed et al., 2023), microplastics (Nelis et al., 2023), pesticides (Rapp-Wright et al., 2023), polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) (Liu et al., 2023), pharmaceuticals (Alharbi et al., 2023), and other endocrine disrupting chemicals (EDCs). The studies used different scientific tools especially simulations and modeling (Semerjian et al., 2018; Shakeri and Nazif, 2018).

Reuse of treated wastewater is of paramount importance in water-poor countries, especially the countries of the Arabian Gulf (Aljeddani, 2023; Tashtush et al., 2023). However, this option is still sensitive and highly complex due to cultural, social, technological and financial reasons (Onu et al., 2023). Generally, these countries do not have fresh water resources (Shomar et al., 2014), and depend entirely on seawater desalination (Shomar and Rovira, 2023), which is a costly process financially and environmentally (Nasrollahi et al., 2023). It is strange that these countries have the most advanced technologies in wastewater treatment (Ramadoss et al., 2022), but this is not in any way parallel with systems and strategic plans to benefit from this highly treated wastewater (Bauer and Wagner, 2022).

The driving force of this study emerged from the Qatar Vision 2030 and Qatar National Development Strategy (QNDS 2018-2022); where natural resources should be protected and used sustainably. Investment on treating wastewater using the highest technologies should lead to secure more water for irrigation and food production. Additionally, the scientific hypothesis behind the study is the potential transport of contaminants (especially ultra-trace inorganic and mostly used antibiotics) from treated wastewater to the crops and environment of arid areas.

The studies conducted in Qatar during the past two decades showed the treated wastewater is with the highest quality (Sherif et al., 2023; Shomar et al., 2020). The current study fills one of the gaps on TWW quality and through this study; accurate and comprehensive specifications of the treated wastewater generated from the three largest and most important plants in Qatar are presented. The results include physical and chemical specifications and the most important the mostly used antibiotics. In order to provide a comprehensive presentation of the characterization of the treated wastewater and help on reuse options in the vital sectors, the study provides an accurate scientific basis for the ecological and human health risks associated with the reuse of this water in Qatar as an example of the arid countries. The novel elements of the study emerge from the fact that broad spectra of people are exposed to treated wastewater depending on the reuse scenarios. The study focuses on the routes of dermal and ingestion exposure for both adults and children. Calculation and computation tools have been used to show the potential risks associated with exposure to treated wastewater in a such arid area.

Therefore, the objectives of this study are to (i) characterize the chemical specifications of wastewater effluent of the three central wastewater treatment plants in Qatar and (ii) investigate the human health risks in adults and children associated with the reuse of this treated wastewater using simulation tools.

2. Methodology

2.1. Wastewater treatment plants

According to the Public Works Authority (Ashghal) and site visits of the three major wastewater treatment plants (WWTPs), [Table 1](#) summarizes their major characteristics.

Table 1. Major characteristic of the three wastewater treatment plants (WWTPs) in Qatar

| Parameter | Doha South WWTP | Doha West WWTP | Doha North WWTP |
|-------------------|-----------------------------|-----------------------------|-----------------------------|
| O&M Company | VEOLIA | SUEZ | KSES |
| Construction date | 2009 | 2005 | 2008 |
| Population served | 830,000 | 650,000 | 900,000 |
| Capacity | 200,000 m ³ /day | 245,000 m ³ /day | 244,000 m ³ /day |
| Advanced WWT | GMF, UF, Chlorination, UV | Same | Same |
| | | | |
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2.2. Sampling and analysis

With the support and coordination with the technical team of the Public Works Authority of Qatar (Ashghal), an access to the three central wastewater treatment plants (WWTPs) in Qatar was obtained ([Table 1](#)). The technical team of the three companies supported the mission to collect the needed samples of final treated wastewater effluent ([September to December 2019](#)). Composite samples were collected according to the international standards ([Ramadoss et al., 2022](#); [Shomar et al., 2020](#)). Details on sample collection, preservation, site measurements, transportation and storage have been described intensively ([Shomar et al., 2004](#); [Shomar et al., 2005](#); [Shomar, 2007](#); [Al-Maadheed et al., 2019](#)). Additionally, the protocols of quality control (QC) and quality assurance (QA) are well described in these references.

Briefly, a portable kit (Hanna Instruments-USA, HI991301, Woonsocket, RI, USA) was used to record the readings of pH, electrical conductivity (EC) and total dissolved solids (TDS) at the same time of sample collection in each WWTP. The final treated wastewater effluent composite sample of each WWTP was divided into three bottles. The first part was used for the determination of total organic carbon (TOC) using (TOC Analyzer-Shimadzu, model TOC-L, Kyoto, Japan) and anions (Cl, F, Br, NO₃, NO₂, SO₄ and PO₄) using an ion chromatograph (Dionex ICS-1100, Sunnyvale, CA, USA). The second part of the sample was used for the determination of cations, metals and metalloids using an inductively coupled plasma mass spectrometry (Agilent 7500ce and 7700x, Santa Clara, CA, USA) ([Shomar and Rovira, 2023](#)). The last part was preserved, extracted and prepared for the determination of the targeted antibiotics using liquid chromatography-mass spectrometry (LC/MS) (SN01757L- Thermo

Fisher Scientific Inc., Whatham, MA, USA) connected to LPG-3400XRS Pump (Thermo Scientific Dionex UltiMate™ 3000 system LPG-3400XRS Pump P/N 5043.0036). The MS system was controlled by the Chromeleon Chromatography Management System and Xcalibur® software (P/N 1288120, Revision C) (Al-Maadheed et al., 2019).

Averages of both COD and BOD₅ in effluent samples were recorded from the lab of each WWTP. The full list of parameters is given in Table 2 and Table 3.

2.3. Human health risk assessment

Treated wastewater (TWW) can be used in irrigation and food production, industrial applications, landscape and recreating, constructed wetlands, district cooling, cleaning, construction, groundwater recharge, etc. Population could be exposed to TWW according to the reuse options and applications (Semerjian et al., 2018). For adults, exposure could be through scenarios of treatment and disposal processes, agricultural applications, urban uses, commercial uses, industrial applications, construction and pavement cleaning, sports, etc. While generally, children (up to 6 years old) are exposed to TWW in playgrounds and gardens leisure activities. For these exposure scenarios both dermal and accidental TWW ingestion were considered as exposure pathways. Equations 1 and 2 based on US EPA risk assessment guidelines (US EPA, 1989) describe the model for TWW accidental ingestion and dermal absorption exposure pathways, respectively.

$$\text{Wateraccidental ingestion} = \frac{C_{\text{water}} \times EF \times IR_{\text{water}} \times ED}{BW \times AT} \quad (1)$$

$$\text{Dermal absorption} = \frac{C_{\text{water}} \times EF \times AF \times |x| \times SA \times ED}{BW \times AT} \quad (2)$$

Parameters description and values for each pf the three scenarios are reported in Table 2.

Table 2. Parameters and values of variables used to exposure assessment.

| Abbreviation | Description | Value | Reference |
|--------------|---|--|------------------------|
| C_{water} | Concentration of a pollutant in treated wastewater | Table 1 | This study |
| EF | Exposure frequency Cleaning (adult) Sport (adult) Leisure (children) | 250 days/year 104 days/year 26 days/year | Semerjian et al., 2018 |
| IR_{water} | Accidental wastewater intake ratio Cleaning (adult) Sport (adult) Leisure (children) | 32 mL/day 4 mL/day 10 mL/day | Semerjian et al., 2018 |
| ED | Exposure duration (adult or children) | 20 or 6 years | Semerjian et al., 2018 |
| AT | Average time (adult or children) | 20 or 6 years | Semerjian et al., 2018 |
| BW | Body weight Adults Children | 70 kg 15 kg | Semerjian et al., 2018 |
| AF | Adherence factor of water to skin | 6.89 $\mu\text{L}/\text{cm}^2$ | Gujral et al., 2011 |
| ABS | Absorption factor Antibiotic (Organic compounds) Metals As | 0.1 0.001 0.03 | Herrero et al., 2019 |
| SA | Skin surface area exposed Cleaning (adult; Forearms, hands, head) Sport (adult; arms, forearms, and lower legs) Leisure (children; hands, forearms and lower legs) | 3300 cm^2 4447 cm^2 1400 cm^2 | Semerjian et al., 2018 |

To assess the non-carcinogenic risks, hazard quotients (HQ) were calculated dividing each exposure by the corresponding oral (RfOD) or dermal (RfdD) reference dose. RfdD were calculated dividing RfOD by the corresponding gastrointestinal absorption factor (GIABS) (Shomar et al., 2023). RfOD and GIABS were obtained from US EPA (USEPA, 2023).

For antibiotics, admissible daily dose intake (ADI) were calculated using minimal therapeutic dose divided by a body weight of 70 kg with an uncertainty factor of one thousand (UF=1,000). Uncertainty factor of 1000 is composed of three factors of 10 to cover sensible groups (children, elderly), differences between individuals, and therapeutic dose do not mean non effect level (Prosser and Sibley, 2015).

3. Results and discussion

3.1. Quality of treated wastewater effluent

The study found excellent agreement among the results of the three WWTPs and Table 3 summarizes the average findings for the physical and chemical parameters. Generally, most of the physical parameters are within the range of high-quality treated wastewater. The effluent TWW is neutral and relatively brackish within arid areas average evapotranspiration of 2 mm/d in December to a maximum of 10 mm/d in June (Issaka et al., 2017). It is very important to confirm that wastewater in Qatar is originated from desalinated water which has the highest quality and all quality parameters are very low (Shomar et al., 2013). The results of COD and BOD₅ are very important indicators for the efficiency of treatment

technologies and their low concentrations in the final effluent confirm that such water can be used in several applications including irrigation, landscaping, recreation, etc. Although the typical average of TOC in the effluent TWW is 1 to 20 mg/L (Park et al., 2022; Wu et al., 2022), it has been found to be 34 mg/L in the effluent TWW of the three WWTPs of Qatar. Such elevated TOC has been found in the effluent of WWTPs in several locations in the world (Wilson, 1993; Ni et al., 2020; Orak et al., 2023). According to these studies and others, the major contributors to the elevation of TOC in wastewater effluent are the food and chemical industry (Stamper and Semmen, 2012).

The major anions of Cl, F, Br, NO₃, NO₂, SO₄ and PO₄ are within the permissible limits of several TWW reuse options (Table 3). NO₂ was not detected in all samples and this reflects that denitrification (nitrate to N₂ gas) process is efficient (Shomar et al., 2008). Generally, these anions (except for Br, F and NO₂) are exceeding their concentrations in the desalinated tap water in Qatar (Nriagu et al., 2018). Average concentrations of Cl, NO₃, SO₄ and PO₄ in tap water of Qatar were 62, 2, 2 and 1.1 mg/L, respectively. The findings of Al-Yamani et al. (2019) showed very similar concentrations for the TWW effluent of Abu Dhabi and the same in Dubai (Alsharhan and Rizk, 2020). Limited reuse options such district cooling call for reducing the concentrations of nutrients (N and P) and organic matter (OM) to be almost zero concentrations to avoid microbial after growth or introducing remediation technologies (e.g. ion exchange) for N and P removal (Pinel et al., 2020; Zhou et al., 2022).

Table 3. Quality parameters of the three WWTPs in Qatar (n=3)

| Parameter | Symbol | Unit | Average | STDEV | Qatar Reuse Guidelines |
|---------------------------|------------------|-----------------------|---------|-------|------------------------|
| | pH | | 7.4 | 0.8 | 6-9 |
| Electrical Conductivity | EC | (μ S/Cm) | 2600 | 600 | 750-2000 |
| Total Dissolved Solids | TDS | (mg/L) | 1710 | 376.3 | 1500 |
| Total Organic Carbon | TOC | (mg/L) | 33.89 | 7.5 | - |
| Total Carbon | TC | (mg/L) | 34.52 | 7.6 | - |
| Inorganic Carbon | IC | (mg/L) | 0.6266 | 0.1 | - |
| Chemical Oxygen Demand | COD | (mgO ₂ /L) | 18.0 | 4.0 | 150 |
| Biochemical Oxygen Demand | BOD ₅ | (mgO ₂ /L) | 2.0 | 0.4 | 10 |
| Major anions | | | | | |
| Chloride | Cl | (mg/L) | 389 | 128 | 40-200 |
| Fluoride | F | (mg/L) | <0.1 | <0.1 | 15 |
| Bromide | Br | (mg/L) | 1.2 | 0.4 | - |
| Nitrate | NO ₃ | (mg/L) | 25.3 | 8.4 | - |
| Nitrite | NO ₂ | (mg/L) | <0.1 | <0.1 | - |
| Sulfate | SO ₄ | (mg/L) | 346 | 114 | 400 |
| Phosphate | PO ₄ | (mg/L) | 2.8 | 0.9 | 10 |
| Major cations | | | | | |
| Calcium | Ca | (mg/L) | 150 | 29 | - |
| Magnesium | Mg | (mg/L) | 32 | 6 | - |
| Sodium | Na | (mg/L) | 213 | 40 | - |

| | | | | | |
|------------------------------|----|---------------------|--------------|------------|-------|
| Potassium | K | (mg/L) | 23 | 4 | - |
| Metalloids and metals | | | | | |
| Lithium | Li | ($\mu\text{g/L}$) | 19.2 | 4.6 | - |
| Beryllium | Be | ($\mu\text{g/L}$) | <0.05 | <0.05 | - |
| Boron | B | (mg/L) | 2.17 | 0.52 | 1.5 |
| Silicon | Si | (mg/L) | 5.85 | 1.40 | - |
| Titanium | Ti | ($\mu\text{g/L}$) | <0.05 | <0.05 | - |
| Aluminum | Al | ($\mu\text{g/L}$) | 10.1 | 2.4 | 15000 |
| Vanadium | V | ($\mu\text{g/L}$) | 6.9 | 1.6 | - |
| Chromium | Cr | ($\mu\text{g/L}$) | 4.1 | 1.0 | 10 |
| Manganese | Mn | ($\mu\text{g/L}$) | 15.1 | 3.6 | 50 |
| Iron | Fe | ($\mu\text{g/L}$) | 7.7 | 1.8 | 1000 |
| Cobalt | Co | ($\mu\text{g/L}$) | 1.1 | 0.3 | 200 |
| Nickel | Ni | ($\mu\text{g/L}$) | 5.8 | 1.4 | 200 |
| Copper | Cu | ($\mu\text{g/L}$) | 5.2 | 1.2 | 200 |
| Zinc | Zn | ($\mu\text{g/L}$) | 15.3 | 3.7 | 500 |
| Gallium | Ga | ($\mu\text{g/L}$) | <0.001 | <0.001 | - |
| Arsenic | As | ($\mu\text{g/L}$) | 14.1 | 3.4 | 100 |
| Selenium | Se | ($\mu\text{g/L}$) | 2.5 | 0.6 | - |
| Strontium | Sr | (mg/L) | 30.13 | 7.2 | - |
| Molybdenum | Mo | ($\mu\text{g/L}$) | 3.5 | 0.8 | - |
| Silver | Ag | ($\mu\text{g/L}$) | <0.05 | <0.05 | - |
| Tin | Sn | ($\mu\text{g/L}$) | 0.267 | 0.06 | - |
| Cadmium | Cd | ($\mu\text{g/L}$) | 0.9 | 0.22 | 50 |
| Indium | In | ($\mu\text{g/L}$) | <0.001 | <0.05 | - |
| Antimony | Sb | ($\mu\text{g/L}$) | 0.4457 | 0.11 | - |
| Barium | Ba | ($\mu\text{g/L}$) | 14 | 3.36 | 2000 |
| Mercury | Hg | ($\mu\text{g/L}$) | 0.04 | 0.01 | - |
| Thallium | Tl | (mg/L) | 12.47 | 2.99 | - |
| Lead | Pb | ($\mu\text{g/L}$) | 7.6 | 1.82 | 100 |
| Bismuth | Bi | ($\mu\text{g/L}$) | 0.133 | 0.03 | - |
| Uranium | U | ($\mu\text{g/L}$) | 1.27 | 0.30 | - |

On the other hand, cations (Ca, Mg, Na and K) are within the permissible limit for reuse options and they are very similar to their concentrations in the Gulf Cooperation Council (GCC) wastewater effluents (Aleisa and Al-Zubari, 2017; Al Rashed et al., 2023; Qureshi, 2020).

The average concentrations of the tested metals and metalloids are low (Table 3) and all are less than the available Qatari guidelines of TWW used for irrigation purposes. Two elements only showed elevated concentrations in the effluent of the three WWTPs; boron and strontium. While Boron (B) average concentrations in the desalinated tap water of Qatar was 23 $\mu\text{g/L}$ (Nriagu et al., 2018), its average concentration in the effluent TWW is 2.1 mg/L. Such slight elevation needs investigation as the permissible limit of B in the Qatari guidelines for reuse is 1.5 mg/L. Boron could enter the WWTP through the industrial wastes where (Kim et

al., 2023) mentioned 300 different industries and this could be behind the slight elevation of B compared to its concentration in the domestic tap water. It is important to mention that although international health authorities (e.g. WHO and USEPA) mentioned that no human health risks associated with B in drinking water, B may cause toxicity to crops at high concentrations.

Generally, Sr is naturally occurred in water (Theissen and Paces, 2023) and the permissible limit of Sr in drinking water is 4 mg/L (ATSDR, 2004). Qatari guidelines have no limit yet for Sr in TWW. However, Sr average concentrations in the TWW effluent of the three WWTPs in Qatar was 30 mg/L. Such elevated concentrations of Sr in TWW need further investigation in terms of sources, transport mechanism to the crops and potential risks.

Table 4 shows the results of major antibiotics in the effluent of the three WWTPs. The findings of the study for the three WWTPs agree with the results of Al-Maadheed (2019) which was conducted for one plant which is Doha West WWTP (Table 1). This reveals that the treatment technologies of the three plants resulted in same quality of the targeted and mostly used antibiotics in Qatar. The study of Al-Maadheed (2019) explained the reasons behind the selected and consumption of these seven antibiotics. Our study is linking the findings of antibiotics in TWW of Qatar, water reuse in irrigation and potential ecological and human health risks. The advanced treatment technology in Qatar did not remove all antibiotics occurred in WW and such conclusion was also observed in the WWTPs of two Indian states (Kotwani et al., 2023).

Table 4. Major antibiotics in the treated wastewater effluent of the three WWTPs in Qatar

| Antibiotics | Unit | Average Influent | Average Effluent | Effluent STDEV | Removal Rate (%) | Cases of wastewater | Reference |
|-----------------|------|------------------|------------------|----------------|------------------|---------------------|-------------------------|
| Clavulanic acid | µg/L | 99.636 | 12.51 | 2.127 | 87.4 | 10-20 | Pantanella et al., 2020 |
| Metronidazole | µg/L | 0.705 | 0.331 | 0.056 | 53.0 | 3-4 | K'oreje et al., 2016 |
| Amoxicillin | µg/L | 0.125 | 0.05 | 0.009 | 60.0 | 0.01–7 | Dubey et al., 2023 |
| Ciprofloxacin | µg/L | 0.537 | 0.238 | 0.040 | 55.7 | 0.5-460 | Booth et al., 2020 |
| Tetracycline | µg/L | 0.218 | 0.01 | 0.0017 | 95.4 | 0.01–12 | Dubey et al., 2023 |
| Penicillin | µg/L | 0.11 | 0.01 | 0.0017 | 90.9 | 0.001-0.02 | Wang et al. 2022 |
| Erythromycin | µg/L | 0.146 | 0.01 | 0.0017 | 93.2 | 0.01–4 | Dubey et al., 2023 |

Table 3 shows the average concentrations of the antibiotics in the wastewater of Qatar and their ranges in the wastewater of several locations in the world. Averages of clavulanic acid in TWW of Qatar were 13 µg/L, which is very close to the findings of Zhang et al. (2009) for the effluent of WWTPs in China. Metronidazole averages in the TWW of Qatar were 0.33 µg/L. In the study of Yu et al. (2023), metronidazole in WW was 5 mg/L and was 100% removed by enzymes and hydroxylation. Over the past few years, amoxicillin in wastewater (averages 0.01-7 µg/L) was heavily investigated. Amoxicillin sources, transport, kinetics and removal were discussed recently by Dias et al. (2023). Moreover, Ajala et al. (2023) found elevated amoxicillin concentrations in wastewater and the study used biomass/biochar-based adsorbents to remove it. The study of Sagasetta de Ilurdoz et al. (2022) selected three antibiotics which are sulfamethoxazole, trimethoprim and ciprofloxacin. The study found that reverse osmosis (RO) was able to remove 93 and 99% of these three antibiotics. This may explain the presence of ciprofloxacin in the effluent of the WWTPs of Qatar with average

concentrations of 0.53 $\mu\text{g/L}$. Tetracycline has been found in wastewater and aquatic environments of several locations in the world (Ding et al., 2023; Liu et al., 2023). According to the study of Dubey et al. (2023), tetracycline average concentrations in domestic wastewater was 0.01-12 $\mu\text{g/L}$. Amangelsin et al. (2023) studied the negative impacts of tetracycline on the environment and listed the most appropriate technologies for removal. Finally, according to Mishra et al. (2023), erythromycin was found in the domestic wastewater with ranges of 0.01-4 $\mu\text{g/L}$ while our findings in the TWW of Qatar show 0.01 $\mu\text{g/L}$ as averages of erythromycin.

3.2. Human health risk assessment of metals, metalloids and antibiotics

Regrading metals and metalloids accidental ingestion were clearly the main exposure routes due to lower absorption factor compared with antibiotics. Again, cleaning activities using treated wastewater followed by children leisure in gardens and parks presented highest exposure. All metals and metalloids presented *HQ* for all scenarios and routes far the unity except for Thallium (TI). Thallium present mean values of *HQ* above 0.1 ($HQ=0.4$) for accidental ingestion for commercial, industrial and urban cleaning pavement activities.

Regrading antibiotics, the highest exposure scenario is accidental ingestion during commercial, industrial, and urban cleaning due to higher exposure days a year and ingestion rates (Figure 1). Second highest exposure levels scenario was children accidental ingestion during garden and park leisure activities. Clavulanic acid followed by Metronidazole presented the highest exposure levels. However, all antibiotics presented *HQ* between 4 to 8 orders of magnitude lower than their respective ADI.

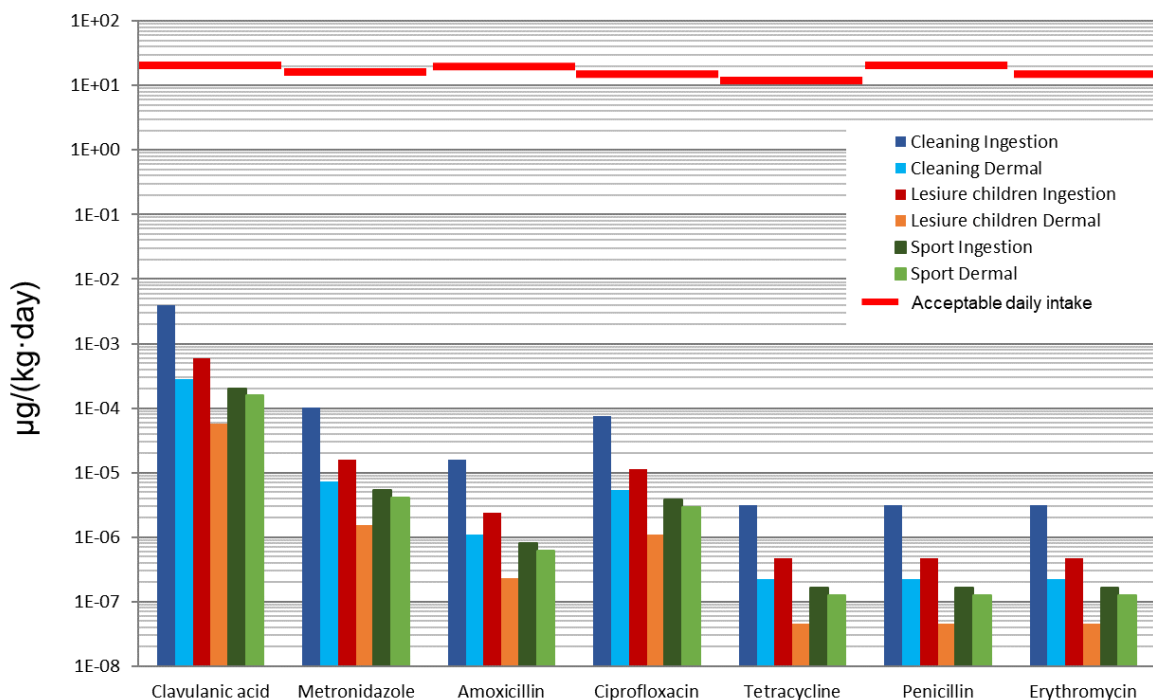


Figure 1. Antibiotic exposure through dermal absorption and accidental ingestion during the use of treated wastewater and acceptable daily intakes

Despite any human health adverse effects are expected to happen taking into account the present results, more research is needed regarding how intestinal microbiota are affected by antibiotics accidentally consumed due to use of TWW in pavement cleaning or irrigation of gardens, sport field or even irrigation in agriculture (Compagni et al., 2020). In addition, special focus should be paid to multiple antibiotic resistant microorganisms' presence in gardens and parks as a potential threat to human health (Zagui et al., 2022).

Finally, other chemical and biological pollutants associated to TWW should be consider to complete human health risk assessment of use of TWW such as pharmaceuticals, personal care products, illicit drugs, and microplastics (Qin et al., 2015; Dronjak et al., 2023; Miino et al., 2023).

4. Conclusion

Qatar invested in the construction of the state-of-the-art wastewater treatment plants. The three central WWTPs serve more than 2,300,000 inhabitants in the Capital Doha and surrounding. They have the highest treatment technologies and able to produce high quality effluents. They showed very similar quality in terms of physico-chemical characteristics, anions, cations, metals, metalloids and the targeted mostly-used antibiotics in the country. All parameters characterized in this study were very low and all within the international guidelines and standards where Qatar does not have standards for all parameters yet. Two parameters only (Cl and B) showed slightly high concentrations and expected sources are associated with the original source of TWW which is desalinated water as well as the high evaporation rates of the open lagoons of the WWTPs.

Despite metals, metalloids and antibiotics levels detected in treated wastewater, non-human health risks are found ($HQ < 1$) due to the potential exposure to these contaminants via dermal and ingestion routes (e.g. cleaning, pavements, irrigation of gardens and parks, playgrounds in adults and children). However, for thallium (Tl) hazard quotient (HQ) exposure during cleaning pavements were above 10% of oral reference dose and more investigation should be conducted in order to consider other exposure sources that may pose risks to workers. Antibiotics exposure in all scenarios considered were quite below the admissible daily intake based on the minimum therapeutic dose and considering uncertainty factors ($UF=1000$).

In this very arid region, further investigations on a long-term strategy are still needed on the water-soil-plant-health interlinkages and contaminant transport under natural and anthropogenic influences of the reuse technology options. Although the country owns the most advanced wastewater technologies and beside the chemical contaminants, special care should be given to the microbial contaminants and potential risks.

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Ethical approval

This article does not contain any studies with human or animals performed by any of the authors.

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Data availability

The dataset produced for this study is available within this article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authorship Contribution

Basem Shomar led the research project, coordinated with the relevant officials in Ashghal and wastewater Treatment Plants to get the samples and the data. He organized the sampling campaigns and gave instructions for sample preservation and analysis in Qatar and Germany. He drafted the manuscript and he is the corresponding author.

Joaquim Rovira carried out the risk calculations, wrote the relevant sections, and reviewed the manuscript.

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