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Review

Worldwide Regulations and Guidelines for Agricultural Water Reuse: A Critical Review

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Abstract: Water reuse is gaining momentum as a beneficial practice to address the water crisis, especially in the agricultural sector as the largest water consumer worldwide. With recent advancements in wastewater treatment technologies, it is possible to produce almost any water quality. However, the main human and environmental concerns are still to determine what constituents must be removed and to what extent. The main objectives of this study were to compile, evaluate, and compare the current agricultural water reuse regulations and guidelines worldwide, and identify the gaps. In total, 70 regulations and guidelines, including Environmental Protection Agency (EPA), International Organization for Standardization (ISO), Food and Agriculture Organization of the United Nations (FAO), World Health Organization (WHO), the United States (state by state), European Commission, Canada (all provinces), Australia, Mexico, Iran, Egypt, Tunisia, Jordan, Palestine, Oman, China, Kuwait, Israel, Saudi Arabia, France, Cyprus, Spain, Greece, Portugal, and Italy were investigated in this study. These regulations and guidelines were examined to compile a comprehensive database, including all of the water quality monitoring parameters, and necessary treatment processes. In summary, results showed that the regulations and guidelines are mainly human-health centered, insufficient regarding some of the potentially dangerous pollutants such as emerging constituents, and with large discrepancies when compared with each other. In addition, some of the important water quality parameters such as some of the pathogens, heavy metals, and salinity are only included in a small group of regulations and guidelines investigated in this study. Finally, specific treatment processes have been only mentioned in some of the regulations and guidelines, and with high levels of discrepancy.

Keywords: water reuse; agriculture; irrigation; regulation; guideline; standard; recycled water

1. Introduction

Climate change, industrialization, high rate of urbanization, and population growth are among the main reasons that have made many countries, especially in the arid and semi-arid areas, suffer from the water crisis [1]. For instance, water scarcity in Australia has caused population losses in north-eastern, south-eastern, and western rural areas. These areas have experienced further unemployment, lack of success in local businesses, and downtrend in irrigation [2]. Countries in the Middle East, Central Asia, and some parts of Southeast Asia have been struggling on water-related issues. It is anticipated that these struggles may result in conflicts over shared water resources in these regions [3]. Considering the adverse consequences of the water crisis, countries around the world have been trying to increasingly cope with this problem by implementing sustainable water management plans and looking for alternative water supply sources [1]. Water conservation, water reuse, and desalination of seawater and brackish groundwater are among those strategies that have been tried to address the water crisis [1].

In recent years, more and more countries are considering water reuse as an alternative water supply to supplement the freshwater sources [1,4,5]. Water reuse decreases the pressure on the freshwater resources, reduces the pollution that is being discharged to water bodies, and can be a reliable source compared to other water resources that are directly dependent on rainfall [1]. Due to these advantages and along with the recent developments in wastewater treatment technologies, scientists reported that the worldwide volume of recycled water in the 2010–2015 period was increased from 33.7 (million m^3/d) to 54.5 (million m^3/d) [6].

1.1. Water Reuse History

Water reuse has been practiced by humans for a very long time, of course, sometimes not in an appropriate way. Ancient civilizations during the Bronze age, 3200–1100 BC, used their domestic wastewater to irrigate their crops [7]. Ancient Greeks conveyed their domestic wastewater to a storage chamber using a sewer system in public latrines [8]. Moreover, Greeks and Romans used wastewater in agricultural irrigation, preparing fertilizer for crops and orchards [9]. During early modern history (1550–1700), direct use of wastewater in agriculture was being applied in Germany, Scotland, and England [8]. Beginning in the 19th century, irrigation with wastewater gained more popularity in some European and U.S. cities such as Paris, London, and Boston [8]. About the same time, the first wastewater irrigation in agriculture happened in Australia [9,10]. However, conveying and discharging the untreated wastewater in urban fields caused waterborne disease epidemics, such as cholera and typhoid fever outbreaks [8]. Unsafe application of wastewater in urban and agricultural areas, industrialization, and urbanization resulted in unhealthy situations for the societies in the 19th century [8]. To address the existing problems, some helpful efforts were as follows: (1) establishing the Great Britain's Public Health Act, (2) holding a lot of sanitary conferences on sanitation and demography, (3) the constitution of International Office of Public Hygiene, and (4) constructing the underground sewage systems [8].

Generally, the application of recycled water can be divided into seven categories including urban reuse, agricultural reuse, impoundments, environmental reuse, industrial reuse, groundwater recharge/non-potable reuse, and potable reuse [11]. Of note is water reuse applications are different in various countries and depend on several factors such as levels of treatment, the conditions of water resources, environmental status, and public willingness [11]. Agricultural water reuse, by far, is the most dominant application of water reuse in the world [1]. In total, 91% of the recycled water in this section is allocated for crops and pastures irrigation, including the growing of fruit, tree nut, vegetables, cotton, and grain farming [1]. The residual 9% is dedicated to the cleaning of piggeries, and drinking water for stock and dairy [1].

Agricultural water reuse has multiple advantages such as reducing pressure on fresh water sources [8,12], nutrients management and recovery [13,14], and higher reliability due to constant yield [12,15]. However, wastewater needs to be adequately treated to be used for agricultural irrigation, especially for food crop irrigation due to potential health risks [16]. Other major limiting factors in agricultural water reuse include technical feasibility (e.g., treatment technologies and management), economic factors (e.g., water distribution cost), social factors (e.g., social acceptance and consumer response), and regulatory considerations (e.g., lack of regulations or guidelines) [17,18]. Of note is while the focus of this study was agricultural water reuse, there might be some other challenges in the future related to water reuse in general (such as developing methods of coupling advanced wastewater treatment with seawater desalination facilities; developing efficient methods of risk assessment for water reuse practices; establishing regulations and guidelines which ensure promoting and regulating water reuse practices) [19]. A list of benefits and constraints of water reuse in agriculture is provided in Table 1. It should be noted that not every water reuse project will result in all of these benefits immediately, nor will face all of these challenges at the same time [4].

Table 1. Benefits and challenges of agricultural water reuse (adapted from [4] and modified).

Benefits	Challenges
Sustainable development: Increasing food production [20]. Improving aquatic life/fish production [21]. Sustainable development of dry regions [20].	Technical issues: Operation/maintenace reliability [22]. Increasing water system complexity [23]. Proper design of treatment processes [24]. Water reuse infrastructure resilience [25]. Available knowledge/expertise/experience [26].
Water conservation: Closing water cycle [27]. More efficient water use [28]. Saving high-quality water [29].	Social concerns: Unequal development. Social acceptance [30,31]. Consumer response/crops marketability [32]. Conflicts between different stakeholders. Socioeconomic/cropping patterns change [33].
Water supply: Reliable/secure/drought-proof water source [1]. Alternative/efficient/independent water supply [1].	Future challenges: Developing methods of coupling advanced wastewater treatment with seawater desalination facilities [19]. Developing efficient methods of risk assessment [19]. Establishing regulations and guidelines which ensure promoting and regulating water reuse practices [19].
Health benefits: Improving public health [34]. Improving health/environmental justice [1,4].	Health concerns: Microbial/chemical polluion [35]. The health of farmers/workers/consumers [35]. Inadvertent exposure/unreliable operation [35].
Environmental benefits: Linking rural-urban areas [36]. Reducing pollutants discharge [34]. Avoiding groundwater pollution [34]. Avoiding new water supply impacts [37]. Effective use of wastewater nutrients [34]. Improving recreational value of waterways [38]. Alternative to wastewater permits restrictions [39].	Environmental concerns: Polluting soils [34]. Endangering wildlife [40]. Polluting water bodies [41]. Greenhouse gas emissions [42]. Negative effects on crops/food [43].
Legal benefits: Policy awareness [44]. Compatible with treatment regulations [45].	Legal issues: Water rights. Lack of reuse regulations/guidelines [46].
Economic benefits: Avoiding development cost [47]. Increasing land/property value [48]. Increasing tourism activities in dry regions [49]. Additional revenue from recycled water sale [50]. Secondary revenue for costumers/industries [50]. Reducing/eliminating commercial fertilizers [51]. Lowering water treatment costs for downstream [34].	Economic challenges: Water pricing. Demand variations. Vulnerability to market change [50]. Difficult revenue and cost recovery [50]. Large storage capacity requirement [52]. Cost of water reuse infrastructure/operation and maintenance [50]. Need for well-adapted economic approach [50].

1.2. Current Status of Water Reuse

FAO (Food and Agriculture Organization of the United Nations) has estimated that 3.928×10^{12} m^3 of freshwater was withdrawn from existing water sources in the world in 2010. In total, 11% of the total water withdrawal in the world was municipal water demand, of which 3% was consumed and 8% was discharged as municipal wastewater [53]. There was 2.75×10^6 million m^2 of land consisting of irrigated agriculture worldwide, of which about 15% (4×10^5 million m^2) could be irrigated by the municipal wastewater [53]. Moreover, 32% of the world wide water withdrawal was discharged as agricultural wastewater and drainage [53]. The majority of wastewater that is recycled in agriculture is municipal wastewater, but these results show the need to change the focus of water reuse policies and plans from municipal wastewater management to sustainable management of municipal and agricultural (drainage and return flow) wastewater [1]. Furthermore, approximately, 5×10^4 to 2×10^5 million m^2

of the irrigated land is irrigated by raw and diluted wastewater, with the largest portion being in China [53]. This just includes 2–7% of the world's total irrigated area. Accordingly, there is a great potential for implementing planned and safe water reuse in agriculture.

While irrigation with recycled water is recognized as an alternative source to reduce the pressure on fresh water sources, the ultimate goal is safe implementation of water reuse practices [1]. One of the basic necessities for safe application of recycled water is to make sure that it has the desired quality and poses no harm to human health and the environment [16]. Started by the state of California in 1918, countries around the world alongside international organizations (e.g., World Health Organization (WHO) and FAO) have started to establish their water reuse regulations and guidelines to ensure safe water reuse practices [7]. In general, countries and organizations have taken different approaches to establish regulations and guidelines [54]. For instance, some countries like Canada, Australia, and many states in the U.S. have issued more restrictive regulations, while others have chosen to take less restrictive approaches to develop water reuse regulations and guidelines. Of note is that there is no federal regulation or guideline for agricultural water reuse in the U.S. [11]. It is up to the states to establish their own regulations or guidelines [11].

When compared in more details, it becomes apparent that current agricultural water reuse regulations and guidelines vary significantly [1]. For instance, some of the regulations and guidelines do not consider some of the biological and microbial quality parameters, and some others do not consider some of the physico-chemical parameters. Furthermore, even in regulations and guidelines that do consider the same parameters, the threshold levels for those parameters vary significantly. As water reuse in agriculture is becoming popular as a beneficial approach to address the water scarcity, the disparity in regulations and guidelines may become a source of problems, at both regional and global levels [54]. At the regional level, the absence of unified or at least relatively comparable water reuse regulations and guidelines may result in uncertainty among stakeholders (e.g., farmers, consumers, and policy-makers), thereby slowing down the promotion of water reuse in agriculture. The U.S. is a good example in that respect. In the U.S. there are 42 and 28 states that have regulation or guideline for nonfood crop/processed food crop, and food crop irrigation, respectively [11]. Eight states do not have any type of regulation or guideline for agricultural water reuse [11]. When looked at in more details, the water quality parameters and the threshold levels in those regulations and guidelines are different. This not only may create uncertainty among stakeholders, but also may increase the risk of public acceptance, thereby slowing down the process of implementing agricultural water reuse [1]. In addition, agriculture has a global market and agricultural commodities are being imported/exported all around the world. As a result, the difference in regulations and guidelines between the countries of origin and the end-use countries may pose major obstacles in food safety, market acceptability, and import/export relationships.

To date, there are very few studies which investigate and compare the existing agricultural water reuse regulations and guidelines in the U.S. and worldwide. The main objectives of our research were to compile and compare the existing agricultural water reuse regulations and guidelines around the world, and to identify the gaps in those regulations and guidelines. To achieve this goal, the most up to date regulations and guidelines that were issued by national and international organizations (e.g., Environmental Protection Agency (EPA), International Organization for Standardization (ISO), FAO, WHO, European Commission), and by pioneering countries in water reuse (e.g., U.S., Canada, Mexico, Iran, Egypt, Tunisia, Jordan, Israel, Oman, China, Kuwait, Saudi Arabia, Australia, France, Greece, Portugal, Cyprus, Spain, and Italy) were obtained and investigated in this study. In addition, the water quality criteria in those regulations and standards were compared, and the major differences between those criteria were identified. Results from this study identify the discrepancies in the current regulations and guidelines. They also highlight the challenging areas that need to be addressed to promote the agricultural water reuse with respect to the existing regulations and guidelines.

2. Methodology

In order to compile a complete worldwide agricultural water reuse regulations and guidelines database, Google Scholar search engine was used as the first step of this study. In this step, key words including "water reuse", "water reclamation", "water recycling", "wastewater reuse", "wastewater recycling", "recycled water", "reclaimed water", "agriculture", "regulation", "guideline", "standard", and "criteria" were used. Peer reviewed journal articles related to agricultural water reuse regulations and guidelines were compiled and reviewed. In the second step, based on the results obtained from the first step, study cases were identified (e.g., countries, international organizations, and state agencies that have issued/established agricultural water reuse regulations or guidelines). In the third step, the official website of the organizations (e.g., state agencies, ministries, governmental institutes, etc.) were investigated. Moreover, official representatives at organizations/agencies were contacted if needed to make sure that the obtained regulations and guidelines were the latest version. In total, 70 agricultural water reuse regulations and guidelines were gathered for this study. All of these regulations and guidelines were thoroughly analyzed and compared in this study.

2.1. Definitions and Terminologies

2.1.1. Technical Definitions and Terminologies

The use of treated wastewater for beneficial purposes is generally called water reuse [5]. However, there are different terminologies that have been used in various water reuse regulations and guidelines such as water reuse, water recycling, water purification, reclaimed water, recycled water, reused water, repurified water, NEWater, and more. To clarify, in this manuscript, water reuse refers to treatment or processing of wastewater and then the application of the treated wastewater in agriculture. In addition, recycled or reclaimed water refer to the treated wastewater that is used for different applications. Of note is that "recycled" and "reclaimed" water have been used in this manuscript interchangeably.

2.1.2. Legal Definitions and Terminologies

Similar to scientific and technical terminologies, different legal terminologies have been used for water reuse regulations. While the main focus of this manuscript was technical and scientific aspects of agricultural water reuse, it is helpful to clarify these legal terminologies, which are commonly used in the reference documents (Table 2).

Table 2. The definition of standard, criteria, guideline, and regulation [5].

Term	Definition	Comments
Standard	A rule, principle, or measure established by an authority.	Standards are usually quite rigid, official, or quasi-legal. As standards may be written using safety factors, they can be potentially unfair, inequitable, or ignoring scientific knowledge. Standards typically include qualitative restrictions in terms of numerical limits.
Criteria	As the basis for standards, criteria are developed based on available data and scientific opinion. It is common that technical and economic feasibility are not considered in the process of developing criteria.	Effective criteria have the potential to be evaluated quantitatively through suitable analytical procedures. Criteria include qualitative restrictions (these restrictions can be numerical limits and narrative statements).
Guideline	Best practices that are used prior to development of standards or regulations.	Usually, guidelines are voluntary, advisory, and non-enforceable. These guidelines can be used in water reuse permits to become enforceable requirements.
Regulation	When a state legislature or a water pollution control agency officially adopt a standard, criteria or guideline.	Enforceable and mandatory by governmental agencies, water reuse regulations include treatment requirements, cross connection controls, signage, and setback distances.
Act	Passed by Congress, state legislatures or Parliament, depending on each country's type of government, acts set out the broad/policy principles.	

3. Results and Discussion

In total, 70 regulations, guidelines, standards, criteria, and acts were obtained and included in this study (Table 3). The State of California in the U.S. was the first to issue a specific regulation for agricultural water reuse in 1918. After 48 years, the next regulation document was issued by the state of Iowa in the U.S. in 1966, followed by Mexico's standard in 1971. WHO is the first international organization that issued a guideline for agricultural water reuse in 1973. As illustrated in Table 3, among the 70 investigated documents, there were 30 regulations, 29 guidelines, six standards, four criteria, and one act. It was found that most of these regulations and guidelines were issued after 1973, and the majority of them were issued after 1998. Starting from the 1970s and 1980s, international organizations including WHO, FAO, and the World Bank tried to effectively notify countries and organizations around the world the importance of safe water reuse practices, resulting in the propagation of establishing water reuse regulations and guidelines [1].

Table 3. Agricultural water reuse regulations or guidelines included in this study.

#	Year [1]	Country (State)	Current Edition	Type
1	1918	US (California)	Title 22: California Water Recycling Criteria [55], Water Code-division 7–article 7 [56].	Regulation
2	1966	US (Iowa)	567 IAC Chapter 62: Effluent and Pretreatment Standards: Other Effluent Limits or Prohibitions [57].	Regulation
3	1971	Mexico	Standard NOM-001-ECOL-1996 [58,59].	Standard
4	1973	WHO [2]	WHO guideline for the safe use of wastewater, excreta and greywater-volume II—wastewater use in agriculture [60].	Guideline
5	1975	US (Alabama)	Alabama Environmental Regulations and Laws-division 6-volume 3—reclaimed water reuse program [61].	Guideline
6	1976	US (South Carolina)	Regulation 61-9, Water Pollution Control Permits [62].	Regulation
7	1977	Italy	National Inter ministry Committee for the Protection of Waters from Pollution [63].	Regulation
8	1980	EPA [2]	Guidelines for water reuse [11].	Guideline
9	1981	US (Arizona)	Arizona administrative code, title 18, chapters 9 and 11 [64].	Regulation
10	1985	US (Delaware)	Regulations governing the design, installation and operation of on-site wastewater treatment and disposal systems [65].	Regulation
11		US (Wisconsin)	Chapter NR 206—land disposal of municipal and domestic wastewaters [66].	Regulation
12	1987	FAO [2]	Wastewater quality guidelines for agricultural use [67]	Guideline
13	1989	US (North Dakota)	Chapter 33-16-01—North Dakota pollutant discharge elimination system [68].	Guideline
14		Tunisia	Tunisian standards NT 106-03 [69,70].	Standard
15	1990	US (Oregon)	Department of environmental quality-Chapter 340-Division 53—Graywater reuse and disposal systems [71].	Regulation
16	1991	US (Florida)	Reuse of reclaimed water and land application [72].	Regulation
17		France	Water reuse criteria for agricultural and landscape irrigation in France [73].	Criteria
18		US (South Dakota)	Recommended design criteria manual-wastewater collection and treatment facilities [74].	Guideline
19	1992	US (Washington)	Chapter 90.46 RCW [75].	Guideline
20	1993	Oman	Ministerial decision no. 145 of 1993 issuing the regulations on waste water reuse and discharge [76].	Regulation
21	1995	US (Illinois)	Title 35: environmental protection–Subtitle c: water pollution-Chapter ii: environmental protection agency—Part 372 Illinois design standards for slow rate land application of treated wastewater [77].	Regulation
22		US (Montana)	DEQ 2—design standards for wastewater facilities [78].	Regulation
23	1996	CA (Atlantic Canada)	Atlantic Canada wastewater guidelines manual [79].	Guideline
24	1997	US (Texas)	Chapter 210-use of reclaimed water [80].	Regulation
25	1998	US (Indiana)	Article 6.1—land application of bio solid, industrial waste product, and pollutant-bearing water [81].	Regulation

Table 3. *Cont.*

#	Year [1]	Country (State)	Current Edition	Type
26	1999	AU (Australian Capital Territory)	ACT—wastewater reuse for irrigation [82].	Guideline
27		CA (British Columbia)	Chapter 10—use of reclaimed water [83].	Regulation
28		Israel	Israeli guideline for wastewater reuse [84–86]	Guideline
29	2000	CA (Alberta)	Guidelines for municipal wastewater irrigation [87].	Guideline/Act
30		US (Colorado)	Regulation 84: reclaimed water control regulation [88].	Regulation
31		Greece	[89,90]	Criteria
32		Saudi Arabia	[91]	Regulation
33	2001	Kuwait	Standards of the Kuwait environment public authority (KEPA) [92].	Standard
34	2002	China	GB20922-2007 [93].	Standard
35		US (Hawaii)	Volume 1: recycled water facilities [94].	Guideline
36		Jordan	Jordanian standard (JS: 893/2002) [95].	Standard
37		US (Maryland)	Guidelines for use of class iv reclaimed water [96].	Guideline
38		AU (Tasmania)	Environmental guidelines for the use of recycled water in Tasmania [82]	Guideline
39	2003	AU (New South Wales)	The guidelines for sewerage systems: use of reclaimed water (ARMCANZ-ANZECC-NHMRC 2000) [82].	Guideline
40		Palestine	[97]	Regulation
41		AU (Victoria)	The guidelines for environmental management: use of reclaimed water, guidelines for environmental management: dual pipe water recycling schemes—health and environmental risk management [82].	Guideline
42	2004	CA (Saskatchewan)	Treated municipal wastewater irrigation guidelines-EPB 235 [98].	Guideline
43	2005	Cyprus	Cyprus regulation K.D.269/2005 [11].	Regulation
44		Egypt	[99]	Regulation
45		US (New Jersey)	Reclaimed water for beneficial reuse [100]	Guideline
46		Spain	Spanish regulations for water reuse-royal decree 1620/2007 of 7 December [101].	Regulation
47	2006	AU (AGWR)	The Australian guidelines for water recycling: augmentation of drinking water supplies [102].	Guideline
48		Portugal	Portuguese standard NP 4434 [103].	Criteria
49	2007	US (Ohio)	3745-42-13 Land application systems [104].	Guideline
50	2008	US (Idaho)	Rules for the reclamation and reuse of municipal and industrial wastewater [105].	Regulation
51		AU (Queensland)	The water quality guidelines for recycled water schemes (DNRW 2008c) [82].	Guideline
52		US (Virginia)	Chapter 740. Water reclamation and reuse regulation [106].	Regulation
53	2009	US (Massachusetts)	314 CMR 20: Reclaimed water permit program and standards [107].	Regulation
54		AU (Western Australia)	Guidelines for the use of recycled water in western Australia (WA DoH 2009) [82].	Guideline
55	2010	Iran	Criteria for using recycled water (In Farsi) [108].	Criteria
56		ISO [2]	Guidelines for treated wastewater use for irrigation projects [109].	Standard
57		US (Minnesota)	Municipal wastewater reuse [110].	Guideline
58	2011	US (Kansas)	Kansas EPA 503 land application of septage–updated [111].	Guideline
59		US (North Carolina)	Subchapter 02U—reclaimed water [112].	Regulation
60	2012	US (Georgia)	Guidelines for slow-rate land treatment of wastewater [113].	Guideline
61		US (Pennsylvania)	Reuse of treated wastewater guidance manual 385-2188-002 [114].	Guideline
62		US (Rhode Island)	Guidance for wastewater reuse projects [115].	Guideline
63		US (Wyoming)	Department of environmental quality, water quality, chapter 21: reuse of treated water [116].	Regulation
64	2013	US (New Mexico)	Title 20, chapter 7, part 3 [117].	Guideline
65		US (Utah)	Title R317. Environmental quality, water quality [118].	Regulation
66	2014	AU (Northern Territory)	Guidelines for wastewater works design approval of recycled water systems [82].	Guideline
67	2015	US (Oklahoma)	Title 252. chapter 656. Water pollution control facility construction standards [119].	Regulation
68	2016	US (Nevada)	Use of reclaimed water [120].	Regulation
69	2017	European Commission [2]	Minimum quality requirements for water reuse in agricultural irrigation and aquifer recharge [121].	Guideline
70		US (Nebraska)	Title 119, chapter 12 [122].	Regulation

[1] The dates indicate when the documents were established/issued for the first time. [2] Organizations.

3.1. Reference Regulations and Guidelines

In this section, the pioneer agricultural water reuse regulations and guidelines which have been the source of inspiration and adoption for many of other states, countries, and organizations are discussed. They include WHO, EPA, FAO, Australian Guideline for Water Recycling (AGWR) guidelines, ISO standard, California, and European Commission regulations.

3.1.1. World Health Organization (WHO) guideline

WHO issued three guidelines for water reuse in 1973, 1989, and 2006. The first document was published in 1973 entitled "Reuse of effluents: methods of wastewater treatment and health safeguards", which became one of the main references for other international standards. The main goals of this document were to protect the public health and to guide the safe application of wastewater and excreta in agriculture and aquaculture. However, the document had minimal health risk approach and lacked epidemiological studies [8]. Later, the WHO updated its prior guideline in 1989 by implementing a complete epidemiological studies analysis. In this version, entitled "Health guidelines for the use of wastewater in agriculture and aquaculture", WHO focused on the microbiological quality of the recycled water for irrigation. Additionally, risk assessment and necessary information to determine the societies' tolerable risks were included. This guideline lacked to give any information about surveillance guidelines [8]. WHO's final guideline was published in 2006, entitled "Safe use of wastewater, excreta, and greywater", to contribute to forming governmental guidelines, standards, and regulations relating to wastewater management for each country regarding its specific situation. There are significant improvements regarding risk assessment in this guideline including microbiological analysis, based on the information gathered from present pathogens, and health risk management, estimations were made based on person per year (PPY) and disability-adjusted life year (DALY) [8].

This risk-based guideline is mainly focused at microbial health risks, but it also contains recommended maximum tolerable soil concentrations for various organic and inorganic pollutants which are assessed by QMRA (Quantitative Microbial Risk Assessment) and epidemiological evidence. The DALYs are used in this guideline in order to compare the results of a disease from one exposure pathway to another pathway. WHO indicated the determination of DALYs as follows: "DALYs are calculated by adding the years of life lost to premature death to the years lived with a disability", accounting for acute and chronic health effects [60]. A water-borne disease burden of 10^{-6} DALYs per person per year is determined as the tolerable risk by WHO [60]. Critics claim that this is not the most appropriate value to use, especially in low-income countries [123]. In this guideline (volume 2, section 4.5), it is mentioned that the appropriate value is less than 10^{-4} or 10^{-5} DALY (loss) per person per year which Mara et al. supports less than 10^{-4} DALY to be used for water reuse in agriculture [123]. Moreover, this guideline defines two exposure scenarios for agricultural irrigation including unrestricted irrigation and restricted irrigation, suggesting the required log pathogen reductions for each of them (Table S1). Regarding physico-chemical quality of the water, WHO refers to the FAO's requirements for irrigation practices. Of note is that the WHO guideline requires no specific type of treatment for the restrictions mentioned above.

3.1.2. FAO Guideline

FAO issued two guidelines for water reuse in 1987 and 1999. In the latest version, FAO divides the application of recycled water in agriculture into three categories, including (A) Irrigation of crops likely to be eaten uncooked, sports fields, and public parks, (B) Irrigation of cereal crops, industrial crops, fodder crops, pasture, and trees, and (C) localized irrigation of crops in category B if exposure of workers and the public does not occur [67]. Moreover, FAO drafts some requirements for interpretation of water quality for irrigation (Table S2) including three degrees of restriction including severe, slight to moderate, and none, on use of the recycled water based on its quality. Additionally, threshold levels of trace elements for crop production are introduced by FAO in its last guideline in 1999 [67].

In terms of microbial parameters, FAO follows a less restrictive approach, similar to WHO, considering epidemiological evidence. FAO recommends stabilization ponds, category A and B, and at least primary sedimentation, category C. In unrestricted category, A, FAO recommends stricter limitations for fruit trees as Fecal Coliforms <200/100 mL. For physico-chemical parameters, FAO guideline has been the leading guideline to which the standards, criteria, guidelines, and regulations of other organizations, countries, and states agencies have referred.

3.1.3. Environmental Protection Agency (EPA) Guideline

EPA developed four guidelines for water reuse in 1980, 1992, 2004, and 2012. The first guideline was issued as a technical research report in 1980. Later in 1992, EPA updated the first version by including toxicity in crops that were irrigated with wastewater [8]. This version was provided for project planners and state regulatory officials in order to develop water reuse systems in different states. EPA included two new scopes in its updated guideline in 2004 consisting of "indirect potable reuse" and "industrial reuse". New treatment and disinfection technologies, concerning pathogens and emerging chemicals, information about economics, research actions, funding alternatives, and data sources were also elaborated in the 2004 document [8].

The EPA along with the United States Agency for International Development (USAID) issued an updated version of the 2004 EPA guideline in 2012 (Table S3). The ultimate goal of this guideline was to make the water reuse process easy to implement based on global databases. In addition, EPA and USAID included the progresses made in the technologies of wastewater treatment, regional variations of water reuse, best management practices (BMPs) in communities' involvement, case studies of water reuse around the world, and development of safe and sustainable water reuse. In this guideline, EPA suggests some requirements for each of the water reuse categories mentioned in the guideline [8]. Regarding agricultural water reuse, EPA divides agricultural water reuse into two categories including water reuse for food crops and water reuse for processed food crops/nonfood crops irrigation. This guideline also provides some suggestions for the required treatments, recycled water quality, recycled water monitoring, setback distances, and chemical constituents' limits [11]. Secondary treatment, filtration, and disinfection are the required treatments for food crops and secondary treatment and disinfection are the required treatments for processed food crops/nonfood crops which were the most common treatments in existing regulations and guidelines. Furthermore, EPA used a very high-demanding approach for its microbial requirements, resulting in being a restrictive guideline in terms of microbial water quality. Moreover, EPA recommends FAO's water quality criteria for irrigation.

3.1.4. Australian Guideline for Water Recycling (AGWR)

As a national guideline, supply and use of recycled water has been regulated through Australian Guideline for Water Recycling: Managing Health and Environmental Risks (AGWR). This guideline was issued by the Australia's Environment Protection and Heritage Council and the Natural Resource Management Ministerial Council in 2006 to address water crisis, as a result of widespread droughts and population growth in Australia [124]. In order to manage the risks to human and the environment, the guideline focuses on two situations, namely, the effluent of a centralized wastewater treatment plant and recycled water from greywater recycling. The guideline helps to identify major health risks and recommends preventive practices to lower those risks to an acceptable level [124].

Regarding human health, AGWR focuses on microbial risks which are addressed using DALYs. The tolerable risks in AGWR, like WHO 2006 guideline, is 10^{-6} DALYs per person per year. Reference pathogens, including Campylobacter for bacteria, rotavirus and adenovirus for viruses, and Cryptosporidium parvum for protozoa and helminths, are used for risk identification [124]. Additionally, two categories of intended and unintended use are included in the exposure consideration. Moreover, maximum risk, risk with no preventive practices, residual risk, and remaining risk with the presence of preventive practices, are considered for risk characterization in AGWR. For environmental risks, instead of DALYs and health-based targets, environmental values which are related to the impacts on specific endpoints in the environment are used (e.g., native tree species and specific grasses). Eighteen environmental hazards were identified by AGWR, including Boron, Cadmium, Chlorine disinfection residuals, hydraulic loading (water), Nitrogen, Phosphorus, salinity, Chloride and Sodium, Ammonia, Aluminum, Arsenic, Copper, Lead, Mercury, Nickel, and Surfactants [124].

3.1.5. California's Regulation

As was mentioned before, California's regulation (the first version) was the first water reuse regulation worldwide issued in 1918 by the California Department of Health Services. As a pioneer in water reuse regulations, California's regulation has been the basis for many other state agencies as well as other countries and international organizations. This regulation has been considered a very comprehensive and restrictive regulation as it covers a wide range of water quality parameters and other requirements in terms of type of crops and irrigation types (Table S4). Similar to EPA guidelines, California's regulation requires a high level of disinfection along with total coliform inactivation of <2.2 (total coliform/100 mL). Although this regulation is one of the most developed regulations in terms of water quality monitoring, treatment train design, and operation, it lacks any requirement for irrigation rates or storage requirements [4].

Since its first edition establishment, California's agricultural water reuse regulation has been continuously studied and revised. The terms "reclaimed water" and "water reuse" in earlier versions of the regulation have been changed to "recycled water" and "water recycling" in more recent versions, respectively. Additionally, oxidized wastewater which is undisinfected secondary treated wastewater was chosen as the requirement for industrial crops [4]. Moreover, turbidity requirements for high-level recycled water uses were added. Of note is that this regulation requires no other physico-chemical water quality parameter.

3.1.6. International Organization for Standardization (ISO) Standard

The first ISO standard for water reuse was issued in 2010 based on a request from Israel for water reuse in agriculture, titled PC 253 [109]. The next ISO standard for water reuse was proposed by Japan to be established along with Israel and China, titled TC 282, in 2015. WHO guideline (2006), Australian national water reuse regulations (2006), Israeli regulations for agricultural irrigation (1978, 1999, and 2005), and California Code of Regulations (Title 22, division 4, chapter 3, water recycling criteria (2000)) were the references in order to establish the ISO standard [109]. ISO standard consists of three sections: (1) Treated wastewater use for irrigation, (2) Treated wastewater use in urban area, and (3) Risk and performance evaluation of water reuse systems. In the first section, ISO introduces 5 categories of water quality for water reuse applications for irrigation, A: Very high quality treated wastewater, B: High quality treated wastewater, C: Good quality treated wastewater, D: Medium quality treated wastewater, and E: Extensively treated wastewater [109].

As required treatments, combinations of secondary treatment, filtration, and disinfection are used in this guideline, depending on the water quality [109]. Although disinfection is needed for A, B, and C categories, there was no requirements for residual chlorine in this guideline. The microbial approach in this standard is close to the restrictive approach but it also includes the intestinal nematodes. For a higher quality water, A and B, the low concentrations of thermo-tolerant coliforms are considered adequate to make sure the water is suitable for unrestricted and restricted food crops irrigation. Irrigation of nonfood, industrial, and seeded crops, C, D and E, are regulated by thermo-tolerant coliforms and intestinal nematode restrictions. For physico-chemical qualities, ISO includes biological oxygen demand (BOD_5) and total suspended solids (TSS) restrictions, while turbidity is used only for category A recycled water [109].

3.1.7. European Commission Regulation

A proposal has been put forward by European Commission in order to stablish a European regulation for agricultural water reuse, since May 2018 [125]. The proposal goals are to encourage the application of recycled water and to help address the water crisis in Europe [125]. As an EU-wide project, it has been estimated that the project can decrease the water stress in Europe by 5% through increasing the application of recycled water from 1.7 billion m^3 to 6.6 billion m^3, annually [125].

The references used to establish the proposal included a commission impact assessment for the 2012 Blueprint communication [126], a study on guidelines, needs, and barriers related to water reuse [127], a 2017 report on minimum quality requirements for wastewater reuse [128], a 2017 hydro-economic analysis [129], a 2013 report on wastewater reuse in the EU [130], a 2015 report on optimizing water reuse in the EU [131], a 2016 report on EU-level instruments on water reuse [132], and a 2017 report on the patterns of unplanned water reuse [133].

The proposal requires the operators of water reuse practices to comply with minimum recycled water quality requirements summarized in Table S5. Moreover, the proposal requires the operators to establish a risk management plan to ensure addressing the potential additional dangers [125]. The Committee on Environment, Public Health, and Food Safety (ENVI) is the responsible committee for this proposal in the European Parliament.

3.2. Recycled Water Quality Standards

In most cases, agricultural water reuse regulations and guidelines include three categories of water quality, treatment processes, and irrigation technologies [46]. Recycled water quality can be categorized into three groups including human-health parameters, agronomic parameters, and physico-chemical parameters, each of which consists of many specific water quality parameters [4] (Figure 1).

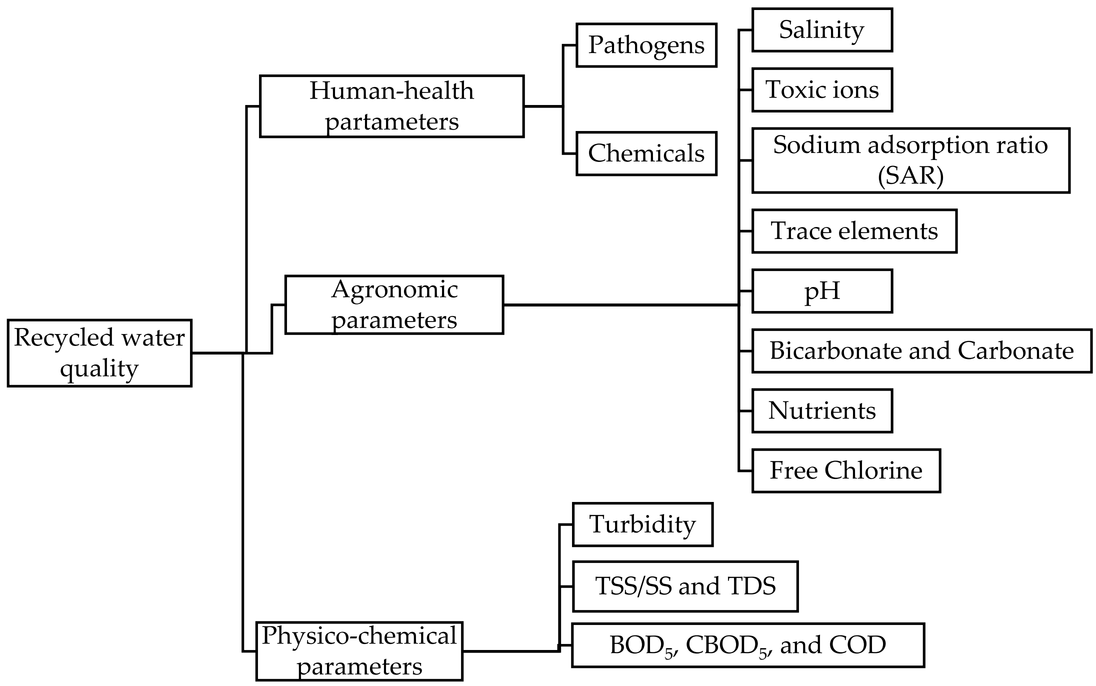

Figure 1. Agricultural water quality parameters.

3.2.1. Human-Health Parameters

Human-health parameters are of prominent importance in safe agricultural water reuse practices. The health of farmers, workers, consumers, and people who live in the close vicinity of farms have to be considered for safe agricultural water reuse practices. This issue has been addressed mainly by including microbial and chemical water quality parameters related to human health.

Pathogens

The presence of pathogens is the main health concern when recycled water is used for irrigation. Scientists and experts have concluded that it is not practical to monitor the existence of all of the pathogens in recycled water. Therefore, the indicator organism concept has been used to monitor the pathogens in a more practical manner [4]. There are many waterborne pathogens and their microbiological indicators, which have been included in the regulations and guidelines. In general, there are two major approaches to microbial water quality including "no fecal indicator bacteria" and "no real risk of infection".

No Fecal Indicator Bacteria in the Water:

In this approach, the assumption is that it is not viable to monitor all of the pathogenic microorganisms [134]. Therefore, coliforms are considered as substitute parameters. Fecal coliforms are the most common bacteria of thermo-tolerant coliforms. Additionally, E. coli is the most common fecal indicator bacterium used by different organizations and countries. Under this approach, no detectable fecal indicator is required using fecal indicator as the microbial indicator. The advantage of this approach is that there is no need to monitor all of the pathogenic microorganisms. The disadvantage of this approach is that it is so strict and costly even though there is no need to monitor all of pathogenic microorganisms [134]. Shuval et al. argued that using this approach would increase cost per case of disease averted [135]. They estimated that the cost of using no detectable fecal coliform/100 mL was near US $330 million more than using 1000 fecal coliform/100 mL per each case of an infectious disease (i.e., hepatitis A) prevented [135]. As the level of endemic enteric diseases in developed counties are low, this higher cost may be justified. However, other countries with high levels of endemic enteric diseases which usually are transmitted through low levels of sanitation and hygiene may not justify this higher cost [134]. Of note is in most cases, the state of California's regulation has been widely used as the benchmark regulation under this approach by other organizations and agencies. In this study, we call regulations and guidelines which used this approach "restrictive".

From the Epidemiological Point of View; no Real Risk of Infection:

According to this approach, epidemiological evidence must be used to issue any microbial quality requirement [134]. The advantage of using this method is that the risk assessment process is done by studying the infection between exposed people to the recycled water. In this method, people exposed to different recycled water qualities would be studied to determine what level of recycled water quality results in no more excess infection cases in the study population. On the other hand, this approach is only valid for the specific time and place that the risk assessment has been conducted. Therefore, to use the results in regulations and guidelines, they must be extrapolated, which requires making some assumptions about the changes to the variables, making it less precise. Additionally, conducting epidemiological studies are not always easy, especially in developing countries. For example, there are critics about insufficiency of these studies and existence of some groups of people who have been immunized to many enteric infections. In addition, there may be a lack of health risk assessment methodologies which were used before for these types of studies [134]. The other disadvantage of this method is that epidemiological studies do not consider the secondary transmission [134]. Of note is in most cases, the WHO guideline has been considered as the benchmark guideline under this approach by other organizations and agencies. In this study, we call regulations and guidelines which used this approach "less restrictive".

Among the regulations and guidelines that were evaluated for this study, there were 49 documents that were considered restrictive, and 15 documents that were less restrictive (Tables 4 and 5). The microbial quality parameters in restrictive agricultural water reuse regulations and guidelines were Fecal Coliforms (25 documents), E. coli (21 documents), Total Coliforms (7 documents), Intestinal Nematodes (6 documents), Thermo-tolerant Coliforms (5 documents), Enterococci (2 documents), Somatic Coliphages (2 documents), Clostridium Perfringens (1 document), and F-RNA Bacteriophages (1 document). In general, the threshold limits for food crops irrigation and unrestricted public access categories have lower limits compared to processed food crops/non-food crops irrigation and restricted public access categories. When compared, regulations and guidelines established by different organizations and agencies sometimes had different threshold levels for the same parameters (Table 4). The comparison also showed a considerable level of discrepancy among the restrictive regulations and guidelines with respect to microbial water quality (Table 4). It was apparent that restrictive regulations or guidelines have been adopted by developed countries in the world due to their costs and high-tech requirements. It was estimated that restrictive regulations and guidelines cost an additional $3–30 million per prevented enteric disease [135].

Table 4. Restrictive agricultural water reuse regulations and guidelines.

Reuse Categories	Required Microbial Quality (cfu/100 mL) (Monitoring)
EPA (2012)	
Food crops	Fecal coliforms (daily): 0 (median of last 7 days), 14 (max)
Processed food crops/non-food crops	Fecal coliforms (daily): 200 (median of last 7 days), 800 (max)
ISO (2015)	
A: very high-quality treated wastewater; unrestricted urban irrigation and agricultural irrigation of food crops consumed raw	Thermo-tolerant coliforms: 10, 100 (max)
B: high quality treated wastewater; restricted urban irrigation and agricultural irrigation of processed food crops	Thermo-tolerant coliforms: 200, 1000 (max)
C: good quality treated wastewater; agricultural irrigation of non-food crops	Thermo-tolerant coliforms: 1000, 10,000 (max) Intestinal nematodes: 1 Egg/L (average)
D: medium quality treated wastewater; restricted irrigation of industrial and seeded crops	Intestinal nematodes: 1 Egg/L (average), 5 Egg/L (max)
E: extensively treated wastewater; restricted irrigation of industrial and seeded crops	Intestinal nematodes: 1 Egg/L (average), 5 Egg/L (max)
British Columbia	
Restricted	Fecal coliform (weekly): 200
Unrestricted	Fecal coliform (daily): 2.2
Alabama	
	E. Coli (daily): 18 (median of the last 7 results), 34 (max)
Atlantic Canada	
Restricted	E. Coli (2/month): 200 (only golf courses and parks)
Unrestricted	E. Coli (2/month): 2 (only golf courses and parks)
Saskatchewan	
Food crops	Fecal Coliform or E. Coli (1/Week): 2.2 (Median), 23 (Max)
Non-food crops	Fecal Coliform or E. Coli (1/Month): 1000
Arizona	
Food crops	Fecal Coliform (Daily): 0 (4 of the last 7 daily samples), 23 (Max)
Processed food crops/non-food crops	Fecal Coliform (Daily): 1000 (4 of the last 7 daily samples), 4000 (Max)
California	
Food crops	Total Coliform Bacteria (Daily): 2.2 (Last 7 Days), 23 (One sample in any 30-day period), 240 (Max)
Colorado	
Processed food crops/non-food crops	E. Coli: 126 (Monthly geometric mean), 235 (Max)
Delaware	
All types	Fecal Coliform (2/Month): 20
Florida	
Food crops	Fecal Coliforms: 0 (75% of samples), 25 (Max)
Processed food crops/non-food crops	Fecal Coliforms: 200 (Average), 800 (Max)
Georgia	
Processed food crops/non-food crops	Fecal Coliform (Daily): 23 (Monthly geometric mean), 46 (Weekly geometric mean), 100 (Max)
Hawaii	
Food crops	R-1: Fecal Coliform (Daily): 2.2 (Last 7 days), 23 (More than 1 sample in any 30-day period), 200 (Max) R-2: Fecal Coliform (Daily): 23 (Last 7 Days), 200 (More than one sample in any 30-day period)

Table 4. *Cont.*

Reuse Categories	Required Microbial Quality (cfu/100 mL) (Monitoring)
Idaho	
Food crops	B: Total Coliform (Daily): 2.2 (Median), 23 (Max) C: Total Coliform (Weekly): 23 (Median), 230 (Max)
Processed food crops/non-food crops	C: Total Coliform (Weekly): 23 (Median), 230 (Max) D: Total Coliform (Monthly): 230 (Median), 2300 (Max)
Indiana	
Food crops	Fecal Coliform (Daily): 0 (Median Value), 14 (Max)
Processed food crops/non-food crops	Fecal Coliform (Daily): 200 (Median Value), 800 (Max)
Kansas	
Restricted	E. Coli (2/Month): 160
Unrestricted	E. Coli (2/Month): 20
Maryland	
Class I (restricted access)	Fecal Coliform: 200 (Monthly geometric mean)
Class II (restricted access)	Fecal Coliform: 3 (Monthly geometric mean)
Class III1 (restricted access)	Fecal Coliform: 2.2 (Monthly geometric mean)
Massachusetts	
A: food crops, unrestricted	Fecal Coliform: 0 (Median, continuous 7-day sampling), 14 (Max)
B: pasture for milking animals, unprocessed food crops (no contact with the edible part of crop), restricted	Fecal Coliform: 14 (Median, continuous 7-day sampling), 100 (Max)
C: orchard and vineyard (no contact with the edible part of crop), processed food crops	Fecal Coliform: 200 (Median)
Minnesota	
Food crops	Total Coliform: 2.2
Processed food crops/non-food crops	Fecal Coliform: 200
Montana	
All types	Total Coliforms (Weekly): 2.2 (Last 7 days), 23 (Max)
Nevada	
Processed food crops/non-food crops	Fecal Coliform: 200 (30-day geometric mean), 400 (Max)
New Jersey	
Food crops	Fecal Coliform: 2.2 (7-day median), 14 (Max)
Processed food crops/non-food crops	Fecal Coliform: 200 (Monthly geometric mean), 400 (Weekly geometric mean)
North Carolina	
All types	E. Coli or Fecal Coliform: 14 (Monthly geometric mean), 25 (Max)
North Dakota	
Processed food crops/non-food crops	E. Coli (Weekly): 126 (Max)
Ohio	
Processed food crops/non-food crops	Fecal Coliform (3/Week): 1000 E. Coli (3/Week): 126
Oklahoma	
Processed food crops/non-food crops	Fecal Coliform (3/Week): 200 (Monthly geometric mean), 400 (Max)
Oregon	
Food crops	Total Coliform: 2.2 (Last 7 days), 23 (Max)
Processed food crops/non-food crops	Total Coliform: 23 (Last 7 days), 240 (Any 2 consecutive samples)
Pennsylvania	
Food crops	Fecal Coliform (2/week): 2.2 (Monthly average), 23 (Max)
Processed food crops/non-food crops	Fecal Coliform (Weekly): 200 (Monthly average), 800 (Max)
Rhode Island	
Processed food crops/non-food crops	Fecal Coliform: 23
Texas	
Food crops	Fecal Coliform or E. Coli (2/Week): 20 (30-day geometric mean), 75 (Max) Enterococci (2/Week): 4 (30-day geometric mean), 9 (Max)
Processed food crops/non-food crops	Fecal Coliform or E. Coli (Weekly): 200 (30-day geometric mean), 800 (Max) Enterococci (Weekly): 35 (30-day geometric mean), 89 (Max)
Utah	
Food crops	E. Coli: 0 (Daily grab samples), 9 (Max)
Processed food crops/non-food crops	E. Coli: 126 (Weekly median), 500 (Max)

Table 4. *Cont.*

Reuse Categories	Required Microbial Quality (cfu/100 mL) (Monitoring)
Virginia	
Food crops	Fecal Coliform: 14 (Monthly geometric mean), Cat [2] > 49/100 mL, E. Coli: 11 (Monthly geometric mean), Cat > 35/100 mL Enterococci: 11 (Monthly geometric mean), Cat > 24/100 mL
Processed food crops/non-food crops	Fecal Coliform: 200 (Monthly geometric mean), Cat > 800/100 mL E. Coli: 126 (Monthly geometric mean), Cat > 235/100 mL Enterococci: 35 (Monthly geometric mean), Cat > 104/100 mL
Washington	
Food crops	Total Coliform (Daily): 2.2 (Median of last 7 days), 23 (Max)
Processed food crops/non-food crops	Total Coliform (Daily): 23 (Median of last 7 days), 240 (Max)
Cyprus	
Agglomerations > 2000 p.e. [3]	E. Coli (1/15 Days): 5 Intestinal Nematodes: 0
Agglomerations < 2000 p.e. [3] all crops	Fecal Coliforms: 5 (80% of samples per month (Min. number of samples = 5)), 15 (Max) Intestinal Nematodes: 0
Agglomerations < 2000 p.e. [3] unlimited access and vegetables eaten cooked (potatoes, beetroots, colocasia)	Fecal Coliforms: 50 (80% of samples per month (Min. number of samples = 5)), 100 (Max) Intestinal Nematodes: 0
Agglomerations < 2000 p.e. [3] limited access and crops for human consumption	Fecal Coliforms: 1000 (80% of samples per month (Min. number of samples = 5)), 5,000 (Max) Intestinal Nematodes: 0
Agglomerations < 2000 p.e. [3] fodder crops	Fecal Coliforms: 1000 (80% of samples per month (Min. number of samples = 5)), 5,000 (Max) Intestinal Nematodes: 0
Italy	
NS	E. Coli: 10
Greece	
Restricted irrigation, fodder and industrial crops, pastures, trees (except fruit trees), provided that fruits are not in contact with the soil, seed crops, and crops whose products are processed before consumption. Sprinkler irrigation is not allowed	E. Coli (Weekly): 200 (Median)
Unrestricted irrigation: all crops including all irrigation methods	E. Coli (4/Week): 5 (80% of samples), 50 (95% of samples)
European Commission	
A:	E. Coli (Weekly): 10 (90% of The Samples) Intestinal Nematodes (2/Month): 1 Egg/L
B:	E. Coli (Weekly): 100 Intestinal Nematodes (2/Month): 1 Egg/L
C:	E. Coli (2/Month): 1000 Intestinal Nematodes (2/Month): 1 Egg/L
D:	E. Coli (2/Month): 10,000 Intestinal Nematodes (2/Month): 1 Egg/L
Israel	
NS	Fecal Coliforms: 10
Jordan	
A: cooked vegetables, parks, playgrounds roadsides in the city	E. Coli or Fecal Coliform: 100 Intestinal Nematodes: 1 Egg/L
B: fruit trees, landscaped roadsides of highways	E. Coli or Fecal Coliform: 1000
C: industrial crops, forest trees	NS
D: cut flowers	E. Coli or Fecal Coliform: 1.1
Kuwait	
NS	Total Coliforms: 400 Fecal Coliforms: 20
Saudi Arabia	
Restricted	Thermo-Tolerant Coliform: 1000 Intestinal Nematodes: 1
Unrestricted	Thermo-Tolerant Coliform: 2.2 Intestinal Nematodes: 1
Act (Australia)	
Pasture and fodder for grazing animals (except pigs)	Thermo-Tolerant Coliforms (Weekly): 1000 (Median)
Silviculture, turf, and non-food crops	Thermo-Tolerant Coliforms (Monthly): 10,000 (Median)
Food crops in direct contact with water e.g., sprays	Thermo-Tolerant Coliforms (Weekly): 10 (Median)
Food crops not in direct contact with water (e.g., flood or furrow) or which will be sold to consumers cooked or processed	Thermo-Tolerant Coliforms (Weekly): 1000 (Median)

Table 4. *Cont.*

Reuse Categories	Required Microbial Quality (cfu/100 mL) (Monitoring)
NSW (Australia)	
Food production, raw human food crops in direct contact with effluent e.g., via sprays, irrigation of salad vegetables	Thermo-Tolerant Coliforms (Weekly): 10 (Median) Intestinal Nematodes: 1 Egg/L
Food production, raw human food crops not in direct contact with effluent (edible product separated from contact with effluent, e.g., use of trickle irrigation) or crops sold to consumers cooked or processed.	Thermo-Tolerant Coliforms (Weekly): 1000 (Median)
Food production, pasture and fodder (for grazing animals except pigs and dairy animals, i.e., cattle, sheep, and goats)	Thermo-Tolerant Coliforms (Weekly): 1000 (Median)
Food production, pasture, and fodder for dairy animals (with withholding period).	Thermo-Tolerant Coliforms (Weekly): 1000 (Median)
Food production, pasture, and fodder for dairy animals (without withholding period). Drinking water (all stock except pigs). Wash-down water for dairies	Thermo-Tolerant Coliforms (Weekly): 100 (Median)
Non-food crops, silviculture, turf and cotton, etc.	Thermo-Tolerant Coliforms (Weekly): 10,000 (Median)
NT (Australia)	
A+: (high level of human contact) commercial food crops consumed raw or unprocessed (e.g., salad crops)	E. Coli (Weekly): 1
B: (medium level human contact) commercial food crops	E. Coli (Weekly): 100
C: (low level of human contact) commercial food crops	E. Coli (Weekly): 1000
D: (very low level of human contact) non-food crops (trees, turf, woodlots, flowers)	E. Coli (Annually): 10,000
QLD (Australia)	
(Minimally processed food crops) a+:	Clostridium Perfringens (Weekly): 1 (95%) E. Coli (Weekly): 1 (95%) F-RNA Bacteriophages (Weekly): 1 (95%) Somatic Coliphages: 1 (95%)
(Minimally processed food crops) a:	E. Coli (Weekly): 10 (95%)
(Minimally processed food crops) b:	E. Coli (Weekly): 100 (95%)
(Minimally processed food crops) c:	E. Coli (Weekly): 1000 (95%)
(Minimally processed food crops) d:	E. Coli (Weekly): 10,000 (95%)
TAS (Australia)	
A: direct contact of reclaimed water with crops consumed raw	Thermo-Tolerant Coliforms (Daily): 10 (Median)
B: crops for human consumption	Thermo-Tolerant Coliforms (Weekly): 1000 (Median)
C: non-human food chain	Thermo-Tolerant Coliforms (Weekly): 10,000 (Median)
VIC (Australia)	
A: commercial food crops consumed raw or unprocessed	E. Coli: 1
B: dairy cattle grazing	E. Coli: 100
C: human food crops/processed, grazing, fodder for livestock	E. Coli: 1000
D: non-food crops including instant turf, woodlots, flowers	E. Coli: 10,000
WA (Australia)	
(High level of human contact) commercial food crops consumed raw or unprocessed (e.g., salad crops)	E. Coli (Weekly): 1 Coliphages (Weekly): 1 Clostridia (Weekly): 1
(Low level of human contact) non-edible crops	E. Coli (Weekly): 1000
D: (extra low level of human contact) non-food crops (subsurface reticulation)	E. Coli (6 monthly): 10,000
AGWR (Australia)	
Commercial food crops consumed raw or unprocessed	E. Coli: 1
Commercial food crops	E. Coli: 100
Commercial food crops	E. Coli: 1000
Non-food crops- trees, turf, woodlots, flowers	E. Coli: 10,000

[1] Irrigation of Class III effluent on fruit and vegetables not commercially processed, including crops eaten raw, is prohibited. Irrigation of Class III effluent on bare soil is prohibited except for providing adequate moisture for seed germination in the seeding area. The irrigation area shall be planted with healthy vegetation cover. Irrigation on high water table or saturated soils which cause persistent surface runoff and ponding is prohibited. [2] Corrective active threshold. [3] Population equivalents.

Table 5. Less restrictive agricultural water reuse regulations and guidelines.

Reuse Categories	Required Microbial Quality (cfu/100 mL) (Monitoring)
FAO	
A: irrigation of crops likely to be eaten uncooked, sports field, public parks	Fecal Coliforms: 1000 (Geometric mean) Fecal Coliforms: 200 (In case of fruit trees, geometric mean) Intestinal Nematodes: 1 Egg/L (Arithmetic mean)
B: irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	Intestinal Nematodes: 1 Egg/L (Arithmetic mean)
C: localized irrigation of crops in category B if exposure of workers and the public does not occur	NS
WHO	
Restricted	E. Coli: 10,000 (Labor), 100,000 (Highly mechanized) Intestinal Nematodes: 1 Egg/L
Unrestricted (Drip irrigated)	E. Coli: 1000 (Low-growing), 100,000 (High-growing) Intestinal Nematodes: 1 Egg/L
Unrestricted	E. Coli: 1000 (Root crops), 10,000 (Leaf crops) Intestinal Nematodes: 1 Egg/L
Alberta	
Restricted	Total Coliform (Weekly or daily): 1000 (Geometric mean) Fecal Coliform (Weekly or daily): 200 (Geometric mean)
Unrestricted	Total Coliform (Weekly or daily): 1000 (Geometric mean) Fecal Coliform (Weekly or daily): 200 (Geometric mean)
Nebraska	
Unrestricted	Fecal Coliform: 200 (30-day geometric mean), 400 (No more than 10% samples)
South Dakota	
Food Crops	Total Coliform: 200 (Geometric mean)
Wyoming	
Food Crops	Fecal Coliform: 200
Processed food crops/non-food crops	Fecal Coliform: 1000
Mexico	
Restricted	Fecal Coliforms: 2,000 (Daily averages), 1000 (Monthly average)
Unrestricted	Fecal Coliforms: 2,000 (Daily average), 1000 (Monthly average)
France	
A: unrestricted irrigation of all crops including these accessed by the public	Enterococci (Weekly): ≥ 4 Logs E. Coli (Weekly): 250
B: all crops except those consumed raw or green areas with public access	Enterococci (1/15 days): ≥ 3 Logs E. Coli (1/15 days): 10,000
C: other ornamental crops, shrubs, cereals; horticultural crops drip irrigated, forests with controlled access	Enterococci (Monthly): ≥ 2 Logs E. Coli (Monthly): 100,000
D: forests with no access	Enterococci: ≥ 2 Logs
Spain	
2.1	E. Coli (Weekly): 100 Intestinal Nematodes: 1 Egg/10L
2.2: quality 2.2 (A) irrigation of crops for human consumption using application methods that do not prevent direct contact of reclaimed water with edible parts of the plants, which are not eaten raw but after an industrial treatment process. (B) irrigation of pasture land for milk- or meat-producing animals. (C) aquaculture.	E. Coli (Weekly): 1000 Intestinal Nematodes: 1 Egg/10L
2.3: (A) localized irrigation of tree crops whereby reclaimed water is not allowed to come into contact with fruit for human consumption. (B) irrigation of ornamental flowers, nurseries and greenhouses whereby reclaimed water does not come into contact with the crops. (C) irrigation of industrial non-food crops, nurseries, silo fodder, cereals and oilseeds.	E. Coli (Weekly): 10,000 Intestinal Nematodes: 1 Egg/10L

Table 5. *Cont.*

Reuse Categories	Required Microbial Quality (cfu/100 mL) (Monitoring)
Iran	
A: irrigation of crops likely to be eaten uncooked, sports field, public parks	Fecal Coliforms: 1000 (Geometric mean) Intestinal Nematodes: 1 (Arithmetic mean)
B: irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	Intestinal Nematodes: 1 (Arithmetic mean)
C: localized irrigation of crops in category b if exposure of workers and the public does not occur	NS
Egypt	
A: plants and trees grown for greenery at touristic villages and hotels and inside residential areas at the new cities	Fecal Coliforms: 1000
B: fodder/feed crops, trees producing fruits with epicarp trees used for green belts around cities and afforestation of highways or roads nursery plants roses and cut flowers fiber crops mulberry for the production of silk	Fecal Coliforms: 5000
C: industrial oil cropswood trees	NS
China	
Fiber crops	Fecal Coliforms: 40,000 Intestinal Nematodes: 2
Dry field corn oil crops	Fecal Coliforms: 40,000 Intestinal Nematodes: 2
Paddy field grain	Fecal Coliforms: 20,000 Intestinal Nematodes: 2
Vegetable	Fecal Coliforms: 20,000 Intestinal Nematodes: 2
Palestine	
A: High quality	Fecal Coliforms (1 sample/2 days): 200
B: Good quality	Fecal Coliforms (1 sample/2 days): 1000
C: Medium quality	Fecal Coliforms (1 sample/2 days): 1000
D: Low quality	Fecal Coliform (1 sample/2 days): 1000
Portugal	
A: vegetables consumed raw	Fecal Coliforms: 100
B: public parks, and gardens, sport lawns, forests with public access	Fecal Coliforms: 200
C: vegetables to be cooked, forage crops, vineyards, orchards	Fecal Coliforms: 1000
D: cereals (except rice), vegetables for industrial process, crops for textile industry, crops for oil extraction, forest and lawns in places of restricted or controlled public access	Fecal Coliforms: 10,000
Oman	
A: vegetables likely to be eaten raw, fruit likely to be eaten raw and within 2 weeks of any irrigation	Fecal Coliform: 200 Intestinal Nematodes: 1 Egg/L
B: vegetables to be cooked or processed, fruit if no irrigation within 2 weeks of cropping, fodder, cereal, seed crops, pasture no public access	Fecal Coliform: 1000 Intestinal Nematodes: 1 Egg/L

Fifteen documents were gathered under less restrictive regulations and guidelines (Table 5). The indicator parameters in these regulations and guidelines included Fecal Coliforms (11 documents), Intestinal Nematodes (6 documents), E. coli (3 documents), Total Coliforms (2 documents), and Enterococci (1 document). Similar to restrictive regulations and guidelines, the threshold limits for food crops irrigation and unrestricted public access categories had lower values than processed food crops/non-food crops and restricted public access categories. In addition, threshold levels for same parameters are sometimes very different, when regulations and guidelines are compared with each other (Table 5).

BY comparing the required microbial quality thresholds, one can simply notice large discrepancies among the existing regulations and guidelines. Of note is that none of the less restrictive regulations and guidelines used thermo-tolerant Coliforms in their documents. To have a better idea of these thresholds, common pathogen indicators were analyzed using descriptive statistical analysis (Table 6). Fecal Coliform was used more than the other indicators in the regulations and guidelines (Table 6). E. Coli thresholds had the largest range, 100,000, among the indicators. Additionally, the most frequent threshold of Fecal Coliform, E. Coli, Total Coliform, Thermo-Tolerant Coliform, Intestinal Nematodes, Enterococci, Coliphages, Clostridia, and F-RNA Bacteriophages were 200, 1000, 23, 1000, 1, 35, 1, 1, and 1, respectively (Table 6).

Table 6. Descriptive statistical analysis of common pathogen indicators included in agricultural water reuse regulations and guidelines.

Microbial Indicator (cfu/100 mL)	Number of Documents	Total Number of Indications	Mean	Standard Error	Median	Mode	Minimum	Maximum
Fecal Coliform	36	100	1810.62	627.08	200	200	0 [1]	40,000 [2]
E. Coli	24	69	6017.74	2465.17	126	1000	0 [3]	100,000 [4]
Total Coliform	9	22	284.18	113.92	23	23	2.2 [5]	2300 [6]
Thermo-tolerant Coliform	5	20	2417.61	875.33	1000	1000	2.2 [7]	10,000 [8]
Intestinal nematodes (Egg/L)	12	33	0.97	0.09	1	1	0 [9]	2 [10]
Enterococci	3	10 [11]	30.5	12.92	23	35	4 [12]	89 [13]
Coliphages	2	2	1	0	1	1	1 [14]	1
Clostridia	2	2	1	0	1	1	1 [15]	1
F-RNA Bacteriophages	1	1	1	0	1	1	1 [16]	1

[1] EPA, Arizona, Florida, Indiana, and Massachusetts. [2] China. [3] Utah. [4] WHO and France. [5] California, Minnesota, Montana, Oregon, and Washington. [6] Idaho. [7] Saudi Arabia. [8] ISO, ACT, NSW, and TAS. [9] Cyprus. [10] China. [11] Four of the Enterococci thresholds, issued by France, are in terms of log reduction, excluded from the statistical analysis. [12] Texas. [13] Texas. [14] QLD and WA. [15] QLD and WA. [16] QLD.

One of the main human health concerns related to water reuse is intestinal parasitic infections [136]. Verbyla et al. [137] showed that the consumption of lettuce irrigated with river water, contaminated with fecal contamination, resulted in an estimated median health burden that represented 37% of Bolivia's overall diarrheal disease burden. However, irrigation with filtered riverbank resulted in an estimated health burden that was only 1.1% of this overall diarrheal disease burden. Median concentrations of different contaminants in the river water were as follows: 3.2×10^8 adenovirus copies/L, 6.4×10^7 pepper mild mottle virus copies/L, 1.8×10^7 E. Coli cfu/L, 1.4×10^7 human-specific HF183 Bacteroides copies/L, 3.6×10^6 human rotavirus group A copies/L, 1.1×10^5 Coliphage pfu/L, 530 Giardia cysts/L, and 4.0 Cryptosporidium oocysts/L [137]. The following contaminants were detected in the filtered riverbank (lower median concentrations): 1.1×10^5 adenovirus copies/L, 7.7×10^4 pepper mild mottle virus copies/L, 3.0×10^3 E. coli cfu/L, 4.5×10^1 human-specific HF183 Bacteroides copies/L, 5.9×10^2 Coliphage pfu/L, 2.0 Giardia cysts/L, and 0.04 Cryptosporidium oocysts/L [137].

Based on Table 5 and the study by Verbyla et al. [137] it is apparent that the microbial parameters and their thresholds in the existing regulations and guidelines are not adequate to make sure agricultural water reuse practices are safe for human health. For example, E. Coli threshold set by WHO and France is 100,000 cfu/100mL, however other studies showed that irrigation with a water with E. Coli concentration of 18,000 cfu/mL caused an estimated median health burden that represented 37% of Bolivia's overall diarrheal disease burden [137].

It has also been reported that the greatest health risk in developing countries is the high concentration of Nematode eggs (>1 Egg/L) when water reuse is practiced using spray irrigation technology, especially in case of vegetables eaten raw by children [4]. Among the regulations and guidelines that were evaluated in this study, only 12 documents have included intestinal nematodes including ISO, Cyprus, E.U., Saudi Arabia, Tunisia, and NSW, from the restrictive group, and FAO, WHO, Spain, Iran, China, and Oman from the less restrictive group (Tables 4 and 5).

Chemicals

Another human health concern related to recycled water use is potential contamination of crops and groundwater by chemical constituents that may be present in water. These chemicals may include heavy metals, pharmaceuticals, personal care products, and compounds which exert endocrine disruption properties such as hormones or other chemicals including PCBs, Octilphenol, Nonilphenol, etc. [4]. These hazardous chemicals are of great concern for human health especially in heavily polluted industrial wastewater [4]. On the other hand, there is still a huge data gap in terms of characterization and treatment of these chemicals which their concentrations are very low in concerning waters. Only a few agricultural water reuse regulations and guidelines included the chemical constituents in their documents (Table 7). Despite the potential negative consequences of these chemical constituents, only 17 regulations and/or guidelines included some of these chemical parameters (Table 7). Among the studied regulations and guidelines, Italy, China, Oman, and AGWR have included the highest number of chemical constituents in their documents (32, 22, 21, and 20 chemical parameters respectively, Table 7).

Table 7. Chemicals and trace elements thresholds in agricultural water reuse regulations and guidelines (numbers in parentheses show the threshold level of chemical constituents and trace elements).

Chemical/Trace Element	Number of Documents that Included this Parameter	Range (mg/L)	Regulation/Guideline (Thresholds as mg/L)
Cadmium (Cd)	17	0.0001–0.2	EPA (0.01), FAO (0.01), WHO (0.01), British Columbia (0.05), Atlantic Canada (0.005), Cyprus (0.2), Italy (0.005), Greece (0.01), Israel (0.01), Jordan (0.01), Kuwait (0.01), Oman (0.01), Saudi Arabia (0.01), Tunisia (0.1), China (0.01), ACT (0.01), AGWR (0.0001–0.005)
Chromium (Cr)	17	0.001–0.15	EPA (0.1), FAO (0.1), WHO (0.1), British Columbia (hexavalent: 0.008), Atlantic Canada (hexavalent:0.008, trivalent:0.005), Cyprus (0.1), Italy (0.1), Greece (0.1), Israel (0.1), Jordan (0.1), Kuwait (0.15), Oman (0.05), Saudi Arabia (0.1), Tunisia (0.1), China (0.1), ACT (0.1), AGWR (0.001–0.021)
Nickel (Ni)	17	0.002–0.2	EPA (0.2), FAO (0.2), WHO (0.2), British Columbia (0.2), Atlantic Canada (0.2), Cyprus (0.2), Italy (0.2), Greece (0.02), Israel (0.2), Jordan (0.2), Kuwait (0.2), Oman (0.1), Saudi Arabia (0.2), Tunisia (0.2), China (0.1), ACT (0.2), AGWR (0.002–0.02)
Iron (Fe)	16	0.3–4.7	EPA (5), FAO (5), WHO (5), British Columbia (5), Atlantic Canada (5), Italy (2), Greece (3), Israel (2), Jordan (5), Kuwait (5), Oman (food crops:1, non-food crops:5), Saudi Arabia (2), Tunisia (0.5), China (1.5), ACT (1), AGWR (0.03–4.725)
Arsenic (As)	16	0.004–0.1	EPA (0.1), FAO (0.1), WHO (0.1), British Columbia (0.1), Atlantic Canada (0.1), Italy (0.02), Greece (0.1), Israel (0.1), Jordan (0.1), Kuwait (0.1), Oman (0.1), Saudi Arabia (0.1), Tunisia (0.1), China (0.05), ACT (0.1), AGWR (0.004)
Copper (Cu)	16	0.002–1	EPA (0.2), FAO (0.2), WHO (0.2), Atlantic Canada (0.2–1), Cyprus (0.1), Italy (1), Greece (0.2), Israel (0.2), Jordan (0.2), Kuwait (0.2), Oman (food crops:0.05, non-food crops:0.1), Saudi Arabia (0.4), Tunisia (0.5), China (1), ACT (0.2), AGWR (0.002–0.091)
Lead (Pb)	16	0.001–5	EPA (5), FAO (5), British Columbia (0.2), Atlantic Canada (0.2), Cyprus (0.15), Italy (0.1), Greece (0.1), Israel (0.1), Jordan (0.2), Kuwait (0.5), Oman (food crops:0.1, non-food crops:0.2), Saudi Arabia (0.1), Tunisia (1), China (0.2), ACT (0.2), AGWR (0.001–0.02)
Cobalt (Co)	15	0.004–1	EPA (0.05), FAO (0.05), WHO (0.05), British Columbia (0.05), Atlantic Canada (0.05), Italy (0.05), Greece (0.05), Israel (0.05), Kuwait (0.2), Oman (0.05), Saudi Arabia (0.05), Tunisia (0.1), China (1), ACT (0.05), AGWR (0.0004–0.0013)

Table 7. *Cont.*

Chemical/Trace Element	Number of Documents that Included this Parameter	Range (mg/L)	Regulation/Guideline (Thresholds as mg/L)
Zinc (Zn)	15	0.5–5	EPA (2), FAO (2), WHO (2), Atlantic Canada (1–5), Cyprus (1), Italy (0.5), Greece (2), Israel (2), Kuwait (2), Oman (5), Saudi Arabia (2), Tunisia (5), China (2), ACT (2), AGWR (0.049–0.11)
Aluminum (Al)	14	0.011–5	EPA (5), FAO (5), WHO (5), British Columbia (5), Atlantic Canada (5), Italy (1), Greece (5), Israel (5), Jordan (5), Kuwait (5), Oman (5), Saudi Arabia (5), ACT (5), AGWR (0.011–0.665)
Manganese (Mn)	14	0.019–0.5	EPA (0.2), FAO (0.2), WHO (0.2), British Columbia (0.2), Atlantic Canada (0.2), Italy (0.2), Greece (0.2), Israel (0.2), Kuwait (0.2), Oman (food crops:0.1, non-food crops:0.5), Saudi Arabia (0.2), China (0.3), ACT (0.2), AGWR (0.019–0.069)
Beryllium (Be)	13	0.002–2	EPA (0.1), FAO (0.1), WHO (0.1), British Columbia (0.1), Atlantic Canada (0.1), Italy (10), Greece (0.1), Israel (0.1), Kuwait (2), Oman (food crops:0.1, non-food crops:0.3), Saudi Arabia (0.1), China (0.002), ACT (0.1)
Selenium (Se)	12	0.02–0.05	EPA (0.02), FAO (0.02), WHO (0.02), Atlantic Canada (0.02–0.05), Italy (0.01), Greece (0.02), Israel (0.02), Oman (0.02), Saudi Arabia (0.02), Tunisia (0.05), China (0.02), ACT (0.02)
Lithium (Li)	11	0.07–2.5	EPA (2.5), FAO (2.5), WHO (2.5), British Columbia (2.5), Atlantic Canada (2.5), Greece (2.5), Israel (2.5), Jordan (2, citrus:0.075), Oman (0.07), Saudi Arabia (0.07), ACT (2.5)
Molybdenum (Mo)	11	0.001–0.05	EPA (0.01), FAO (0.01), WHO (0.01), Atlantic Canada (0.01–0.05), Greece (0.1), Israel (0.01), Oman (food crops: 0.01, non-food crops: 0.05), Saudi Arabia (0.01), China (0.5), ACT (0.01), AGWR (0.001–0.021)
Vanadium (V)	11	0.1	EPA (0.1), FAO (0.1), WHO (0.1), British Columbia (0.1), Atlantic Canada (0.1), Italy (0.1), Greece (0.1), Israel (0.1), Oman (0.1), Saudi Arabia (0.1), China (0.1)
Mercury (Hg)	11	0.0001–0.2	Cyprus (0.005), Italy (0.001), Greece (0.002), Israel (0.002), Jordan (0.02), Kuwait (0.002), Oman (0.001), Saudi Arabia (0.001), Tunisia (0.001), China (0.001), AGWR (0.0001–0.002)
Total phenol	5	0.0005–1	Italy (0.1), Kuwait (1), Oman (food crops:0.001, non-food crops:0.002), Saudi Arabia (0.002), AGWR (0.0005–0.007)
Copernicum (Cn)	3	0.05–0.1	Italy (0.05), Oman (food crops:0.05, non-food crops:0.1), Saudi Arabia (0.05)
Silver (Ag)	3	0.0001–0.5	Oman (0.01), Saudi Arabia (0.5), AGWR (0.0001–0.005)
Magnesium (Mg)	3	0.5–150	Oman (150), Tunisia (0.5), AGWR (6–40)
Uranium (U)	2	0.01	British Columbia (0.01), Atlantic Canada (0.01)
Benzene	2	0.01–2.5	Italy (0.01), China (2.5)
Cyanide (Cn)	2	0.001–0.5	China (0.5), AGWR (0.001)
Calcium (Ca)	1	10–74.00	AGWR (10–74)
Tin (Sn)	1	3	Italy (3)
Titanium (Ti)	1	0.001	Italy (0.001)
Pentachlorophenol	1	0.003	Italy (0.003)
Total aldehydes	1	0.5	Italy (0.5)
Tetrachloroethylene	1	0.01	Italy (0.01)
Total Chlorinated solvents	1	0.04	Italy (0.04)
Total trihalomethanes	1	0.03	Italy (0.03)
Total aromatic solvents	1	0.001	Italy (0.001)
Benzo(a)pyrene	1	0.00001	Italy (10^{-5})
Total organic Nitrogen solvents	1	0.01	Italy (0.01)
Total surfactants	1	0.2–0.5	Italy (0.5), AGWR (anionic:0.2)
Chlorinated biocides	1	0.0001	Italy (0.0001)

Table 7. *Cont.*

Chemical/Trace Element	Number of Documents that Included this Parameter	Range (mg/L)	Regulation/Guideline (Thresholds as mg/L)
Phosphorated pesticides	1	0.00001	Italy (0.00001)
Other pesticides	1	0.05	Italy (0.05)
Volatile Phenol	1	1	China (1)
Linear alkynate sulfunic	1	5	China (5)
Trichloracetic aldehyde	1	0.5	China (0.5)
Acrolein	1	0.5	China (0.5)
Methanol	1	1	China (1)
Barium (Ba)	1	0.001–0.0375	AGWR (0.001–0.0375)

3.2.2. Agronomic Parameters

Agronomic parameters are of prominent importance in safe agricultural water reuse practices. Crops quality and yield, soil productivity, and ecological health have to be considered in safe agricultural water reuse practices.

pH

As the indicator of water acidity and alkalinity, pH is one of the water quality parameters that can be easily measured, and can be an indicator of the presence of toxic ions [4,67]. Although the normal pH range for safe irrigation is 6.5–8.4 [67], different pH ranges are used in the agricultural water reuse regulations and guidelines (Table 8 and Figure 2). Recycled water outside the normal pH range might result in nutritional imbalance, which may alter the crops growth and health, and facilitate the corrosion in pipelines, sprinklers, and control valves [4,138–141]. Lower pH makes heavy metals move easier in the soil, contaminating crops, and water bodies [142]. Out of 70 agricultural water reuse regulations and guidelines studied in this research, 34 documents included pH as one of their requirements (Table 8). The most common ranges are 6–9 and 6.5–8.5 (Figure 2).

Table 8. pH ranges in the agricultural water reuse regulations and guidelines.

6.0–9.0	6.5–8.5	6.5–8.0	6.0–8.5	5.0–10.0	6.0–9.5	5.5–8.5	5.5–8.0	6.2–9.8
EPA British Columbia	Maryland Massachusetts	FAO Alberta	Alabama Saudi Arabia	Mexico	Italy	China	TAS (AU)	AGWR (AU)
Georgia Indiana Iowa Nevada Ohio Rhode Island Utah Virginia Oman VIC (AU)	Cyprus Iran Israel Kuwait Tunisia Act (AU) NSW (AU) NT (AU) WA (AU)							

Salinity

It has been reported that salinity is one of the most important recycled water quality parameters for agricultural water reuse practices. This is due to the fact that high concentration of dissolved salts increases the soil water pressure, requiring more energy from plants to take up water from soil and also resulting in specific ion toxicity [4,142–145]. The salinity of irrigation water often determines the salinity in the soil. Total dissolved solids (TDS (mg/L)) or electric conductivity (EC (dS/m)) are often used as indicators of salinity. While each of these parameters are important individually, there is an approximate correlation between TDS and EC, as shown by Equation (1) [4].

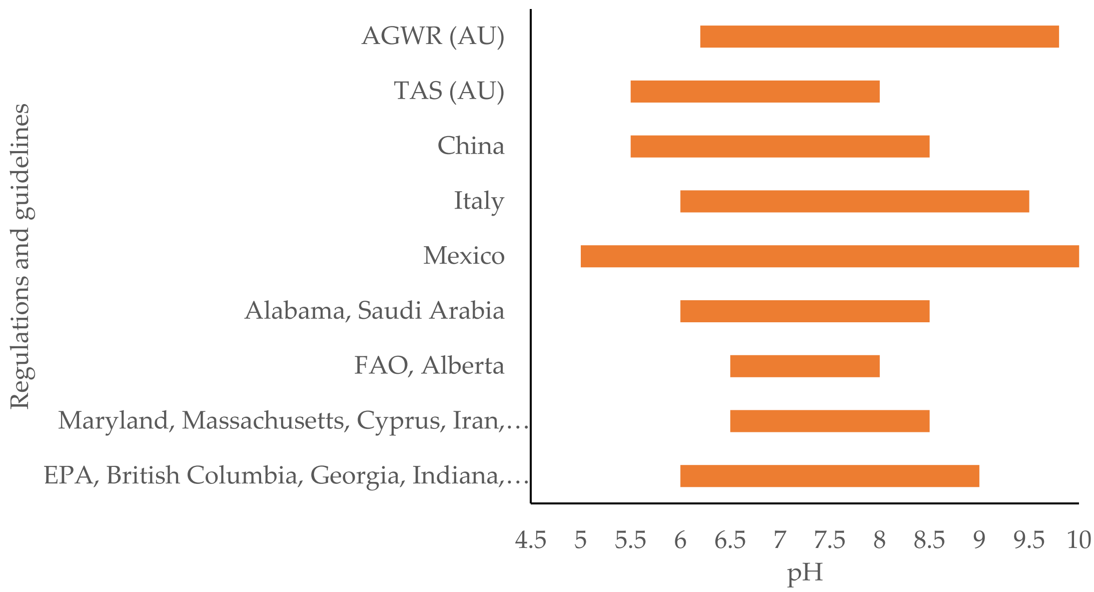

Figure 2. Required pH ranges in agricultural water reuse regulations and guidelines.

Three categories for EC and TDS thresholds are included in FAO's guideline based on the water use restriction as none, slight to moderate, and severe negative impact (Table 9 and Figure 3). Only 13 and 10 regulations and guidelines (out of 70) have included EC and TDS in their agricultural water reuse requirements, respectively (Table 9). FAO, Saskatchewan, Iran, Jordan, Oman, ACT, and AGWR regulations and guidelines have included both of EC and TDS thresholds in their documents. In addition, Kuwait, Saudi Arabia, and China have only included TDS in their regulations and guidelines. Of note is that none of the U.S. states included EC and TDS thresholds in their agricultural water reuse regulations and guidelines.

$$\mathrm{TDS}\left(\frac{\mathrm{mg}}{\mathrm{L}}\right) = \mathrm{EC}\left(\frac{\mathrm{dS}}{\mathrm{m}}\right) \times 640 \quad (1)$$

Table 9. Salinity (electric conductivity (EC) and total dissolved solids (TDS)) thresholds in agricultural water reuse regulations and guidelines.

Regulation/Guideline.	EC (dS/m)	TDS (mg/L)
FAO and Saskatchewan	None: <0.7 Slight to moderate: 0.7–3.0 Severe: >3	None: <450 Slit to moderate: 450–2000 Severe: >2000
Alberta and Atlantic Canada	Unrestricted: <1.0 Restricted: 1.0–2.5 Unacceptable: >2.5	NS [1] NS NS
Oman	Restricted (public access): 2.7 Unrestricted (public access): 2.0	Restricted (public access): 2000 Unrestricted (public access): 1500
China	NS NS	Saline-alkali land: 2000 Non-saline-alkali land: 1000
Cyprus	2.2	NS
Italy	3	NS
Iran	0.7	450
Israel	1.4	NS
Jordan	2.34	1500
Tunisia	7	NS
ACT	0.8	500
AGWR	0.2–2.9	145–1,224
Kuwait	NS	1500
Saudi Arabia	NS	Restricted irrigation: 2000

[1] Not specified.

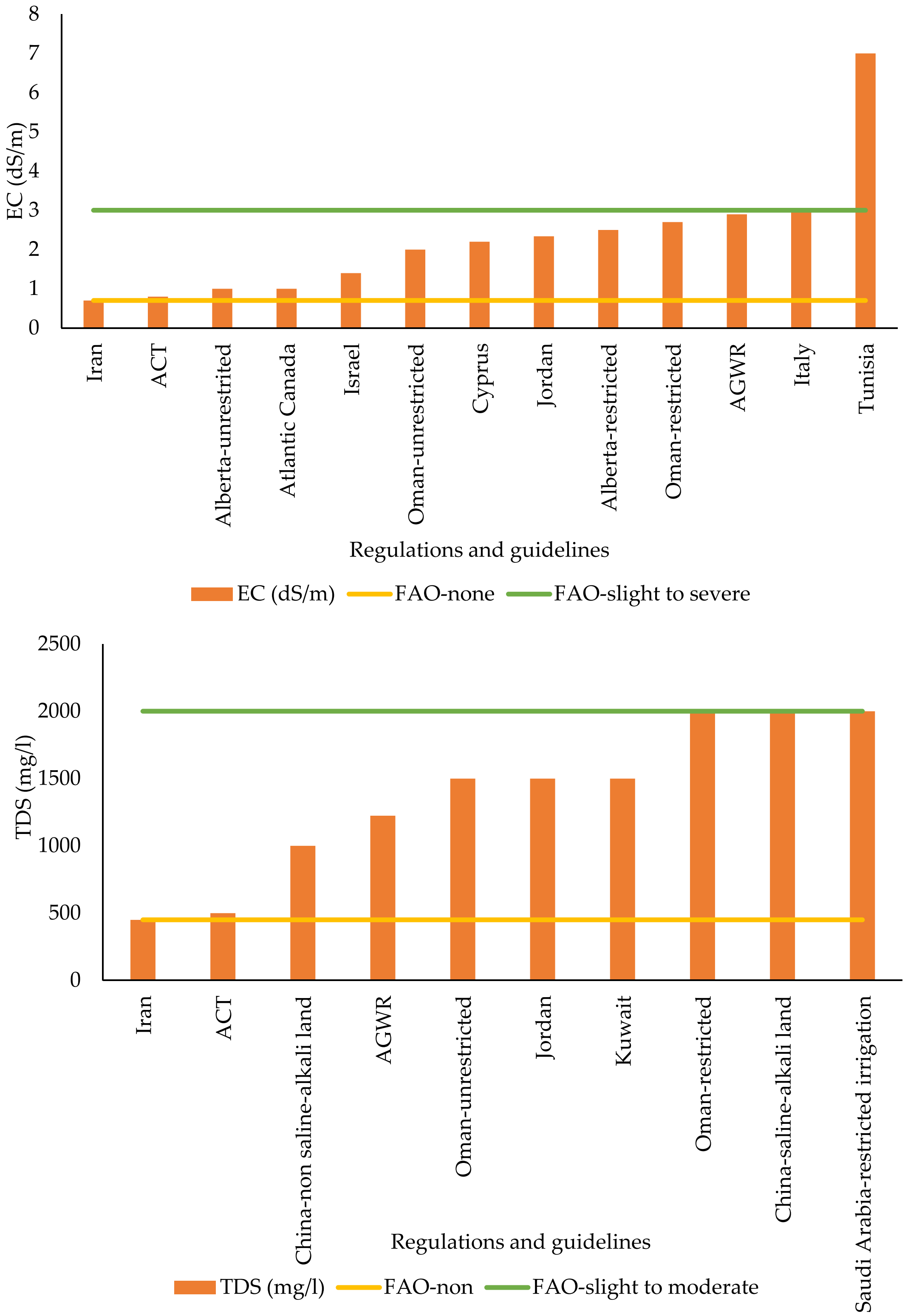

Figure 3. Salinity (electric conductivity (EC) and total dissolved solids (TDS)) thresholds in agricultural water reuse regulations and guidelines.

Sodium Adsorption Ratio (SAR)

Sodium is one of the important ions in irrigation water which has to be regulated for agricultural practices. Its presence in the exchangeable form in soil causes harmful effects on the physical and chemical properties of the soil. Excessive amounts of Sodium results in particle dispersion and reduction of water and air infiltration into the soil [4,143–146]. The most common Sodium indicator which has been used in literature was the sodium adsorption ratio (SAR) index, calculated by Equation (2).

$$SAR = \frac{Na^{+}}{\sqrt{0.5\left(Ca^{2+} + Mg^{2+}\right)}} \quad (2)$$

In this equation, SAR is the amount of Sodium adsorption ration, Na, Ca, and Mg are the concentrations of Sodium, Calcium, and Magnesium in me/L, respectively. There are no states in the U.S. with SAR threshold in their regulations or guidelines. In Canada, provinces of Alberta, Atlantic Canada, and Saskatchewan have included SAR thresholds for restricted and unrestricted agricultural water reuse practices (Table 10 and Figure 4). In Iran's guideline, the SAR threshold is set as 3 when the EC < 0.7 dS/m, which is its required EC threshold. Additionally, Iran includes other SAR thresholds when EC > 0.7 dS/m. Moreover, the highest SAR thresholds we issued by Italy and Oman. In total, 7 out of 70 regulations and guidelines investigated in this study have included SAR in their requirements.

Table 10. The SAR thresholds in the agricultural water reuse regulations and guidelines.

Organizations/Countries/States	SAR	Organizations/Countries/States	SAR
Alberta	4–9, restricted use when EC > 1.0 dS/m <4, unrestricted use	Italy Iran	10 <3, EC < 0.7 3–6, EC > 1.2 6–12, EC > 1.9 12–20, EC > 2.9 20–40, EC > 5
Atlantic Canada	4–9, restricted use <4, unrestricted use	Israel Oman	5 10
Saskatchewan	<3, no restriction 3–9, slight to moderate restriction >9, severe restriction	ACT AGWR	6 3–12.2

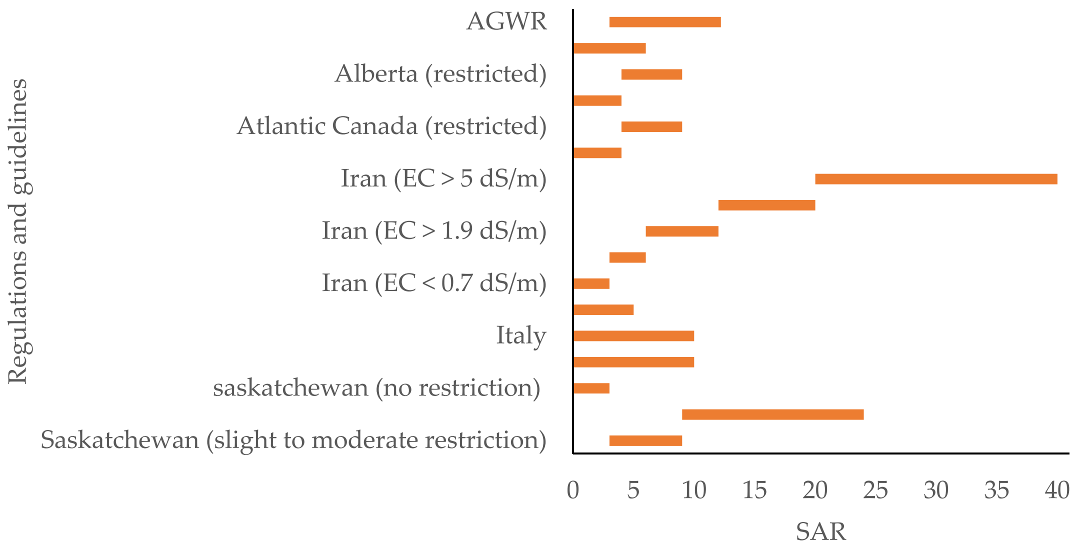

Figure 4. Required sodium adsorption ratio (SAR) ranges in agricultural water reuse regulations and guidelines.

Ions: Chloride, Sodium, and Boron

Resulting in crops growth and yield reduction, morphology changes, and death, the presence of toxic ions can be detrimental to crops if their concentrations are more than the desired levels [147]. Despite this potential negative impact, these ions are beneficial at relatively low concentrations.

Among these ions, Sodium (Na), Chloride (Cl^-), and Boron (B) are of great significance. The crop is affected by these ions which can be either direct by interference with the metabolic processes or indirect by influencing other nutrients [4]. Roots and leaves are the main parts of crops by which Sodium and Chloride can be absorbed. Usually, when the ion is absorbed by leaves, it increases the rate of absorption which results in toxic ion accumulation and can be the primary toxicity source [148].

Due to extensive use of perborate as a bleaching agent, residential wastewater often contains considerable amounts of Boron. While 1 mg/L of Boron is essential for crop growth, if its concentration reaches 2 mg/L or more, most of the crops will suffer from Boron toxicity [4]. The highest and lowest thresholds for Boron were issued by Atlantic Canada and Israel as 6.5 and 0.4 mg/L, respectively. Even though Boron concentrations of more than 2 mg/L can result in toxic crops, Tunisia and Atlantic Canada have set their Boron thresholds as 3 and 6.5 mg/L, respectively. Excess of Chloride can result in acute physiological dysfunctions. A salty taste is another result of more than desired amounts of Chloride, which affects crops market negatively [149]. The lowest chloride thresholds have been issued by Iran and Saudi Arabia, 100 mg/L, and the highest one has been issued by Tunisia, 2000 mg/L (Table 11). Additionally, among the U.S. states, only Delaware has included Chloride in its regulation. Extra Sodium increases osmotic stress and can kill crop cells [150]. For Sodium, just 6 documents out of 70 investigated documents have included Sodium among their water quality parameters. The lowest thresholds were issued by FAO, and Iran as 69 and 70 mg/L, respectively, and highest were issued by AGWR as 312 mg/L, and by Oman for non-food crops as 300 mg/L. Of note is none of the U.S. states have included Sodium thresholds in their regulations and guidelines.

Table 11. Toxic ions (Chloride, Sodium, and Boron) thresholds in agricultural water reuse regulations and guidelines.

Organization/Country/State	Chloride (Cl^-), mg/L	Sodium (Na^+), mg/L	Boron (B), mg/L
EPA			0.75
FAO	surface irrigation: <142 (unrestricted use) 142 < Cl < 355 (restricted use) sprinkler irrigation: <3 m^3/L (unrestricted use) 3 < m^3/L (restricted use)	surface irrigation: <3 SAR (unrestricted use) 3 < Na < 9 SAR (restricted use) sprinkler irrigation: <69 (unrestricted use) 69 < (restricted use)	<0.7 (unrestricted) 0.7 < B < 3 mg/L (restricted)
Atlantic Canada			0.5–6.5
Delaware	250		
Cyprus	300		1
Italy	250		1
Greece			2
Iran	100	70	0.7
Israel	250	150	0.4
Kuwait			2
Oman	650 (food crops) 650 (non-food crops)	200 (food crops) 300 (non-food crops)	0.5 (food crops) 1 (non-food crops)
Saudi Arabia	100		0.5
Tunisia	2000		3
China	350		1
AGWR	340	62 < Na < 312	0.009–0.480

Trace Elements

As mentioned before, trace elements (such as lead, cadmium, mercury, etc.) exist in low concentrations in wastewater but are hardly included in routine irrigation water analysis. Industrial and urban wastewater may contain considerable amount of trace elements and may result in accumulating of these compounds in soil and plants, reducing crop growth and polluting groundwater [4,151,152]. Trace elements accumulation in soils depends on their chemical form, consisting exchangeable, sorbed, organic-bound, carbonate, and sulfide. The uptake of these elements by plants mostly depend on rhizosphere environment, plant root system features, and soil characteristics. The soil pH has the most effect on the plant's uptake. Toxicities caused by trace elements have been mostly reported in acidic soils [4].

The threshold levels indicated by agricultural water reuse regulations and guidelines were issued using limited research by different agencies which have made these thresholds relatively restrictive (Table 7). Therefore, if the suggested threshold is not met, it does not mean that it will always result in phytotoxicity.

Trace elements thresholds were issued to help practice a safe and sustainable agriculture, but as these elements are used extensively nowadays, these thresholds need to be updated regularly. Additionally, more regulations and guidelines should include trace elements. Currently, at the best case, only 17 out of 70 investigated documents include trace elements. Of note is the discrepancies among the trace elements thresholds ranges in the documents. Cadmium (0.0001–0.2 mg/L), Arsenic (0.004–0.1 mg/L), Lead (0.001–0.5 mg/L), Copper (0.002–1 mg/L), and Mercury (0.0001–0.2) are some of the most frequent trace elements in current regulations and guidelines with 17, 16, 16, 16, and 11 number of mentions, respectively (Table 7).

Bicarbonate and Carbonate

Bicarbonate and Carbonate are among important ions for plant health. High concentrations of these ions in the recycled water for irrigation can cause different consequences [153–156]. Irrigation of crops by recycled water which has high concentrations of Bicarbonate and Carbonate, using overhead sprinklers, leaves white lime deposits on the crops leaves during hot irrigation days. These white deposits not only reduce the crops sells due to undesirable look but also result in clogging in the irrigation appurtenances, including spray nozzles and drip emitters [4]. Another issue is increasing the SAR levels in soil. If Bicarbonate ions bond with chemical elements such as Magnesium and Calcium, resulting in its precipitation as Magnesium Carbonate or Calcium Carbonate, it will increase the soil SAR levels owing to dissolved Calcium concentration decrease [67]. Finally, high concentration of Bicarbonate along with Carbonate may result in increase of soil pH, influencing soil permeability [67,156]. Despite these aforementioned consequences of Bicarbonate and Carbonate, they are mentioned in only three agricultural water reuse regulations and guidelines that were investigated including FAO, Iran, and Jordan (Table 12). Of note is only Iran includes Carbonate in its guideline.

Table 12. Bicarbonate and Carbonate thresholds in agricultural water reuse regulations and guidelines.

Organization/Country/State	Bicarbonate (mg/L)	Carbonate (mg/L)
FAO	91.5 (without restriction in use) 520 (with slight to moderate restrictions in use)	
Iran	90	3
Jordan	400	

Nutrients and Micronutrients

Important nutrients and micronutrients for crop growth include Nitrogen (N), Phosphorus (P), Potassium (K), Zinc (Zn), and Sulfur (S). Although Nitrogen is the most important nutrient for crop growth, high concentrations of this nutrient may result in over stimulation of plant growth, lodging, poor crop quality, maturity postponement, and excessive foliar growth [67,157,158]. Additionally, as a long-term consequence of Nitrogen high concentration, stalks, stems, and branches of crops go weak which make the crop incapable to support the weight of vegetation in the case of winds and rain [4]. Moreover, the pasture which has been irrigated with high Nitrogen levels may be an unsafe source for feeding the livestock. Phosphorous is also important for crop and livestock production. However, excess amounts of Phosphorous can increase the rate of eutrophication. EPA identified eutrophication as the major problem of surface waters in the U.S. This phenomenon decreases the amount of available water source for different applications and decreases dissolved Oxygen and sunlight in water which put aquatic health in danger. Groundwater contamination and eutrophication in coastal areas are among other consequences of high concentrations of nutrients [159]. Potassium can stimulate algae and bacteria growth, resulting in clogging the irrigation system [160]. High concentrations of Zinc can cause phytoxicity, including hindering crops and their roots growth, chlorosis, decreasing crops productivity, and killing leaf tips [161]

Comparing all of the nutrients (Table 13), it is apparent that Zinc, Boron, and Nitrogen have gained more attention than other nutrients in existing agricultural water reuse regulations and guidelines. Zinc and Boron were discussed in previous sections. Total Nitrogen and Nitrate have been mentioned more than other Nitrogen forms (Table 13). The common concentrations of total Nitrogen, Nitrate, Ammonium, and total Phosphorus are 20–85 mg/L, 0–30 mg/L, 5–40 mg/L, and 4–15 mg/L, respectively [4]. Regarding total Nitrogen, Jordan almost set its threshold near the common concentration of total Nitrogen in wastewater, however other regulations and guidelines require lower levels of total Nitrogen. Oman and FAO, for restricted irrigation, require almost the same or higher concentrations of Nitrate, but the other regulations and guidelines set relatively lower levels of Nitrate for irrigation by recycled water. For Ammonium, all of the existing regulations and guidelines require lower levels of Ammonium than its common concentration in wastewater. Phosphorus thresholds in the existing regulations and guidelines are also much lower than its average levels in wastewater. Phosphate was mentioned more than total Phosphorous in the studied documents. Comparing countries which issued Phosphate or Phosphorous threshold, of note is developed countries (such as Canada, Israel, Australia, and Italy) are more restrictive than developing countries (such as Iran, Jordan, and Kuwait).

Free Chlorine

Chlorine is used in wastewater treatment plants to disinfect the effluent. Its quantity usually is determined in such a way that there will be some free Chlorine in the treated wastewater to ensure water is protected from recontamination by pathogens in the piping and storage system. The average amount of allowable free Chlorine in recycled water for irrigation is 1 mg/L which does not impose any threat on crops, although there are some sensitive crops which are affected by higher that 0.5 mg/L of free Chlorine. If the concentration of free Chlorine goes higher than the accepted level, severe crop damage will occur including chlorosis, plant growth decrease, leaf discoloration, etc. [162,163]. Due to the free Chlorine nature, high-reactivity, and instability, if the recycled water is stored for a few hours before use, its excess free Chlorine will dissipate [4].

The most residual Chlorine threshold that are set in regulations and guidelines are 1 mg/L with 12 out of 25 regulations and guidelines and 0.5 mg/L with 6 out of 25 regulations and guidelines (Table 14). Moreover, China (1.5 mg/L) and two Australian guidelines, NT and WA (2 mg/L), require higher concentrations of 1 mg/L for residual Chlorine. Totally, 25 out of 70 regulations and guidelines require residual Chlorine monitoring as a part of their recycled water quality requirements.

Table 13. Nutrients thresholds in agricultural water reuse regulations and guidelines.

Organization /Country/State	Organic Nitrogen (mg/L)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)	Nitrate (NO_3^-) (mg/L)	Phosphate (PO_4^{-3}) (mg/L)	Ammonium (NH_4^+) (mg/L)	Ammonia (NH_3) (mg/L)
FAO	-	-	-	5 (without restriction) 30 (with slight to moderate restrictions)	-	-	-
Alabama	-	-	-	10 (Nitrates + Nitrites)	-	-	-
Saskatchewan	-	4 (food crops) 7 (non-food crops)	20 (food crops) 40 (non-food crops)	-	-	-	-
Massachusetts	-	-	10	-	-	-	-
Montana	-	-	5	-	-	-	-
New Jersey	-	-	10 (NO_3 + NH_3)	-	-	-	-
North Carolina	-	-	-	-	-	-	4 (NH_3) (monthly average) 6 (NH_3) (maximum)
Ohio	-	-	10	-	-	-	-
Rhode Island	-	-	15	-	-	-	-
South Carolina	-	-	-	10	-	-	2 (NH_3)
Cyprus	-	-	-	15	10	-	-
Italy	-	-	-	15	2	2	-
Iran	-	-	-	-	50	5	-
Israel	-	5	25	-	-	20	-
Jordan	-	-	45 (unrestricted, food crops) 70 (fruit trees) 100 (industrial crops, forest trees) 70 (cut flowers)	6.8 (unrestricted, food crops) 10.4 (fruit trees) 16.1 (industrial crops, forest trees) 10.4 (cut flowers)	30 (all of the categories)	-	-
Kuwait	-	-	35	-	30	15	-
Oman	5 (food crops) 10 (non-food crops)	-	-	50 (food crops) 50 (non-food crops)	-	5 (food crops) 10 (non-food crops)	-
Saudi Arabia	-	-	-	10 (unrestricted)	-	5 (unrestricted)	-
AGWR	-	12 (non-food crops)	39 (non-food crops)	-	-	34 (non-food crops)	-

Table 14. Residual Chlorine thresholds in agricultural water reuse regulations and guidelines.

Residual Chlorine (mg/L)	Number of Regulations and Guidelines	Organization/Country/State
2	2	NT (AU) and WA (AU)
1.5	1	China
1	12	NSW (AU), ACT (AU), Israel, Cyprus, Virginia, Utah, Pennsylvania, Ohio, New Jersey, Indiana, Idaho and EPA
0.5	6	QLD (AU), Kuwait, Rhode Island, Hawaii, Florida and Alabama
0.2	3	Saudi Arabia, Oklahoma and Italy
0.1	1	Kansas

3.2.3. Physico-Chemical Parameters

Turbidity

Turbidity is among important parameters with both human-health and agronomic significance. Disturbance to irrigation facilities, reduction in soil hydraulic conductivity, and polluting soil surface are among the potential negative impacts of excessive turbidity in recycled water [164,165]. One of the main reasons why suspended solids are measured and controlled in recycled water is that germs are able to move along with soils particles by attaching to them. So, agencies considered turbidity, TSS or SS in their agricultural water reuse regulations and guidelines as an indicator parameter. In total, 27 out of 70 regulations and guidelines included turbidity as one of their requirements (Table 15). There are five different methods of monitoring turbidity in the regulations and guidelines including 24-h average, more than 5% of the time in a 24-h period, maximum of anytime, maximum of anytime in case of using membranes and monthly average (Table 15). For the 24-h average, 2 NTU (Nephelometric Turbidity Units) is used in all of the regulations and guidelines, EPA, ISO, Arizona, Hawaii, Idaho, Maryland, Massachusetts, Minnesota, Oregon, Utah, Virginia, Washington, and NSW.

Table 15. Turbidity thresholds in agricultural water reuse regulations and guidelines.

Reuse Categories	Turbidity (NTU) (Monitoring)
EPA	
Food crops	2 (24-h average), 5 (Any time), 0.2 (Any time, if membranes are used) (continuous)
ISO	
A: very high-quality treated wastewater; unrestricted urban irrigation and agricultural irrigation of food crops consumed raw	2 (average), 5 (max)
British Columbia	
Unrestricted	2 (Continuous)
Arizona	
Food crops	2 (24-h average), 5 (Max) (continuous)
California	
Food crops	2 NTU (Continuous)
Delaware	
All types	5 (Continuous)
Georgia	
Processed food crops/non-food crops	3 (Continuous)
Hawaii	
Food crops	2 (Media filtration) (24-h average), 5 (Media filtration) (More than 5% of the time in a 24-h period), 10 (Media filtration) (Max); 0.2 (Membrane filtration) (More than 5% of the time in a 24-h period), 0.5 (Media filtration) (Max) (Continuous)

Table 15. *Cont.*

Reuse Categories	Turbidity (NTU) (Monitoring)
Idaho	
Food crops	2 (Arithmetic mean of all daily measurements), 5 (Max) (Continuous)
Maryland	
Class III (restricted access)	2 (Daily average)
Massachusetts	
A	2 (24-h average), 5 (More than 5% of the time within a 24-h period), 10 (Max)
Minnesota	
Food crops	2 (Daily average)
New Jersey	
Food crops	2
North Carolina	
All types	10
Oregon	
Food crops	2 (Before disinfection, within a 24-h period), 5 (Before disinfection, more than 5% of the time within a 24-h period), 10 (Max)
Pennsylvania	
Food crops	10 (Monthly average), 15 (Max) (Continuous)
Rhode Island	
Processed food crops/non-food crops	2
Texas	
Food crops	3 (2/week)
Utah	
Food crops	2 (Daily arithmetic mean), 5 (Max) (Continuous)
Processed food crops/non-food crops	25 (Daily arithmetic mean), 35 (Weekly mean) (Continuous)
Virginia	
Food crops	2 (Daily average of discrete measurements recorded over a 24-h period); CAT > 5 NTU
Washington	
Food crops	2 (Monthly average), 5 (Max) (Continuous)
Processed food crops/non-food crops	2 (Monthly average), 5 (Max) (Continuous)
Spain	
2.1	10 (1/week)
Greece	
Unrestricted irrigation: All crops including all irrigation methods	2
E.U.	
A:	5 (90% of the samples), 10 (Max)
Saudi Arabia	
Unrestricted	5
ACT (Australia)	
Food crops in direct contact with water e.g., sprays	2
NSW (Australia)	
Food production, raw human food crops in direct contact with effluent e.g., via sprays, irrigation of salad vegetables	2 (24-h mean), 5 (Max) (Continuous)

Table 15. *Cont.*

Reuse Categories	Turbidity (NTU) (Monitoring)
NT (Australia)	
A+: (high level of human contact) commercial food crops consumed raw or unprocessed (e.g., salad crops)	2 (95%), 5 (Max) (Continuous)
B: (medium level human contact) commercial food crops	5 (95%) (Continuous)
QLD (Australia)	
(Minimally processed food crops) A+:	2 (95%)
WA (Australia)	
(High level of human contact) commercial food crops consumed raw or unprocessed (e.g., salad crops)	2 (95%), 5 (Max) (Continuous)

Regarding the second category, more than 5% of the time in a 24-h period, 2 NTU is used by Australian states, NT, QLD, and WA, and 5 NTU is used by the U.S. states, Hawaii, Massachusetts, Oregon, and European Commission. The next category, maximum of anytime, is used more than the others by 27 regulations and guidelines. In this category, Pennsylvania requires the highest threshold and British Columbia, California, New Jersey, Rhode Island, Greece, and ACT require the lowest threshold for turbidity in agricultural water reuse practices. The last two categories are not used as the others. Hawaii and EPA, as two of the restrictive guidelines, set 0.2 NTU for their turbidity threshold when membranes are used for treating the recycled water. The monthly average is only used by the state of Pennsylvania, 10 NTU.

Total Suspended Solids (TSS)/SS and TS

The TS consists of total suspended solids (TSS) and TDS which are separated from each other by a filtration process. Solids which remain on the filter are suspended solids and those that pass the filter are dissolved solids. According to WHO [60], TSS consists of a diverse range of materials, namely industrial waste, decaying plants and animal matter, and silts, while TDS consists of dissolved organic matter and inorganic salts in water. As these two parameters are easily measured and they can be used as indicators of recycled water quality, many organizations and agencies have included them in their agricultural water reuse regulations and guidelines (Tables 9 and 16). Of note is that the allowable concentration of TDS in those regulations and guidelines which included both TDS and TSS thresholds are much higher than the allowable concentration of TSS for using recycled water in agriculture (Figure 5), preventing erosion, corrosion, and clogging in irrigation facilities, and damaging crops. In total, TSS is mentioned in agricultural water reuse regulations and guidelines by 43 documents.

Biological Oxygen Demand (BOD_5), Carbonaceous Oxygen Demand ($CBOD_5$), and Chemical Oxygen Demand (COD)

Biological oxygen demand (BOD), carbonaceous oxygen demand (CBOD), and chemical oxygen demand (COD) are different indicators of organic matter in water. Organic matter in the water may alter the water's color and odor, provide nutrients for microbial growth, and negatively impact the disinfection process [142]. To prevent these adverse effects, different organizations and agencies have included BOD_5, $CBOD_5$, and COD thresholds in their regulations and guidelines (Tables 17–19). In total, 7, 42, and 8 regulations and guidelines included $CBOD_5$, BOD_5, and COD in their requirements, respectively. The highest and lowest $CBOD_5$ thresholds are issued by Alberta (restricted and unrestricted public access) and Texas (food crops) as 100 and 5 mg/L, respectively (Table 17). The highest BOD_5 thresholds is issued by Egypt (C: industrial oil crops and wood trees) as 400 mg/L (Table 18). The lowest BOD_5 threshold are issued by Texas (food crops), Hawaii (food crops), and Georgia (non-food crops/processed food crops), and ISO (unrestricted/food crops) as 5 mg/L (Table 18). The highest and lowest COD thresholds are issued by Jordan (B: fruit trees, landscaped roadsides of highways and C: industrial crops, forest trees) China (vegetables) as 500 and 40 mg/L, respectively (Table 19).

Table 16. TSS/SS thresholds in agricultural water reuse regulations and guidelines.

Reuse Categories	TSS (mg/L) (Monitoring)
EPA	
(1) Food crops	5, 0.5 (If membranes are used)
(2) Process food crops and non-food crops	30 (Daily)
ISO	
A: very high-quality treated wastewater; unrestricted urban irrigation and agricultural irrigation of food crops consumed raw	5 (Average), 10 (Max)
B: high quality treated wastewater; restricted urban irrigation and agricultural irrigation of processed food crops	10 (Average), 25 (Max)
C: good quality treated wastewater; agricultural irrigation of non-food crops	30 (Average), 50 (Max)
D: medium quality treated wastewater; restricted irrigation of industrial and seeded crops	90 (Average), 140 (Max)
British Columbia	
Restricted	45 (Daily)
Alberta	
Restricted	100 (2/year)
Unrestricted	100 (2/year)
Alabama	
	30 (Monthly average) (Weekly)
Colorado	
Processed food crops/non-food crops	30 (Daily)
Delaware	
All types	10 (2/month)
Florida	
Food crops	5
Processed food crops/non-food crops	10
Georgia	
Processed food crops/non-food crops	5 (Weekly)
Hawaii	
Food crops	10
Processed food crops/non-food crops	30 (Monthly average of composite samples)
Indiana	
Food crops	5 (24-h average) (Daily)
Processed food crops/non-food crops	30 (24-h average) (Daily)
Iowa	
Processed food crops/non-food crops	30 (30-day average), 45 (7-day average)
Maryland	
Class I (restricted access)	90 (Monthly average)
Class II (restricted access)	10 (Monthly average)
Massachusetts	
A	5
C	30
Nevada	
Processed food crops/non-food crops	30
New Jersey	
Food Crops	5

Table 16. *Cont.*

Reuse Categories	TSS (mg/L) (Monitoring)
New Mexico	
All types (in case of food crops: just food trees and nut trees)	30
North Carolina	
All types	5 (Monthly average), 10 (Max)
North Dakota	
Processed food crops/non-food crops	45 (Maximum) (Daily)
Ohio	
Processed food crops/non-food crops	45 (2/week)
Pennsylvania	
Processed food crops/non-food crops	30 (Average), 45 (Maximum) (Weekly)
Rhode Island	
Processed food crops/non-food crops	8
Virginia	
Processed food crops/non-food crops	30 (Monthly average), 45 (Maximum weekly average)
Washington	
Food crops	30 (Arithmetic mean of all samples collected during the month) (Daily)
Processed food crops/non-food crops	30 (Arithmetic mean of all samples collected during the month) (Daily)
Cyprus	
Agglomerations > 2000 p.e.*	10 (1/15 days)
Agglomerations < 2000 p.e.* all crops	10 (80% of samples per month (minimum number of samples = 5))
Agglomerations < 2000 p.e.* unlimited access and vegetables eaten cooked (potatoes, beetroots, colocasia)	10 (80% of samples per month (minimum number of samples = 5)), 15 (Max)
Agglomerations < 2000 p.e.* limited access and Crops for human consumption	30 (80% of samples per month (minimum number of samples = 5)), 45 (Max)
Agglomerations < 2000 p.e.* fodder crops	30 (80% of samples per month (minimum number of samples = 5)), 45 (Max)
France	
A: unrestricted irrigation of all crops including these accessed by the public	15 (Weekly)
Italy	
	10
Spain	
2.1	20 (Weekly)
2.2: QUALITY 2.2 (a) Irrigation of crops for human consumption using application methods that do not prevent direct contact of reclaimed with edible parts of the plants, which are not eaten raw but after an industrial treatment process. (b) Irrigation of pasture land for milk- or meat-producing animals. (c) Aquaculture.	35 (Weekly)
2.3: (a) Localized irrigation of tree crops whereby reclaimed water is not allowed to come into contact with fruit for human consumption. (b) Irrigation of ornamental flowers, nurseries and greenhouses whereby reclaimed water does not come into contact with the crops. (c) Irrigation of industrial non-food crops, nurseries, silo fodder, cereals and oilseeds.	35 (Weekly)

Table 16. *Cont.*

Reuse Categories	TSS (mg/L) (Monitoring)
Greece	
Restricted irrigation: Areas where public access is not expected, fodder and industrial crops, pastures, trees (except fruit trees), provided that fruits are not in contact with the soil, seed crops and crops whose products are processed before consumption. Sprinkler irrigation is not allowed	35
Unrestricted irrigation: All crops including all irrigation methods	10 (80% of samples)
E.U.	
A:	10 (90% of samples), 20 (maximum)
B:	35
C:	35
D:	35
Iran	
A: Irrigation of crops likely to be eaten uncooked, sports field, public parks	40
B: Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	40
C: Localized irrigation of crops in category B if exposure of workers and the public does not occur	40
Israel	
	10
Jordan	
A: cooked vegetables, parks, playgrounds roadsides in the city	50
B: fruit trees, landscaped roadsides of highways	200
C: industrial crops, forest trees	300
D: cut flowers	15
Kuwait	
	15
Oman	
A: vegetables likely to be eaten raw, fruit likely to be eaten raw and within 2 weeks of any irrigation	15
B: vegetables to be cooked or processed, fruit if no irrigation within 2 weeks of cropping fodder, cereal seed crops, pasture, no public access	30
Saudi Arabia	
Restricted	40
Unrestricted	10
Egypt	
A: plants and trees grown for greenery at touristic villages and hotels and inside residential areas at the new cities	20
B: fodder/feed crops, trees producing fruits with epicarp, trees used for green belts around cities and afforestation of highways or roads, nursery plants, roses and cut flowers, fiber crops, mulberry for the production of silk	50
C: industrial oil crops, wood trees	250
Tunisia	
	30
China	
Fiber crops	100
Dry field corn oil crops	90
Paddy field grain	80
Vegetable	60

Table 16. *Cont.*

Reuse Categories	TSS (mg/L) (Monitoring)
NSW (Australia)	
Food production, raw human food crops not in direct contact with effluent (edible product separated from contact with effluent, e.g., use of trickle irrigation) or crops sold to consumers cooked or processed.	30 (Weekly)
Food production, pasture and fodder (for grazing animals except pigs and dairy animals, i.e., cattle, sheep and goats)	30 (Weekly)
Food production, pasture and fodder for dairy animals (with withholding period).	30 (Weekly)
Food production, pasture and fodder for dairy animals (without withholding period). Drinking water (all stock except pigs). Wash-down water for dairies.	30 (Weekly)
Non-food crops, Silviculture, turf and cotton, etc.	30 (Weekly)
NT (Australia)	
A+: (high level of human contact) commercial food crops consumed raw or unprocessed (e.g., salad crops)	10 (Weekly)
B: (medium level human contact) commercial food crops	30 (Weekly)
C: (low level of human contact) commercial food crops	30 (Weekly)
VIC (Australia)	
B: dairy cattle grazing	30
C: human food crops/processed, grazing, fodder for livestock	30
D: non-food crops including instant turf, woodlots, flowers	30
WA (Australia)	
(High level of human contact) commercial food crops consumed raw or unprocessed (e.g., Salad crops)	10 (Weekly)
(Low level of human contact) non-edible crops	30 (Weekly)
AGWR (Australia)	
Commercial food crops	30

* Population equivalents.

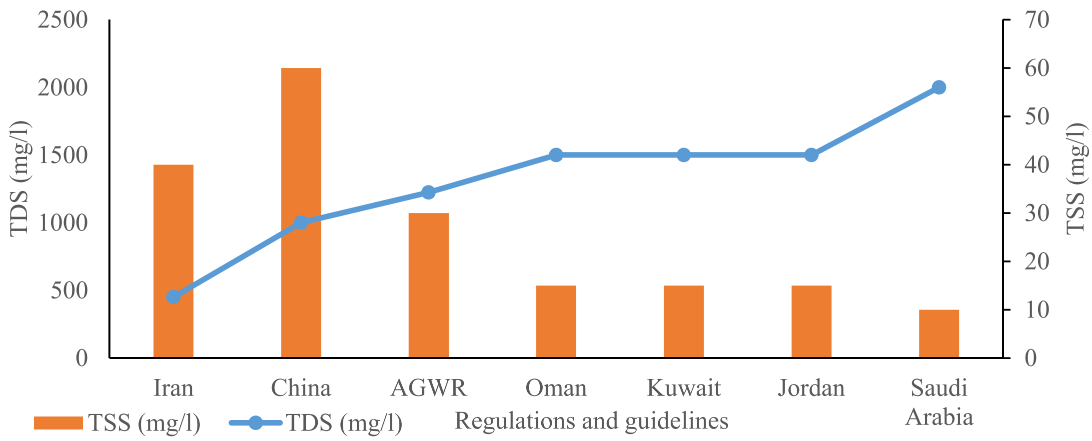

Figure 5. Comparison of the TDS and selected total suspended solids (TSS) thresholds, required in agricultural water reuse regulations and guidelines which included both of TDS and TSS thresholds.

Table 17. $CBOD_5$ thresholds in agricultural water reuse regulations and guidelines.

Reuse Categories	$CBOD_5$ (mg/L) (Monitoring)
Alberta	
Restricted	100 (2/year)
Unrestricted	100 (2/year)
Alabama	
	10 (Monthly average) (Weekly)
Iowa	
Processed food crops/non-food crops	25 (30-day average), 40 (7-day average)
Ohio	
Processed food crops/non-food crops	40 (2/week)
Oklahoma	
Processed food crops/non-food crops	20 (Weekly)
Texas	
Food crops	5 (2/week)
Processed food crops/non-food crops	15 (weekly)
Virginia	
Food crops	8 (Monthly average)
Processed food crops/non-food crops	25 (Monthly average), 40 (Max weekly average)

Table 18. BOD_5 thresholds in agricultural water reuse regulations and guidelines.

Reuse Categories	BOD_5 (mg/L) (Monitoring)
EPA	
(1) Food crops	10 (Weekly)
(2) Process food crops/non-food crops	30 (Weekly)
ISO	
A: very high-quality treated wastewater; unrestricted urban irrigation and agricultural irrigation of food crops consumed raw	5 (Average), 10 (Max)
B: high quality treated wastewater; restricted urban irrigation and agricultural irrigation of processed food crops	10 (Average), 20 (Max)
C: good quality treated wastewater; agricultural irrigation of non-food crops	20 (Average), 35 (Max)
D: medium quality treated wastewater; restricted irrigation of industrial and seeded crops	60 (Average), 100 (Max)
E: extensively treated wastewater; restricted irrigation of industrial and seeded crops	20 (Average), 35 (Max)
British Columbia	
Restricted	45 (Weekly)
Unrestricted	10 (Weekly)
Delaware	
All types	10 (2/month)
Georgia	
Processed food crops/non-food crops	5 (Weekly)
Hawaii	
Food crops	5 (R-1), 10 (R-2)
Processed food crops/non-food crops	30 (Monthly average of composite samples)
Indiana	
Food crops	10 (Weekly)
Processed food crops/non-food crops	30 (Weekly)

Table 18. *Cont.*

Reuse Categories	BOD_5 (mg/L) (Monitoring)
Maryland	
Class I (restricted access)	70 (Monthly average)
Class II (restricted access)	10 (Monthly average)
Class III (restricted access)	10 (Monthly average)
Massachusetts	
A	10
C	30
Nevada	
Processed food crops/non-food crops	30
New Mexico	
All types (in case of food crops: just food trees and nut trees)	30
North Carolina	
All types	10 (Monthly average), 15 (Daily max)
North Dakota	
Processed food crops/non-food crops	30 (Daily max) (1/14 days)
Oklahoma	
Processed food crops/non-food crops	20 (Weekly)
Pennsylvania	
Food crops	10 (Monthly average), 20 (Max) (Weekly)
Processed food crops/non-food crops	30 (Monthly average), 45 (Max) (Weekly)
Rhode Island	
Processed food crops/non-food crops	10
South Carolina	
Processed food crops/non-food crops	10
Texas	
Food crops	5 (2/week)
Processed food crops/non-food crops	20 (1/week)
Utah	
Food crops	10 (Monthly arithmetic mean) (Weekly)
Processed food crops/non-food crops	25 (Monthly arithmetic mean) (Weekly)
Virginia	
Food crops	10 (Monthly average)
Processed food crops/non-food crops	30 (Monthly average), 45 (Max weekly average)
Washington	
Food crops	30 (Monthly arithmetic mean) (Weekly)
Processed Food Crops/Non-Food Crops	30 (Monthly arithmetic mean) (Weekly)
Wisconsin	
All types	50
Cyprus	
Agglomerations > 2000 p.e.*	10 (1/15 days)
Agglomerations < 2000 p.e.* all crops	10 (80% of samples per month (minimum number of samples = 5))
Agglomerations < 2000 p.e.* unlimited access and vegetables eaten cooked (potatoes, beetroots, colocasia)	10 (80% of samples per month (minimum number of samples = 5)), 15 (Max)
Agglomerations < 2000 p.e.* limited access and Crops for human consumption	20 (80% of samples per month (minimum number of samples = 5)), 30 (Max)
Agglomerations < 2000 p.e.* fodder crops	20 (80% of samples per month (minimum number of samples = 5)), 30 (Max)
Italy	
	20

Table 18. *Cont.*

Reuse Categories	BOD_5 (mg/L) (Monitoring)
Greece	
Restricted irrigation: Areas where public access is not expected, fodder and industrial crops, pastures, trees (except fruit trees), provided that fruits are not in contact with the soil, seed crops and crops whose products are processed before consumption. Sprinkler irrigation is not allowed	25
Unrestricted irrigation: All crops including all irrigation methods	10 (80% of samples)
E.U.	
A:	10 (90% of samples), 20 (Max) (weekly)
B:	25
C:	25
D:	25
Iran	
A: Irrigation of crops likely to be eaten uncooked, sports field, public parks	21
B: Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	21
C: Localized irrigation of crops in category B if exposure of workers and the public does not occur	21
Israel	
	10
Jordan	
A: cooked vegetables, parks, playgrounds roadsides in the city	30
B: fruit trees, landscaped roadsides of highways	200
C: industrial crops, forest trees	300
D: cut flowers	30
Kuwait	
	20
Oman	
A: vegetables likely to be eaten raw, fruit likely to be eaten raw and within 2 weeks of any irrigation	15
B: vegetables to be cooked or processed, fruit if no irrigation within 2 weeks of cropping, fodder, cereal seed crops, pasture, no public access	20
Saudi Arabia	
Restricted	40
Unrestricted	10
Egypt	
A: plants and trees grown for greenery at touristic villages and hotels and inside residential areas at the new cities	20
B: fodder/feed crops, trees producing fruits with epicarp, trees used for green belts around cities and afforestation of highways or roads, nursery plants, roses and cut flowers, fiber crops, mulberry for the production of silk	60
C: industrial oil crops, wood trees	400
Tunisia	
	30
China	
Fiber crops	100
Dry field corn oil crops	80
Paddy field grain	60
Vegetable	40

Table 18. *Cont.*

Reuse Categories	BOD_5 (mg/L) (Monitoring)
ACT (Australia)	
Pasture and fodder for grazing animals (except pigs)	40 (kg/ha/day) (< 3 ML/year: initial and 6 monthly), (> 3 ML/year: initial and 3 monthly)
Silviculture, turf and non-food crops	40 (kg/ha/day) (< 3 ML/year: initial and 6 monthly), (> 3 ML/year: initial and 3 monthly)
Food crops in direct contact with water e.g., sprays	40 (kg/ha/day) (< 3 ML/year: initial and 6 monthly), (> 3 ML/year: initial and 3 monthly)
Food crops not in direct contact with water (e.g., flood or furrow) or which will be sold to consumers cooked or processed	40 (kg/ha/day) (< 3 ML/year: initial and 6 monthly), (> 3 ML/year: initial and 3 monthly)
NSW (Australia)	
Food production, Raw human food crops not in direct contact with effluent (edible product separated from contact with effluent, e.g., use of trickle irrigation) or crops sold to consumers cooked or processed.	30 (Weekly)
Non-food crops, Silviculture, turf and cotton, etc.	30 (Weekly)
NT (Australia)	
A+: (high level of human contact) commercial food crops consumed raw or unprocessed (e.g., salad crops)	10 (Weekly)
B: (medium level human contact) commercial food crops	20 (Weekly)
C: (low level of human contact) commercial food crops	20 (Weekly)
TAS (Australia)	
A: direct contact of reclaimed water with crops consumed raw	10 (Weekly)
B: crops for human consumption	50 (Weekly)
C: non-human food chain	80 (Monthly)
VIC (Australia)	
B: dairy cattle grazing	20
C: human food crops/processed, grazing, fodder for livestock	20
D: non-food crops including instant turf, woodlots, flowers	20
WA (Australia)	
(High level of human contact) commercial food crops consumed raw or unprocessed (e.g., Salad crops)	10 (Weekly)
(low level of human contact) non-edible crops	20 (Weekly)
AGWR (Australia)	
Commercial food crops	20

* Population equivalents.

Table 19. COD thresholds in agricultural water reuse regulations and guidelines.

Reuse Categories	COD (mg/L) (Monitoring)
Cyprus	
Agglomerations > 2000 p.e.	70 (1/15 days)
France	
A: unrestricted irrigation of all crops including these accessed by the public	60 (Weekly)
Israel	
	100
Jordan	
A: cooked vegetables, parks, playgrounds roadsides in the city	100
B: fruit trees, landscaped roadsides of highways	500
C: industrial crops, forest trees	500
D: cut flowers	100
Kuwait	
	100
Oman	
A: vegetables likely to be eaten raw fruit likely to be eaten raw and within 2 weeks of any irrigation	150
B: vegetables to be cooked or processed, fruit if no irrigation within 2 weeks of cropping, fodder, cereal seed crops, pasture, no public access	200
Tunisia	
	90
China	
Fiber crops	200
Dry field corn oil crops	180
Paddy field grain	60
Vegetable	40

3.3. Treatment Levels

As it was mentioned before, one of the main considerations of water reuse practices is to ensure that the recycled water is safe for reuse. Appropriate treatment technologies must be used to provide a biologically and chemically safe water for use in agriculture. Accordingly, different agencies and organizations have required various treatment technologies in their agricultural water reuse regulations and guidelines, considering recycled water quality, type of crops, irrigation methods, soil characteristics, and public access (Tables 20 and 21). The secondary treatment is the most frequent treatment requirement mentioned in the regulations and guidelines. Of note is that 38 out of 70 regulations and guidelines have required disinfection as part of the treatment process. When compared, it is obvious that there is a large discrepancy in the required treatment methods in the regulations and guidelines (Table 20). As different treatment methods are able to remove different contaminants from wastewater, it likely results in treated water with significantly different water quality. Therefore, there is more investigation that need to be done in terms of required treatment methods in the regulations and guidelines by agencies.

Table 20. Required treatment technologies in agricultural water reuse regulations and guidelines.

Organizations/Countries/States	Reuse Categories	Treatment
EPA	Food crops Process food crops/non-food crops	Secondary, filtration, disinfection Secondary, disinfection
FAO	A: Irrigation of crops likely to be eaten uncooked, sports field, public parks B: Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees C: Localized irrigation of crops in category B if exposure of workers and the public does not occur	A series of stabilization ponds or equivalent treatment Retention in stabilization ponds for 8–10 days or equivalent helminth and fecal coliform removal Pretreatment as required by the irrigation technology, but not less than primary sedimentation
ISO	A: Very high-quality treated wastewater; unrestricted urban irrigation and agricultural irrigation of food crops consumed raw B: high quality treated wastewater; restricted urban irrigation and agricultural irrigation of processed food crops C: good quality treated wastewater; agricultural irrigation of non-food crops D: medium quality treated wastewater; restricted irrigation of industrial and seeded crops E: extensively treated wastewater; restricted irrigation of industrial and seeded crops	Secondary, contact filtration or membrane filtration, and disinfection Secondary, filtration, and disinfection Secondary and disinfection Secondary or high rate clarification with coagulation, flocculation Stabilization ponds and wetlands
British Columbia	Restricted Unrestricted	Secondary, disinfection Secondary, chemical addition, filtration, disinfection, and emergency storage
Alberta	Restricted Unrestricted	A best practicable treatment approach, providing the required effluent quality (essentially secondary treatment with disinfection) A best practicable treatment approach, providing the required effluent quality (essentially secondary treatment with disinfection)
Alabama		Secondary, disinfection
Atlantic Canada	Restricted Unrestricted	At least secondary with disinfection At least secondary with disinfection
Saskatchewan	Food crops Non-food crops	Lagoons followed by a storage cell of holding at least 210–230 days of sewage flow or secondary treatment with adequate storage facilities, disinfection is required Lagoons followed by a storage cell of holding at least 210–230 days of sewage flow or secondary treatment with adequate storage facilities
Arizona	Food crops Processed food crops/non-food crops	A: Secondary, filtration and disinfection C: Secondary in a series of wastewater stabilization ponds, including aeration, with or without disinfection
California	Food crops Processed food crops/non-food crops	A disinfected tertiary recycled water: Filtration, disinfection Undisinfected secondary recycled water: Oxidized wastewater
Colorado	Processed food crops/non-food crops	Category 1 and 2 and 3: Secondary treatment and disinfection
Florida	Food crops Processed food crops/non-food crops	Secondary treatment and high-level disinfection Secondary treatment and basic level disinfection
Georgia	Processed food crops/non-food crops	Secondary treatment, filtration and disinfection
Hawaii	Food crops Processed food crops/non-food crops	R-1: Oxidization, filtration, and disinfection R-2: Oxidization and disinfection R-3: Oxidization
Idaho	Food crops Processed food crops/non-food crops	B: Oxidization, coagulation, clarification, and filtration C: Oxidization and disinfection C: Oxidization and disinfection D: Oxidization and disinfection

Table 20. *Cont.*

Organizations/Countries/States	Reuse Categories	Treatment
Illinois	Processed food crops/non-food crops	A two-cell lagoon system or a mechanical secondary treatment facility
Indiana	Food crops	Secondary treatment: (A) activated sludge processes, (B) trickling filters, (C) rotating biological contactors, (D) stabilization pond systems or (E) other secondary treatment approved by the commissioner in the permit Domestic wastewater: (A) chlorination, (B) ozonation, (C) chemical disinfectants, (D) UV irradiation, (E) membrane processes or (F) other processes approved by the commissioner in the permit
	Processed food crops/non-food crops	Secondary treatment: (A) activated sludge processes, (B) trickling filters, (C) rotating biological contactors, (D) stabilization pond systems or (E) other secondary treatment approved by the commissioner in the permitDomestic wastewater: (A) chlorination, (B) ozonation, (C) chemical disinfectants, (D) UV irradiation, (E) membrane processes or (F) other processes approved by the commissioner in the permit
Iowa	Processed food crops/non-food crops	Secondary treatment
Minnesota	Food crops	Disinfected tertiary: Secondary, filtration, and disinfection
	Processed food crops/non-food crops	Disinfected secondary 200: Secondary and disinfection
Montana	All types	B-1: Oxidized, settled, and disinfected
Nebraska	Unrestricted	Disinfection
Nevada	Processed food crops/non-food crops	D: At least secondary treatment
New jersey	Food crops	Secondary treatment and filtration
	Processed food crops/non-food crops	Secondary treatment
New Mexico	All types (in case of food crops: just food trees and nut trees)	Secondary treatment
North Carolina	All types	Tertiary treatment (filtration or equivalent)
North Dakota	Processed food crops/non-food crops	Secondary treatment or tertiary treatment
Oklahoma	Processed food crops/non-food crops	Secondary treatment, nutrient removal, and disinfection
Oregon	Food crops	A: Oxidization, filtration, and disinfection
	Processed food crops/non-food crops	C: Oxidization and disinfection
Pennsylvania	Food crops	B: Secondary treatment, filtration and disinfection
	Processed food crops/non-food crops	C: Secondary treatment and disinfection
Utah	Food crops	Type I: Filtration and disinfection
	Processed food crops/non-food crops	Type II: Disinfection
Virginia	Food crops	Level 1: Secondary treatment, filtration, and high-level disinfection
	Processed food crops/non-food crops	Level 2: Secondary treatment and standard disinfection
Washington	Food crops	Class A: Oxidization, coagulation, filtration, and disinfection
	Processed food crops/non-food crops	Class C: Oxidization and disinfection
Wyoming	Food crops	Class B: Secondary treatment and disinfection
	Processed food crops/non-food crops	Class C: Primary treatment and disinfection
Cyprus	Agglomerations > 2000 (p.e.)	NS
	Agglomerations < 2000 (p.e.): all crops	Tertiary and disinfection
	Agglomerations < 2000 (p.e.): unlimited access and vegetables eaten cooked (potatoes, beetroots, colocasia)	Tertiary and disinfection
	Agglomerations < 2000 (p.e.): limited access and crops for human consumption	Secondary, disinfection, and storage > 7 days or tertiary and disinfection
	Agglomerations < 2000 (p.e.): fodder crops	Secondary, disinfection, and storage > 7 days or tertiary and disinfection
Portugal	A: vegetables consumed raw	Secondary, filtration, and disinfection or tertiary, filtration and disinfection
	B: public parks, and gardens, sport lawns, forests with public access	Secondary, filtration, and disinfection or tertiary, filtration and disinfection
	C: vegetables to be cooked, forage crops, vineyards, orchards	Secondary, filtration, and disinfection or tertiary, filtration, and disinfection or waste stabilization ponds (≥3 ponds and retention time ≥ 25 days)
	D: Cereals (except rice), vegetables for industrial process, crops for textile industry, crops for oil extraction, forest and lawns in places of restricted or controlled public access	Secondary and maturation ponds (retention time ≥ 10 days) or Secondary, filtration, and disinfection

Table 20. *Cont.*

Organizations/Countries/States	Reuse Categories	Treatment
Greece	Restricted irrigation: Areas where public access is not expected, fodder and industrial crops, pastures, trees (except fruit trees), provided that fruits are not in contact with the soil, seed crops and crops whose products are processed before consumption. Sprinkler irrigation is not allowed	Secondary treatment and disinfection
	Unrestricted irrigation: All crops including all irrigation methods	Secondary or higher and disinfection
E.U.	A:	Secondary treatment, filtration, and disinfection
	B:	Secondary treatment and disinfection
	C:	Secondary treatment and disinfection
	D:	Secondary treatment and disinfection
Egypt	A: plants and trees grown for greenery at touristic villages and hotels and inside residential areas at the new cities	Advanced or tertiary treatment that can be attained through upgrading the secondary treatment plants to include sand filtration, disinfection, and other processes.
	B: fodder/feed crops, trees producing fruits with epicarp, trees used for green belts around cities and afforestation of highways or roads, nursery plants, roses and cut flowers, fiber crops, mulberry for the production of silk	Secondary treatment
	C: industrial oil crops, wood trees	Primary treatment that is limited to sand and oil removal basins and use of sedimentation basins.
China	Fiber crops	Primary treatment
	Dry field corn oil crops	Primary treatment
	Paddy field grain	Secondary treatment
	Vegetable	Secondary treatment
ACT	Pasture and fodder for grazing animals (except pigs)	Secondary, pathogen reduction by disinfection or detention in ponds or lagoons
	Silviculture, turf, and non-food crops	Secondary treatment
	Food crops in direct contact with water e.g., sprays	Secondary treatment, filtration, and pathogen reduction
	Food crops not in direct contact with water (e.g., flood or furrow) or which will be sold to consumers cooked or processed	Secondary treatment and pathogen reduction
NSW	Food production: Raw human food crops in direct contact with effluent e.g., via sprays, irrigation of salad vegetables	Tertiary treatment and pathogen reduction
	Food production: Raw human food crops not in direct contact with effluent (edible product separated from contact with effluent, e.g., use of trickle irrigation) or crops sold to consumers cooked or processed.	Secondary treatment and pathogen reduction
	Food production: Pasture and fodder (for grazing animals except pigs and dairy animals, i.e., cattle, sheep and goats)	Secondary treatment and pathogen reduction
	Food production: Pasture and fodder for dairy animals (with withholding period).	Secondary treatment and pathogen reduction
	Food production: Pasture and fodder for dairy animals (without withholding period), drinking water (all stock except pigs) and wash-down water for dairies	Secondary treatment and pathogen reduction
	Non-food crops: Silviculture, turf and cotton, etc.	Secondary treatment and pathogen reduction
TAS	A: direct contact of reclaimed water with crops consumed raw	Advanced treatment
	B: crops for human consumption	Secondary with disinfection
	C: non-human food chain	Secondary treatment
VIC	A: commercial food crops consumed raw or unprocessed	Advanced treatment
	B: dairy cattle grazing	Secondary and pathogen reduction
	C: human food crops/processed, grazing, fodder for livestock	Secondary and pathogen reduction
	D: non-food crops including instant turf, woodlots, flowers	Secondary treatment
AGWR	Commercial food crops consumed raw or unprocessed	Advanced treatment to achieve total pathogen removal
	Commercial food crops	Secondary treatment with >25 days lagoon detention and disinfection
	Commercial food crops	Secondary treatment or primary treatment with lagoon detention
	Non-food crops- trees, turf, woodlots, flowers	Secondary treatment or primary treatment with lagoon detention

Table 21. The number of regulations and guidelines which indicated different treatments.

Treatment	Description	Process	Number of Appearances in Regulations and Guidelines	Regulations and Guidelines
Primary			4	Wyoming, Egypt, China, AGWR
	Eliminating suspended solids	Sedimentation/settlement	3	Montana, Egypt and FAO
		Physico-chemical clarification: coagulation/flocculation	3	ISO, Idaho and Washington
Secondary	Removing Carbon and sometimes nutrients		35	EPA, ISO, British Columbia, Alberta, Alabama, Atlantic Canada, Saskatchewan, Arizona, California, Colorado, Florida, Georgia, Illinois, Indiana, Iowa, Minnesota, Nevada, New Jersey, New Mexico, North Dakota, Oklahoma, Pennsylvania, Virginia, Wyoming, Cyprus, Portugal, Greece, E.U., Egypt, China, ACT, NSW, TAS, VIC, AGWR.
		Wetland	1	ISO
		Lagoons	4	Saskatchewan, Illinois, ACT, AGWR.
		Oxidization	6	California, Hawaii, Idaho, Montana, Oregon, Washington
		Rotating biological contactors	1	Indiana
		Clarification	2	ISO and Idaho
		Stabilization ponds/maturation ponds	5	FAO, ISO, Arizona, Indiana, Portugal
Tertiary	Effluent polishing		8	California, Minnesota, North Carolina, North Dakota, Cyprus, Portugal, Egypt, NSW.
		Filtration	20	EPA, ISO, British Columbia, Arizona, California, Georgia, Hawaii, Idaho, Minnesota, New Jersey, North Carolina, Oregon, Pennsylvania, Utah, Virginia, Washington, Portugal, E.U., Egypt, ACT.
Disinfection	Removing suspended particulate matter, viruses, and pathogens.		33	EPA, ISO, British Columbia, Alberta, Alabama, Atlantic Canada, Saskatchewan, Arizona, California, Colorado, Florida, Georgia, Indiana, Minnesota, Oklahoma, Pennsylvania, Virginia, Wyoming, Hawaii, Idaho, Montana, Nebraska, Oregon, Utah, Washington, Cyprus, Portugal, Greece, E.U., Egypt, ACT, TAS, AGWR.
		Chlorination	1	Indiana
		Ozonation	1	Indiana
		UV irradiation	1	Indiana
		Membrane processes	2	ISO, Indiana

4. Summary of Findings

4.1. Constituents in Reclaimed Water

In general, the occurrence of constituents in reclaimed water are subject to treatment processes in wastewater treatment plants. Constituents in wastewater can be divided into three groups of conventional, nonconventional, and emerging. The constituents that have been the basis of the design of most conventional wastewater treatment plants are expected to be mostly removed during the treatment processes (e.g., TSS, BOD, Nitrate, Nitrite, Phosphorus, and Bacteria) [166]. There is also a group of constituents that may be removed or reduced using the advanced treatment processes (e.g., metals, TDS) [166]. Finally, there are the emerging constituents that are present in micro or nanogram/L, which may pose negative health and environmental concerns [167]. These compounds sometimes cannot be removed effectively even with advanced treatment processes [4]. In what follows, the knowledge gaps related to microbial constituents, agronomic, and physico-chemical properties, and emerging constituents of reclaimed water that are of concern in water reuse for agricultural irrigation were briefly discussed. In addition, the findings from the investigation of regulations and guidelines with respect to each of these groups of constituents were summarized.

4.1.1. Microbial Quality

As noted in Section 3.2.1., in the vast majority of the regulations and guidelines, Total Coliforms, Fecal coliforms, and E. coli were used as the indicator microorganism to assess the microbial quality of the reclaimed water for irrigation. In the regulations and guidelines investigated in this study, Fecal Coliform, E. Coli, and Total Coliform were the most frequent indicator microorganisms with 36, 24, and

9 cases, respectively (Figure 6). However, indicator microorganisms do not represent all of the existing pathogens in the recycled water. Regulations and guidelines need to consider the fact that pathogens in recycled water are part of larger microbial communities [168,169]. Kulkarni et al. claimed that microbial communities in the recycled water can be affected by "wastewater treatment processes, operational parameters, organic and inorganic wastewater constituents, and water reuse site practices" [168].

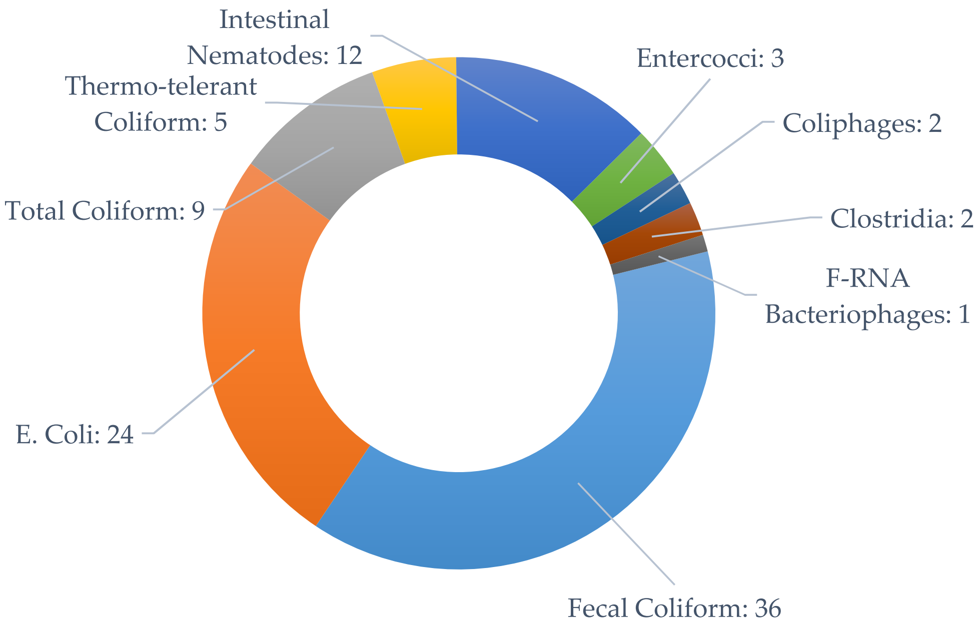

Figure 6. The number of regulations and guidelines which indicated different indicator microorganisms.

Another shortcoming of bacterial indicators is in the prediction of parasites and viruses, which can be more resistant to disinfection. In addition, the information derived from the microbiological analysis is not immediate and it is not obtained in a continuous manner as well. These drawbacks have motivated the development of more preventive approaches, such as the Water Safety Plans proposed by the WHO [170]. The recent advancement in detection methods such as use of molecular markers and real-time monitoring techniques necessitates the modification of existing official detection methods in regulations and guidelines [171,172]. In summary, more information is still needed to assist regulatory agencies in improving or verifying the effectiveness of their criteria for microbial quality of recycled water such as:

- Better selection of indicator organisms for estimation of microbial pathogens in reclaimed water
- Improvement in risk assessment methodologies to make it more useful during the regulation development
- Development of real-time biomonitoring methods
- Better verification of treatment effectiveness and reliability of removal of microbial pathogens during various treatment processes

4.1.2. Agronomic and Physico-Chemical Parameters

The agronomic and physico-chemical parameters that were evaluated in this study comprise a complete list of the necessary parameters, which can increase the safety of crops, soil, and in general agricultural water reuse practices. However, those parameters were not used by all of the regulations and guidelines investigated in this study. For instance, pH (34), free Chlorine (25), and nutrients (21) were the most frequent parameters respectively (Figure 7). TSS (43), BOD_5 (42), and turbidity (27) were the most frequent among physico-chemical parameters used in the studied regulations and guidelines (Figure 8). In addition, even in the regulations and guidelines that have included these parameters, large discrepancies exist in the threshold levels. This not only could be a threat to recycled water irrigation practices, but also might affect the farmers' tendency toward implementing water reuse.

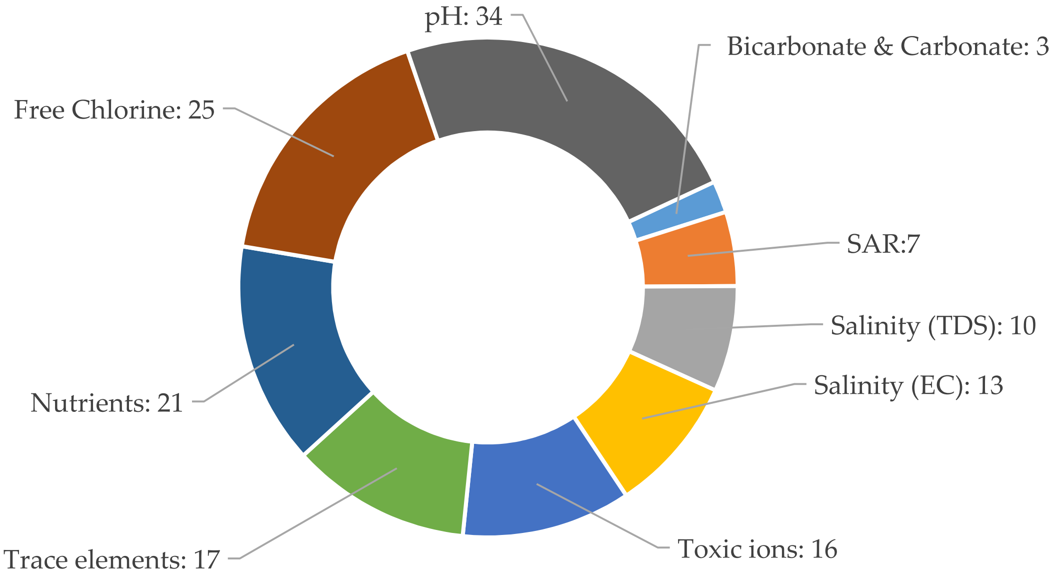

Figure 7. The number of regulations and guidelines which included different agronomic parameters.

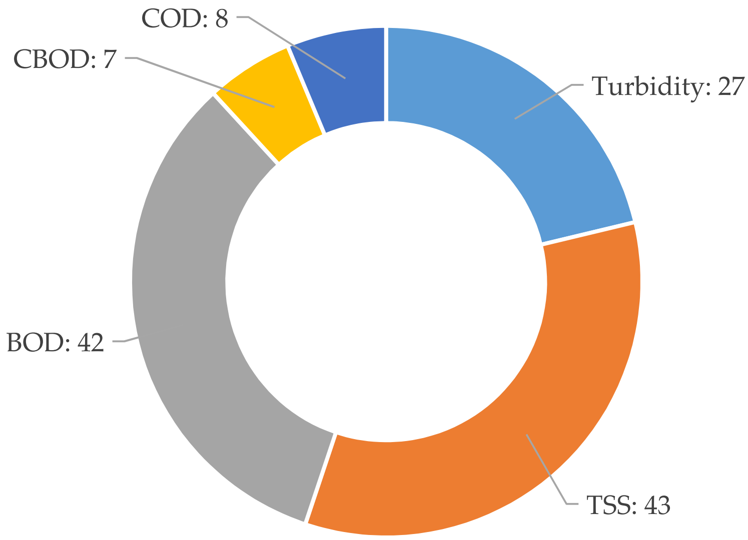

Figure 8. The number of regulations and guidelines which used different physico-chemical parameters.

Based on the results (Sections 3.2.2 and 3.2.3), the main gap of agricultural water reuse regulations and guidelines regarding the agronomic and physico-chemical parameters are the absence of some of the important parameters, and the discrepancies among their existing thresholds. Due to the importance of agriculture and technological advancements, there is significant knowledge and expertise about these parameters, their measurement methods and instruments. So, regulations and guidelines need to include all of these parameters with similar thresholds. For instance, the potential negative impacts of low or high pH was clearly clarified in this paper according to literature. Additionally, pH measurement is one of the easiest tests that can be done. However, only about half of the investigated regulations and guidelines (34 out of 70) have included pH as one of the water quality parameters.

4.1.3. Constituents of Emerging Concern

With the advancement of analytical instrumentation, it is now possible to measure a long list of trace constituents in the environment. Contaminants of emerging concern (CECs) include a wide range of trace constituents such as pharmaceuticals, personal care products, household products, drugs, flame retardants, etc. [173]. Many of these compounds are found in raw wastewater in considerable concentrations [173]. Conventional wastewater treatment technologies are not able to remove many of these compounds during the treatment process because they are not designed to do so. In addition, many of these constituents are not included in the discharge regulations, thus, are not monitored by the wastewater treatment facilities. As a result, many of these CECs could be present in the treated water (Table 22).

Table 22. Some of the existing contaminants of emerging concern (CECs) in recycled water reported by literature [174].

CEC	Concentration (ng/L)
1,4-Dioxane	7160
4,4-DDT	50
Acetaminophen	26
Atenolol	400
Azithromycin	650
Caffeine	25
Carbamazepine	200
Ibuprofen	160
Iopromide	2600
Sucralose	40,000

Despite their potential negative effects on the ecological and public health (e.g., abnormalities in the reproductive systems of creatures, increasing the resistance of humans and animals to antibiotics, and changing the development processes of creatures), none of the regulations or guidelines have included CECs [175–180]. It should be noted that there is an enormous variety of these compounds, which make their assessment a very challenging task. For instance, Huang et al. reported that there are approximately 7700 pharmaceuticals that humans use, which may potentially end up in the residential wastewater. In addition, these constituents have a wide range of physio-chemical properties and biodegradability [181]. Agencies should consider several factors including rates of consumption, risks to human/ecological health, physio-chemical properties, biodegradability, pharmacological class, and sustainability index, in order to include the CECs in the regulations and guidelines [182,183]. As a result, an enormous effort is still required to close the regulatory gaps with respect to emerging contaminants.

In a nutshell, this study highlights some of the large discrepancies among current agricultural water reuse regulations and guidelines. Brissaud [54] argued that the countries rationale for setting up or adapting other regulations or guidelines are not clear. Most of the countries' rationale reflect a perception of a risk hierarchy (which is different among various countries) instead of using an scientifically based rationale [54]. In order to address this challenge, Brissaud [54] suggested that countries should base their agricultural regulations and guidelines on epidemiologic studies and quantitative microbiological health risk assessment. This will pave the way for countries to share their knowledge and experiences, find common policies, and determine the uncertainties of their regulations and guidelines, which will shed light on the needs for future scientific research [54]. Moreover, these discrepancies might be the result of differences between countries and states approach to their public health; their economic, development, and education status; as well as their local climatic and geographical conditions. In general, countries and states with high economic status can afford high level technologies for treating wastewater to meet restrictive thresholds. Therefore, regulations and guidelines in high economic status societies are most likely to be more restrictive. In addition, people who live in semi-arid or arid areas of the world usually deal with water crisis in their everyday life, making them more interested in agricultural water reuse practices [31]. As they are more interested, their government is forced to issue agricultural water reuse regulations or guidelines. The state of California can be a good example for this, as this state is in a semi-arid area and its citizens are well aware and interested in agricultural water reuse practices. It should be mentioned that public health, economic, development, and education statuses of this state are high which has made this state one of the pioneers of agricultural water reuse practices with a restrictive regulation.

5. Conclusions

With recent advancements in wastewater treatment technologies, it is possible to produce almost any water quality. However, the main human and environmental concerns are still to determine what constituents must be removed and to what extent. To ensure safe water reuse practices, different national and international organizations and agencies have issued their own regulations and guidelines. To do a comprehensive and comparative study of the existing water reuse regulations and guidelines, this paper has evaluated the current status of existing regulations and guidelines for water reuse in agriculture throughout the world. In total, 83 cases were studied, among which 70 regulations and guidelines for agricultural water reuse were identified, and the latest version of the documents were obtained. These regulations and guidelines were collected from EPA, ISO, FAO, WHO, U.S. (statewide), European Commission, Canada (by provinces), Australia, Mexico, Iran, Egypt, Tunisia, Jordan, Israel, Palestine, Oman, China, Kuwait, Saudi Arabia, France, Cyprus, Spain Greece, Portugal, and Italy. The main focus of this study was to evaluate, compare, and identify the gaps in the current agricultural water reuse regulations and guidelines.

Recycled water quality parameters were categorized into three major groups, including human-health parameters (pathogens and chemicals), agronomic parameters (salinity, toxic ions, SAR, trace elements, pH, Bicarbonate/Carbonate, nutrients, and free Chlorine), and physico-chemical parameters (turbidity, TSS, BOD_5, $CBOD_5$ and COD). Regulations and guidelines were categorized into two groups based on their microbiological requirements. Those which were high-cost/low-risk, requiring zero detection of microbial indicators in recycled water, were named as “restrictive” regulations and guidelines with California’s regulation be their benchmark regulation. On the other hand, those which were low-cost/high-risk, requiring no real risk of infection, were named as “less restrictive” regulations and guidelines with WHO’s guideline be their benchmark guideline.

Results showed that, to a larger extent, water reuse regulations and guidelines are mainly based on the control of conventional water quality parameters such as coliforms, BOD_5, turbidity, and TSS. Thus, most of the existing regulations and guidelines do not include emerging pathogens (such as salmonella and hepatitis), heavy metals or contaminants of emerging concern. Pathogen thresholds were indicated by 64 out of 70 regulations and guidelines. The most frequent microbial indicator used by regulations and guidelines was Fecal Coliforms. Despite a wide range of chemicals and trace elements that have been detected in treated wastewater, only a few of them have been regulated in agricultural water reuse regulations and guidelines. Among the long list of trace elements and chemicals, Chromium, Cadmium, and Nickel had the maximum number of indications with inclusion in only 17 out of 70 regulation and guidelines investigated in this study. Considering the detrimental effects of chemicals and trace elements on human and environmental health, agricultural regulations and guidelines need to include more chemicals and trace elements in their requirements.

Thirty-four out of seventy regulations and guidelines included pH, most of which considered 6.5–8 range to be the best pH range for agricultural water reuse practices. Although salinity, reported as EC and TDS thresholds, is the most important agronomic parameter, none of the U.S. states’ regulations and guidelines included EC and TDS thresholds in their agricultural water reuse regulations and guidelines. SAR thresholds were included in only 7 out of 70 regulations and guidelines investigated in this study, none of which were from U.S. states. Canadian provinces and Iran’s guideline contain the most comprehensive SAR thresholds Compared with others. As the most frequent indicated nutrients in regulations and guidelines, Zinc, Boron, and total Nitrogen ranges in regulations and guidelines were in severe restriction range of FAO's guideline. Turbidity, TSS, and BOD were mostly used by U.S. states as water quality indicators in the regulations and guidelines (17, 19, and 19 documents, respectively). Secondary treatment and tertiary treatment are the most frequent treatment processes required by different regulations and guidelines. In summary, the most frequent recycled water quality parameters required by the regulations and guidelines were as follows: (1) Pathogens; (2) TSS; (3) BOD_5; (4) pH; (5) Turbidity; (6) Chemicals/trace elements; (7) Nutrients; (8) Free Chlorine; (9) EC; (10) TDS; (11) COD; (12) $CBOD_5$; (13) SAR and Bicarbonate/Carbonate.

To summarize, results showed that the regulations and guidelines are mainly human-health centered, insufficient regarding some of the potentially dangerous pollutants such as emerging constituents, and with large discrepancies when compared with each other. In addition, some of the important water quality parameters such as some of the pathogens, heavy metals, and salinity are only included in a few of regulations and guidelines investigated in this study. Finally, specific treatment processes have been only mentioned in some of the regulations and guidelines, and with high levels of discrepancy. While agricultural water reuse gives us a means to address the water crisis, the discrepancies in regulations and guidelines are one of the main barriers for successful implementation of water reuse practices. However, this does not mean that the practice of water reuse in agriculture should be construed as unsafe compared to other sources of available water such as rivers, streams, and pond water. The focus rather should be on defining the acceptable level of risks by the regulatory agencies and endorsing by the public to promote the water reuse as part of the integrated water resources management. As to all types of water sources, special care is required to ensure recycled water quality is matched to crop needs, public health is protected, salinity is controlled, and both soil and groundwater conditions are kept sustainable.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/4/971/s1, Table S1: Health-based targets for recycled water use in agriculture, Table S2: Water quality for irrigation, Table S3: EPA guideline for agricultural water reuse, Table S4: Water quality for irrigation in California's regulation, Table S5: The E.U. commission proposal for minimum recycled water quality in order to use in agriculture.

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