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Irrigation Water Quality Standards for Indirect Wastewater Reuse in Agriculture: A Contribution toward Sustainable Wastewater Reuse in South Korea

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Academic Editor: Andreas N. Angelakis
Received: 12 January 2016; Accepted: 14 April 2016; Published: 23 April 2016

Abstract: Climate change and the subsequent change in agricultural conditions increase the vulnerability of agricultural water use. Wastewater reuse is a common practice around the globe and is considered as an alternative water resource in a changing agricultural environment. Due to rapid urbanization, indirect wastewater reuse, which is the type of agricultural wastewater reuse that is predominantly practiced, will increase, and this can cause issues of unplanned reuse. Therefore, water quality standards are needed for the safe and sustainable practice of indirect wastewater reuse in agriculture. In this study, irrigation water quality criteria for wastewater reuse were discussed, and the standards and guidelines of various countries and organizations were reviewed to suggest preliminary standards for indirect wastewater reuse in South Korea. The proposed standards adopted a probabilistic consideration of practicality and classified the use of irrigation water into two categories: upland and rice paddy. The standards suggest guidelines for *E. coli*, electric conductivity (EC), turbidity, suspended solids (SS), biochemical oxygen demand (BOD), pH, odor, and trace elements. Through proposing the standards, this study attempts to combine features of both the conservative and liberal approaches, which in turn could suggest a new and sustainable practice of agricultural wastewater reuse.

Keywords: indirect wastewater reuse; irrigation water quality; paddy irrigation; wastewater reuse; water quality standards

1. Introduction

The lack of freshwater resources due to population growth and the degradation of water quality is becoming a big challenge for agricultural water [1,2]. Severe droughts due to climate change and the increase in protected cultivation are making it difficult to provide a stable supply of agricultural water [3,4]. As an alternative water resource, wastewater reuse for agriculture is gaining international interest [5–7]. Treated wastewater, which in many ways is ideal for agricultural water [8–10], is already being widely used throughout the world [11], and previous studies suggest that more than 10% of the world's population is consuming agricultural products cultivated by wastewater irrigation [12].

Agricultural wastewater reuse can be classified into direct and indirect wastewater reuses [13]. Direct wastewater reuse refers to the method whereby irrigation water is supplied directly from the wastewater treatment plant (WWTP), while indirect wastewater reuse is a method where effluent from the WWTP or untreated wastewater is collected downstream. In the case of direct wastewater reuse, the irrigation water quality is determined by the quality of WWTP effluent. Therefore, the target water quality can be easily achieved by controlling the quality of the effluent. In the case of indirect wastewater reuse, however, controlling the irrigation water quality is difficult because it is dependent on various factors such as treated wastewater effluent quality and the hydrological conditions of the stream which the effluent flows into [14]. The increase in the number of WWTPs due to rapid urbanization is intensifying the effect of indirect wastewater reuse on irrigation water [14].

When using treated wastewater for irrigation, water quality must be strictly controlled considering factors such as the possible accumulation of substances which are harmful for crop growth, the potential damage to soil by the transformation of its physical and chemical characteristics [15,16], and microbe infection [17,18]. Using diluted treated wastewater could somewhat mitigate the side effects but nonetheless cannot prevent it from damaging the commercial value of crops. Therefore, without additional treatment, it is suggested that diluted treated wastewater be used restrictively [19]. In addition, when using treated wastewater for rice paddy irrigation, the water showed a significant level of salinity compared to conventional irrigation water, and total coliform concentration surpassed the levels of the water quality standards for direct wastewater reuse [20,21]. Previous studies suggest that the quality of irrigation water from streams fails to meet the agricultural water quality standards due to the effects of WWTP effluent [14,22]; thus, the water quality needs to be managed to ensure safe and sound crop production.

Angelakis *et al.* [23], Brissaud [24], Kalavrouziotis *et al.* [25], and Paranychianakis *et al.* [26] researched the current status of wastewater reuse for agriculture, assessed its standards and guidelines for water quality, and asserted the necessity for a common criterion based on scientific evidence. Kretschmer *et al.* [27] examined the standardization of water quality for agricultural wastewater reuse in terms of technology, economy, and human safety. Jimenez [28] studied practical criteria and treatment technologies for safe wastewater reuse in Mexico, where a significant amount of wastewater is used for agriculture. Organizations such as the Word Health Organization (WHO) [12,29] and the United States Environmental Protection Agency (US EPA) [30–33], and many countries such as Cyprus [34], France [26], Greece [35], Israel [36], Italy [34], Portugal [37], and Spain [38], have all recently suggested and modified water quality guidelines or standards for safe wastewater reuse. South Korea also laid out guidelines for irrigation water quality in 2005, and proclaimed irrigation water quality standards for direct wastewater reuse in 2011.

Most of the currently suggested water quality standards are based on the direct wastewater reuse rather than the indirect wastewater reuse, which is a predominant manner in agricultural wastewater reuse [39]. They have also focused on the upland irrigation including vegetables and have not well considered the characteristics of irrigation water in paddy fields: Irrigation water for paddy rice production accounts for more than 70% of the total irrigation water in Asia [40], and paddy rice is the largest consumer of freshwater resources in South and Southeast Asia [41,42]. This study, therefore, examines existing water quality criteria for irrigation water and wastewater reuse, and analyzes the water quality standards of other countries to set agricultural water quality standards for indirect wastewater reuse considering both paddy and upland irrigation.

2. Considerations of Water Quality Standards for Indirect Wastewater Reuse

2.1. Irrigation Water Quality Criteria

In the case of indirect wastewater reuse, the irrigation water quality is affected by water with which the treated wastewater is diluted such as stream water or lake water. Therefore, to examine the water quality standards for indirect wastewater reuse, irrigation water quality criteria should be considered.

2.1.1. Salinity

Salinity has been deemed as the most important factor of agricultural water quality because high salinity in soil can create a hostile environment for the crop to absorb nutrients and provoke specific ion toxicity [12,43,44]. The Food and Agriculture Organization (FAO) has established guidelines for agricultural water primarily based on salinity. These guidelines have been modified by Ayers and Westcot in 1985 [45] and are being internationally accepted.

2.1.2. Nutrients

Nitrogen (N) and phosphorus (P) are the primary nutrients for crop growth but nonetheless when applied excessively can give a negative effect. Especially for paddy rice, excessive N and P can cause the crop to over-grow which leads to lodging [46]. This is why Taiwan and Japan, which have farming conditions similar to South Korea, limit the total nitrogen (T-N) content for paddy irrigation water [47,48]. Excessive nutrients in water can also cause groundwater contamination as well as eutrophication in coastal areas or lakes [49,50] and this is why, in South Korea, N and P contents are included in agricultural water quality standards.

2.1.3. Organic Matters

Generally, biochemical oxygen demand (BOD) is used as an index for organic matter. In a high BOD environment, oxygen in water is consumed for decomposing organic matters to create an anaerobic state, and, during the process of decomposition, oxides in the soil such as Fe^{3+}, Mn^{5+}, and $SO_4{}^{2-}$ consume oxygen to lower the oxidation-reduction potential [51]. In the end, the generated iron, manganese, and sulfide along with organic acids can disrupt the paddy rice to absorb nutrients [52].

2.1.4. Hydrogen Ion Concentration

Hydrogen ion concentration represented by pH is an index upon which irrigation water is quickly assessed for its suitability. Normally, the pH of irrigation water ranges from 6.5 to 8.4. The pH outside of the normal range might be suitable for irrigating, but has the potential to cause an imbalance of nutrients or contain poisonous ions [45]. The biggest hazard related to an abnormal pH in water is its effect on irrigation facilities. Exceptionally low pH in irrigation water can expedite the corrosion process of facilities, and irrigation water containing high levels of alkalinity can lower the efficiency of the trickle irrigation system [44].

2.1.5. Trace Elements

Trace elements are necessary for crop growth but when the amount of heavy metals in irrigation water is excessive, it can cause harm. Copper (Cu) can cause leaf chlorosis as well as the suppression of root growth [52]. Zinc (Zn) and arsenic (As) both have side effects of stem chlorosis and root growth suppression [52]. Aluminum (Al), in acid soil, can decrease productivity [52]. Lead (Pb), cyan (CN), and cadmium (Cd) are normally strictly restricted since, when dissolved in water or soil, they can be accumulated in the crop and in turn harmful to the human body [53]. The FAO's irrigation water quality guidelines, therefore, has set limits on concentrations of trace elements in irrigation water [45].

2.2. Conditions of Water Quality for Wastewater Reuse

Wastewater irrigation should consider human health risk along with the conventional irrigation water quality standards. The water quality standards for agricultural wastewater reuse can be classified into the conservative standards of California and the liberal standards of the WHO. This classification is well reflected in the microbe-related categories [24]. The WHO, in 1989 and 2006, suggested health-based targets for safe agricultural wastewater reuse. The WHO limits the permitted wastewater to domestic and/or urban wastewater and does not recommend using wastewater that contains excessive amount of industrial wastewater. Using untreated wastewater for agriculture can cause parasitosis or water-borne epidemics, and there have been numerous reports on the break of infectious diseases due to inappropriate wastewater reuse [29].

In the United States (US), the EPA suggests the water quality guidelines for wastewater reuse and each state government sets their own water quality standards based on these guidelines. Compared to the WHO guidelines, the US applies strict standards, and each state's microbe standard of irrigation water and treatment requirement are shown in Table 1. Texas and Florida prohibit the direct contact of irrigation water. Although California, which set the very first regulations for using wastewater for irrigation in 1918 [54], does not list specific prohibition laws, the water quality for wastewater is managed by strict standards similar to those for drinking water.

Table 1. Water quality standards of bacterial indicators for food and non-food crop irrigation in United States (modified from US EPA [33]).

Classification		California	Florida [1]	New Jersey	North Carolina	Texas [1]	Virginia [2]
Food [(a)]	Bacterial indicators (cfu/100 mL)	Total coliform: −2.2 (7 days median) −23 (not more than one sample exceeds this value in 30 days) −240 (max)	Fecal coliform: −75% of samples below detection −25 (max)	Fecal coliform: −2.2 (weak median) −14 (max)	Fecal coliform or *E. coli*: −3 (monthly mean) −25 (monthly mean)	Fecal coliform or *E. coli*: −20 (30-day geom) −75 (max)	Fecal coliform: −14 (monthly geom), CAT > 49*E. coli*: −11 (monthly geom), CAT > 35
	Treatment requirements	Oxidized, coagulated, filtered, disinfected	Secondary treatment, filtration, high-level disinfection	Filtration, high-level disinfection	Filtration, dual UV/chlorination (or equivalent)	NS	Secondary treatment, filtration, high-level disinfection
Non-food [(b)]	Bacterial indicators (cfu/100 mL)	NS	Fecal coliform: −200 (avg) −800 (max)	Fecal coliform: −200 (monthly geom) −400 (weak geom)	Fecal coliform or *E. coli*: −14 (monthly mean) −25 (daily max)	Fecal coliform or *E. coli*: −200 (30-day geom) −800 (max)	Fecal coliform: −200 (monthly geom), CAT > 800*E. coli*: −126 (monthly geom), CAT > 235
	Treatment requirements	Oxidized	Secondary treatment, basic disinfection	Case-by-case	Filtration (or equivalent)	NS	Secondary treatment, disinfection

NS = not specified by the state's reuse regulation; NP = not permitted by the state; CAT = corrective action threshold; geom = geometric mean. [1] In Florida and Texas, spray irrigation (*i.e.*, direct contact) is not permitted on foods that may be consumed raw, and only irrigation types that avoid reclaimed water contact with edible portions of food crops. [2] The requirements presented for Virginia are for food crops eaten raw. [(a)] Food crops: The use of reclaimed water to irrigate food crops that are intended for human consumption. [(b)] Non-food crops and processed food crops: The use of reclaimed water to irrigate crops that are either processed before human consumption or not consumed by humans.

3. Guidelines and Standards for Agricultural Wastewater Reuse

Water quality of agricultural wastewater reuse is presented in criteria, guidelines, and standards. Water quality criteria are the result of scientific examinations on the suitability of water to be used for certain purposes. Kretschmer *et al.* [27] and Tsagarakis *et al.* [55] have suggested water quality criteria for safe wastewater reuse. Water quality guidelines refer to a set of management targets based on the water quality criteria, the following of which is recommended but nevertheless not restricted by law. Organizations and countries (e.g., WHO [12], US EPA [33], and Australia [56]) have recommended guidelines for safe reuse of wastewater as agricultural water. In terms of water quality standards, which are the actual regulations restricted by law, Greece and the US set state-based standards, respectively [33,35]. In South Korea, the Ministry of Environment (MOE) [57] has proclaimed water quality standards for treated wastewater based on its specific purpose of use. In this study, the water quality standards of countries (Cyprus, France, Greece, Israel, Italy, Portugal, Spain, and South Korea), which have recently revised their standards and widely use treated wastewater for agriculture, as well as the guidelines of WHO [12] and US EPA [33], two major influences on water reuse criteria worldwide [23,24,26], are examined (Table 2).

3.1. WHO

The WHO first devised guidelines for wastewater reuse for irrigation in 1973, and this has become the international standard [12,29]. Many European and South American countries have adopted the WHO guidelines [29] and modified it to correspond to the geographical, epidemiological idiosyncrasies, as well as the economic conditions, of each country. However, there have been controversies regarding the fact that the WHO guidelines provide a low microbe standard for unrestricted irrigation since it was based on epidemiological studies of developing countries where much of the population have now acquired immunity towards enteric infection [34,39]. On this note, the WHO [12] has since recommended new guidelines for wastewater irrigation which consider the human health risk through epidemiological studies and quantitative microbial risk assessment (QMRA), a process for estimating the risk of exposure to microorganisms (Table 3). The new recommended guidelines differ in microbe limit, depending on the irrigation method and crop type. It also takes into account the risk mitigation effect that comes from the entire process of agricultural production-from the irrigation system to the pre-consumption cleansing-in determining the permitted microbe limits.

3.2. US EPA

The US EPA adopts strict standards where it totally eliminates the risk of infection [39]. These strict standards require an excessive cost for the prevention of infectious diseases. Shuval *et al.* [58] estimated that the guidelines of US EPA, compared to those of WHO, will cost an additional $3 to $30 million per prevented enteric disease. In addition, there have been criticisms towards the strict US EPA guidelines since it might be impossible for developing countries to adopt them due to the required cost and technology [12].

3.3. Cyprus

Cyprus proclaimed water quality standards for wastewater reuse in 2005 [34] and is prohibiting the irrigation of treated wastewater for vegetables that are consumed raw, crops for exporting, and ornamental plants [24]. Water quality standards for vegetables that are consumed cooked and other crops are stricter than the WHO guidelines, but relaxed compared to the US EPA guidelines. Different water quality standards are recommended depending on the method of water treatment. The maximum allowable value and the value of which 80% of samples should not exceed are each presented.

Table 2. Irrigation water quality guidelines and standards for wastewater reuse in agriculture.

Parameters	South Korea [1] [57]		WHO [2] [12]		US EPA [33]		Cyprus [3] [26]		France [26]		Greece [35]		Israel [4] [36]	Italy [34]	Portugal [37]		Spain [38]	
Coliform (/100 mL)	Food Crops	ND TC	Unrestricted	*E. coli* (cfu) ≤ 1000	Food crops	ND FC (median)	Cooked vegetables	FC (MPN) ≤ 100	Unrestricted	*E. coli* (cfu) ≤ 250	Unrestricted	*E. coli* (cfu) ≤ 5 (80%) ≤ 50 (95%)	FC (cfu) ≤ 10	*E. coli* (cfu) ≤ 100 (max) ≤ 10 (80%)	Vegetables consumed raw [(a)]	FC (cfu) ≤ 100	Uncooked vegetables	*E. coli* (cfu) ≤ 100
	Processed food crops	TC (MPN) ≤ 200	Restricted	*E. coli* (cfu) ≤ 10,000	Processed food crops	FC (cfu) ≤ 200 (median)	Crops for human consumption	FC (MPN) ≤ 1000	All crops except those consumed raw	*E. coli* (cfu) ≤ 10,000	Restricted	*E. coli* (cfu) ≤ 200 (median)			Cooked vegetables	FC (cfu) ≤ 1000	Crops for human consumption	*E. coli* (cfu) ≤ 1000
Turbidity (NTU)	Food crops	≤2	–[(b)]		Food crops	≤2 (average)	–		–		Unrestricted	≤2 (median)	–	–	–		Uncooked vegetables	≤10
	Processed food crops	≤5			Processed food crops	–					Restricted	–		–			Crops for human consumption	–
Suspended solids (mg/L)	–		–		Food crops	–	Cooked vegetables	≤15	Unrestricted	<15	Unrestricted	≤10 (80%)	TSS ≤ 10	TSS ≤ 10	TSS ≤ 60		Uncooked vegetables	≤20
					Processed food crops	TSS ≤ 30	Crops for human consumption	≤45	All crops except those consumed raw	Varies [(c)]	Restricted	≤35					Crops for human consumption	≤35
BOD (mg/L)	≤8		–		Food crops	≤10	Cooked vegetables	≤15	–		Unrestricted	≤10 (80%)	≤10	≤20	–		–	–
					Processed food crops	≤30	Crops for human consumption	≤30			Restricted	≤25					–	–
COD (mg/L)	–		–		–		–		Unrestricted	<60	–		≤100	≤100	–		–	
									All crops except those consumed raw	Varies								
Odor	Do not unpleasant		–		–		–		–		–		–	–	–		–	
T-N (mg/L)	–		–		–		–		–		–		≤25	≤15	–		–	
T-P (mg/L)	–		–		–		–		–		–		≤5	≤2	–		–	
Intestinal nematodes (No./L)	–		≤1		–		ND		–		–		–	–	≤1		≤1(/10 L)	
pH	5.8–8.5		–		6.0–9.0		–		–		–		6.5–8.5	6.0–9.5	6.5–8.4		–	
EC (μs/cm)	Food crops	≤700	–		–		–		–		–		≤1400	≤3000	≤1000		–	
	Processed food crops	≤2,000																

ND = not detected; TC = total coliform; FC = fecal coliform; TSS = total suspended solids. [1] Standards for direct wastewater reuse. [2] The most stringent verification monitoring level, which refers to what has previously been referred to as effluent guideline levels, for each irrigation type and arithmetic mean value. [3] For vegetables eaten raw is not allowed and maximum value allowed. [4] Maximum monthly averages for unrestricted irrigation. [(a)] Vegetables whose edible parts are in close contact with the irrigated soil are not included and drip irrigation can be only employed. [(b)] No recommendation. [(c)] In accordance with wastewater treatment standards.

Table 3. Recommended minimum verification monitoring of microbial performance targets for wastewater use in agriculture (modified from WHO [12]).

Type of Irrigation	*E. coli* (cfu/100 mL) (Arithmetic Mean)	Helminth Eggs (No./L) (Arithmetic Mean)
Unrestricted [1]		
Root crops [(a)]	$\leqslant 10^3$	
Leaf crops [(b)]	$\leqslant 10^4$	$\leqslant 1$
Drip irrigation, low-growing crops	$\leqslant 10^3$	
Drip irrigation, high-growing crops [(c)]	$\leqslant 10^5$	- [(d)]
Restricted [2]		
Labor-intensive, high-contact agriculture	$\leqslant 10^4$	$\leqslant 1$
Highly mechanized agriculture	$\leqslant 10^5$	$\leqslant 1$
Pathogen removal in a septic tank	$\leqslant 10^6$	$\leqslant 1$

[1] Use of treated wastewater to grow crops that are normally eaten raw. [2] Use of treated wastewater to grow crops that are not eaten raw by human. [(a)] Crops that may be eaten uncooked. [(b)] Vegetables eaten uncooked such as lettuce and cabbage. [(c)] Crops such as fruit trees and olives. [(d)] No recommendation.

3.4. France

In 1991, France issued wastewater reuse standards, which essentially follow the WHO guidelines [29] but add restrictions for irrigation techniques and setback distances to mitigate health risks [59]. Updated standards were devised in 2010, and they follow the principles of the revised WHO's guidelines [12] but include five other criteria for total suspended solids (TSS), chemical oxygen demand (COD), Enterococci, F-specific RNA phages, and spores of anaerobic bacteria in addition to limits for *E. coli* [26].

3.5. Greece

The water reuse standards of Greece took effect in 2011 and were advised to apply different standards for restricted irrigation and unrestricted irrigation in relation to subjects such as crop type, irrigation method, and accessibility of the public. Restricted irrigation refers to the method whereby sprinklers are not permitted and the irrigation area is inaccessible. This type of irrigation is subjected to crops that are either non-edible, consumed after being processed, or the yielding part is not in direct contact with the soil [35]. Unrestricted irrigation is independent from the irrigation method, applied to all types of crop, and also does not restrict public access to the irrigation area [35]. For certain water quality factors which require a strict standard, a probabilistic consideration is adopted for all water quality samples.

3.6. Israel

In 1952, Israel established legalized water quality standards for reusing wastewater for agriculture [54]. After that, new irrigation water quality standards for wastewater reuse-which require a more advanced wastewater treatment system than the existing-were devised in 2010 to minimize the damage of the water environment as well as crop and soil [60]. The new standards, to which factors such as the five-day BOD, TSS, COD, fecal coliform, residual chlorine, and sodium adsorption ratio (SAR) are subjected, aim to use the entire amount of wastewater for unrestricted irrigation [36]. A notable change compared to the 1999 standards is the consideration of nutrients such as T-N, total phosphorus (T-P), residual chlorine, and trace elements such as boron (B).

3.7. Italy

Italy started to regulate the irrigation of treated wastewater by law in 1977, and new national standards were enacted in 2006 [25,59]. Microbiological factors such as enteric nematodes, which are normally considered important, were excluded in the new standards, whereas germs such as salmonella and trace elements were included. 20% of all the categories apply the same standard as drinking water, and 37% are categories which do not exist for drinking water quality standards [59]. The strict water quality standards of Italy are not differentiated by crop types or irrigation methods but can be a factor in limiting the broad use of wastewater reuse.

3.8. Portugal

The first standards on the use of treated wastewater for irrigation were published in Portugal in 2006 [37]. The standards distinguished into four classes according to the level of risk of microbiological contamination generated by wastewater irrigation [37]. The standards also provide guidelines for the selection of irrigation equipment and methods and for environmental protection and environmental impact monitoring in areas irrigated with treated wastewater [37]. According to the Portuguese standards, wastewater irrigation is not allowed in areas with high slopes (>20%) or very permeable soil (e.g., karstic areas), while the groundwater table should be at depth greater than 1–4 m during irrigation, depending on the type of irrigation method [37].

3.9. Spain

The water quality standards for wastewater reuse in Spain were established and proclaimed in 2007. Even before the establishment of nation-wide standards, the local governments of Catalonia, Valencia, and the Balearic Islands have advised their own standards based on the WHO water quality guidelines [38]. The recently established standards regulate the level of microbes and suspended solids: The regulation of germs such as Legionella is an especially notable feature.

4. Water Quality Standards for Indirect Wastewater Reuse

4.1. Comparison and Importance of Each Water Quality Criteria

4.1.1. Coliform Bacteria

Based on the total number of *E. coli*, the standards of California recommend a 7-day median value of 2.2 cfu/100 mL, and a maximum value of 240 cfu/100 mL. On the contrary, the WHO [12] guidelines recommend 1000 cfu/100 mL, even for the strictest standards for unrestricted irrigation. Since the number of *E. coli* is smaller than the number of total coliform, the relative strictness of the standards of California compared to that of WHO could be even greater. The water quality standards of most countries that are examined in this study adopt the concept of the standards of California, except for France, whose standards are based on the revised WHO guidelines. Portugal and Spain are also currently using standards that have been tightened compared to the WHO guidelines and can be classified as an intermediate-level regulation [26].

The current coliform bacteria regulation for direct wastewater reuse by the MOE is much stricter than that of the WHO. Compared to the US EPA, which only involves fecal coliform, the MOE, which involves total coliform, applies stricter water quality standards. Out of the 44 WWTPs which directly reuse the treated wastewater for agriculture in South Korea, 8 WWTPs exceed the coliform bacteria standard for processed food crops of 200 MPN/100 mL. The average total coliform for all 44 WWTPs was 139 MPN/100 mL [61]. Therefore, it is inappropriate to use treated wastewater to irrigate food crops with the current level of treatment and water quality standards. Even for processed food crops, additional treatment is needed. Especially, considering the current water quality standards that use the maximum allowable value and the treated wastewater quality report of the MOE, which is based on the annual average value, it can be said that most of the reused wastewater for agriculture exceeds the coliform bacteria standard.

Through examining the water quality of sites that adopt indirect wastewater reuse for paddy irrigation in South Korea, an average of 19,000 MPN/100 mL of total coliform was detected during the irrigation period [20]. Even for sites irrigated by relatively clean water derived from a reservoir, an average of about 15,700 MPN/100 mL of total coliform was detected [20]. It was also found that the total coliform of the irrigation water containing untreated wastewater was about 77,000 MPN/100 mL [21]. QMRA on paddy irrigation showed that the human health risk of irrigating treated wastewater is nine times higher than that of irrigating groundwater [42], but even with the extremely high level of total coliform, there have rarely been any reports of human harm from using treated or untreated wastewater for rice paddy irrigation. This indicates that the subjected level of total coliform can be easily found in nature and is inadequate as an indicator for microbes. The *E. coli* concentration of irrigation water with high levels of total coliform concentration was measured to be 13, 46, and 107 MPN/100 mL for reservoir water, indirect wastewater reuse water, and irrigation water containing untreated wastewater, respectively [20,21]. For fecal coliform, the concentrations for the subjects above were 5000, 180, and 633 MPN/100 mL, respectively [20,21]. Considering the high measurement of fecal coliform, even for conventional irrigation water derived from a reservoir, there needs to be a practical regulation using *E. coli*, which can well reflect the pathogenic microorganism such as the regulations of Spain, Greece, and Italy.

There have been numerous studies of human health risk regarding crops that are consumed raw, but, as has been proven through many QMRAs, results can vary depending on the initial conditions or the design of the experiment [62,63]. Therefore, there needs to be an attempt to lower the public concern of wastewater reuse practices and to eliminate human health risk by looking at the problem conservatively. To achieve such goals, it is recommended that reference countries adopt strict and conservative wastewater reuse standards, especially for crops that are consumed raw.

Generally, the paddy rice has a low risk of pathogenic bacteria infection since it goes through polishing processes and is consumed after being cooked. However, due to the nature of rice paddy cultivation, the irrigated water is contained for a certain period in paddy fields; therefore, when using treated wastewater for irrigation, issues of hygiene and safety of the farmer should be considered. Through QMRA of the *E. coli* concentration of paddy rice irrigation water, it was examined that the human health risk is very low when irrigating reclaimed wastewater. This means that additionally treated effluent after the regular WWTP processes meets the requirement for irrigation water [17]. However, when irrigating with treated wastewater diluted with stream water, the *E. coli* concentration exceeded the enteric disease risk value of 10^{-4}, and this has been reported to cause infection to farmers [17]. Yoon *et al.* [64] reported that the above risk can be drastically mitigated when farming activities take place 24 h after irrigation. Therefore, an additional treatment process or safer farming practices for indirect wastewater reuse is necessary.

4.1.2. Salinity

Treated wastewater contains high salt content which can immensely affect crop growth; thus, there needs to be a standard for salinity [65]. Salinity is usually described in electric conductivity (EC). The effect that salinity gives to crop growth differs by crop type. Generally, if the EC of irrigation water is below 700 µs/cm, it does not affect crop growth; when above 3000 µs/cm, it can cause severe damage [45]. Israel and Italy aim for unrestricted irrigation and have EC standards for wastewater reuse of 1400 and 3000 µs/cm, respectively. Portugal has a fairly strict EC standard of 1000 µs/cm. In South Korea, the MOE sets the EC standard for direct wastewater reuse differently for food crops and processed food crops; the standards are 700 and 2000 µs/cm, respectively. When monitoring the average EC values of irrigation waters, the reservoir irrigation water displayed 170 µs/cm, indirect wastewater irrigation water 960 µs/cm, and irrigation water containing untreated wastewater 330 µs/cm [20,21]. The salinity level of indirect wastewater irrigation could exceed the directly consumed crop's tolerance level, and additional treatments are therefore needed. The allowed EC for paddy rice was reported to be 2000 µs/cm [66,67]. The EC standard of direct wastewater reuse for processed food crops can thus be applied to that of indirect reuse for rice paddy irrigation.

4.1.3. Turbidity or Suspended Solids

Other than South Korea, countries that advise a standard for turbidity are the US EPA, Spain, and Greece, where the standards are usually subjected to unrestricted irrigation. The US EPA and Greece recommend a level lower than 2 NTU only for directly consumed crops and unrestricted irrigation, and Spain recommends a level lower than 10 NTU for vegetables. The MOE sets the standards at under 2 NTU for food crops, and under 5 NTU for processed food crops. Most countries that do not have a standard for turbidity have a standard for suspended solids instead. Spain and Greece have both standards for turbidity and suspended solids regarding irrigation water for vegetables.

A high level of turbidity can affect the performance of the irrigation facility, and can lower the hydraulic conductivity of the soil and in turn pollute the soil surface through surface flow [68,69]. In addition, since various viruses and bacteria can be attached to and migrate along with the solid particles, the elimination of suspended solids is related to the elimination of germs [33]. Therefore, the standard for turbidity can be set up based on the turbidity's influence on the irrigation facility performance, or vegetables which are vulnerable to germ infection. In the case of indirect wastewater reuse, a strict standard of 2 NTU can be applied for directly consumed crops, and, for indirectly consumed crops, a specific standard that can prevent the adverse effects is needed. Many countries apply the suspended solids standards for indirectly consumed crops, and South Korea can use the 15 mg/L standard, which is a standard for using lake water as agricultural irrigation. In the case of paddy rice, where water is supplied through surface irrigation, adverse effects to irrigation facilities do not exist, and the human health risk can be controlled through a microbe standard. Thus, it can be said that an additional standard regarding suspended solids is not necessary.

4.1.4. Organic Matter

Organic matters not only negatively affect the odor and color of the water, but also act as nutrients for microbes and bring various adverse effects during the disinfection process [33]. Israel and Italy, which have the most strict water quality standards for wastewater reuse, have standards for BOD and COD. However, there are cases such as the US EPA and France where they only have regulations for BOD and COD, respectively, while there are no standards for organic matters at all in WHO, Portugal, or Spain. Even when comparing with Israel's 10 mg/L, South Korea has a very strict BOD standard because of the emphasis on the regulation in terms of stream water quality management. In examining water quality of the treated wastewater effluents from the 44 WWTPs of South Korea, the average BOD measurement was 2.6 mg/L [61]. The BOD measurement of irrigation water as indirect wastewater reuse was 2.0 mg/L [20]; even for irrigation water containing untreated wastewater, BOD showed an extremely low level of 2.6 mg/L [21]. Therefore, it can be said that applying the current strict standards of the MOE for direct wastewater reuse is adequate enough even considering the regional idiosyncrasies.

4.1.5. Nutrients

Israel and Italy have set standards for nutrients regarding wastewater reuse. Israel sets standards for T-N and T-P as 25 and 5 mg/L, respectively, and the same standards for Italy are 15 and 2 mg/L, respectively. South Korea does not have standards for nutrients specifically for wastewater reuse, but nevertheless have strict water quality standards for stream water quality management: The regulation levels of T-N and T-P are 1 and 0.1 mg/L, respectively. When examining the reservoir irrigation water in South Korea, results confirmed a T-N value of 1.1 mg/L and a T-P value of 0.05 mg/L, which are relatively good [21]. In the case of indirect wastewater reuse, T-N and T-P were measured at 3.3 and 1.6 mg/L, respectively [20]. Irrigation water containing untreated wastewater confirmed T-N and T-P values of 14.0 and 2.8 mg/L, respectively [21]. The above results, even when examined against the relatively strict standards of Israel and Italy, are fairly descent.

In South Korea, during the dry season of May to June, which is when most of the irrigation activity occurs, irrigation water by indirect wastewater reuse contains a high level of T-N concentration due to the decrease in streamflow volume [14]. This can lead to a decrease in production due to lodging [46,70]. In consideration of the above negative effects of nitrogen on paddy rice growth, Taiwan and Japan have set standards for T-N to be under 3.0 [46] and 1.0 mg/L [70], respectively. Therefore, for better quality of paddy rice, a stricter standard should be applied. Depending on circumstances, a lowering of T-N concentration via additional treatment or via an application of appropriate fertilization practices in paddy farming might also be needed [10]. Phosphate can stimulate the growth of bacteria or algae, which can cause the clogging of irrigation facilities [71]; however, since the South Korean standard for T-P of effluent discharge is strict (being 0.2–2.0 mg/L), and considering the fact that effluent discharge from a WWTP in South Korea is usually used after being diluted with lake or stream water, there seems to be no need for additional restrictions for phosphate.

4.1.6. pH

The US EPA recommends the appropriate pH range to be 6.0–9.0, Israel 6.5–9.5, Italy 6.0–9.5, and Portugal 6.5–8.4. The MOE sets the pH standard for direct wastewater reuse as 5.8–8.5, the lower limit being somewhat low compared to the standards of other countries. Low pH values affect the mobility of heavy metals in the soil and can be absorbed by crops and contaminate water bodies [12]. Taking into account the existing agricultural water standards of pH 6.0–8.5 applied to stream, lake, and groundwater in South Korea, and considering the effect of pH on irrigation facilities, raising the lower limit of the current pH standard for the direct wastewater reuse seems appropriate for upland crops, which requires additional irrigation facilities.

4.1.7. Trace Elements

While the South Korean standards for direct wastewater reuse regarding trace elements are stricter than that of FAO [45] or US EPA [33] and similar to those of Cyprus, Greece, Israel, and Italy, it lacks the standards for elements such as beryllium (Be), fluorine (F), iron (Fe), molybdenum (Mo), and vanadium (V), for which many countries have standards (Table 4). Be, although having different effects on crops depending on the crop type, can be consumed by humans as a carcinogen through root crop, tuber crop, and forage crop [72]. F can damage the crops by accumulating in the leaf and fruit [73]. Fe, while not harmful for crops in aerated soil, can cause immense damage by decreasing the vital P in irrigated paddy of acid soil [74,75]. In addition, the forage crops which grow in soil with a high concentration of Mo can be poisonous to livestock [76], and V is known to be harmful to many crops even in relatively low concentrations [33].

Treated wastewater after secondary treatment is adequate for reuse since the level of heavy metals in the effluent is similar to that in nature [45]. In monitoring the water quality of three types of irrigation water in regards to categories of Al, Cu, Ni, Zn, As, Cd, Cr, Co, Pb, Li, Mn, Hg, Se, and CN, reservoir water did not exceed any of the direct wastewater reuse standards, indirectly reused wastewater exceeded levels of Al and Mn, and irrigation water containing untreated wastewater exceeded the levels of Al, Cu, Zn, and Mn [20,21]. Considering the average concentration during the irrigation period and the standards of other countries, the detected high levels of Cu and Zn were negligible, whereas the results for Al and Mn were concerning. Additional treatment for Al and Mn is needed since they can be poisonous to crops or decrease crop yields [52]. South Korea should set standards for elements such as Be, F, Fe, Mo, and V considering the specific conditions of the country; since there are no preceding studies on the subject, it seems practical to adopt the standards of other countries.

4.1.8. Odor

There are normally no specific standards for odor in agricultural wastewater reuse, but the South Korean standards state that the odor "should not be unpleasant", and this could have a positive effect of reducing the animosity towards the idea of wastewater reuse. The perception of farmers towards wastewater reuse can be an important criterion in establishing water quality standards [77], and physical characteristics such as odor have a strong influence on farmers' perceptions. Therefore, including a factor of odor for water quality standards could be a good approach in considering stakeholders.

Table 4. Comparison of recommended maximum concentrations of trace elements in irrigation water.

Parameters	Korea [56]	FAO [45]	US EPA [33]	Cyprus [25]	Greece [25]	Israel [36]	Italy [34]
Aluminum, Al	5.0	5.0	5.0	5.0	5.0	5.0	1.0
Arsenic, As	0.05	0.1	0.1	0.1	0.1	0.1	0.02
Beryllium, Be	- [(a)]	0.1	0.1	0.1	0.1	0.1	-
Boron, B	0.75	0.7	0.75	0.75	2.0	0.4	1.0
Cadmium, Cd	0.01	0.01	0.01	0.01	0.01	0.01	0.005
Chromium, Cr	0.05	0.1	0.1	0.1	0.1	0.1	0.1
Cobalt, Co	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Copper, Cu	0.2	0.2	0.2	0.2	0.2	0.2	1.0
Cyanide, CN	ND [(b)]	–	–	–	–	0.1	0.05
Fluoride, F	–	1.0	1.0	–	1.0	2.0	1.5
Iron, Fe	–	5.0	5.0	5.0	3.0	2.0	2.0
Lead, Pb	0.1	5.0	5.0	5.0	0.1	0.1	0.1
Lithium, Li	2.5	2.5	2.5	2.5	2.5	2.5	–
Manganese, Mn	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mercury, Hg	0.001	–	–	–	0.002	0.002	0.001
Molybdenum, Mo	–	0.01	0.01	0.01	0.01	0.01	–
Nickel, Ni	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Selenium, Se	0.02	0.02	0.02	0.02	0.02	0.02	0.01
Tin, Sn	–	–	–	–	–	–	3.0
Thallium, Tl	–	–	–	–	–	–	0.001
Vanadium, V	–	0.1	0.2	2.0	0.1	0.1	0.1
Zinc, Zn	2.0	2.0	2.0	0.005	2.0	2.0	0.5

[(a)] No recommendation; [(b)] Not detected.

4.1.9. Level of Treatment

The US EPA [33] sets the water quality guidelines so that wastewater is disinfected to a certain level regardless of the purpose of use. This is to prevent side effects to the human body that might occur from accidental contact with the treated wastewater. However, a water treatment technology to fulfill the given water quality standards is inevitable, albeit the absence of specific treatment guidelines for wastewater reuse. Israel and Italy require advanced and expensive treatment systems to meet its water quality standards [34,36], and Portugal also has treatment requirements as per its standards [37]. South Korea also requires more than secondary treatment for direct wastewater reuse, and, depending on the occasion, RO (Reverse Osmosis) and advanced treatment are applied as well.

4.2. Draft Water Quality Standards for Indirect Wastewater Reuse in South Korea

4.2.1. Differentiation by Crop Type

Generally, the water quality standards for wastewater irrigation are established depending on the type of subjected crop. The WHO's differentiation of unrestricted irrigation and restricted irrigation is based on whether the subjected crop is consumed raw or not, and the US EPA [33] also classifies crops into either food crops or non-food/processed food crops. Cyprus sets different water quality standards for processed food vegetables, human consumed crops, forage crops, and industrial crops. Portugal only has different standards of a microbiological parameter (FC) according to a crop's intended use. Spain has separate standards for raw consumed vegetables, human consumed crops, and industrial crops. Israel and Italy, due to their goal of unrestricted irrigation, do not differentiate water quality standards based on crop type. France sets different standards for four effluent qualities based on its potential use for crops and the accessibility of the public. Greece applies different standards of restricted irrigation and unrestricted irrigation based on not only crop type, but also the irrigation method and the accessibility of the public. The MOE sets different standards for direct wastewater reuse based on whether the subjected crop can be consumed raw or not.

Indirect wastewater reuse is usually practiced haphazardly, and this indicates that the water quality cannot be manually controlled unless the treated wastewater is additionally treated. Therefore, introducing an economical treatment system seems implausible in the case of rice paddy, where a large quantity of irrigation water is required. Still, in the case of upland crops, including vegetables raised through protected cultivation, the irrigation water quality standards need to consider the way the crop is consumed and the irrigation method. In addition, considering the change in the farming environment and the economic feasibility of using agricultural water, specific standards should be established for fodder crops and industrial crops as well.

4.2.2. Probabilistic Consideration

Like France, Portugal, and Spain, the water quality standards for direct wastewater reuse of South Korea use the maximum allowable value, yet are much stricter than those countries. The WHO [12] uses arithmetic mean as criteria for the water quality guidelines, and Israel uses the monthly average. The water quality guidelines of the US EPA use the median or average value depending on the subjected category. The state standards of the US are based on either geometric mean or exceeded number per sample, and, in the case of fecal coliform, apply additional factors of median value or a greatly mitigated maximum allowable value. Greece and Italy apply probabilistic considerations to their water quality standards. Each monitored value of the water quality categories are greatly influenced by the hydrological changes of the environment at which the samples are collected; therefore, using a strict maximum allowable value does not well reflect reality. Thus, as most countries do, applying the average value or the exceedance probability to the water quality standards is recommended.

4.2.3. Draft Water Quality Standards

From the above examination, a draft proposal for the water quality standards of indirect wastewater reuse was suggested, as seen in Table 5. The proposed water quality standards, while referencing the existing standards of direct wastewater reuse as well as reflecting the farming environment of South Korea, classified the use of irrigation water into rice paddy and upland. The standards also considered the categories of *E. coli*, EC, turbidity, SS, BOD, pH, and odor. Additionally, for trace elements, categories of the FAO standards such as Be, F, Fe, Mo, and V were added to the existing direct wastewater reuse standards. Wastewater treatment system or reuse system is needed to satisfy the water quality standards if irrigation water quality exceeds the standards.

The conservative Californian approach was adopted for the irrigation water of upland crops which can be consumed raw. For rice paddy irrigation water, the liberal approach of the WHO was adopted to prepare for the changes in water resources-such as water shortage and climate change-by vitalizing wastewater reuse for rice paddy irrigation, which takes up most of the freshwater resource demand. This kind of approach corresponds to the endeavor of Angelakis *et al.* [23], who asserted a third way which hybridizes a conservative approach and a liberal approach.

Table 5. A draft proposal for the water quality standards of indirect wastewater reuse in South Korea.

Parameters	Upland Irrigation		Rice Paddy Irrigation [(a)]
	Food Crops	Processed Food Crops	
E. coli (MPN/100 mL)	≤10 [(b)]	≤10 (monthly mean) ≤ 200 (max)	≤1000 (max)
EC (μs/cm)	≤700 (max)	≤2000 (max)	≤2000 (max)
Turbidity (NTU)	≤2 (monthly mean)	– [(c)]	–
Suspended solids (mg/L)	–	≤15 (monthly mean)	–
BOD (mg/L)	≤8 (monthly mean)		
pH	6.0–8.5		
Odor	Do not unpleasant		
Al, As, B, Cd, Cr, Co, Cu, CN, Pb, Li, Mn, Hg, Ni, Se, Zn	Korean standards for direct wastewater reuse standards [(d)]		
Be, F, Fe, Mo, V	FAO standards [(e)]		

[(a)] Agricultural activities should be carried out 24 h later after wastewater irrigation and 20% to 50% reduced fertilizer rate compared to the standard fertilizer rate is recommended. [(b)] 80% of samples below detection. [(c)] No recommendation. [(d)] The Korean standards for direct wastewater reuse standards were presented in Table 4. [(e)] The FAO standards were presented in Table 4.

4.3. Implication of the Proposed Standards

There can be many kinds of agricultural wastewater reuse, depending on the different agricultural environments and types of agricultural practices. Due to the lack of information on wastewater reuse environments, especially in developing countries, it is hard to devise an appropriate policy which can promote the practice of sustainable wastewater reuse. Indirect wastewater reuse-which is practiced more commonly in water-rich environments-and rice paddy-oriented agriculture are the key characteristics of wastewater reuse in South and East Asia. These regions, unfortunately, face serious water quality issues, which in turn cause freshwater scarcity, ill-health, and even fatalities [78]. Agricultural water is gradually deteriorating mainly due to polluted domestic and industrial effluents. Many of the rivers in South and East Asia contain up to three times the world average of fecal bacteria measure [79]. Asian countries are making concerted efforts to address these problems [78], and it was subsequently addressed by a variety of measures, including statutory regulation of water pollution control and other legislations [80]. Technologies and guidelines for indirect wastewater reuse could be appropriate measures for the safe and sustainable practices regarding water resources. In addition, international political pledges have been made at the national and local levels [80]. Therefore, the proposed draft standards would contribute to overcoming water problems by providing suitable criteria for practicing sustainable wastewater reuse in Asia.

5. Conclusions

Indirect wastewater reuse has been increasing due to urbanization and the increase of WWTPs, which in turn influences the irrigation water of the treated wastewater. For safe and sustainable practices of wastewater reuse, there needs to be appropriate water quality standards for indirect wastewater reuse. In this study, draft standards were proposed referencing the standards of the countries which already have, or have modified, water quality standards for agricultural wastewater reuse. In doing so, the water quality requirements for irrigation water and wastewater reuse were examined, and the standards of other countries on wastewater reuse were compared and analyzed. The proposed standards for indirect wastewater reuse classified the use of irrigation water into rice paddy and upland, and adopt probabilistic considerations for their practicality of use. Categories of *E. coli*, EC, turbidity, SS, BOD, pH, and odor were also considered, and trace elements such as Be, F, Fe, Mo, and V, which did not exist in the current standards for direct wastewater reuse, were added. The conservative Californian approach was adopted for the irrigation water of upland crops, and the liberal approach of the WHO was adopted for paddy irrigation water: Thus, a hybridization of the two was attempted. The proposed standards of this study are expected to vitalize wastewater reuse for rice paddy irrigation, which constitutes most of the freshwater resource demand, and to provide suitable criteria for practicing sustainable wastewater reuse.

Acknowledgments: This work was supported by the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries (IPET) through Agri-Bio industry Technology Development Program, funded by Ministry of Agriculture, Food, and Rural Affairs (MAFRA) (grant number 114060-3).

Author Contributions: Hanseok Jeong and Hakkwan Kim developed the conceptual framework for this manuscript, collected and analyzed the data for the standards and guidelines of various countries and organizations, suggested the appropriate water quality standards, produced the tables, and wrote the paper. Taeil Jang helped to choose a proper method for data display, suggested the appropriate water quality standards, and produced the final tables. Hanseok Jeong, Hakkwan Kim, and Taeil Jang all read and made improvements to the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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