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Review

The WHO Guidelines for Safe Wastewater Use in Agriculture: A Review of Implementation Challenges and Possible Solutions in the Global South

Pay Drechsel [1,*], Manzoor Qadir [2,3] and David Galibourg [4]

[1] International Water Management Institute, Colombo 10120, Sri Lanka
[2] United Nations University Institute for Water, Environment and Health, 204-175 Longwood Road South, Hamilton, ON L8P 0A1, Canada; manzoor.qadir@unu.edu
[3] School of Earth, Environment & Society, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4K1, Canada
[4] Water Engineering & Development Centre (WEDC), School of Civil Engineering, Loughborough University, Leicestershire LE11 3TU, UK; d.galibourg@lboro.ac.uk
* Correspondence: p.drechsel@cgiar.org

Abstract: Globally, the use of untreated, often diluted, or partly treated wastewater in agriculture covers about 30 million ha, far exceeding the area under the planned use of well-treated (reclaimed) wastewater which has been estimated in this paper at around 1.0 million ha. This gap has likely increased over the last decade despite significant investments in treatment capacities, due to the even larger increases in population, water consumption, and wastewater generation. To minimize the human health risks from unsafe wastewater irrigation, the WHO's related 2006 guidelines suggest a broader concept than the previous (1989) edition by emphasizing, especially for low-income countries, the importance of risk-reducing practices from 'farm to fork'. This shift from relying on technical solutions to facilitating and monitoring human behaviour change is, however, challenging. Another challenge concerns local capacities for quantitative risk assessment and the determination of a risk reduction target. Being aware of these challenges, the WHO has invested in a sanitation safety planning manual which has helped to operationalize the rather academic 2006 guidelines, but without addressing key questions, e.g., on how to trigger, support, and sustain the expected behaviour change, as training alone is unlikely to increase the adoption of health-related practices. This review summarizes the perceived challenges and suggests several considerations for further editions or national adaptations of the WHO guidelines.

Keywords: risk awareness; behaviour change; food safety; social marketing; WHO guidelines; wastewater irrigation

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Citation: Drechsel, P.; Qadir, M.; Galibourg, D. The WHO Guidelines for Safe Wastewater Use in Agriculture: A Review of Implementation Challenges and Possible Solutions in the Global South. *Water* **2022**, *14*, 864. https://doi.org/10.3390/w14060864

Academic Editor: Edward Laws

Received: 8 February 2022
Accepted: 7 March 2022
Published: 10 March 2022

1. Introduction

Wastewater is broadly defined as 'used' water that has been contaminated because of human activities (in the context of this paper this includes urban but not agricultural runoff) [1]. It can be raw (grey and/or black water) or diluted, and can potentially create significant harm for human and environmental health, but has also been increasingly recognised as a reliable and cost-effective source of water, particularly for agricultural or industrial applications if appropriately treated [2,3].

Information on the current levels of generated, available, and reused wastewater volumes at different scales is, however, very scattered, infrequently monitored and reported, and unavailable in many countries [1,4]. Thus, any 'global' data must be used with care; moreover, 'treatment' can result in very different levels of quality, and treatment plants might operate at capacities (far) below those reported from individual countries [5,6]. In addition, data regarding on-site wastewater treatment are often lacking, although on-site systems might be regionally representative of most of the population. Even in high-income countries, significant numbers of people rely on on-site systems such as septic tanks and are not connected to sewer systems. For example, about one in five households in the United States depends on individual on-site or small community cluster systems (septic systems) to treat their wastewater [7].

As in the 1973 and 1989 edition, the 2006 WHO guidelines for the safe use of wastewater, excreta, and greywater in agriculture [8] focus mostly on pathogenic risks but give an increasing emphasis to those countries where treatment alone will not be able to break the pathogen cycle, and additional non- (or post-) treatment practices are needed to achieve acceptable risk reduction. This does not imply different standards for different countries. On the contrary, all countries should aim at the same tolerable disease burden per person per year. How quickly this target can be achieved will, however, depend on the country's current situation, context, and managerial and human resource capacity to progress. A stepwise approach is recommended as each risk reduction is better than none; it is important to recognize that the approach chosen via different treatment and post-treatment options might change as the country develops [9]. It is possible in this context that the objectives of public health, food security, and environmental protection can—at times—conflict with one another [10].

The need for a more complex risk management approach has led to the adoption of health-based targets by the WHO (2006) and a move away from relying only on water treatment levels which had to be achieved before irrigation was permitted. While effluent quality thresholds would work where regulations can be enforced, such as in planned wastewater reuse schemes, practitioners struggle with the concept in areas with no or limited treatment and widespread unplanned and unregulated direct or indirect wastewater use, with potentially high pathogen concentrations depending on the degree of wastewater dilution. In other words, where wastewater cannot be (sufficiently) treated, and farmers have no alternative water source, treatment target values are not a functional concept for risk management unless crop restrictions can be enforced.

The adopted broader focus of the WHO guidelines [8] on health-based targets, expressed in disability-adjusted life years (DALYs) allows, via risk modelling, the comparison of hazards and diseases as well as the quantification of the risk and the effectiveness of different pathogen barriers in risk reduction towards the targets. The support of alternative barriers along the food chain beyond wastewater treatment and common, but often unrealistic, recommendations such as crop restrictions, was an overdue change [11].

Unfortunately, such a broad and flexible approach did not translate into simple 'global' guidelines, like the previous WHO 1989 edition [12], especially in view of the pathogenic risks which receive priority attention by the WHO in support of low-income and lower-middle-income countries.

As the unplanned use and planned use of wastewater require different risk management approaches, the question arises of whether the WHO should not better distinguish between these two scenarios in its guidelines which would make them easier to read and to translate into national guidelines and regulations. A common reaction of agencies, officials, and others charged with managing wastewater (reuse) in sub-Saharan Africa, Latin America, or South(East) Asia has, however, been that the four-volume 2006 guidelines appear too data-demanding or too complex to understand, while policymakers or practicing engineers of more advanced institutions which are able to treat wastewater for direct reuse struggle to translate the guidelines into numerical thresholds that are (for them) easy to implement—as was the case in the 1989 edition [12–15]. Against this background, the WHO initiated the development of the Sanitation Safety Planning manual [16] in line with its Water Safety Plans with the aim of providing simple, step-by-step guidance on how to use and apply the 2006 guidelines. The selected differences between the WHO 1989 and 2006 editions are simplified in Table 1.

Table 1. Selected differences between the WHO's 1989 and 2006 wastewater use guidelines.

	WHO 1989	**WHO 2006**
Base for deciding if reuse is allowed or not	Reliance on the ability of wastewater treatment. Emphasis on irrigation water quality thresholds as management targets which determine if the water can be used or not for restricted or unrestricted irrigation	Reliance on combinations of pathogen barriers from treatment to farm and fork. The management target is expressed in DALYs and moved from the irrigation water to the actual intake of contaminated food. This allows the use of more barriers to minimize infection risks
Stakeholder capacity assumptions	Needs institutional capacities for functional treatment plants, enforced restrictions, and farmers' acceptance of self-protecting gear.	Needs capacities for risk modelling, wastewater treatment, and value chain actors' risk awareness and willingness to adopt risk reduction measures.
Risk assessment	Irrigation water quality analysis and comparison with water quality thresholds for excreta-based contaminants.	Quantitative microbiological risk modeling (based on dose-response functions). Human intake estimate for chemical contaminants.
Risk mitigation	Wastewater treatment for restricted or unrestricted irrigation (reliance on treatment or enforced restrictions); expected self-protection against occupational risks.	Treatment only where possible; otherwise reliance on the adoption of risk reduction options by different food chain actors (multi-barrier approach including crop restriction) and self-protection.
Effectiveness under external stress such as floods, disasters, lightning, power cuts	Limited, as treatment plants might be shut down with no control of the quality of wastewater treatment.	Multi-barrier system remains in place, likely with enhanced risk reduction measures compared with the pre-disaster situation.
Implementation potential	Limited scope in countries with low wastewater treatment (coverage) to achieve the thresholds. Larger scope and use in settings with high treatment capacity although those countries might have their own guidelines.	Large scope in countries with low or limited wastewater treatment coverage or capacity. Little scope in countries with stringent wastewater treatment systems and well-developed water quality reuse protocols in place.
Flexibility	Limited where treatment coverage is low.	Adaptable to various situations and low to high technical capacities.
Stakeholder involvement and ownership	Limited; but this can also be a strength (lower dependence on human compliance).	Key role in risk mitigation, well described in the Sanitation Safety Planning manual [16].
Adoption in low- and middle-income countries	Widely referenced, adopted, and/or adapted.	Very limited adoption or adaptation.

2. Materials and Methods

This paper is an opinion piece supported by searches of Web of Science, Scopus, ProQuest, Google Scholar, and the library of the Sustainable Sanitation Alliance (SuSanA) involving over 1000 publications from low- and middle-income countries in the Global South referencing the 2006 WHO guidelines and/or Sanitation Safety Planning manual. In addition, this paper draws on more than a decade of research by IWMI, UNU, and partners on the application of the WHO guidelines in those parts of Africa, Latin America, and Asia where treatment plants face challenges or have a very low coverage, and the 2006 edition offers a unique framework to assess and manage possible health risks from wastewater irrigation.

As shown in Figure 1, the 2006 edition has gained significant attention over the last decade, at least in academic circles. Despite this attention, the adoption and/or implementation of the 2006 guidelines have remained limited until now, including in those countries for which they were revised [9,14,15,17–19], in contrast to the 1989 edition.

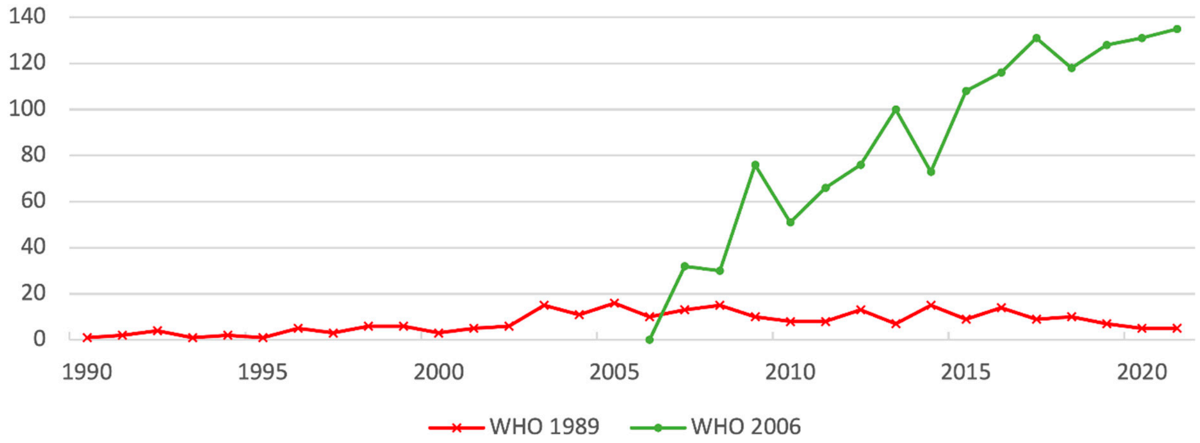

Figure 1. Number of WHO wastewater use guideline citations in academic journals (based on extractions from Scopus on 13 January 2022). While Figure 1 implies an increasing interest in the 2006 guidelines, many of the papers referencing the 2006 edition use only the 1989 water quality thresholds in their texts.

This review was catalysed by limited progress, reported in particular from Ghana which was one of the principal countries where, for more than a decade, the WHO, FAO, and IWMI had analysed, alongside national and international partners, the pathogenic and non-pathogenic risks related to wastewater-irrigated vegetable farming along the food chain [20–22]; and verified and pioneered the development of a large variety of so called non-treatment options for farmers, traders, and kitchen staff to minimize the health risks for consumers of raw salad greens [23–25]. However, more than a decade later, the data from the same cities do not indicate any reduced risks, changed risk perception, or behaviour [26–29]. This is also discouraging as Ghana references, as maybe the only African country, the 2006 WHO guidelines in its Irrigation Policy in support of safe wastewater irrigation. However, without related legislation (like municipal bylaws) and regulations that empower institutions to implement them, the policy reference remains a 'paper tiger' without any significant impact [30]. It should be noted that the impact pathway of the research in Ghana, including urban bylaw revisions, has relied on the follow-up funding of a national food safety campaign, among others, to roll out and implement the results, funding which has never materialized.

3. Results and Discussion

More than 75% of the screened literature targets risk assessments (water, groundwater, soil, food, and so forth), while risk management through wastewater treatment was the subject of 16% of the papers, followed by 7% with a focus on non-treatment options. The compiled experiences from the review permit several observations for possible consideration to further develop the WHO wastewater use guidelines for agriculture or related national adaptations.

3.1. Adapting the Guidelines and Types of Health Targets to Common (Regional) Challenges and Capacities

Based on the feedback received on the 2006 edition, it appears that a dissection of the guidelines tailored to the specific challenges and institutional capacity constraints that particular groups of countries face, would result in higher adoption (and use). From a risk management perspective, Scott et al. [9] suggested the differentiation of at least two types of wastewater irrigation—unplanned and planned water reuse (Table 2). This is an important differentiation, which has also been guiding the WHO's increasing emphasis on solutions for unplanned reuse where treatment capacities are insufficient.

Table 2. Characteristics of two principal wastewater irrigation types.

	Unplanned Use	**Planned Use**
Management status	Unplanned, usually informal farming activities along streams in and downstream urban areas	Planned (formal) water reuse at a particular downstream location of a treatment plant
Reuse guideline availability	Low, need guidance from WHO	High, usually own national guidelines available
Direct versus indirect use	Mostly indirect use of diluted wastewater, in part direct use	Mostly direct use (treated, raw) wastewater, sometimes mixed wastewater and freshwater
Estimated global scale	About 29.3 million hectares [31]	0.7–1.35 million hectares
Climates	All climates, mostly driven by poor sanitation	Mostly arid, but also driven by economic water scarcity
Physical locations	Any open plot near a water body	Near treatment plants to allow wastewater to be channelled to agriculture sites
Official recognition	Low, usually informal sector	High, usually formal sector
Water quality	Varies largely from untreated to (partially) treated to seasonally or generally diluted wastewater with spatial and temporal variations	Relatively smaller variation in treated wastewater quality
Health risk mitigation focus	A combination of risk barriers between farm and fork depending on risk awareness and institutional support	Compliance with Sanitation Safety Plans, incl. water quality monitoring and crop restrictions as additional risk barriers
Existing institutional capacity	Low to moderate; laboratory testing uncommon, except for occasional screening	Moderate to high; laboratory testing of water quality part of a monitoring plan
Risk mitigation challenge	To identify incentives to support adoption of low-cost risk mitigation measures, and related compliance monitoring	To maintain institutional capacities for plant maintenance and effluent monitoring
Main policy challenge	To balance farmer livelihoods and community benefits against risks; to enforce source pollution control	To build wastewater governance for safe and productive reuse; ensuring fit-for-purpose use
Expectations from a Water Reuse Guideline	Risk assessment and mitigation measures which do not require special capacities or data	Water quality thresholds to monitor treatment performance

Source: Scott et al. [9], modified and extended.

1. Unplanned use of wastewater in agriculture is very common and is likely taking place on 29.3 Mha in and downstream of urban centres [31]. This is a primary result of inadequate sanitation and no treatment capacity, and consequently there is widespread pollution of surface water bodies. This results in crops being irrigated with

wastewater which can be untreated, or partially treated, and is—in most cases—diluted (indirect reuse). As such, farmers might not always be aware of water pollution and its related risks. The reuse of unsafe water occurs on farms in humid and arid regions alike and will continue to expand as long as investments in wastewater collection and treatment do not keep pace with population growth, water demand, and urbanization in general (Box 1). Without treatment capacities, in some regions, authorities tend to adopt a 'laissez-faire' attitude vis-à-vis direct or indirect reuse [32]; in other regions, water quality standards for indirect wastewater reuse have been suggested [33].

Box 1. Outpaced sewer access.

A recent assessment based on the 2000–2015 data [34] suggests that of the data obtained from 113 countries, 66 countries have experienced an annual sewer access growth (2.9%) surpassing the annual urban population growth (2.7%). The reverse was the case for 35 countries in which the average annual increase in sewer access (2.0%) fell significantly behind the annual urban population growth (3.1%). For the remaining countries, a decrease in the annual sewer access of 5.5% (due to breakage of the system, or no or little maintenance) was recorded, while urban populations grew at 3.2% per year. Beyond the 113 countries with available data, progress might be worse in those countries which are not reporting data. The countries with less coverage of sewer access than urban population growth or with a decrease in sewer access are usually addressing the infrastructure gap through on-site sanitation systems such as septic tanks and improved latrines.

2. Planned use of treated wastewater is more common in drier regions to offset water shortages. This practice is increasingly gaining ground given the prevailing water scarcity context and support by the SDG 6.3. Treated-wastewater reuse is particularly substantial in the Middle East and North Africa (15 %) and western Europe (16 %), and prohibitively low in regions with low wastewater treatment rates, such as sub-Saharan Africa, Latin America, and South and South-East Asia (e.g., Pakistan, India, and China), or where conventional water sources are abundant as in Scandinavia [35].

National data on the area under planned wastewater irrigation date back to before 2008, suggesting in total about 0.5 million ha [36]. Since then, the use of treated wastewater has increased, although globally more for industrial purposes and landscaping than agriculture. While estimates on the acreage under irrigation are missing, estimates on the volume of wastewater for planned reuse are available [35]. Based on the global volume of treated wastewater made available for reuse (40.7 km^3), of which about 30% are used for crop irrigation [37], the cropping intensity of 1.5 crops/year for wastewater-irrigated areas [38], and the average crop water requirement of 6000 m^3/ha [39], we estimate that up to 1.35 million ha might be today under planned reuse. As the cropping intensity in some wastewater irrigation settings reaches 3 crops/year (18,000 m^3/ha), a lower estimate would be 0.7 million ha. The share of agricultural reuse can be much higher than 30%, like in Spain or Jordan (about 90%), but also lower (10–20%) like in China or, e.g., California [40,41] where reuse for urban (industrial processes, landscaping) or groundwater recharge are today dominant. Agricultural reuse is often disadvantaged as many urban areas are in coastal zones, far downstream from agricultural regions.

Yet, planned wastewater use for irrigation remains important e.g., in western North America, Australia, and southern Europe, given the increasing competition for water between agriculture and other sectors. An often cited success story comes from Jordan [3,16,19], where the authorities are promoting reuse and adopted the flexible combination of treatment and non-treatment options as described by the WHO [8,16]. An important lesson was that enabling stakeholder involvement and capacity development as early as possible are crucially important to ensure the productivity and sustainability of the planned wastewater reuse projects [19].

Keraita et al. [42] and Drechsel and Keraita [43] went a step further than Scott et al. [3] and proposed differentiation between the common situations found in low-, middle-, and high-income countries for target selection and the interpretation and implementation of risk assessments under the 2006 guidelines (Table 3).

Table 3. Examples of possible health-based targets suitable for countries with different levels of wastewater collection and treatment (Drechsel and Keraita [43], modified).

	High Level of Wastewater Collection and Safe Treatment (Common in High-Income Countries)	**Increasing Urban Wastewater Collection and Treatment (Many Middle-Income Countries)**	**Limited Wastewater Collection and/or Treatment (Common in Low-Income Countries)**
Examples of health target types	Health outcome targets (averted DALYs) Water and food quality targets Technical standards	Water and food quality targets Performance targets	Water and food quality targets Performance targets
	Characteristics of selected health-based targets		
	Health outcome targets	**Water and food quality targets**	**Performance or technical targets**
Nature of target	Defined as the additional tolerable burden of disease (measured in DALYs)	Low- or no-risk thresholds for chemicals or pathogen indicators for water and crops usually based on international guidelines	Low- or no-risk thresholds or observational compliance targets for adopted best practices
Risk assessment approach	Quantitative methods (e.g., QMRA)	Semi-quantitative risk assessment using a matrix of likelihood and severity	Team-based descriptive risk assessment (ranking) decisions
Integration of chemical risks	Difficult to model due to lack of (local) dose-response functions	Can be added to a semi-quantitative matrix ranking	Limited lab capacity for routine analysis of organic chemicals
Typical application	High-level health-based targets. Adoption of WHO manual [16] for overall risk monitoring	Compliance monitoring (technical and non-technical) as part of sanitation safety planning at exposure hotspots	Based on achievable risk reduction (like pollutant concentration changes) and compliance monitoring
Data needs for monitoring	High	Medium	Low

In this proposition, the concept of DALYs as health-based targets and quantitative microbiological risk assessments (QMRAs) would only get attention where they are supported by local capacities. Where this is not the case, other types (or proxies) of health-based targets, such as (i) food or water quality thresholds, (ii) intervention performance targets, and (iii) technology-related standards, as postulated by the WHO in its drinking water guidelines [44], could be easier adoptable alternatives until institutional capacities and data support more advanced approaches and modelling. Where these are missing [45], the WHO [16] suggests semi-quantitative risk assessments, which in urban areas usually result in a high-risk scenario, especially where crop restrictions cannot be enforced (Box 2).

The traditionally preferred targets remain water (or crop) contamination thresholds as postulated in [12]. However, where such technical thresholds cannot be achieved or maintained, or where achieving them would not change the actual risk (for example, where highly treated effluent enters a larger untreated wastewater stream), their monitoring would only cost money without safeguarding public health. Targets should thus be realistic and relevant to the local context (considering, for example, the receiving waterbody's quality and absorption capacity) including its financial, technical, and institutional resources. With improving resources, targets and risk reduction measures can be progressively adjusted.

3.2. DALY Aversion and Cost-Effectiveness of Risk Reduction

With the target of healthy fieldworkers and consumers, risk reduction according to the WHO 2006 guidelines [8] can draw on a variety of measures apart from wastewater treatment, including post-treatment options such as safer methods of wastewater fetching, irrigation, crop processing, food handling in markets, and food preparation/washing in kitchens. Compared to well-designed wastewater treatment, very few alternative measures will provide individually a similarly high level of pathogen removal, and a combination of measures (multi-barriers) is required, which in addition might be 'safer' against the failure of individual barriers, in line with the concept of *hazard analysis and critical control points* (HACCP).

Box 2. Simplifying risk assessment.

Through its flexible step-by-step approach, combined with clear guidance and a broad toolset, sanitation safety planning can be relatively easily adapted to different settings, including those with too few data and resources for QMRA modelling [16]. The proposed semi-quantitative risk-assessment approach (tools # 3.2 to 3.4 in [16]) using a matrix of likelihood and severity, requires, however, multiple individuals in order to avoid subjective judgements and produce a consolidated rating [46]. If wastewater treatment is lacking or of questionable quality, severe crop contamination is likely in or downstream of urban areas. This implies, for unrestricted irrigation, the need for a log unit reduction of 6 for non-root crops and 7 for root crops, which can be achieved through cooking where the choice of crops can be restricted to traditional vegetables. For unrestricted irrigation and exotic salad greens eaten raw, a 6–7 log reduction without treatment (4 logs) will be a challenge unless farmers adopt drip kits and the vegetables are washed before consumption with a strong chlorine solution [24,47]. In addition. at least a 2-log unit reduction is likely due to die-off in warm climates, adding a safety margin of at least one order of magnitude [13]. Keraita et al. [25] summarize log unit reductions for particular interventions on farms, in markets, and in kitchens as verified in West Africa. Following Mara and Kramer [13], a tolerable additional burden of disease of $\leq 10^{-4}$ DALY per person per year instead of 10^{-6} is still safe, but more realistic and more manageable in developing countries as it will result in a reduction target of 4 log units, for example, 2 from the wastewater treatment via ponds or vegetable washing, and 2 from pathogen die-off.

The advantage of the QMRA would become apparent where the actual risk is much lower and fewer efforts (and related costs or behaviour changes) are required to safeguard health. On the other hand, the QMRA assumptions are conservative and tend to overestimate the potential risks [48].

In the case of Ghana, an in-depth QMRA analysis for five cities showed that building smaller, new wastewater treatment plants (WWTPs) upstream of the dominant irrigated vegetable farming areas could avert over 90% of the annual DALYs if the vegetable farmers would agree to (stay on or) move to those sites [49]. However, the plants would not protect against cross-contamination, e.g., in markets due to poor food hygiene, and are in real life usually not well-situated to serve irrigated farming areas. Alternative risk-reducing options include improved farming practices or improved vegetable washing in kitchens, each averting around 66–69% of the DALYs assuming an optimistic 75% adoption. A multi-barrier approach combining waste stabilization ponds with different on- and/or off-farm safety practices could also avert over 90% of the DALYs, assuming again 75% adoption. The cost effectiveness would be about USD 60 per DALY averted if the five treatment ponds only require rehabilitation, compared to USD 350 if the plants are to be constructed [49].

Scenarios calculated for 25, 50, 75, and 100% adoption showed that only a high and lasting adoption of risk mitigation options can achieve a significant impact on the DALY targets and be reasonably cost-effective, allowing a USD 5 to 1 economic return on investment (RoI) [50]. Priority should thus be given to those risk reduction options with the highest likelihood of sustainability (highest adoption rate or technical lifetime) rather than selecting those highly effective in reducing pathogen levels, but less likely to be widely adopted or long-lasting. With a more realistic 25 to 50% adoption rate, the health-based target should be modest, as only a similar percentage of DALY can be averted [49], which shows the importance of investing in well-designed behaviour change strategies [51].

Reports from the WHO [16] show examples of how risk mitigation strategies could be selected including an approach used in Peru for comparing the criteria for possible options (Table 4). Technical effectiveness is an important adoption criterium as some risk reduction measures tested on farms (such as water filters) can significantly decelerate irrigation efficiency, while other measures might require additional space, labour, time, or capital, or even reduce crop yield [52], which could strongly influence adoption. In an example from Tanzania, cost was the criterion that influenced the prioritisation of control measures more than others, and received a higher weight to encourage the adoption of less capital-intensive solutions [53]. Where risk awareness is low, the 'acceptability' of a recommended practice should get a high 'weighting' compared to the actual risk reduction 'potential' from an epidemiological perspective ('*do not let perfection be the enemy of good*'). However, where risk awareness is growing, the opposite case can prevail [53].

Table 4. A ranking chart for comparing possible risk reduction measures from three different perspectives ([16], modified).

Potential for Risk Reduction	**Technical Effectiveness of Proposed Measures**	**Likelihood of Acceptability of Proposed Measures**
Weighting: 1.5	Weighting: 1	Weighting: 1.5
High = 3	High = 3	High = 3
Medium = 2	Medium = 2	Medium = 2
Low = 1	Low = 1	Low = 1
Priority score = (potential × its weighting) × (effectiveness × its weighting) × (acceptability × its weighting). The weightings will change with the context.		

3.3. *Targeting Kitchens, Not (Only) Farms within the Multi-Barrier Approach*

There are several reasons why those who work in household, restaurant, or street food kitchens might be a better and more receptive target group for behaviour change than vegetable farmers, not to mention that kitchens, as the last stop before consumption, are the ultimate risk barrier:

1. As farmers or traders of exotic vegetables might in some cultures never eat their crops and thus not gain awareness of the possible problems consumers can face, risk reduction strategies should focus on consumers or those gate-keepers (such as kitchen staff) who are closest to food consumption. Negative feedback from consumers might then trigger safety concerns down the 'fork to farm' food chain. There are regional differences: farmers, for example, in Ghana grow highly profitable exotic vegetables for the street food market, not for self-consumption, as exotic salad greens are not part of the local diet at home. This can be different in Francophone Africa, influenced by the French cuisine. In general, leafy exotic vegetables, such as lettuce, are less adapted to the hot West African climate than indigenous vegetables and require more frequent watering, exposing them constantly to pathogens. This is a particular concern as lettuce is eaten raw, while local vegetables are commonly cooked [22,24];
2. Farmers usually show low occupational risk awareness in view of the water used [29], and object to or neglect recommended safety measures, such as protective clothing (Box 3); likewise the cessation of irrigation before harvesting, as this can easily result in lower yield. Drip irrigation kits, which allow a 2–4 log pathogen reduction, are often not practical as the kits cost money, might not fit farmers' planting density, get clogged as the water is not clean, and can be easily stolen. Most ignored, however, are the recommendations to change crops, as farmers will only grow what gives the highest revenues unless crop restrictions are enforced [24];
3. While changing water, fetching, or irrigation practices can be a significant effort in terms of labour, capital, or time input, improved vegetable washing is not costly and entails only a minor change but can reduce pathogenic risks by 2–3 log units [45];
4. Last but certainly not least, whatever risk reductions farmers might achieve can be futile if the vegetables are again exposed to pathogens during or after harvest [54–56]. As vegetable handling in markets and kitchens can cause new contamination, the promotion of food hygiene, including appropriate vegetable decontamination in

kitchens, is eventually the most cost-effective risk barrier even where the irrigation water appears safe [2].

Box 3. Occupational risks.

Fieldworkers are best protected through wastewater treatment. Where this might not be possible, alternative or additional interventions are required. A tolerable pathogen level can be assumed provided that the workers and farmers are (i) informed of their risks and accept risk-reducing measures, e.g., wearing protective clothing, avoiding water contact while fetching water (pumping instead of immersion), and applying water (furrows instead of overhead watering, using cans), and (ii) stick to personal hygiene and/or regular antihelminthic treatment [24]. However, in practice, farmers' awareness of risks is often low, protective gear is considered impractical for the task and climate, and any observed health problems, such as skin irritations, are accepted as a professional challenge well balanced by the economic benefit [39]. A review of cases from Africa and Asia showed that risks, risk awareness, and risk reduction can have distinct gender dimensions from farm to fork which have to be considered to make risk reduction successful [57].

3.4. Gain Overall Efficiency by Thinking Out of the Wastewater Domain

Especially in low-income countries, where wastewater-irrigated food is only one of several risk factors, health-based targets should consider the larger context of likely hazards to compare the cost-effectiveness of (linking) different interventions addressing different risk factors. While we should pursue research questions such as "which risk factors and pathways in my city are the most likely to cause a disease outbreak?" [58,59], it is likely that there are win-win options for capacity development not only across the water, sanitation, and hygiene (WASH) sector but including improved food hygiene. For example, awareness creation regarding kitchen hygiene and food safety including hand and vegetable washing can address multiple water- and food-based infections within the same training programme [60]. Such an integrated approach would also allow further learning, e.g., from handwash campaigns which might equally struggle with low-risk awareness.

3.5. Investing in Research on How to Best Facilitate Behaviour Change

Where wastewater collection and treatment have limited coverage and impact, human behaviour change is needed to implement risk mitigation measures between farm and fork. The commonly low level of health risk awareness already cited is a key challenge that calls for intervention to support the adoption of safe practices. Social marketing and nudging could trigger and support a more consumer-based change as alternatives or additional options to the educational and training programmes promoted thus far by the WHO [9,16]. In the past, many health promotion campaigns were based on educating people about the threat of disease in order to change their behaviours [61]. However, there is little evidence that approaches based on health education have had the anticipated impact, in particular in developing countries [62–64].

Social marketing is the use of marketing principles and techniques to advance a social cause, idea, or behaviour. It does not advertise a specific product or service but a new behaviour. For promoting water or food safety, social marketing can be key, as many customers will not be aware of the health risks and the willingness to pay for 'safe' water or food is not yet in place [65]. As different stakeholders will have different perceptions and limitations, social marketing strategies will likely differ between farmers, traders, and households. The target is that safe food or water is perceived as socially desirable and crucial for family health and image, i.e., a benefit in exchange for the new behaviour.

Nudging is a low-cost strategy that subtly directs people towards positive behavioural choices, which has recently gained attention in global health promotion. Nudge strategies have been applied to a wide range of health-promoting behaviour such as handwashing, but also water disinfection and food hygiene. The most common nudge strategies are those targeting decision assistance, such as fostering commitment and memory joggers [66], both crucial in the context of sanitation safety planning.

Aside from understanding the limiting factors, behaviour change will require significant applied social science research to analyse what might trigger it. Such studies must segment the population into distinct subgroups and understand the social and cultural environments in which people act to make decisions to better promote and communicate a desired behaviour [67]. The applied and participatory research process can be summarized in the following six steps:

1. Assess current food-handling behaviours related to the problem(s) of concern and the target group's underlying knowledge, risk awareness, and risk perceptions;
2. Identify the safe practices that best fit the target group and their local situation (see e.g., Table 4);
3. Identify and test with different focus groups (with risk awareness as a confounding variable) possible nudges and triggers, as well as entry points for social marketing (prestige, 'yuck' factor, business image/branding, beliefs, opportunity, costs, etc.) that could steer the adoption of the identified best practices;
4. Identify and test, with the focus groups, the barriers and possible enabling factors (external and internal) in support of the expected behaviour change (Tables 5 and 6). A key barrier could be implementation costs in terms of capital, land, labour, or time requirements to adopt a new practice or change an old one, resulting at least in hesitation and perceived inconvenience ('*old habits die hard*'). A key enabler could be institutional support, a direct financial benefit in terms of subsidies (e.g., input), or higher revenues from serving risk-conscious customers willing to pay a premium [68]. Non-financial incentives could be awards, tenure security, and so on (Box 4);
5. Identify appropriate communication channels (*inter alia* peers, extension officers, religious leaders, motivational speakers, medical staff) and media (such as radio, TV, training events, poster campaigns) which the target group will recognize and follow;
6. Consider private sector stakeholders (such as Unilever promoting soap or Nestlé promoting food hygiene and safety along with its Maggi® products) as important partners for developing, promoting, implementing, and monitoring effective change strategies.

Table 5. Example of external and internal behaviour determinants and possible intervention strategies for **vegetable farmers** in Ghana (Drechsel and Karg [51], modified).

Category	Barriers (−)	Enabling Factors (+)	Possible Response Strategy
Farm work	Farmers prefer only slight changes in their current (over years optimised) practices or those which require low (labour, etc.) investments	Some farmers already apply (unconsciously) risk-reductive irrigation methods to reduce workload (such as pond creation where worm eggs settle)	Risk-reduction measures should focus on cross-benefits where local practices and innovations support health risk mitigation
Socioeconomic conditions	Farmers are very concerned about their business which is their livelihood and ranks higher than most health problems (if a link is perceived)	Farmers do care about public perceptions for the sake of business (bad experience with critical media)	Promotion of safe produce and related branding could have business advantages
Education	Training on health risks from wastewater irrigation (etc.) has not been incorporated in educational curricula	Farmers are increasingly exposed to the issue, mostly through research projects, and awareness is growing	Applied and jointly tested risk-reductive measures should be incorporated in agricultural extension programmes
Institutional settings	Harassment from media and authorities results in negative public perceptions and defensive strategies	Authorities are in place and maintain pressure	Positive media reports can incentivise compliance with safety protocols (awards)

Table 5. *Cont.*

Category	Barriers (−)	Enabling Factors (+)	Possible Response Strategy
Social groupings	Farmers work as an association on each site, but do not link across sites	Innovations are more likely to spread from farmer to farmer than through external facilitation	Existing social networks should be central for communication strategies while observing local power structures
Farmer/consumer interaction (for feedback)	No direct interaction, as consumers are far down the value chain. Gender roles can prevent farmers from trading	Urban farm and market proximity supports elimination of intermediaries. Niche markets can bypass traditional gender roles	Special (safe food) direct marketing channels have been created for farmers, also linking them to supermarkets, canteens, etc.
Risk awareness	Health risk awareness is very low, for the farmers and for consumers who do not know the food source	Particular health knowledge is not needed to trigger or nudge behaviour change (e.g., via social marketing)	With or without direct risk awareness, nudging and/or social marketing could encourage positive choices
Scientific knowledge of pathogens	Very little awareness of invisible risks (micro-organisms) and knowledge on pathogen pathways	Increasing awareness and interest in health-risks and risk mitigation through research and training	Unless invisible risks can be made 'visible' (e.g., via GlitterBug®), nudging could bypass pathogen knowledge
Practical knowledge	Among all risk reduction measures those practices with high adoption potential in Ghana have not yet been identified and promoted	Farmers prefer field demonstration and/or learning by doing	Participatory approaches to identify suitable practice are needed and clear incentives for adoption (see Table 4)
Intention	Most farmers do not see the need to change their practices and deny risks and/or responsibility	Pressure induced by media and the authorities could facilitate farmers' responsiveness given that most have no tenure security	A balanced approach of locally best strategies (nudging, education, social marketing, regulatory pressure, incentives) is needed

Table 6. Example of external and internal behaviour determinants and possible intervention strategies for Ghana's informal **street restaurant sector** (Drechsel and Karg [51], modified).

Category	Barriers (−)	Enabling Factors (+)	Possible Response Strategy
Input supply	Effective disinfectants are generally not known, although available. Thus, vegetable washing is not effectively reducing pathogens	Vegetable washing to remove dirt is done by over 90% of stakeholders; this is an excellent starting point for effective pathogen removal	Promote available disinfectants (bleach, chlorine tablets, potassium permanganate) suitable for different classes of restaurants
Socioeconomic conditions	Vendors are concerned about the costs of required inputs or training	Public and private sectors offer free training. Some ingredients (bleach varieties) are very cheap	Make options known. Engage with the private sector for promotion and subsidies. Training certificates might motivate and increase sales
Education	In catering schools, practical food safety and hygiene does not receive much attention	Teaching materials are available, e.g., from the WHO and UNICEF on food hygiene, and WASH	Establish early links with the educational sector to facilitate adoption of results in curricula
Environmental conditions	Unsafe environment of street restaurants—tap water and toilets might be missing	Interventions have to consider local possibilities and limitations	Step-wise approach of improvements needed, as well as close support by public works.

Table 6. *Cont.*

Category	Barriers (−)	Enabling Factors (+)	Possible Response Strategy
Institutional settings	Regulating authorities are under-resourced, which might facilitate corruption	Authorities are in place	Institutional capacity building for compliance monitoring required
Social groupings	Few members in catering associations due to internal problems. Most associations have weak governance and funding	Social clubs, church groups and professional associations are common and possible communication channels	Associations should be strengthened, and memberships promoted. Support loan schemes/credit for safer behaviour
Vendor/customer interaction	Customers are more concerned about price, neatness, and quantity of the food, rather than food safety	Customers have much influence on vendors who want to satisfy them. Vendors are willing to learn to please customers	Customers' awareness about food-safety issues has to be increased to trigger demand across the value chain
Neatness as part of cultural norms	Neatness is important but does not necessarily include cleanliness and safe food	Controllers, vendors and customers are very concerned about neatness which is closely associated with trust and respect	The term neatness has to be extended to visible and invisible cleanliness; or positively linked (nudging) to disinfectants
Branding	Customers do not ask about food origin related to safety which is considered disrespectful and less important. Anyway, structures to verify (monitor) safety claims are missing	Food origin could be a 'brand', e.g., carrots from Togo are preferred in Ghana to those from Ghana	More an option for niche markets, unless nudging or social marketing can link safety with accepted norms, e.g., 'visually clean', 'neat', 'tasty'

Box 4. Market demand for safe food.

A common example for financial incentives for food safety can be found in the related sector of organic food production and corresponding branding. While in Ghana, risk awareness and a willingness to pay for safe food are largely limited to the educated upper class [69–71], the situation can be different elsewhere. In Vietnam, for example, the emerging middle class is increasingly demanding safe or organic vegetables. Farmers who are responding could qualify for loans and safety certificates, although it is not easy to enter dedicated marketing channels, e.g., of organic food. Those cooperatives which have managed to build specific channels, supplying canteens, supermarkets, or shops reduced or removed intermediate actors in the food supply chain to increase source transparency, consumer contact, trust, and their (40–90% higher) profits [72,73]. However, the health benefits are limited to a niche market, not supporting the poor who are most at risk of disease transmission. Thus, the creation of niche markets will only benefit public health if they are used, for instance, as examples for broader awareness creation. Finally, certified ('pathogen-free') farm produce cannot be marketed in the same manner as certified organic food as postharvest pathogen contamination is common, which would undermine the safety label unless the safety procedures are applied all along the value chain [71].

These steps reflect the interplay between behaviour change and the components that make this change possible and sustainable: opportunity, (cap)ability, and motivation [74,75]. The opportunity is largely fostered by an enabling environment, e.g., ensuring the alignment of the behaviour promoted and existing regulations or norms. The ability or capacity for behaviour change can be developed through training or education, and the motivation by minimizing the costs and maximizing the tangible or intangible benefits. Social marketing and nudging become interesting entry points where health education and risk awareness are low and alternative triggers are needed to catalyse and sustain behaviour change. The nudges do not require any specific knowledge or conscious decision from the target group.

Approaches to promote positive, sustained behaviour change in the WASH or food safety sectors must have a strong element of human psychology to support knowledge- and technology-based interventions. Several models, such as Risks, Attitudes, Norms, Abilities, and Self-Regulation (RANAS), Behaviour Centred Design (BCD), and SaniFOAM have achieved this in low-income countries [64]. Another framework is the Behaviour Change Wheel (Figure 2) which has been widely applied in the public health domain [75] and covers all components considered important to achieving food safety under wastewater irrigation [51]. The comprehensive nature of the wheel should allow robust behaviour analyses and evidence-based designs to induce sustainable behaviour change in support of a multi-barrier approach, which would add value to the WHO's sanitation safety planning manual [16].

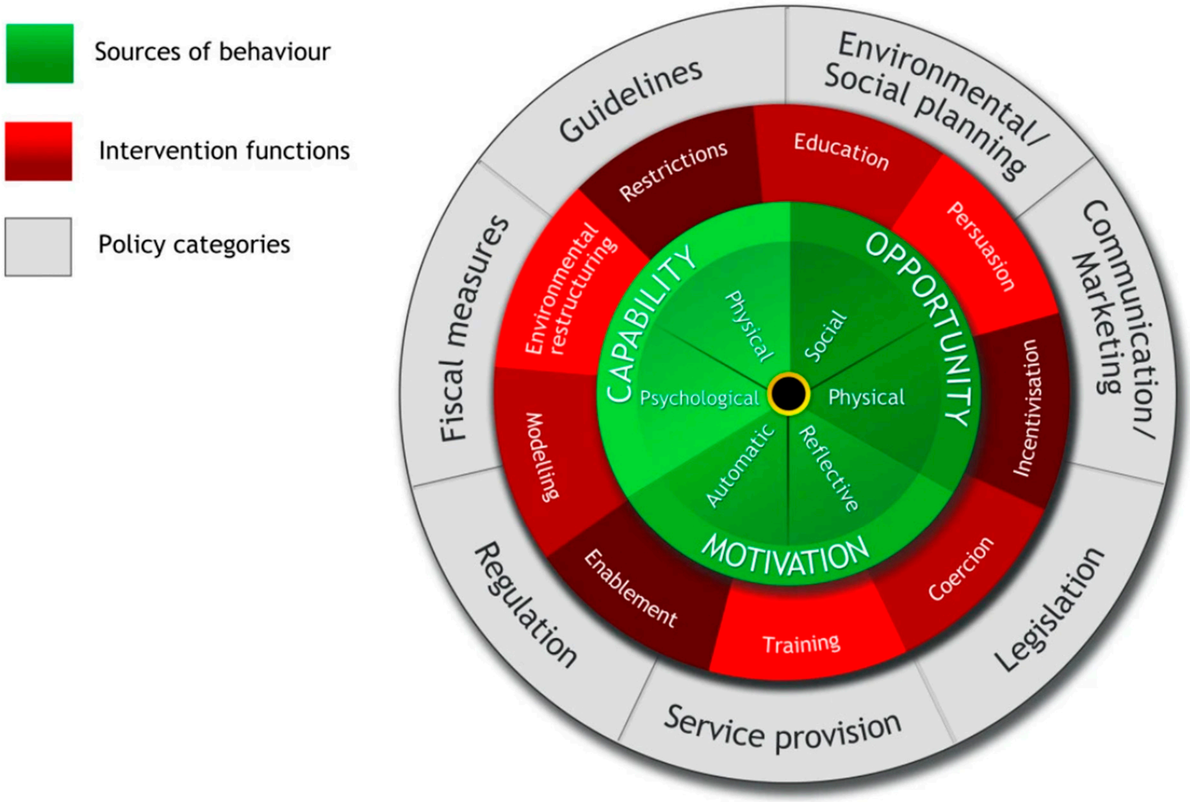

Figure 2. The Behaviour Change Wheel [75].

3.6. Monitoring Risks and Risk Mitigation

In the case of flooding, electricity cuts, or lightning strikes, treatment plants may be rendered inoperable [76,77], undermining their roles as risk barriers and risk-monitoring control points. Multiple control points are thus important within [78] and beyond the plant, as well as occasional random sampling and analysis of water and/or farm produce to verify that the risk reduction measures are working, and to act as an early warning system; this is also applicable for the large variety of chemical water contaminants. In fact, as in the application of HACCP, the use of microbiological testing is seldom an effective means of monitoring control points because of the time required to obtain results. In most instances, monitoring can best be accomplished using simple physical and chemical tests, and through visual observations. Microbiological criteria do, however, play a role in verifying that the overall system is working. The potential of such diagnostic testing and monitoring has been emphasized for wastewater during the ongoing COVID-19 pandemic [79] and could equally be applied to wastewater-polluted irrigation water, given the absence of sewer systems in most low-income and many lower-middle income countries [35]. While for COVID-19, there is thus far no evidence of virus transfer through wastewater irrigation [80], the situation could be different for pathogens that are more resistant against environmental stressors.

4. Conclusions

The main challenge of wastewater irrigation is the common reality of its unplanned use in urban and peri-urban areas, and to a more minor extent, the much smaller area where (well) treated wastewater is used in high-income countries in support of SDG 6.3 and the circular economy. In fact, most countries investing in planned reuse have their own reuse guidelines, in contrast to those countries struggling with unplanned reuse and in dire need of WHO assistance.

In those geographical areas where public health cannot be safeguarded through adequate wastewater treatment, the WHO [8] recommends additional on- or off-farm-based safety measures. In contrast to wastewater treatment, which relies on institutional capacities to maintain technical functionality, alternative options require individuals along the food chain to change their behaviour. Supporting policies and training programmes might be important steps in this process, but are not enough to trigger and sustain behaviour changes, which call for a stronger integration of social science research on incentive structures in the strongholds of engineering and epidemiology in order to address key adoption barriers, such as:

- Missing educational basics and risk awareness about invisible pathogenic threats;
- Missing direct benefits of increased food safety measures which can require more resources (labour, capital, land) than current practices;
- Missing local capacities to implement international guidelines, such as the 2006 WHO guidelines, which can be perceived as rather academic and counterproductive to the promotion of safe water reuse.

This paper fully supports the reasoning of the 2006 edition but sees a need for adjustments to improve the adoption and implementation of the guidelines. Based on this review and more than a decade of research mostly in West Africa and South Asia, this paper recommends the following considerations for further developing the WHO guidelines on safe wastewater irrigation or national adaptations, especially in low- and middle-income countries of the Global South:

1. To become easier to apply, the risk assessment and mitigation sections could be differentiated for regionally common risk scenarios such as planned reuse and unplanned reuse, while considering different institutional capacities and available data. This includes moving the DALY and QMRA concepts more into the background for the benefit of non-academic readers and to flag alternative targets and proxies, based on semi-quantitative or at least descriptive risk assessment approaches. This is well-exemplified in [16], but ideally, there should be no need for a 138-page manual to 'operationalize' a 196-page guideline;
2. National governments must decide whether the baseline value of $\leq 10^{-6}$ DALY loss per person per year is appropriate or whether to adopt, at least initially, a less stringent value ($\leq 10^{-5}$ or even 10^{-4} DALY loss per person per year) which has a higher probability of achievement via non-treatment options [13,23];
3. Risk-reducing options should be primarily based on their local feasibility and adoption potential, followed by their risk reduction capability. Options close to the consumer are often simpler, more cost-effective, and better perceived, than farm-based risk reduction;
4. To be on the safe side where no detailed risk assessment is possible, risk reduction should aim as high as locally possible if (i) conventional wastewater treatment is missing or not defined, (ii) the choice of irrigated crops cannot be restricted, and (iii) the crops are typically consumed uncooked (such as raw salad). This situation is very common across sub-Saharan Africa, for example, limiting the need for a detailed risk assessment;

5. Educational measures for increasing risk awareness are important but should not be considered as sufficient for best practice adoption. Additional measures and incentives to support behaviour change will be crucial to reach even modest health-based targets. Where risk awareness is low, tools such as nudging, e.g., as part of social marketing, could be a consideration;
6. To identify the best behaviour change strategy, research on specific pathways is needed per target group to facilitate the adoption of safety measures within a local context with its own internal and external factors that might motivate or discourage stakeholders from adopting and maintaining the recommended technologies;
7. Thinking outside of the wastewater domain can create win-win situations for health campaigns to identify common triggers and cost-effective mitigation measures within the larger WASH, food hygiene, and food safety nexus, including synergies in view of compliance monitoring.

While this paper focuses on pathogenic risks, similar to the WHO 1989 and 2006 guidelines, chemical threats should not be underestimated and require more attention [81,82]. This refers to point pollution from mining or other industries, which calls for source treatment but also carries potential threats from contaminants of emerging concern (CEC) which can derive similar to pathogens from domestic non-point sources. Related risk assessments are under development [83] but are challenged in low- and middle-income countries by (i) no facilities for their routine detection and analysis, and (ii) inappropriate wastewater treatment processes to remove them [84]. Minimally, as interim measures, diagnostic sampling and the analysis of irrigation water sources and irrigated crops are recommended, which will also be important in terms of pathogen identification to verify the fact that the risk reduction measures promoted can prevent water-borne pathogens from becoming food-borne diseases within the larger system.

The widespread challenge of water pollution might explain why most screened papers of the literature review (over 70%) focused on risk assessments and field trials, with limited reflection on actual risk mitigation. What is urgently needed is further feedback on the actual WHO 2006 guideline implementation, in particular the successful promotion and adoption of risk reduction measures along the food chain, and the achievement of defined health-based targets to verify, *inter alia*, the here-reported bottlenecks and suggestions, ideally from different countries and regions.

Moving from unsafe to safe, informal to formal, or unplanned to planned water reuse is for many countries a significant challenge and will require much more than reuse guidelines. Research is needed for understanding this trajectory in different geographical contexts of the Global South. Key drivers to consider will be regionally appropriate technical solutions which support unrestrictive reuse, a strong political will to adopt and implement supportive regulations, good governance to monitor the quality of treatment and/or any other risk barriers, and effective public engagement in building socially acceptable systems and clearly identified institutional responsibilities [9,85].

Author Contributions: Conceptualization: P.D., M.Q. and D.G.; literature search by D.G. and P.D.; writing—original draft preparation, P.D. and M.Q.; writing—review and editing, PD.; graphical support, D.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Acknowledgments: David Galibourg is supported by the British Engineering and Physical Sciences Research Council. The review has been supported by the donors of the CGIAR Trust Fund for the One-CGIAR initiatives on Resilient Cities and One-Health.

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

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