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The Use of (Treated) Domestic Wastewater for Irrigation: Current Situation and Future Challenges

María L Gatto D'Andrea[1], Ariela GJ Salas Barboza[1], Valeria Garcés[1,2], María S Rodríguez Alvarez[1,2], Martín A Iribarnegaray[1], Viviana I Liberal[1,3], Graciela E Fasciolo[4], Jules B van Lier[5] and Lucas Seghezzo[1*]

[1]*Instituto de Investigaciones en Energía No Convencional [INENCO], Consejo Nacional de Investigaciones Científicas y Técnicas [CONICET], Universidad Nacional de Salta (UNSa), Argentina*

[2]*Faculty of Natural Sciences (UNSa), Universidad Nacional de Salta (UNSa), Argentina*

[3]*Faculty of Engineering (UNSa), Universidad Nacional de Salta (UNSa), Argentina*

[4]*Centro de Economía, Legislación y Administración del Agua (CELA), Instituto Nacional del Agua (INA), Argentina*

[5]*Faculty of Civil Engineering and Geosciences, Department of Water Management, Section Sanitary Engineering, Delft University of Technology, The Netherlands*

***Corresponding author:** Lucas Seghezzo, Instituto de Investigaciones en Energía No Convencional [INENCO], Consejo Nacional de Investigaciones Científicas y Técnicas [CONICET], Universidad Nacional de Salta (UNSa), Avenida Bolivia 5150, A4400FVY, Salta, Argentina, Tel: +54-387-4255516; **E-mail:** Lucas.Seghezzo@conicet.gov.ar

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Abstract

The use of treated, diluted, and even raw domestic wastewater for agricultural irrigation is becoming an essential component of a more sustainable and integrated water resources management, especially in water-scarce regions. More than 20 million hectares are currently being irrigated with wastewater worldwide by about 200 million farmers. This paper provides an overview of some developments in the field of water reuse in agriculture, with a specific focus on Latin America, where this practice is rapidly growing. It also summarizes the benefits and risks of (treated) wastewater irrigation and discusses some of its social, cultural, institutional, and political aspects. The paper also highlights a number of technical, social, environmental, and political challenges that deserve special attention and further research. The use of (treated) wastewater in agriculture has great potential but cannot be dealt with in isolation from local, regional, and global water and sanitation management systems.

Keywords: Agricultural irrigation; Domestic wastewater; Latin America; Reclamation; Sustainable water resources management; Wastewater irrigation; Water reuse

Introduction

Irrigation with treated, poorly treated, diluted, and even raw domestic wastewater is a widespread practice in urban and peri-urban areas in most developing countries [1-3]. In some areas, driven by water droughts and acute water scarcity, urban water reuse is rapidly becoming a necessity [4-8]. Water scarcity is not the only driving force of this practice. Nutrient recovery, water source reliability and proximity to (peri) urban farmers, contributions to food and water security, improvements of the livelihoods of poor farmers, and a range of environmental aspects are also important incentives for water reuse [9-11]. Water reuse can also help mitigate climate change impacts on crop yields and dwindling water resources [12]. Landscape irrigation, groundwater recharge, and industrial applications, among other activities, are also being performed with treated wastewater [13-15].

Different types of water reuse have been identified. A common classification defines wastewater irrigation as: i) direct, in which wastewater is used as such in the field or ii) indirect, in which wastewater is first discharged into a water body from which water is later taken for irrigation [16]. Wastewater irrigation can also be planned or unplanned, also referred to as formal or informal, depending on the irrigation infrastructure available, the degree of social acceptance, and the level of control from state agencies [5]. Terms such as "recycled" or "reclaimed" wastewater usually refer to fully or partially treated wastewater (not to raw wastewater) [17].

The terms "domestic wastewater" and "sewage" will be used as synonyms in this paper [18]. Wastewater from households and buildings connected to sewerage systems is the main contributor to domestic wastewater, but raw or treated discharges from industries and urban runoff can also make significant and usually non-defined contributions. Urban water supplies ensure the constant availability of wastewater, since the fraction of non-collected domestic and residential water is only 15 to 25% and the rest returns to urban water systems [3]. There are several technological options for sewage treatment, ranging from traditional waste stabilization ponds (WSP) and conventional aerobic systems (like trickling filters or activated sludge), to high-rate anaerobic reactors such as the up flow anaerobic sludge blanket (UASB) reactor and other, more complex integrated systems [19,20]. A detailed description of these systems is out of the scope of this paper. Suffice to say here that the feasibility of water reuse is highly dependent on the type of wastewater treatment system applied.

Since almost 70% of all domestic wastewater generated globally is released untreated into the environment, of which about 90% in developing countries [1,21], it is not surprising that most direct reuse activities are performed with raw wastewater. This is critical to assess the feasibility of water reuse, since wastewater flow rate and composition vary from place to place with respect to availability. Water reuse is also dependent on economic aspects, social behaviour, local industries, climatic conditions, and water consumption, among other factors [20,22]. The main pollutants in sewage are: (a) suspended solids; (b) soluble organic compounds; (c) (in) organic nutrients and (d) pathogenic microorganisms. The types of pathogens, for example, are markedly different in industrialized and developing countries [23]. The same could be said of the concentration of a variety of chemicals like heavy metals, trace elements, detergents, solvents, pesticides, and other compounds like pharmaceuticals, antibiotics, and hormones, which can make wastewater unsuitable for irrigation. Wastewater treatment systems are usually selected in terms of technical and economic criteria, such as removal efficiency of specific pollutants, construction costs, but rarely based on their appropriateness for potential reuse [24-28]. Yet, recycling and reuse affect the entire "water chain", from supply to final disposal [5]. Therefore, these practices will necessarily influence the way we design, build, and operate water and sanitation infrastructure. They will also impose new challenges on existing institutions, government policies, and current modes of water governance [29,30]. To cope with this situation, most water institutions need to adapt and incorporate new management concepts [31]. Among these concepts, we should also mention a variety of alternative non-treatment options that could be part of water reuse schemes as long as risks are appropriately assessed and addressed [10,32].

Even though activities related to wastewater reclamation, recycling, and reuse have been traced back many centuries, the development of programs for the planned use of wastewater only took impulse in the late 19th and early 20th centuries [16,33-36]. With the rapid rise of sewage systems in the second half of the 1800s, "sewage farms" became a common method of wastewater treatment and disposal in Europe, North America, and Australia [37]. In most cases, wastewater disposal was the main purpose and agricultural benefits were incidental [21]. In fact, the first wastewater treatment process applied on a large scale at that time was land treatment [38]. Urban development in the early 1900s and some health problems derived of this practice resulted in the loss of interest and abandoning of almost all sewage farm projects [37]. Since the 1950s, wastewater for irrigation use has had a significant increase, especially in water-stressed areas [27].

Over the recent decades, important advances in wastewater treatment technologies have been made, while the amount of regulations and guidelines for water reuse have also increased in several countries. However, information regarding wastewater generation, treatment and reuse is often unavailable, incomplete, limited, or outdated [39]. Moreover, official and unofficial estimates of the areas under wastewater irrigation are largely different [40]. A recent effort to compile information at country level was performed by Sato et al. [41]. They concluded that only 55 out of 181 countries surveyed had data available on wastewater production, treatment and reuse. As pointed out by Jiménez and Asano [15], two issues affect the collection of accurate information: (a) water reuse is measured in different ways in each country, such as total volume reused and reuse per capita; and (b) a country totals hide locally-relevant information. Some governments also fear disclosing information as it may have negative effects on exports or imports [42]. In spite of these constraints, it has been estimated that more than 20 million hectares are irrigated worldwide with treated or untreated wastewater (around 10 percent of the total irrigated land), involving about 200 million farmers and probably four out of five cities [15,43]. It is also believed that one-tenth of the world's population consumes wastewater-irrigated crops [44].

Planned or unplanned water reuse has been well documented in Europe [13,14,45], Africa [46,47] North America [48,49], Asia [50,51], and Oceania [52,53]. Additional efforts are needed in other regions, in order to obtain a more clear picture of the development of this practice, especially since the new Sustainable Development Goals (SDGs) stated by the United Nations aim to significantly increase the percentage of recycling and safe water reuse by 2030 [54]. Water reuse is receiving increasing attention worldwide and additional research efforts in this area are highly needed [55].

In this paper we provide an overview of some developments in the field of water reuse in agriculture, with a special focus on Latin America, where this practice is rapidly growing and where an extra effort is needed to assess and standardize it. This paper is not meant to be a totally comprehensive review. It is rather an attempt to highlight the main features of water reuse, contribute to the ongoing debate about its advantages and disadvantages, and promote a wiser and safer use of all available water resources. We will briefly discuss some of the technical, social, environmental, and political aspects of this practice. This paper draws from published and unpublished reports, regional travels, and personal communication with scholars and practitioners in this field.

Benefits and Risks of Wastewater Irrigation

According to Keraita et al. [2], the main advantages of domestic water reuse are: (a) provision of nutrients; (b) reliability in water supply; (c) contribution to the urban food supply; (d) income generation; and (e) livelihood sustenance. These aspects are especially important for small-scale farmers who can obtain enhanced water and food security by using recycled or even raw wastewater for irrigation [56,57]. From an environmental point of view, the use of a new source of irrigation water will impact positively on the overall water balance and will slightly reduce the water "footprint" of agriculture [58], although the impact is merely near urban areas. Water reuse can also contribute to the generation of renewable energy through the irrigation of energy crops [59]. The use of reclaimed wastewater is also said to compete well with desalinated water in countries like Saudi Arabia [60] and with the costs of transporting freshwater for domestic purposes from distant locations in Namibia [61]. Beyond some of the intangible benefits that can be difficult to assess, water reuse can also generate economic profits [62-64].

On the other hand, commonly cited disadvantages of water reuse are mainly environmental impacts and health risks [2]. These drawbacks are mostly associated with the uncontrolled use of wastewater that promotes the spread of excreta-related pathogens, chemicals, and other undesirable constituents [65]. Negative effects frequently reported in soils are salinization, sodification, and accumulation of heavy metals and various unknown compounds that can negatively affect agricultural production in the long run [66]. Some studies address the influence that wastewater irrigation can have on the soil microbial community [67-69].

Sewage contains a variety of different organisms that can survive wastewater treatment including bacteria, protozoa, helminths, and viruses, which concentration vary depending, among other factors, on the sanitary status of the population [10,70]. Exposure routes are mostly contact with wastewater (farmers, field workers, and nearby communities) and consumption of wastewater-grown produce such as crops, meat, and milk (general consumers) [23]. Most pathogenic organisms are capable of remaining in the environment (in the wastewater, on the crops, or in the soil) long enough to be transmitted to humans [71]. Survival periods vary from a few days up to one year for the extremely resistant helminth eggs [10]. That is why helminthiases (infestation with parasitic worms) are recognized as the greatest health risk of the use of wastewater for irrigation [10,42]. The most common helminthiasis is ascariasis, which is endemic in Latin America, Africa, and the Far East [42]. Other diseases related to the use of wastewater include cholera, typhoid fever, shigellosis, gastric ulcers, giardiasis, amebiasis, and skin problems [72]. Negative health impacts from the use of raw or poorly treated wastewater have been documented in many studies [23,37,72-75]. Biological health risks have a rather immediate outcome whereas chemical risks are translated into time-delayed illnesses, such as chronic toxic effects or different types of cancer [10,76]. Secondary risks may also arise from the creation of habitats that facilitate the survival and breeding of vectors and a subsequent increase in the transmission of vector-borne diseases in irrigated areas [32,77,78].

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Since the publication of the World Health Organization guidelines for the microbiological quality of treated wastewater used in agriculture [79], health risks have been investigated through epidemiological studies [72] but also by applying Quantitative Microbial Risk Analysis (QMRA). The latter approach has been broadly used to establish health risks associated with water reuse in developed and developing countries under different scenarios, including unrestricted and restricted crop irrigation [80-85]. The presence of endocrine disruptors and pharmaceutical products in wastewater is also an emerging concern, despite the fact that risk assessment is difficult for these compounds [65,86]. Shuval [87] highlighted the potential risk for infectious diseases in animals grazing sewage-irrigated pastures. However, it has also been reported that, in some cases, animals exposed to high loads of pathogens in wastewater-irrigated forage crops show no symptoms of infection [88].

All in all, it seems clear that the benefits and risks of wastewater irrigation need to be assessed on a site-specific basis, since the characteristics of the wastewater are highly dependent on local circumstances, and so is the vulnerability of both the environment and the society in which water reuse is practiced. This is particularly sensitive in the case of health risks, which should not be considered in isolation but addressed in the general context of water supply and sanitation [89,90].

Social, Cultural, Institutional, and Political Aspects

Water reuse often raises public concern [91,92], especially because of the existence of real or perceived health and environmental risks. Therefore, the social acceptance of this practice becomes particularly important [93-95]. Varying degrees of public reluctance to reuse water have been reported [96]. Willingness to use (treated) wastewater in agriculture and willingness to pay for crops grown with recycled water depend on several underlying factors such as awareness of present or future water scarcity [97], educational level [93,98], costs and benefits [99], magnitude of [real or perceived] health risks [65], aesthetic attributes of the water [100], and even religious issues [98,101].

Direct or indirect potable reuse, which can be achieved via methods such as aquifer storage and other types of reservoir augmentation [102], usually face strong opposition due to the increased likelihood of human contact with wastewater, the so-called "yuck factor" [92,103,104]. However, as suggested by Ching and Yu [105], the social construction of water reuse by the mass media, in other words the way in which the media portrays, positively or negatively, the "yuck" factor, might be even more significant than public opinion itself. Therefore, despite the fact that public acceptance (or rejection) of reclaimed water has often been a critical factor for the feasibility of several projects [13,14], public opinion can be reshaped when governments take an active role in communicating accurate scientific facts and making a persuasive case for water reuse initiatives [105]. A remarkable example in this respect is the government of Singapore, who started a positive oriented campaign on water reuse in the public debate. Very carefully, the word "wastewater" has been abandoned and replaced by "used water" in all communications. Moreover, all "wastewater treatment plants" were renamed "water reclamation plants". This communicative strategy was part of the master plan to close the water balance deficit in Singapore upgrading the urban wastewaters to drinking water quality. The process of social engagement also means opening the decision making process to actors and stakeholders who have usually been ignored or misrepresented in water and wastewater management systems, such as farmers, NGOs, environmental advocacy groups, water and social scientists, minorities, indigenous peoples, and consumers [102, 106-109]. It is increasingly accepted that participation of relevant stakeholders is vital for water reuse schemes to succeed [5,13,110,111]. This consideration guided studies and surveys on the importance of stakeholders' preferences and the degree of public acceptance of different water reuse practices [112-114].

A suitable legal framework is indispensable to manage water reuse in an integrated way, namely a way in which irrigation, fertilization, and disposal receive equal attention [21,115,116]. Efforts to establish a minimum set of conditions and regulations enabling the safe use of wastewater are not new [16]. Yet at times, overly strict guidelines may not result in a significant change on the background level of disease and they also tend to be ignored because they are unachievable in practice [117]. There are some examples of guidelines for water reuse [49], but the most common standards in many countries, particularly developing ones, have been influenced by the World Health Organization [10,79]. Some studies have called for a more flexible legal framework, less worried about issues of potential liability and more focused on the integral analysis of the water chain [110,118]. An incremental approach for the introduction of water quality standards is recommended, particularly for countries with high levels of excreta-related diseases and deficient wastewater treatment systems [10,119].

Water reuse also has inescapable political facets that are usually overlooked behind discussions of risks, legal frameworks, and environmental or economic issues. The notion that water, and thus also wastewater, are merely "resources" (or even "commodities") fails to take into account the deep social and cultural meaning of water management in favour of a homogeneous, rationalized, and materialist perspective. As indicated by Schmidt and Shrubsole [120], context- and place-specific characteristics make water and wastewater management highly political and call for modes of governance adapted to local circumstances in order to avoid ecological and cultural violence. This discussion is central to the search for new ways to manage water and sanitation in the future, including water reuse, as it promotes an open and place-specific array of possible alternatives instead of advocating for universal solutions [121]. Central to the political nature of water reuse is the fact that this activity has traditionally been in the domain of small-scale farmers in poor and often marginalized communities. Even though the initial motivation for water use is usually the lack of alternative water sources, farmers rapidly recognized additional benefits, such as availability of nutrients, low salinity levels, a constant water provision, and reduced transport lines/closeness to food markets. Issues of scale, income, and power relationships are therefore relevant, when assessing and promoting the agricultural use of (treated) wastewater, especially in the current context of increasing "co modification", regulation, and eventual privatization of water and wastewater [122,123]. It has been indicated that lack of political will has often hindered the adoption and formalization of water reuse practices [31]. Yet allowing or formalizing the use of wastewater for agriculture can affect the rights of poor farmers who had been informally using raw wastewater for irrigation for a long time [124-127].

The Situation in Latin America

The need for municipal water reuse in Latin America was acknowledged long ago [128]. Several countries in this region report large areas irrigated with both treated and untreated wastewater [15,129]. Cities such as Lima (Peru), Mexico D.F. (Mexico), and Santiago (Chile) have been practicing wastewater irrigation for years [130]. In Mendoza (Argentina), planned water reuse started in the 1990s after several decades of informal wastewater irrigation [131,132]. A regional inventory indicated that the area irrigated with (almost untreated) sewage amounts to more than 1.5 million hectares [133]. Figures are not completely reliable, since only 9 out of 32 countries in Latin America have updated information relating to wastewater production, treatment, and reuse [41]. Some attempts have been made in order to develop policies and strategies for safe water use in the region. In Bolivia, for example, a recent survey reports 111 different reuse experiences [134]. Some of the authors of this paper are also involved in a number of projects to reuse the domestic wastewater produced in Tarija, one of the main Bolivian cities, for the irrigation of

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vineyards and other crops. Such experiences or projects have not yet made it to scientific journals or international databases, but are increasingly being discussed in regional workshops and reported in local media, raising the awareness of governments and producers with respect to the issue of wastewater irrigation.

A summary of wastewater irrigation practices in ten countries of the region is shown in Table 1. As we can see in this table, a wide variety of vegetables are being produced with wastewater-irrigated agriculture in the region, fostering better food security, but since most reuse is performed with untreated wastewater, some concerns have been raised about the safety of current practices. Different wastewater treatment systems are used in the region to treat domestic wastewater, as indicated in Table 1. Even though municipal water reuse is probably being carried out in all Latin American countries, not all cases have been reported in readily available documents such as journals or congress proceedings. Therefore, the information in Table 1 should not be seen as a comprehensive account of the extent of agricultural use of (treated) wastewater in the region.

In most Latin American countries, lack of enabling legislation, deficits in sanitation infrastructure and weak government institutions support unplanned and informal reuse schemes, intensifying the negative effects of the practice [129]. As a consequence, the use of untreated or diluted sewage for crop irrigation is a widespread practice, as indicated in Table 1. In the valley of Cochabamba (Bolivia), for example, the Rocha River is a large recipient of untreated wastewater used downstream for irrigation [145]. Similar situations have been documented in the surroundings of Santiago, Chile [136], and in Brazil [146]. Treated wastewater is increasingly being used in some coastal cities of the Argentinian Patagonia to irrigate trees, public spaces, and golf courses [147,148]. In the North of Argentina, vineyards and other crops have been irrigated with poorly treated wastewater for over 40 years [149,150]. The Dominican Republic, Ecuador, Guatemala, and Nicaragua report a small number of direct reuse schemes [133,138,141]. In Colombia, in spite of its abundant water resources, irrigation with treated or untreated sewage represents almost 37% of the total irrigated area [151,152]. Water scarcity is the main driver for water reuse in dry areas of Mexico and Peru [49]. It can be said that wastewater from almost all Mexican cities with a sewerage system is currently being used in agriculture despite the fact that only a small percentage receives treatment prior to discharge [129]. The Mezquital Valley, receiving wastewater from Mexico City, is probably the largest and longest-standing wastewater use system worldwide. Given the health problems and risks identified in this valley and other sites, a number of wastewater treatment plants are now projected or under construction in Mexico [56], particularly since the creation of Conagua (National Water Commission) in 1989 [153]. Contrary to other Latin America countries, Mexican farmers seem to have a rather positive perception about wastewater irrigation [15,153]. In many Caribbean islands, including Cuba and the Dominican Republic, wastewater is commonly reclaimed in hotels for gardening and/or irrigating urban green spaces [139,152]. In the case of Cuba, indirect reuse is also performed for sugar cane irrigation [154]. In Brazil, water reuse also involves a variety of industrial applications such as cooling processes, cleaning of public spaces, and car washing [146]. In this country, some technical, economic, and environmental studies were carried out in order to standardize the practice of wastewater irrigation [155].

Future Challenges and Concluding remarks

Despite widespread irrigation with raw or treated wastewater, a number of technical, economic, social, regulatory, and institutional challenges remain. In this section we will sketch a number of issues that deserve special attention or further research. These remarks are mostly based on the Latin American context, but may also apply to other cultural and geographical settings.

Before a wastewater irrigation scheme can be proposed or upgraded, local and regional practices related to sanitation, wastewater management, agriculture, irrigation, and wastewater use need to be carefully documented. Ideally, such an inventory should combine literature retrieval, collection of field data, and interviews with local policy makers, farmers, and scholars. Wastewater treatment systems that are appropriate to local conditions and suitable for ulterior irrigation must also be identified, adapted, and promoted by local water companies and practitioners. Additional efforts have to be made to combine wastewater collection, transport and treatment with the storage facilities and distribution networks needed for irrigation with treated wastewater. To optimize the use of resources, wastewater treatment systems have to be flexible in the removal of nutrients according to local agricultural demands. Irrigation and water management techniques have to be adaptable to multiple water sources including (treated) wastewater. These techniques and other agricultural practices will be most sustainable if they are locally designed in order to minimize negative effects caused by, for instance, surface runoff and seepage. The feasibility of non-treatment options should also be considered by means of site-specific risk assessments. Irrigation strategies and technological innovations developed by local farmers have to be taken into account, since they are often useful to increase or maintain yields and minimize health risks [2].

For each particular case, the area that would be suitable for irrigation with domestic wastewater needs to be determined by carrying out a feasibility study. As described in [156,157]; such suitability study could involve the next steps: i) the selection of criteria and variables that allow or constrain wastewater irrigation, ii) the establishment of suitability thresholds for the variables selected, iii) the quantification of wastewater availability, iv) a preliminary estimation of crop requirements, v) a spatial representation of the variables using Geographic Information Systems (GIS) tools, and vi) the construction of suitability maps. The latter maps can give a quick idea of the areas that are suitable for wastewater irrigation and can help decision makers to allocate resources to promote this activity. Several feasibility studies following this or similar approaches have been reported [156,158,159]. Variables for the selection of appropriate sites might include type of soil, slope, crops, and the distance to wastewater sources, vulnerable sites and urban areas, among others.

A local assessment of the environmental and health impacts of wastewater irrigation is also required. Past experiences are paramount in this respect. For instance, the effects on human health and food chains of micro pollutants (e.g. endocrine disrupting agents) are largely unknown and therefore rarely included in guidelines for the use of adequately treated wastewater. The more understanding about the risks posed by pathogens, the greater the confidence the public will have in wastewater use [160]. Since major public health problems are related to pathogens, developing reliable procedures to screen them is essential for an appropriate risk assessment [161] and also to establish regulations [10]. Current methods for the detection of pathogenic viruses, bacteria, protozoa and helminthes tend to be inaccurate, time-consuming and difficult [24,161]. Culture-based E. coli detection methods, for example, proved to be insufficient in differentiating between pathogenic and nonpathogenic strains [162]. As a result, molecular techniques, including DNA or RNA sequencing, are been used to improve the detection, monitoring and track of specific pathogens in order to understand outbreaks occurrences, forecast transmission dynamics, and detect antibiotic-resistant bacteria, among other objectives [163-165]. Microarrays (hybridization assay method) and quantitative polymerase chain reaction (qPCR) are being used to detect specific pathogens in wastewater [165-170]. Molecular techniques are highly sensitive, relatively cheap in the long run, and significantly reduce detection times [165]. Molecular detection tools (qPCR) and QMRA modeling have been used to assess the risk of Salmonella infections resulting from the consumption of edible crops irrigated with treated

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Country (main cities)	Area[a] (ha)		Main crops	First reuse experience	WWTS[b]	Sources
	Treated	Untreated				
Argentina (Mendoza, Chubut, Salta)	>3000	20000	Vegetables, grapevines, pastures, forests, olives, fruit trees	1920	SP	[131-133]
Bolivia (Cochabamba, La Paz, Tarija)	ND	5700	Potatoes, corn, vegetables, grass, grapevines	ND	SP, IT	[134]
Chile (Antofagasta, Santiago)	ND	130000	Vegetables, fruit trees, vineyards, cereals	ND	AS, AP	[136]
Colombia (Ibagué, Bogotá)	330000	>900000	Rice, vegetables, pastures, tobacco, corn, fruit trees	1960s	AP, AS, UASB, TF	[133,137]
Dominican Republic (La Vega, San Francisco de Macoria)	500	ND	Rice, corn, tomatoes, fodder	ND	AP, UASB, AS	[138,139]
Ecuador (Porto Viejo)	80	ND	Corn, tomatoes, pepper, cucumber, watermelons	ND	SP	[140]
Guatemala (Sololá)	5	ND	Pastures, fodder, beans, tomatoes	ND	UASB, SP, IT	[141]
Mexico (Mezquital Valley, Ciudad Juárez, Texcoco)	70000	190000	Cereals, fodder, fruit trees, vegetables	1900s	AS, SP, UASB	[15]
Nicaragua (Rivas, Granada, Matagalpa)	250	ND	Banana, forage grass and corn, sugar cane, vegetables	ND	SP, IT	[142]
Peru (Lima, Ica, Tacna)	4000	16000	Vegetables, fodder, cotton, fruit trees, aromatic herbs	1964	SP, AP, TF, AS	[143,144]

Table 1: Wastewater irrigation practices in Latin America. WWTS: wastewater treatment system; ND: no data available; SP: stabilization ponds; IT: Imhoff tank; AS: activated sludge; AP: aerated ponds; TF: trickling filters; UASB: up flow anaerobic sludge blanket reactors.

[a]Figures were rounded up to facilitate comparisons.

[b]WWTS typology from [135].

wastewater [171]. Further research is needed to refine and standardize some of these techniques in the field of wastewater assessment and (re) use [165].

Further insight into the fate of chemicals in the soil system, plants, and groundwater is needed. The possibility of an increase in soil salinity and the special case of soil sodicity and alkalinity (which affects the availability of a range of trace nutrients) is also an issue that requires further research. Environmentally-safe dosages of nutrients needs to be identified for each particular situation, since the processes affecting the bioavailability and mobility in the soil-plant system of a number of chemical or biological contaminants normally present in wastewater are largely unknown and very likely site-specific. In order to maximize year-round nutrient uptake, the crops and cropping systems also need to be carefully selected according to the characteristics of each site [172].

The long-term economic implications of water reclamation and reuse need to be elucidated on a site-specific basis. Economic analyses of the entire water chain will help to understand its complexities and detect options for improvement on the basis of efficiency analysis and sustainable design. Some issues related to these analyses are incentive structures for the actors along the chain, institutional and economic barriers for optimal water management, information requirements, and the impacts of alternative water management systems in the long run, including discounting and analysis of irreversible impacts. Better assessments of the economic benefits of the use of wastewater for agricultural irrigation, including potential payments to agricultural producers for their wastewater treatment services, will help convince producers and policy makers of the importance of this practice.

In many places, the appropriate institutions required to manage wastewater irrigation need to be created from scratch. The same goes for enabling legislation. Regional laws focus mostly on specific wastewater discharge standards, disregarding or even banning all reuse activities altogether [49]. When reuse standards do exist, national legislation tends to be based on guidelines proposed by the WHO [59]. In Argentina, for example, only two provinces have regulations on water reuse and a national law on the subject has been under discussion for years at the national Parliament without a positive outcome so far [173]. Such federal laws, however, are difficult to pass since water management has been traditionally under the jurisdiction of provincial administrations. In some countries such as Bolivia, the absence of specific legislation has been seen as a constraint for water reuse [145]. However, as reported for Nicaragua, overly strict legal frameworks can also be detrimental for the promotion of this activity [142]. Some regulations only focus on microbiological aspects, which are not enough to accurately assess the wastewater quality [71], since they exclude indicators such as the content of helminth eggs [15]. The establishment of realistic, enforceable discharge and reuse standards based on appropriate decision criteria is required to minimize health risks and allow for the beneficial use of scarce resources. It is also necessary to establish and/or strengthen mechanisms for monitoring standards, where public agencies interact with farmers. The role of water user organizations and other stakeholders in those institutions and in wastewater irrigation schemes have to be properly established, while efficient mechanisms for the dissemination of information on water quality have to be created. For that purpose, the driving forces of farmers and institutions ought to be clearly understood. Training of analytical staff is also necessary. Public perception, social acceptance, and legal aspects of the use of (treated) wastewater in irrigated agriculture also need further site-specific research.

It is important to highlight that farmers benefiting from informal reuse schemes might lose their traditional rights once the practice is legalized or formalized. To minimize water conflicts and guarantee water justice, livelihoods depending on wastewater irrigation must be protected by adequate laws, institutions, policies, and implementation mechanisms at the local level. To that end, the impact of sewage treatment and reuse on the social and economic status of farmers and consumers must be assessed for each location. Because of the prospects of increasing water shortages in the future, a new paradigm for water and sanitation management is needed, based on the principles of sustainability and environmental ethics. Although some efforts have been made worldwide to regulate water reuse [49,174], developed and developing countries still need to establish concrete policies and practices to encourage safe water reuse in order to take advantage of all its potential benefits for the food supply and livelihoods, while reducing health and environmental risks.

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