Toward an agenda for improving wastewater use in agriculture

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Abstract

This paper sets out the trends and challenges of wastewater use in agriculture; identifies the risks and benefits of wastewater irrigation; describes the risk assessment and management framework adopted by WHO, FAO and other international and national organizations; and proposes measures for applying the framework to reduce health risks by moving from unplanned to a planned, integrated approach to wastewater use for irrigation.

Keywords: reuse, treatment, irrigation, urban agriculture, risk assessment and management, integrated water resources management

Trends and challenges of wastewater use in agriculture

As freshwater sources become scarcer, wastewater use is becoming an attractive option for conserving and expanding available water supplies. Wastewater can have many applications, including irrigating farmland, aquaculture, landscape irrigation, urban and industrial uses, recreation, environmental uses, and groundwater recharge. In principle, wastewater can be used for all purposes for which freshwater is used, given appropriate treatment or alternative safety precautions.

Wastewater use in agriculture is by far the most established application, with the longest tradition (Jiménez *et al*. 2010). In most cases the irrigated lands are located in or around the urban areas where the wastewater is generated. The United Nations (2003) report that wastewater is used on 20 million hectares, or about 10% of the world's total irrigated farmland. Scott *et al*. (2010) report that *unplanned use* (direct and indirect use of untreated wastewater) is an order of magnitude greater than *planned use*. In China alone, 4.1 million hectares – some 7.4% of the nation's total irrigated area – are irrigated with polluted water (Xie *et al*. 2009).

Powerful drivers for the expansion of wastewater irrigation

A number of key drivers, and their interactions, are leading to a growing use of wastewater in agriculture in and around urban centers:

- *Increasing water scarcity*. Many parts of the world are experiencing growing water stress and scarcity due to competition for water and climate change, and more of the world's poor are expected to be impacted by a higher frequency and intensity of droughts (Meehl *et al*. 2007). Projections show that the share of the world's population living in water-stressed areas will grow from 7% in 1995 (Hinrichsen *et al*. 1998) to 44% by 2050 (Molden 2007). Climate change will also affect water quality in water scarce regions, with rivers losing assimilative capacity and salinity increasing (Sadoff and Muller 2009). As a result of these changes, the demand for irrigation water and, in particular, for wastewater as a reliable water resource will rise, and wastewater will need to be considered an integral component of local water resources.
- *Growing urbanization and increasing urban wastewater flows*. In developing countries, burgeoning urban populations and the associated expansion of water supply and sewerage services are resulting in growing "rivers" of treated and untreated sewage flowing from cities, making wastewater management a necessity. Summarizing data from the WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, Locussol et al. (2009) show that between 1990 and 2004 the urban population in developing countries grew by 53%, from 1.4 billion to 2.2 billion, while the urban population connected to sewers grew by 78%, from 506 to 901 million. Survey data from the World Bank also indicate that urban sewer connections rose rapidly as household incomes grew (Komives *et al*. 2003).
- *More agricultural activities in and near urban centers*. Driven by the need for income, employment generation, and food security, urban households in developing countries are increasingly engaged in agricultural activities. Data on the extent of urban farming are limited. UNDP (1996) estimated that in the early 1990s, more than 800 million people, a third of all urban households, were involved in urban farming, producing about 15% of the world's food. More recent estimates for West Africa suggests that about one-fifth of an urban population of 100 million are engaged in urban agriculture; in many cities they produce 60% to 100% of the consumed perishable vegetables (Drechsel *et al*. 2006)

> Urban farmers have a number of advantages, including direct access to urban consumers and markets; proximity to institutions that provide market information, credit, and technical advice; and the availability of reliable and cheap inputs such as nutrients from human waste and wastewater for irrigation (van Veenhuizen and Danso, 2007).

Increasing use of untreated wastewater

In many low-income and middle-income countries, wastewater irrigation either involves the direct use of untreated wastewater or its indirect use from rivers and streams that receive untreated wastewater discharges. With freshwater either unavailable or relatively expensive, and wastewater treatment not keeping up with urban growth, urban farmers often have no alternative but to use polluted water. Many of them belong to the urban poor who depend on agricultural activities as a source of food and income.

With the advent of modern sewerage systems and wastewater treatment processes in the early 20th century, developed countries established regulatory frameworks for controlling the treatment of wastewater and its use for irrigation. These frameworks have evolved over time, but continue to rely heavily on capital-intensive wastewater treatment as the principal intervention for addressing public health and environmental risks. In many of these countries universal municipal wastewater treatment has not yet been achieved because of financial and institutional constraints. Less developed countries are usually even more constrained. Other, complementary solutions are therefore needed.

Levels of economic development and wastewater irrigation issues

A country's economic conditions influence how wastewater is generated, collected and treated, and how urban wastewater is used in agriculture. A low level of economic development is usually associated with inadequate urban water supply and sanitation, and the *unplanned* use of untreated wastewater, while a high level of economic development is associated with the provision of adequate water supply and sanitation for the vast majority of urban population, and the *planned* use of treated wastewater. As countries develop economically, they tend to gradually improve their wastewater treatment and use for agriculture.

Table 1 illustrates this evolution. Based on 2008 national GNI per capita data from the World Bank's World Development Indicators (2010), it distinguishes between four levels of economic development and presents characteristic indicators for each level of development. Urbanization and the provision of improved water supply and sanitation services increase significantly with income growth, and services reach close to 100% in high-income countries. Disease burdens for diarrhea and ascariasis—both linked to the irrigation of food crops with inadequately treated wastewater—rapidly decrease with development (Shuval *et al*. 1986, WHO 2006). Table 1 also lists countries with significant wastewater irrigation by level of development. With a few exceptions, such as Vietnam and Japan, most countries are grappling with the problem of water stress or at least seasonal scarcity, and have increasingly turned toward using wastewater for agricultural activities.

Based on the four levels of development, Table 2 shows how access to urban sanitation and wastewater treatment typically changes as countries develop. This evolution is also captured in the 'sanitation ladder' which is often used to illustrate how countries tend to progress from open defecation to basic sanitation and improved sanitation, and then to sewerage services and wastewater treatment as incomes grow (UNEP 2004, van de Guchte and Vandeweerd 2004, Keraita *et al*. 2010). Table 2 also presents the percentage of urban population sewered and of urban wastewater treated in a number of water-stressed countries. It indicates enormous improvements from lower-middle to upper-middle-income levels. It should be noted, though, that substantial variations exist among countries in the same income group. Water scarcity may force improvements in some countries. Within countries, the capital is often better served than second-tier cities.

Some of the information presented in Table 2 needs to be interpreted with caution. For example, in low-income countries wastewater treatment plants, if they exist, often function poorly and basic sanitation is the primary focus (WHO-UNICEF 2010). Table 2 mentions Ghana where 4% of the urban population is sewered. Urban areas have about 70 mostly decentralized wastewater and fecal sludge treatment plants that treat less than 10% of the generated wastewater. Of the 70 plants, about 10 function more or less as designed, with most of them belonging to larger hotels (Murray and Drechsel 2011). Under these circumstances, the key pollution concern is to protect public health by isolating households from fecal sludge and raw domestic sewage in the streets. Alternative risk mitigation measures are needed where polluted surface water is used for irrigation.

Furthermore, the efforts of low- and middle-income countries to expand wastewater treatment can not be adequately represented in simple coverage indicators. A recent study of some 852 municipal wastewater treatment plants in South Africa, for example, found that almost half of them (403 plants) could not be assessed due to the lack of operating data. Of the plants evaluated, only 32 (7%) sufficiently complied with regulatory and best practice requirements to earn the local Green Drop Certification (Department of Water Affairs 2009). The majority of the wastewater treatment plants failed to meet at least three or more effluent discharge standards, operated close to or over design capacities, were aging or used inappropriate technologies, or experienced operational problems such as shortage of skills and experience and funding constraints. Such operational, design, and compliance problems were found in an assessment of wastewater treatment plants in China (Xie *et al*. 2009), and in a survey of 1,251 wastewater treatment plants in Latin America (Egocheaga and Moscoso 2004). This situation calls for additional risk barriers (see below).

As countries move to higher income levels, their approach to wastewater us for irrigation changes from unplanned to planned. While in low-income countries the direct and indirect use of untreated sewage tends to be widespread, in middle- and high-income countries the direct use of treated wastewater becomes ever more prevalent and the indirect use of untreated effluents more regulated. The development and implementation of wastewater use policies also becomes a higher priority, often within a broader water resources management framework. While in low-income countries a wastewater use policy framework is usually non-existent or not enforced, as incomes grow policy formation and enforcement capacity improves. At the same time, wastewater pollution concerns tend to change from predominantly fecal contamination (in low-income countries) to pollution from mixed municipal and industrial discharges (in middle-income countries) to emerging pollutants of concern (EPOCs), such as endocrine disruptors and pharmaceutical wastes (in high-income countries).

Risks and benefits of wastewater use in agriculture

Wastewater use in agriculture has substantial benefits for agriculture and water resources management, but can also pose substantial risks to public health, especially when used untreated for irrigating edible crops (Faruqui *et al*. 2004, WHO 2006, Bos *et al*. 2010). There can also be chemical risks to plant health, and risks to the environment, from soil and groundwater pollution.

Countries seeking to improve wastewater use in agriculture must reduce the risks, in particular those to public health, and maximize the benefits through properly planned and implemented wastewater irrigation practices.

Risks of wastewater use in agriculture

Microbial risks to public health. In low- and middle-income countries, the greatest risks are to public health from the microbial pathogens contained in domestic wastewater, including bacteria, viruses, protozoa and helminths. Epidemiological studies carried out over the past four decades have linked the unplanned use of untreated or partially treated wastewater for edible crop irrigation to the transmission of endemic and epidemic diseases to farmers and crop consumers (e.g., Shuval *et al*. 1986, Blumenthal and Peasey 2002). There is an increased prevalence of helminthic diseases such as ascariasis and hookworm in field workers and consumers of uncooked vegetables, and bacterial and viral diseases such as diarrhea, typhoid, and cholera in those consuming salad crops and raw vegetables.

Chemical risks to public health. Chemical risks are greater for middle- and high-income countries where l wastewater from growing industries is discharged to public sewers, contaminating municipal wastewaters. The associated risks to public health are caused by heavy metals, such as cadmium, lead, and mercury; and by many organic compounds, such as pesticides (Chang *et al*. 2002). In high-income countries there is also increasing concern about an emerging class of anthropogenic chemical compounds, including pharmaceuticals, hormones and endocrine disruptors, antibiotics, and personal care products.

Risks to plant health. The principal risk to plants is reduced crop yields if the wastewater used for irrigation is unsuitable—for example, by being too saline or having excessive concentrations of boron, heavy metals or other industrial toxicants, nitrogen, or sodium (Ayers and Westcot 1985). Risks to plant health are reduced if industrial effluent is minimized. Other key parameters to be monitored are electrical conductivity, the sodium adsorption ratio, boron, total nitrogen, and pH.

Environmental risks. The microbiological and chemical pollution of soils, crops and groundwater are the main environmental risks of using wastewater in agriculture. The microbiological pollution of groundwater tends to be a lesser risk as most soils retain pathogens in the top few meters of soil, except in certain situations like limestone formations. Chemical risks include nitrates in groundwater from sewage irrigation, salination of soils and aquifers, changes in soil structure from high sodium levels, and plant toxicity from boron compounds common in industrial and domestic detergents.

The key to controlling many of the chemical risks to humans, plants and the environment is to put in place effective industrial wastewater pretreatment and control programs (Chang *et al*. 2002). Because effective programs are not the norm in many developing countries, special attention needs to be paid to chemical risks, as well as to alternative protection measures (Simmons *et al*. 2010).

Benefits of wastewater use in agriculture

Wastewater, even when untreated, offers a number of benefits for farmers. Even more benefits accrue to agriculture, water resources management, and the environment when wastewater irrigation is properly planned and implemented (Mara and Cairncross 1989).

Agricultural benefits. Agricultural benefits may include reliable, and often less costly, irrigation water supply; increased crop yields, often boosted by the wastewater's nutrient content; and improved food security and livelihoods of urban agriculturalists, many of whom are women and/or poor subsistence farmers.

Water resources management benefits. Water resources management benefits comprise additional drought-proof water supply, and increased climate change resilience—often with lower cost than if supplies are expanded through storage, transfers, or desalinization; more local sourcing of water; more integrated urban water resources management by including wastewater in broader water resources management.

Environmental benefits. Among the environmental benefits that accrue to well-managed wastewater irrigation schemes is the avoidance of impacts which would occur if the wastewater were instead discharged into rivers or lakes—such as reduced dissolved oxygen depletion, eutrophication, foaming, and fish kills; the more rational allocation of freshwater resources to urban water supply; reduced application of artificial fertilizers, reducing off-farm energy use and industrial pollution; soil conservation through humus build-up and the prevention of land erosion; and, where applicable, desertification control and desert reclamation through the irrigation of tree belts.

Objectives for improving wastewater irrigation

Facing these risks and benefits, countries seeking to improve wastewater use in agriculture may seek to: (i) minimize risk to public health; (ii) minimize risk to the environment; (iii) improve livelihoods for urban agriculturists; and/or (iv) integrate wastewater into broader water resources management. Table 3 shows typical wastewater irrigation objectives by level of economic development. For example, low-income countries are likely to put highest priority on minimizing the microbial risks to public health while also trying to improve the livelihoods of urban farmers. Middle- and high-income countries would give higher priority to reducing environmental risks and industrial discharges and, especially when they are water stressed, a fuller integration of wastewater into their water resources management system.

Microbial risk assessment and management framework for public health protection

The first international guidelines for the safe use of wastewater in agriculture were developed by the World Health Organization (WHO) in 1973, and revised in 1989 taking into account new epidemiological evidence of actual versus potential microbial risks (WHO 1989). The 1989 Guidelines recommended that for unrestricted irrigation (i.e., irrigation of crops eaten raw) wastewater should contain a concentrations of less than 1,000 fecal coliforms per 100 ml and less than one viable nematode egg per liter; and for restricted irrigation (i.e., irrigation of crops not for direct human consumption) wastewater should achieve a concentration of less than one nematode egg per liter, primarily to protect field workers and their households.

The 1989 Guidelines proved difficult to implement. Many low- and medium-income countries were unable to effectively treat wastewater to achieve the guideline concentrations. Yet even proper treatment for irrigation use will not significantly reduce the overall microbial risk to public health if drinking water and sanitation services remain inadequate.

In 2006 new *Guidelines for the safe use of wastewater, excreta and greywater* were issued that promote a radically different approach from the 1989 Guidelines (WHO 2006). The 2006 Guidelines are based on a risk assessment and management framework that follows the Stockholm Framework (for details, see Fewtrell and Bartram 2001), and the framework used to develop the 2006 Australian National Guidelines for wastewater use (EPCH-NRMMC-AHMC 2006). The risk assessment and management framework is now recommended by WHO for all decisions about drinking water and sanitation interventions. By accepting that health risks can be addressed beyond or even without wastewater treatment, the 2006 Guidelines shift the focus from water thresholds to consumer-based targets.

The approach for microbial risks involves: (i) to select a tolerable maximum additional burden of disease, from which it is possible (ii) to derive tolerable risks of disease and infection, (iii) to set health-based targets for pathogen reductions, (iv) to determine how the required pathogen reductions can be achieved, and (v) to put in place a system for verification monitoring (WHO, 2006).

Step 1: Select a tolerable burden of disease

The metric for disease burden is the 'disability-adjusted life year' (DALY). Introduced by WHO and the World Bank in 1993, it allows one to define a tolerable additional burden of disease and to compare disease burdens resulting from different health risks (World Bank 1993, Murray and Lopez 1996). The 2006 Guidelines use a default value of one-millionth of a DALY loss per person per year (10^{-6} DALY loss pppy).[1]

The 2006 Guidelines also point out that for low-income countries with a high background level of diarrheal disease due to overall poor urban water supply and sanitation conditions, and a lack of effective wastewater treatment capacity, a more reasonable initial tolerable maximum additional burden of disease would be 10^{-4} DALY loss pppy. As a country develops, it can work toward the more restrictive default value. Thus it is recognized that substantial improvements in wastewater irrigation practices alone will do little to lower background levels of diarrhea without corresponding improvements in water supply and sanitation services as well as food hygiene.

Step 2: Derive tolerable risks of disease and infection

Once the tolerable additional burden of disease resulting from exposure to a particular activity (such as the consumption of wastewater-irrigated food) has been selected, the DALY loss pppy has to be translated into tolerable disease and infection risks pppy. The tolerable risk of a disease per person per year is equal to the tolerable DALY loss pppy divided by the DALY loss per case

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[1] This tolerable maximum burden of disease is the same as the one used in the 2004 WHO *Guidelines for Drinking-water Quality* (WHO, 2004). It corresponds to a 70-year lifetime additional cancer risk of about 10^{-5} per person due to drinking fully treated water (i.e., one additional case of cancer per 100,000 people), or an annual diarrheal disease risk of 10^{-4} (i.e., one additional case of diarrhea per 10,000 people per year).

of the disease, and the tolerable risk of infection pppy is equal to the tolerable disease risk divided by the disease/infection ratio.

Step 3: Set health-based targets for pathogen reduction

Another principal recommendation of the 2006 Guidelines is the application of quantitative microbial risk analysis (QMRA) to wastewater use in agriculture. QMRA provides a rational basis for microbial risk assessment and management in wastewater irrigation (Mara *et al*. 2007).

QMRA has been applied to a number of reference pathogens associated with wastewater irrigation for which dose-response data are available, in order to determine the corresponding required pathogen reduction targets.

Initially, WHO (2006) applied the framework to the reference pathogens rotavirus (a viral pathogen), *Campylobacter* (a bacterial pathogen), and *Cryptosporidium* (a protozoan pathogen). More recently, dose-response data have become available for norovirus (a viral pathogen deemed to be a more important cause of diarrhea in adults than rotavirus) and *Ascaris lumbricoides* (a nematode pathogen closely linked to irrigation with untreated wastewater). Countries can now apply QMRA for the latter two reference pathogens and determine the pathogen reduction targets that they should meet now and in the future (for details, see Scheierling *et al*. 2010).

Step 4: Use multiple barriers to achieve required pathogen reduction

Once total pathogen reduction targets are determined with the QMRA methodology, they can be achieved by a combination of wastewater treatment and a selection of post-treatment health protection control measures (Bos *et al*. 2010).

Where restricted irrigation can be enforced, consumers are protected as only crops are grown which are not eaten raw. In order to protect the health of fieldworkers, especially from *Ascaris*, the remaining required pathogen reduction has to be primarily achieved by wastewater treatment.

Where restrictions cannot be enforced or unrestricted irrigation with wastewater is permitted, the 2006 Guidelines promote a ‘multiple barrier’ approach to risk management that includes wastewater treatment together with post-treatment health-protection control measures such as crop restrictions, safer irrigation methods, and human exposure control through hygienic produce handling and safe food preparation that can be used singly or in combination when typical wastewater treatment alone may not achieve the pathogen reduction targets. Alternatively, but requiring additional cost and operational capacity, the degree of wastewater treatment may be increased.

Step 5: Verification monitoring

Once pathogen reduction targets are established, and an appropriate combination of treatment and post-treatment health protection control measures has been determined, verification monitoring is needed to ensure that the measures are effective. In the case of unrestricted irrigation, in order to ensure continuous protection of consumer health, a Hazard Analysis Critical Control Point (HACCP) system can be put in place following the 2003 FAO/WHO HACCP Guidelines (FAO 2003). The HACCP system helps to monitor the efficacy of both treatment and post-treatment health protection measures.

Measures for reducing public health risks

The experience of middle and high-income countries that have relatively successfully improved wastewater use in irrigation suggests that measures to reduce public health and other risks associated with the use of wastewater need to be planned and implemented progressively over a relatively long time period (Scheierling *et al*. 2010). Depending on their situation, countries should adopt measures that over time will allow them to move from unplanned to planned wastewater irrigation and achieve phase in improvements in wastewater treatment. To control chemical risks, they can also introduce measures for the pre-treatment and control of industrial wastewater discharges. To reach the goal of planned wastewater irrigation, it is useful to develop a multi-phased strategic plan, aimed at steady and measurable progress toward the goal. Finally, to successfully implement a strategic plan in the area of wastewater irrigation, the various measures should be designed to promote and contribute toward more comprehensive and integrated water resources management.

Progressing from unplanned to planned wastewater irrigation

A country’s path toward achieving planned wastewater irrigation depends on its starting point of. Low-income countries facing water scarcity usually lack the financial resources and institutional capacity to immediately build and operate the needed wastewater treatment systems that would ensure minimal health risks from wastewater irrigation. They must rely initially on multi-barrier options for post-treatment health-protection control. However, they can also begin to introduce low-cost rudimentary treatment that, combined with policy reforms and non-structural interventions, will lay the foundation for subsequent more progressive measures.

Middle-income countries may already have established some of the policies, institutions, and regulations needed for a more comprehensive water resources management framework, and introduced some degree of wastewater treatment. The experience gained, assuming appropriate monitoring is in place, can provide the foundation for moving to subsequent stages. Affordability continues to be a critical issue, and attention should be focused on improving financial management and identifying opportunities for mobilizing funds to maintain existing treatment systems and to steadily upgrade and expand them.

High-income countries facing water scarcity often continue to make stepwise adjustments and improvements to policies and regulations, moving toward more stringent standards for wastewater quality and use for irrigation and a more integrated approach to urban water management.

The challenge for countries at lower levels of development is not to copy the steps taken by the more advanced countries, but to learn from them and jumpstart the process by applying the risk assessment and management framework and developing a multi-phased plan that can be achieved in time intervals of 15 to 20 years. At each stage of the process, countries should seek to identify and implement the most affordable and cost-effective measures for achieving a desired level of risk reduction.

Phasing improvements in wastewater treatment

The introduction and progressive improvement of appropriate wastewater treatment—particularly affordable treatments systems that can positively impact the safety of wastewater irrigation—is an important goal for moving toward planned unrestricted wastewater irrigation in developing countries. Low-income countries should seek to introduce non-treatment options and simple low-cost treatment options as a first step. As financial and operational capacities grow, they can move toward expanded sewerage systems and more robust treatment technologies. An important part of the first step is to clearly define responsibilities for household, community, and public sanitation service provision, and to put in place the capability to monitor operations and verify that treatment targets are met.

Scale of wastewater treatment and irrigation activities

An array of appropriate technology treatment options of differing scale can be considered, along with possible pathways to expand sewerage and treatment as development occurs. Four scales are important:

- *On-site wastewater treatment and use.* These non-sewered sanitation options can provide greywater from household storage tanks to be used for household gardens, wastewater that has been processed by soil infiltration, or composted human waste for adding nutrients.
- *Communal wastewater treatment and use.* Wastewater from a cluster of homes can be collected by non-conventional systems like small-bore sewers or condominial sewers, treated by low-cost options, and used nearby on small agricultural plots.
- *Decentralized wastewater treatment and use.* Wastewater from isolated medium-size communities, or portions of larger urban areas, can be collected, treated, and used nearby to irrigate larger urban or peri-urban plots. Low-cost, unconventional treatment options can often provide the needed levels of pathogen removal.
- *Centralized wastewater treatment and use.* In large cities, treatment facilities may be centralized at the level of major drainage basins.[2] Wastewater, and sometimes stormwater, is generally drained by an extensive network of pumps and piping for transport to a central location for treatment and reclamation, usually near a point of convenient irrigation use. While unconventional treatment options, such as wastewater stabilization pond systems, are a feasible alternative for medium-sized cities, large city wastewater treatment systems will sometimes have to be based on conventional technologies due to land constraints.

Paradigm shift for decision-making on wastewater treatment

[2] A single, fully centralized wastewater treatment plant at the drainage basin level is less common as it usually entails additional pumping costs while not providing sufficient system redundancy compared to multiple large treatment plants.

Standards for the design of wastewater treatment plants are usually based on environmental legislation aimed at protecting receiving water bodies from polluting discharges. In developing countries such treatment plants are often viewed as a costly means of preparing wastewater for unproductive disposal; as a result, resource-constrained governments seldom rank wastewater treatment high on their agendas. There is a need to shift the paradigm so that wastewater is seen as an asset, and that water, wastewater, pollution control, and wastewater irrigation are managed in a more integrated way while ensuring public health protection (Bahri 2009). Treatment facilities are then not designed for waste disposal but to conserve the resources in wastewater—including the water resource itself, the nutrients it contains, and biogas energy—and to reduce pathogen risks (Murray and Buckley 2010).

Fundamental to achieving this paradigm shift is choosing appropriate treatment technologies for wastewater irrigation schemes. Libhaber (2007) has described a number of unconventional treatment technologies based on simple processes that are less costly than conventional processes in terms of investment as well as operation and maintenance, simple to operate, and with the capacity of yielding an effluent quality suitable for safe irrigation. These include waste stabilization pond systems comprising a combination of anaerobic lagoons, facultative ponds and polishing ponds; upflow anaerobic sludge blanket reactors; anaerobic filters; constructed wetlands; wastewater storage treatment reservoirs; chemically enhanced primary treatment, sometimes in combination with sand filtration and disinfection; and lower-cost membrane technologies, such as microfiltration and nanofiltration. Some of these technologies, such as chemically enhanced primary treatment followed by sand filtration and disinfection, can serve even larger cities in upper-middle income countries.

Unconventional treatment technologies can be applied progressively in developing countries. Technologies such as waste stabilization ponds and constructed wetlands can be the most appropriate and economically best treatment option for small- and medium-sized communities even in high-income countries. For example, thousands of such natural wastewater treatment systems are operating in Europe and their performance, including with regard to effluent irrigation, is excellent (European Community 2001, Wendland and Albold 2010). The treatment design goal for wastewater irrigation should be to find locally appropriate wastewater use systems where treatment levels are based on pathogen reduction targets, nutrient conservation, and receiving water bodies' absorption capacity, and where the technology relies on locally viable options (Libhaber 2007, Murray and Buckley 2010).

An example of the combination of appropriate low-cost treatment with effluent irrigation is provided by Mendoza, a city in Argentina with a population of about one million, where the *Campo Espejo* waste stabilization pond system operated by a private contractor treats wastewater from more than half of the city (Idelovitch and Ringskog 1997). Built in 1976 and upgraded in 1993, the system continues to provide high quality treated effluent that is rich in nutrients. It is used to irrigate a special restricted area of 1,900 hectares where animal feed and poplar biomass are grown as well as vegetables and fruits such as grapes, peaches and pears.

Controlling industrial wastewater

In cities where industries contribute a significant amount of wastewater, the enforcement of industrial pretreatment and control programs is essential for minimizing chemical risks and successfully operating any treatment plant and effluent irrigation scheme.

Quality standards are usually established for industrial wastewater discharged into municipal sewerage systems in order to ensure that heavy metals, organic toxins, salts, and other harmful contaminants generated by industrial activity do not reach levels that may damage pipes, inhibit biological treatment processes, remain in the effluent in higher concentrations than permitted for irrigation use or environmental discharge, or accumulate in the sludge and limit or even prevent its disposal or reuse. The establishment of industrial discharge standards is important in order to promote industrial pretreatment programs and control certain industrial discharges that may be critical to the operation of wastewater treatment plants and the quality of treated effluents and sludge byproducts. Industrial discharges that cannot meet quality standards should be prohibited from municipal sewers.

Important elements of a proven industrial pretreatment and control program are the following (Idelovitch and Ringskog 1997):

- A discharge inventory and information system;
- An industrial discharge permit system establishing limits for discharging into sewers and requirements for presenting a compliance plan;
- Self-reporting requirements that involve the use of certified laboratories;
- Inspection and monitoring by the wastewater authority;

- Sanctions for noncompliance;
- Sewer use tariffs based on both the volume discharged and the organic load;
- Industrial participation, for example, through a joint water quality council, in all phases of the program, including design, the setting of standards, and implementation;
- Some form of technical and financial assistance for industrial plants, particularly small and medium enterprises;
- A training and institutional development program to help the wastewater authority prepare itself for the new area of responsibility; and
- Close coordination between the wastewater authority and the environmental regulator to ensure that industrial wastes are not improperly discharged into sewers, and effluent and sludge adequately disposed.

Developing and implementing a strategic plan

A strategic plan—comprising a long-term strategy and a phased action plan to meet the strategic goals, along with the needed policy reforms—is often useful to reach the goal of moving from unplanned to planned wastewater irrigation that meets internationally-accepted health-based targets (for example, pathogen reduction targets based on the 2006 WHO Guidelines). Recognizing that this goal cannot be achieved in the short-term or in one phase, the action plan should be multi-phased and aim at steady and measurable progress toward the goal within an agreed and realistic timeframe (e.g., 15 to 20 years). The experience of country regulators in adapting to new WHO Guidelines also shows that it may take a decade or more until a new regulatory framework is fully implemented.[3]

It is advantageous if the strategic plan for wastewater use in agriculture is developed within a broader multi-sectoral planning framework for integrated water resources management because it helps to optimize the economic net benefit from the use of an increasingly scarce resource. The incorporation of microbial and chemical protocols for safe wastewater use into national water plans is important, not only to protect water quality but also to minimize wastewater treatment costs, to safeguard public health, and to use as much as possible the nutrients and organic matter contained in wastewater for agricultural production.

[3] J. Bartram, personal communication, 7 August 2010.

Carr *et al.* (2004) suggest possible steps to help develop a strategic plan for implementing health risk reduction measures: (i) conduct surveys of wastewater and excreta use practices; (ii) evaluate and prioritize health risks in the context of the national burden of disease, using methods such as QMRA; (iii) conduct stakeholder consultation workshops to formulate appropriate strategies for mitigating health impacts; (iv) develop an action plan considering the cost-effectiveness of potential multi-barrier interventions, with time-bound interim health targets for the medium and long term; (v) strengthen institutional capacity to monitor and enforce safe wastewater and excreta use practices; and (vi) review and revise the action plan and policies as needed.

Examples of countries with evolving plans are the following:

- Ghana, a low-income country that is trying to improve wastewater treatment and has tested a range of post-treatment options; and is beginning to more systematically develop a strategic plan (Seidu and Drechsel 2010);
- Jordan, a lower-middle-income country that has seen a steady evolution of standards since 1982; has treated the wastewater of the capital Amman in waste stabilization ponds since 1985; and recently upgraded treatment through a private sector build-own-operate scheme (Kfouri *et al*. 2009);
- Tunisia, a lower-middle-income country that treats most of its urban wastewater; uses 30% of the treated effluent to irrigate 7,000 ha of fruit trees and fodder following strict sanitary standards; and plans to expand wastewater irrigation to 20,000-30,000 ha by 2020 as part of the government's overall water resources management and pollution control strategy (Louati and Bucknall 2009);
- Chile, an upper-middle-income country that first began restricting wastewater irrigation in the capital Santiago in 1983 after the occurrence of hyper-endemic typhoid; successfully implemented an emergency control program of non-treatment options in 1991 in response to the threat of a cholera outbreak; developed a Sanitation Plan for Santiago in 1998 that called for the beginning of wastewater treatment; and is expected to reach full wastewater treatment for the entire Santiago metropolitan region by 2012 (Bartone 2011); and
- Israel, a high-income country that declared sewage as a water resource in 1959, instituted strict wastewater irrigation regulations in response to a cholera outbreak in the capital

Jerusalem in 1970; progressively tightened regulations (in 1977, 1995 and 1999), set new environmental requirements in 2010 covering nutrients, salts, metals and other pollutants; and is now using 72% of the country's sewage for irrigation (amounting to half of all irrigation water) through both large-scale treatment and aquifer recharge and storage schemes that produces high-quality effluent for unrestricted irrigation, and myriad small-scale projects that use appropriate technologies and produce treated effluent of lower quality suitable for restricted irrigation (Arlosoroff 2006, Juanicó 2008).

These examples show that safer wastewater irrigation can be achieved with phased planning, and that the process often requires decades of consistent improvements.

Promoting a more integrated approach to planned wastewater use for irrigation

While the risk assessment and management framework allows for reducing risks associated with wastewater irrigation, and strategic planning can help choose the needed combination of treatment and multi-barrier options for achieving health targets, the successful implementation of planned wastewater irrigation also requires that agricultural wastewater use be embedded in a broader waster resources management context.

The main reason for this is the multi-sectoral nature of wastewater use for urban farming. It requires coordinated decision-making across the areas of urban water supply and sanitation, land use policies, agriculture, public health and environmental aspects, and poverty alleviation. The varying sectoral interests and responsibilities are to be considered and reconciled for improving wastewater use. Furthermore, a number of constraints need to be addressed beyond technological and regulatory issues, such as the choice of wastewater treatment, and the design and enforcement of wastewater use guidelines and standards. They include institutional challenges (e.g., coordination among the various stakeholders), financial and economic issues (e.g., design of the cost recovery arrangements, and proper wastewater pricing), and social issues (e.g., perception of the safety of wastewater use, and promotion of risk awareness among urban farmers and consumers).

Conclusions and recommendations

Particularly in low-income countries, but also in other water-scarce countries, wastewater use for urban and peri-urban agriculture is an emerging priority. Wastewater use for irrigation can help offset water scarcity and provide a reliable source of water, improve agricultural productivity, reduce pollution, and improve food security and livelihoods for urban households. However, there are tradeoffs that need to be managed including the risks to human health, plant health, and the environment.

The 2006 WHO Guidelines present a new concept for reducing microbial health risks based on a risk assessment and management framework. They provide countries at any level of development with the means to rationally take targeted steps to reduce health risks, even when wastewater treatment is not yet an option.

Many middle-income countries have progressed toward some degree of planned wastewater irrigation, including planning approaches, policy instruments, and investments. Some of the countries have labored for decades to achieve safe wastewater use.

While each country is unique, the experience of these countries can provide important insights for those wishing to move toward an agenda for improved wastewater use in agriculture:

- As water scarcity grows, investment in wastewater treatment and effluent irrigation become more viable. To encourage such investments, governments can adopt enabling policies, establish a clear regulatory framework based on the 2006 WHO Guidelines, and develop a strategic plan for moving from unplanned to planned wastewater use for irrigation;
- Wastewater use policy, the regulatory framework, and the strategic plan will benefit from being embedded within a broader water resources management context that addresses the related technological, institutional, economic/financial, and social issues; and
- The experience of relatively successful countries, such as Jordan, Chile and Israel, suggests that achieving safe wastewater irrigation requires steady progress on all of these fronts over several decades. Governments should be prepared to make a long-term commitment and be supported in this endeavor by the international community.

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Table 1. Urban population, urban water supply and sanitation coverage, selected national disease burdens, and key wastewater use countries, by level of development

Characteristics by level of economic development	Low-income countries (43 countries) <$975 GNI/cap	Lower-middle-income countries (55 countries) $976-3,855 GNI/cap	Upper-middle-income countries (46 countries) $3,586-11,905 GNI/cap	High-income countries (66 countries, of which 27 are OECD countries) >$11,906 GNI/cap
Total urban population (millions)	280.4	1,528.3	709.7	812.1 (OECD 750.9)
Percent of total population that is urban (%)	28.7	41.3	74.8	76.0 (OECD 77.3)
Urban population with improved drinking-water (%)	86.2	94.6	95.2	99.3 (OECD 100.0)
Urban population with improved sanitation (%)	49.6	60.3	86.6	99.4 (OECD 100.0)
Diarrheal disease burden (thousand DALYs)	59,207	11,798	1,309	438
Ascariasis disease burden (thousand DALYs)	661	304	34	6
Key wastewater use countries	Sub-Saharan Africa except South Africa; Vietnam, Yemen	Bolivia, China, Egypt, India, Iran, Jordan, Morocco, Pakistan, Sudan, Syria, Tunisia, West Bank and Gaza	Argentina, Chile, Colombia, Lebanon, Libya, Mexico, Peru, South Africa	*Non-OECD:* Bahrain, Cyprus, Israel, Kuwait, Malta, Oman, Qatar, Saudi Arabia, UAE *OECD:* Australia, France, Greece, Italy, Japan, Portugal, Spain, United States

Sources: Economic and urban population data from World Bank (2010); improved water and sanitation data from WHO-UNICEF 2010; disease burden data from WHO 2008; key wastewater use countries from Jiménez and Asano 2008.
DALY = Disability-Adjusted Life Years, a measure of the burden of disease due to a specific risk factor.
Note: Improved drinking-water is defined by WHO-UNICEF (2010) as using one of the following water sources: piped water into the dwelling, yard or plot; public tap or standpipe; tubewell or borehole; protected dug well; protected spring; and rainwater collection. Improved sanitation is defined by WHO-UNICEF (2010) as using facilities that ensure hygienic separation of human excreta from human contact. They include flush or pour-flush toilets/latrines that are connected to a piped sewer system, septic tank or pit latrine; ventilated improved pit (VIP) latrines; pit latrines with slab; and composting toilets.

Table 2. Urban sanitation and wastewater treatment characteristics, and country examples by level of economic development

Characteristics by level of economic development	Low-income countries	Lower-middle-income countries	Upper-middle-income countries	High-income countries
Access to basic urban sanitation services	•Low coverage, especially for urban poor •Mainly non-sewered options	•Increasing coverage, but low access for poor •Increasing use of sewerage	•Generally acceptable coverage •Higher sewerage levels	•Good coverage •Mainly sewerage
Urban wastewater treatment	•Few or no wastewater treatment plants (WWTPs) •Severe operational deficiencies •Affordability issues dominate	•Some WWTPs, especially in large cities •Often poorly operated or design capacity exceeded •Affordability issues persist	•Increasing treatment capacity •Continued operational deficiencies •Difficult to mobilize needed investments	•Generally high treatment levels •Non-OECD: increasing investments over 20 years •OECD: major investments over 50-60 years
Country examples* (% of urban population sewered, % of urban wastewater treated)	•Ghana (4% sewered, <10% treated)	•China (56% sewered, 18-42% treated**) •Jordan (67% sewered, 90% treated) •Tunisia (79% sewered, 83% treated) •Egypt (74% sewered, 68% treated)	•Chile (95% sewered, 83% treated) •Mexico (95% sewered, 40% treated) •South Africa (75% sewered, 77% treated)	•Cyprus (73% sewered, 66% treated) •Israel (100% sewered, 90% treated) •Spain (98% sewered, 62% treated)

Sources: Typology adapted by authors from Bartone 1997; sewerage data WHO-UNICEF 2010; treatment data for Ghana: Murray and Drechsel 2011; for China: Xie *et al*. 2009; for Jordan: Al- Zboon and Al-Ananzeh 2008; for Tunisia: Louati and Bucknall 2009; for Egypt: Abdel-Gawad 2008; for Chile: Superintendant of Sanitary Services 2009; for Mexico: National Water Commission of Mexico 2010; for South Africa: Manus and van der Merwe-Botha 2009, Department of Water Affairs 2009; for Cyprus: Eliades 2010; for Israel: Israel National Water Company 2006; for Spain: European Commission 2004.
*Selected examples from key wastewater use countries in Table 1.
**18% in medium and small cities, up to 42% in large cities in China (Xie *et al*. 2009).

Table 3. Typical wastewater irrigation objectives by level of economic development

Level of economic development	Objective 1: Minimize risk to public health (priority)		Objective 2: Minimize risk to environment (priority)	Objective 3: Improve livelihoods in Urban Agriculture (priority)	Objective 4: Integrate wastewater into water resources management (status)
	Microbial Risks	Chemical risks			
Low-income countries	Urgent	Low	Low	Urgent	Low
Lower-middle-income countries	High	Emerging (High in industrial cities)	Emerging	High	Incipient
Upper-middle-income countries	High	Urgent	Urgent	High	Evolving
High-income non-OECD countries	High	High	High	Low	Advanced
High-income OECD countries	Low	High	High	Nil	Advanced

Source: Adapted from Scheierling *et al*. 2010.

Table 1. Urban population, urban water supply and sanitation coverage, selected national disease burdens, and key wastewater use countries, by level of development

Table 2. Urban sanitation and wastewater treatment characteristics, and country examples by level of economic development

Table 3. Typical wastewater irrigation objectives by level of economic development