Evaluating Wastewater Reuse in Urban Agriculture from a Systems Perspective: Focus on Linkages with Water, Energy, and Health

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Abstract

When cities grow rapidly, they often displace surrounding agricultural lands and appropriate water previously used for irrigation. Sanitation infrastructure may struggle to contain flows and urban agriculture tends to move downstream of urban/riverine discharges. Irrigation of urban agriculture with domestic wastewater provides an opportunity for capturing valuable nutrients and water prior to release into nearby waterbodies. Cities invest capital and energy resources in wastewater treatment infrastructure in efforts to provide environmental and health benefits. Complex interactions in this food-energy-water-health (FEW-Health) nexus are location-specific; therefore, multiple impacts are explored in a site study in Hyderabad, India. Varying qualities of irrigation water (treated wastewater, untreated surface water, and groundwater) were evaluated, and the following impacts were quantified: water use, energy use and GHG emissions, nutrient uptake, and crop pathogen quality. Treatment plus reuse is shown to provide GHG mitigation when compared to the untreated case; however, land use needs are high to extract nutrients from dilute effluents. Also, harvesting practices and environmental factors contribute to crop pathogen content. Urban agriculture together with wastewater treatment and reuse is beneficial, but system-wide tradeoffs are complex. This chapter reveals key environmental, physical, and behavioral factors that constrain achievable benefits at the urban FEW-health nexus.

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8.1 Introduction

Food, energy, and water (FEW) systems are vital in providing materials to city residents. Environmental conditions both inside and outside city limits can affect the availability of FEW supplies, and the urban demand for FEW supplies impacts the local and surrounding environment (Ramaswami et al. 2017). Although cities generally cannot provision all FEW materials from within their boundaries, urban agriculture is one small piece of the larger, transboundary, urban food system that is local. Urban agriculture provides fresh produce to substitute for food grown elsewhere.

In many low- and middle-income cities, a large proportion of domestic wastewater is not treated, and nearby rivers receive the contaminated water (WWAP 2017). Urban agriculture can utilize nutrient-rich domestic wastewater, either treated or untreated including blackwater and greywater (Drechsel et al. 2010), as a source of irrigation water. In this way, water and nutrients are reutilized, and low-income urban households have greater access to fresh/healthy foods (Hanjra et al. 2015; Makoni et al. 2016). The fresh produce provided by urban agriculture is a valuable benefit in addressing food insecurity and undernourishment (Boyer and Ramaswami 2017). Urban agriculture also provides land treatment of wastewater, which affects emissions of greenhouse gases (GHGs). In cities where wastewater collection systems are not complete, wastewater treatment infrastructure is currently being implemented, which is expected to affect system-wide energy and GHG emissions; therefore, understanding linkages across sectors in the food, energy, water, and health (FEW-health) nexus in the context of such cities is important (Ramaswami et al. 2018). In high-income countries, wastewater effluent is not used in urban agriculture (biosolids are applied, but not effluent directly), so this situation does not arise.

As city populations grow, urban metabolism of FEW materials (resource consumption, energy use, and waste generation) also increases (Kennedy et al. 2007; Wolman 1965). Often in low-income nations, cities displace surrounding agricultural land and irrigation water, forcing agriculture downstream of urban riverine/wastewater discharges (Van Rooijen et al. 2005; Dutta 2012). Wastewater is a nutrient-rich resource that is valuable to farmers who are seeking a widely available and consistent source of irrigation water for their crops. Wastewater reuse in urban agriculture is not new or rare; in fact, it stems from ancient Greece, and today an estimated 200 million farmers irrigate at least 20 million hectares with raw or partially treated wastewater (Raschid-Sally and Jayakody 2008). This number accounts for approximately 8% of total worldwide irrigated land (263 million hectares in 1996), of which two-thirds lies in Asia (Howell 2001), and supports a population of farmers that represents approximately 15% of the total amount of people economically active in agriculture worldwide (FAOSTAT 2009). Wastewater reuse is employed to irrigate a variety of vegetable, fruit, and herb crops in cities in the Americas, Africa, and Asia (van der Hoek 2004). Because wastewater reuse in urban agriculture is widespread and legislation is difficult, the question is no longer if wastewater should be used for irrigation, but how it can be made more sustainable and safer (van Rooijen et al. 2005; Scott et al. 2004).

8.2 Advantages of Wastewater Reuse for Urban Agriculture

This practice has numerous advantages:

- Conservation of water: Water reused for urban agriculture means that less freshwater/groundwater is needed, which is important given increasing water scarcity (van der Hoek et al. 2002).
- Nutrient recycling: Wastewater contains nutrients, leading many farmers to prefer wastewater for irrigation because it is thought to increase productivity (Qadir et al. 2007).
- Avoided fertilizer (Asano 1998): Nutrients (nitrogen, phosphorus, potassium, and organic carbon) in wastewater could save the farmers money and have the indirect impact of saving energy and GHGs (Pitterle and Ramaswami 2009).
- Land treatment of wastewater: Without other treatment options, land application may provide some decrease in surface freshwater contamination (Raschid-Sally and Jayakody 2008) and GHG emission reductions.
- Spatial and temporal accessibility of irrigation water: Oftentimes, farmers have better access to wastewater as a source of irrigation water because it is in constant supply in urban and peri-urban areas, even in the dry season. This is because cities draw municipal drinking water from outside their boundaries and discharge it as wastewater after use (Qadir et al. 2007).
- Decreased need for expensive refrigerated transport or storage facilities: This is most valued in low-income countries with hot climates (Qadir et al. 2008).
- Nutrition: Urban agriculture, facilitated by wastewater reuse in many rapidly-urbanizing cities, provides both farmers and consumers with a local, fresh supply of vegetables (Qadir et al. 2008).
- Better livelihoods: Wastewater is an inexpensive source of water and nutrients allowing farming families to grow high-value and high-demand crops like vegetables (Kilelu 2004), which generates more income and raises living standards, including indirect benefits like education (Raschid-Sally and Jayakody 2008).

For these reasons, wastewater is considered a valuable resource for many. The articles/reports above are largely qualitative studies. Many of these benefits, along with savings in energy, greenhouse gas emissions, and water, are not well-understood quantitatively.

8.3 Disadvantages of Wastewater Reuse for Urban Agriculture

While there are many advantages, the practice of wastewater reuse in urban agriculture also poses public health and environmental problems as water, soil, and crops become increasingly contaminated.

- Contaminants: Wastewater contains a variety of pollutants including salts, metals, metalloids, pathogens, residual drugs, organic compounds, endocrine disruptor compounds, and active residues of personal care products (Qadir et al. 2007). Pathogens associated with wastewater irrigation include: hookworm, roundworm (*Ascaris lumbricoides*), *E. coli*, giardia (*Giardia lamblia*), hepatitis A virus, typhoid (*Salmonella typhi*), and cholera (*Vibrio cholerae*).
- Human health: Both acute and chronic diseases can result from exposure to contaminants in wastewater. The main threat to human health in the short term is pathogens, specifically intestinal nematode infections (Ensink et al. 2008).
- Soil and crop quality: Heavy metals and salts in wastewater adversely affect soil quality (Ganjegunte et al. 2018; Abd-Elwahed Mohammed 2018). Crop production is also hindered by high levels of heavy metals and soil salinity (Morugán-Coronado et al. 2011; Shahid et al. 2015).

Farmers in low-income countries often use water from a polluted stream, diluted wastewater, or untreated sewage directly on crops. Wastewater from any source is seldom treated before being applied to crops (Qadir et al. 2007).

8.4 Wastewater Treatment Plants for Water Reuse for Urban Agriculture

Domestic wastewater treatment plants (WWTPs) are large, centralized facilities that collect wastewater via piped systems that are connected to homes and businesses throughout a city. WWTPs utilize a variety of physical, chemical, and biological processes to remove contaminants from wastewater. They generally release the cleaner effluent water into a nearby surface water body. WWTPs are effective in removing pathogens and other harmful substances from water and have been shown to decrease health risks (Asano 1998). Rapidly-urbanizing cities that lack adequate collection and WWTP infrastructure face a large proportion of their sewage being released directly to the environment; therefore, they are implementing WWTP infrastructure to address this need for treatment of sewage-polluted water. With this infrastructure development, municipal energy use is expected to increase because WWTPs are energy intensive (Miller et al. 2013). However, energy investments are expected to offer various benefits in terms of pathogen reduction and may help in more sustainable wastewater reuse for agriculture. Also, overall reductions in carbon- and nitrogen-related GHG emissions may be achieved due to WWTP processes removing them from water, and via subsequent application of effluent to farmlands.

In this research, a systems approach was taken to explore linkages across sectors and outcomes in the FEW-Health nexus. Based on the above review, there are multiple and conflicting impacts: GHG emissions (energy- and non-energy related), economic benefits to farmer (food production), water reuse (water savings), monetary cost (infrastructure), and health benefits to society (pathogen risk reduction in food). In order to quantify these impacts, this chapter evaluates tradeoffs for three farm sites in a case study, irrigated by differing sources of water: groundwater, treated effluent from a WWTP, and untreated surface water representative of the sewage-contaminated riverine system.

8.5 Case Study in Hyderabad, India

Many location-specific factors affect the tradeoffs between GHG emissions, infrastructure costs, food production, pathogen risk reduction, and water savings; therefore, a case study approach was necessary. Hyderabad, India was chosen for the following reasons: centralized WWTP infrastructure is newly implemented (secondary treatment within the last 15 years), wastewater contamination of surface water is ubiquitous, and wastewater-polluted water is reused for urban agriculture.

For Hyderabad, 80% of the water supply is released as sewage (Ramachandraiah and Vedakumar 2007). According to a Ministry of Urban Development Report (2010), 40% of the produced wastewater in Hyderabad is collected and treated before discharge into the Musi River, which runs through the center of Hyderabad. This leaves an average of 175 million gallons of untreated wastewater entering the riverine system daily. For most of the year, which is dry season, the Musi River would not flow without the input of sewage water (van Rooijen et al. 2005; Ramachandraiah and Vedakumar 2007).

Downstream of Hyderabad, the Musi River is used extensively for irrigation, with nearly 40,000 hectares of farmland irrigated from the river (Hamilton et al. 2007). This has resulted in severe groundwater pollution (Foster et al. 2003) and an overall long-term decline in the productivity of untreated wastewater-irrigated lands by more than 50% (Devi et al. 2009). A few scientists have studied wastewater reuse in Hyderabad and the effect on the environment and the people (Gopal 2004; Srinivasan and Reddy 2009). Others have studied the role of Hyderabad's water supply network and sewage network in urban recharge of groundwater (Wakode et al. 2018), and the stresses on already-scarce surface and groundwater sources due to growing competition from the agriculture and urban-industrial sectors (van Rooijen et al. 2009; Celio et al. 2010; Venot et al. 2010a, b). The International Water Management Institute (IWMI) has pioneered much of the work in Hyderabad and throughout the world (Devi et al. 2009; Buechler and Devi 2003; Jacobi 2009; Amerasinghe et al. 2013). The Resource Centres on Urban Agriculture and Food Security (RUAF) are also active in Hyderabad and globally, with the primary aim to promote and institutionalize urban agriculture processes in cities (RUAF 2010).

There were four operating WWTPs in Hyderabad at the time of this case study, collecting and treating water in the south-east area of the city (Fig. 8.1a). The

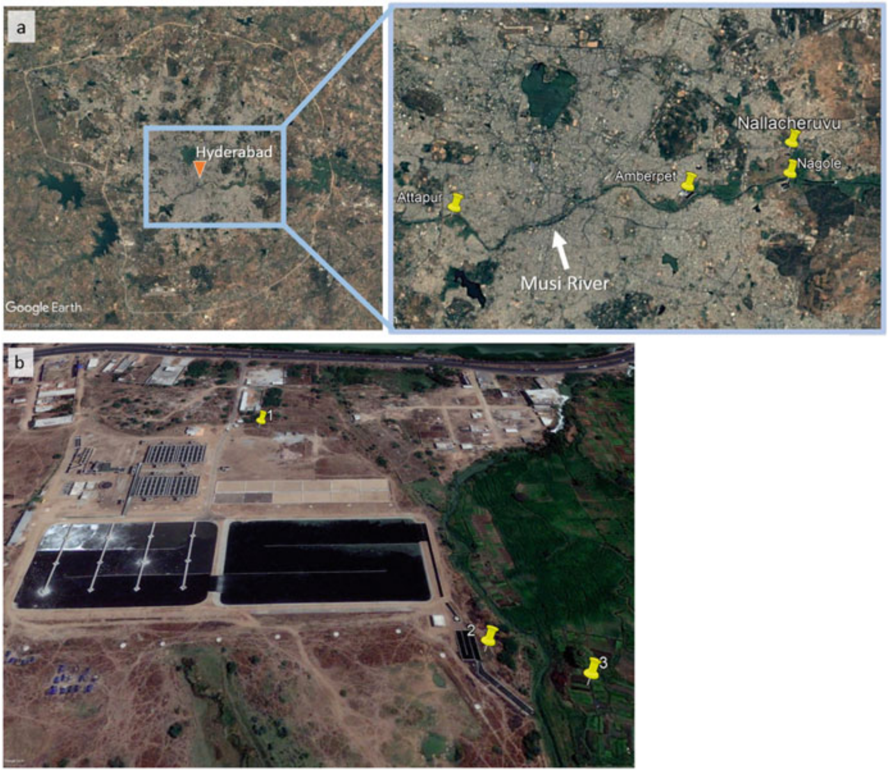

Fig. 8.1 (**a**) Aerial view of Hyderabad, India showing the location of N-WWTP (Nallacheruvu) and the other three WWTPs (Attapur, Amberpet, and Nagole) near the Musi River, which flows from west to east (left to right); (**b**) Aerial view of N-WWTP showing co-location of urban agriculture plots (each 12 m^2) irrigated with: (1) groundwater from 50 ft deep; (2) N-WWTP effluent; (3) untreated surface water located on the other side of a stream from the WWTP effluent (retrieved from Google Earth Pro for years 2010 and 2011)

building of the Nallacheruvu WWTP (N-WWTP) in 2007 displaced urban farmers that had been farming in the area for up to 40 years (McCartney et al. 2008). Because the farmers used surface water to irrigate their crops, the area has a long history of wastewater contamination in both soil and groundwater. Today, adjacent to the N-WWTP, farmers grow crops such as spinach, coriander, mint, chilies, papaya, amaranth, fenugreek, fennel, and others.

The farming site at Nallacheruvu (Fig. 8.1b) was chosen for the following reasons: (1) its co-location of WWTP and urban agriculture, (2) ready access to three different qualities of water (groundwater, treated wastewater, and untreated surface water), (3) the availability of an experienced farmer, and (4) permission from the Hyderabad Metropolitan Water Supply and Sewerage Board for use of the study site and willingness to share data for N-WWTP. This field study took place during the dry season from March to May 2010, when water levels were at their lowest and stormwater would not dilute irrigation sources. Initial testing was done to choose plots that were similar in soil characteristics (physical texture and nutrient content) and distance, orientation, and slope to the nearby stream. The intent was to make all attributes between plots as similar as possible, with the exception of irrigation water quality. For the site study, the following parameters were measured during irrigation events throughout one crop growth cycle: irrigation water quality (pH, electrical conductivity (EC), total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), nitrogen (N), phosphorus (P), potassium (K), *E. coli*, total coliform, Ascaris ova, Hookworm ova), irrigation water quantity (volume), soil quality (pH, EC, TOC, N, P, K, *E. coli*, total coliform, Ascaris ova, Hookworm ova), soil water quality (N, P, K, *E. coli*, total coliform), crop quality (N, P, K, *E. coli*, total coliform, Ascaris ova, Hookworm ova), and crop quantity (harvested bunches).

8.6 System-Wide Energy and Greenhouse Gas Impacts

System-wide energy and GHG emissions were evaluated for nearby streams, throughout the N-WWTP (Miller-Robbie et al. 2013), and for irrigating urban agriculture (Miller-Robbie et al. 2017). The values described below in the text are in terms of mg CO_2e per liter water as opposed to metric tonnes CO_2e per year (Fig. 8.2), as both are useful; the flow rate from March 2009 to March 2010 was 6570 million liters per year (MLY).

8.6.1 Untreated Wastewater in Streams

Uncontrolled release of untreated wastewater into streams results in the release of methane (CH_4) and nitrous oxide (N_2O), both potent greenhouse gases. Methane-related GHG emissions from wastewater were estimated using IPCC methods as the product of the maximum CH_4 producing capacity for domestic wastewater (0.25 kg CH_4 per kg COD (as measured via lab testing of water)) and a methane correction factor that was applied to represent the anoxic status of the receiving water body (Miller-Robbie et al. 2017; IPCC 2006). The estimation of N_2O emissions from rivers was based on a meta-analysis of several stream N_2O field studies (Beaulieu et al. 2011), which estimated 0.0075 kg N_2O per kg dissolved inorganic nitrogen (DIN) (measured via lab testing of ammonia, nitrate, and nitrite) discharged to rivers is converted via denitrification and nitrification. Untreated wastewater contained an average of 514 mg/L COD and 84 mg/L DIN, resulting in 643 mg CO_2e/L attributed to CH_4, and 187 mg CO_2e/L attributed to N_2O emissions (Miller-Robbie et al. 2017), for a total of 830 mg CO_2e/L untreated wastewater.

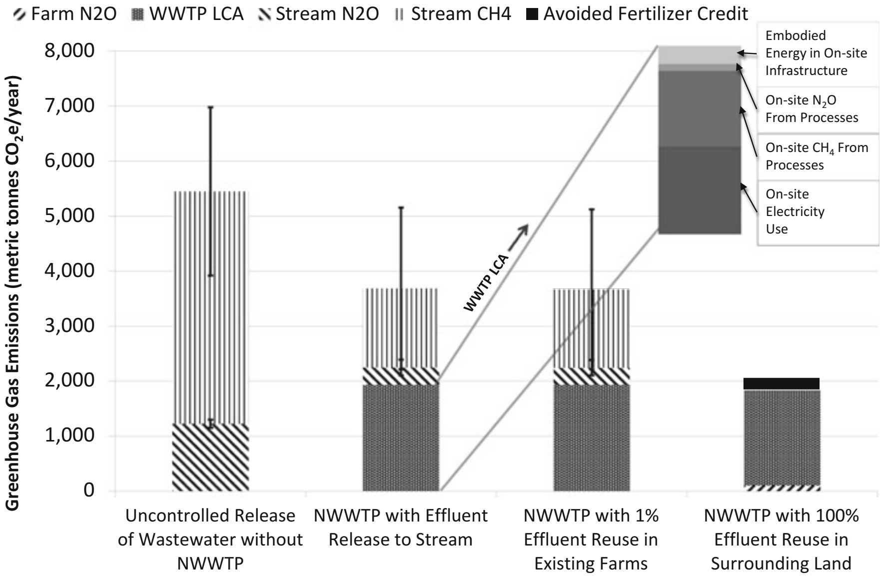

Fig. 8.2 Results for the combination of wastewater treatment and reuse in agriculture, comparing the GHG emission impact from releasing untreated wastewater to various interventions. Error bars are based on the standard deviation in the concentration of COD or DIN in water. March 2009 to March 2010 flow rate of 6570 MLY (Miller-Robbie et al. 2017)

8.6.2 Wastewater Treatment Plant with Effluent Release to Stream

WWTP processes can be resource-intensive in terms of energy use and energy-related GHGs, and direct GHG emissions from the water surface. A life-cycle assessment (LCA) was employed to quantify energy consumed and GHGs emitted to achieve water quality improvements with WWTP infrastructure (Miller-Robbie et al. 2013). The four on-site components included were end-use energy in WWTP operations, embodied energy of infrastructure, process emissions of CH_4, and process emissions of N_2O. Total life-cycle GHG emissions were calculated as 295 mg CO_2e/L treated wastewater.

When treated effluent was released to the stream, it contained an average of 175 mg/L COD and 21 mg/L DIN (both measured in lab tests), resulting in 219 mg CO_2e/L attributed to CH_4, and 47 mg CO_2e/L attributed to N_2O emissions (Miller-Robbie et al. 2017), for total life-cycle GHG emissions of 561 mg CO_2e/L treated wastewater. When compared to the emissions from untreated wastewater in streams in the previous section, a reduction of about 32% was estimated; the majority was due to the reduction in COD (and CH_4) and DIN (and N_2O) by WWTP operations. Contrary to expectations that the addition of a WWTP may increase system-wide GHG emissions, this study found that investing in energy and GHG emissions actually reduced overall GHG emissions because significant CH_4 and N_2O were generated from untreated wastewater.

8.6.3 Wastewater Reuse for Urban Agriculture

GHG emissions from urban agriculture irrigated with treated wastewater were evaluated using the DAYCENT model, developed by the Natural Resource Ecology Laboratory at Colorado State University. DAYCENT is well-documented and widely used to estimate GHG emissions from cropped fields, usually with major crops such as corn, soybean, wheat, alfalfa, and cotton in the USA (Del Grosso et al. 2005, 2009; Jarecki et al. 2007; USEPA 2011). This study utilized DAYCENT for wastewater irrigation of vegetables in the context of India. The DAYCENT model utilizes multiple parameters for input data: local weather, historical data on land use, physical and chemical soil characteristics, irrigation events, crop characteristics, nitrogen, phosphorus, and organic matter addition events, carbon/nitrogen ratio, and relative concentrations of nitrogen species. An N_2O emission factor was the model result of interest because it is the only GHG produced from agriculture under non-flooded conditions; the aerobic environment of agriculture does not facilitate COD (or BOD) conversion to CH_4, so CH_4 is negligible in this case. Based on the treated effluent plot, the DAYCENT model estimated an emission factor of 0.00070 gN_2O-N flux/g DIN applied to agriculture—about tenfold less than the river emission factor of 0.0075 gN_2O-N/g DIN (Beaulieu et al. 2011). If all of the treated wastewater was reused for irrigation, the emissions would be only 23 mg CO_2e/L, attributed to N_2O emissions from cropped fields (Miller-Robbie et al. 2017), for total life-cycle GHG emissions of 318 mg CO_2e/L treated wastewater. Thus, in general, the DAYCENT model shows that urban agriculture would be effective in further reducing the production of GHGs as compared to the release of treated wastewater to the stream. This is an important and counter-intuitive result which indicates that both water and GHG benefits can arise due to applying WWTP-treated wastewater to urban agriculture.

8.7 Practical Constraints of Treated Wastewater Reuse in Urban Agriculture

WWTPs are commonly placed at a low elevation near a river at the outflow from a city. Therefore, the potential to irrigate urban agriculture with treated wastewater is limited by terrain, in the absence of additional piping and pumping infrastructure. Approximately 562,000 m^2 of available land is adjacent to the flow between the outlet of N-WWTP boundary and inflow to the Musi River; however, farmers employ gravity-driven irrigation with surface water and the actual land under farming that is readily gravity-fed from the effluent channel was estimated to be only 1% (approximately 5500 m^2). While nutrients in the water suffice for the crops (according to lab test results and the success of the crops in the absence of additional fertilizer), the limiting factor is the topography; since only 1% of water can be readily diverted by gravity to urban agriculture in this case study, the impact of urban agriculture on nutrient cycling and GHG mitigation is relatively small (Fig. 8.2). In the event that 100% of N-WWTP effluent could be reused in agriculture, the hypothetical reduction in system-wide GHG is ~66%; however, the additional energy associated with diverting irrigation water is not included in the model. For this particular site, extensive infrastructure and energy would be required to pump water above the stream banks to irrigate land, illustrating practical constraints.

8.8 Environmental and Behavioral Causes of Crop Contamination

The water quality of the three irrigation waters (groundwater, N-WWTP effluent, and untreated surface water) at the three different sites differed consistently throughout the study, as determined by lab testing of composite water samples taken during irrigation events. For example, average total nitrogen measured was at 3, 37, and 48 mg/L for groundwater, treated effluent, and untreated surface water, respectively. Nitrogen levels were relatively high in the treated effluent because nitrogen is not one of the primary treatment targets of N-WWTP; the treatment is focused on meeting the Indian disposal standards of 5-day BOD below 30 mg/L and fecal coliforms below 10,000 MPN/100 mL, among other parameters (Miller-Robbie et al. 2013). The higher nutrient and organic matter content of the irrigation water was beneficial to crops (Miller-Robbie et al. 2017), with the treated effluent and untreated surface water plots producing the highest crop yields; the groundwater plot yielded only 12% of the sellable bundles as compared to the other two plots at harvest.

Although the water quality improved by several orders of magnitude due to WWTP treatment (Fig. 8.3a), crop quality did not improve significantly, as measured by indicator organisms, *E. coli* and nematode ova (Miller-Robbie et al. 2017). As seen in the crop *E. coli* results (Fig. 8.3b), there were clear differences of at least two orders of magnitude, on average, between the *E. coli* content of the three irrigation waters throughout the study. However, the *E. coli* content on the spinach at harvest was not as different as in the irrigation water; at harvest the crop samples were within one order of magnitude of each other when crops were harvested by the farmer using his usual harvesting practices. Even the spinach grown with relatively clean groundwater was not significantly different from that grown with treated effluent ($p > 0.1$), which had a much higher irrigation water *E. coli* content. However, the spinach grown with WWTP effluent had significantly lower *E. coli* content than that grown with untreated water ($p < 0.025$). Similar results were seen for Ascaris and hookworm content of water, soil, and crops (Miller-Robbie et al. 2017).

Several behavioral and environmental factors were explored to identify reasons why the *E. coli* on spinach were not dissimilar across the three farm plots, even though irrigation water quality differed by orders of magnitude. First, the researcher observed farmer handling at the time of mid-point crop sampling, and noticed the farmer-harvested spinach with great speed, resulting in frequent contact between the leaves and the soil, which contained high levels of *E. coli* in all three plots. The farmer also placed the harvest under a pre-moistened (wastewater-soaked) gunnysack to prevent wilting in the heat. The researcher collected samples at final harvest

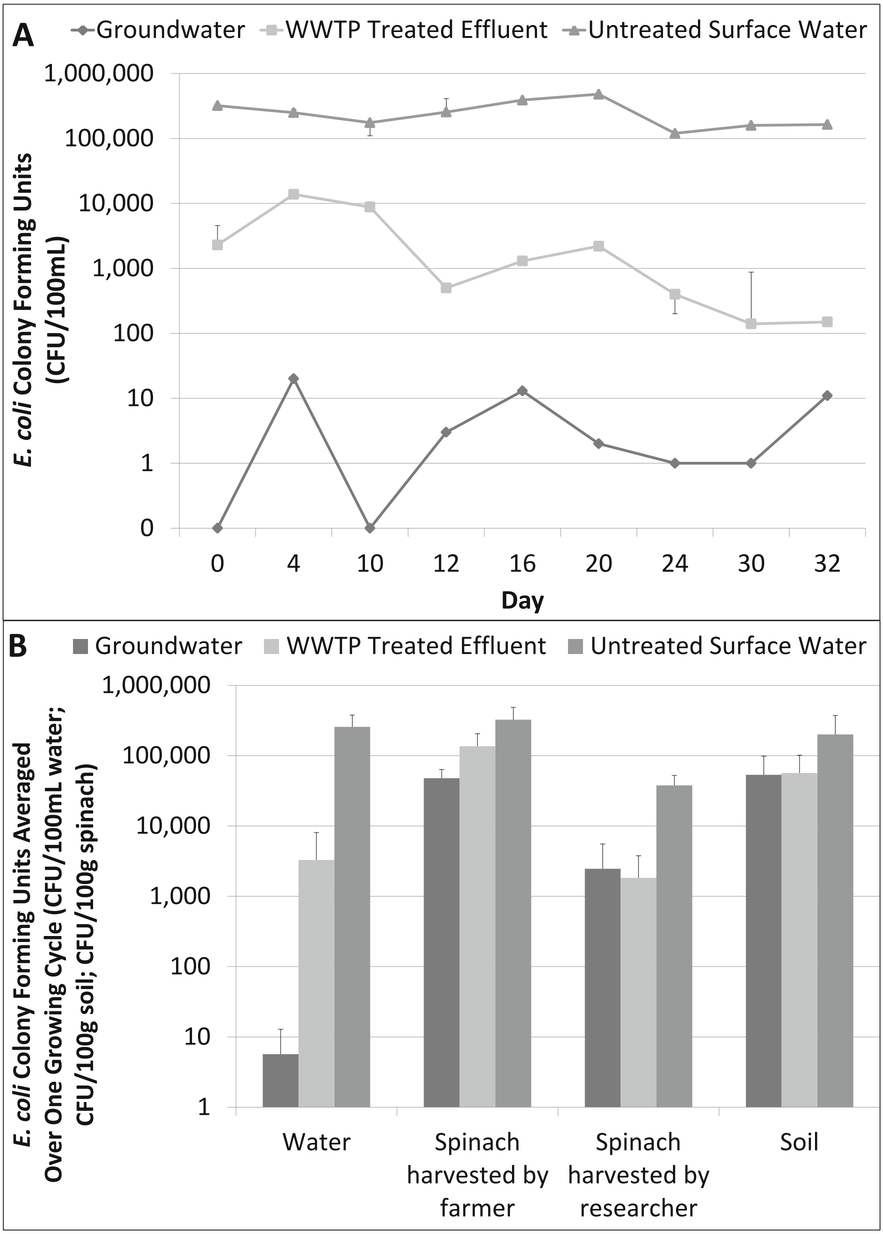

Fig. 8.3 (**a**) Daily average *E. coli* in irrigation water over the course of the study. (**b**) *E. coli* averaged over one growing cycle for all media: irrigation water, spinach harvested by farmer and by researcher, and soil. *CFU* colony forming units (Miller-Robbie et al. 2017)

in an effort to minimize recontamination by using hand sanitizer between samples and taking care to not touch anything except the crop and sterile sample bag.

The researcher-harvest yielded crop samples were at least one order of magnitude less for *E. coli* content than the farmer-harvested samples (statistically significant at $p < 0.1$) (Fig. 8.3b). However, as seen with farmer harvesting, there was not a significant difference ($p > 0.1$) between groundwater and treated effluent irrigated crops, but both were considerably different from crops irrigated with untreated surface water (Fig. 8.3b). Thus, the data show that the WWTP did reduce microorganism concentration on crops, but not as dramatically as in the irrigation water.

Other factors such as extreme summer heat (soil temperatures as high as 58 °C in direct sunlight), wind-blown dust, soil, and aerosol particles from the WWTP could also be important. Therefore, this field study demonstrates that energy investments in WWTP reduce *E. coli* in water by several orders of magnitude, but have a significantly smaller effect for crops produced from urban agriculture due to a combination of environmental and behavioral factors.

8.9 Determining Health Risks Associated with Crop Microorganism Content

To determine the health risk due to ingesting pathogens on leafy vegetables irrigated with treated and untreated wastewater, a basic quantitative microbial risk analysis model was used (Mara 2008), in accordance with World Health Organization 2006 Guidelines. The measured *E. coli* content of the farmer-harvested spinach (Fig. 8.3b) was used as an indicator bacterium to estimate rotavirus concentration. Assumptions included: 0.1 to 1 rotavirus expected per 10^5 *E. coli*; 10^{-2} to 10^{-3} rotavirus die-off between last irrigation and consumption (Mara 2008), and that this lettuce-based model was appropriate for spinach. Consumption of wastewater-irrigated crops was the focus of this study and farmer exposure was not quantified. In addition to consumption, farmers are exposed to pathogens in wastewater through their skin (e.g., hookworm species) and orally (aerosols and via unwashed hands/other items) (van der Hoek 2004). The probability of infection calculation considers consumption of uncooked wastewater-irrigated spinach, which can be considered as a worse-case scenario in comparison to consumption of cooked spinach. There are education programs to encourage farmers to grow crops that are more suitable for irrigation with wastewater, i.e., trees, shrubs, flowers, livestock fodder, and crops that are not eaten raw (RUAF 2020).

To estimate the probability of infection due to one dose (100 g) of spinach, the β-Poisson dose-response model was used:

$$\mathrm{PI}(d) = 1 - \left[1 + \left(\frac{d}{\mathrm{N50}}\right)\left(\frac{21}{\alpha} - 1\right)\right] - \alpha \tag{8.1}$$

where

PI(d) = probability of infection in an individual due to ingestion of a single dose, d
N50 = median infective dose; 6.17 for rotavirus (Mara 2008).
α = pathogen infectivity constants; 0.253 for rotavirus (Mara 2008).

One dose of spinach (100 g) irrigated with groundwater, WWTP effluent, and untreated surface water was estimated to contain 0.4, 1.2, and 2.9 rotaviruses, respectively, due to the *E. coli* indicator concentration; using Eq. (8.1), the probability of infection from these single doses was 0.16, 0.29, and 0.41, respectively. When compared with the tolerable infection risk for rotavirus in developing countries of 7.7×10^{-4} per person per year (given by WHO 2006 guidelines), which equates to a dose per exposure event of 3.9×10^{-5} rotaviruses (Mara 2008), the amounts contained in one dose from this study were orders of magnitude larger; therefore, the health risks are exceedingly high for all three farm plots.

8.10 Assessment of System-Wide Tradeoffs

System-wide tradeoffs, between energy use/GHG emissions, food production, groundwater use, infrastructure monetary cost, and health risk reduction, were assessed and relative comparisons were made between the three farm sites (Table 8.1). This study found that the urban agriculture groundwater scenario was the least beneficial for food production and groundwater use categories, and had a minimal impact on energy use/GHG emissions and infrastructure monetary cost, and the lowest spinach pathogen indicator (*E. coli*) content, although enough to pose a health risk. Use of treated effluent and untreated surface water for urban agriculture were more similar for some categories; they yielded higher food productivities, while avoiding groundwater extraction. Despite the added embodied energy and GHG emissions in WWTP infrastructure, the treated effluent case did emit fewer GHGs overall than the untreated surface water case due to reduced COD and DIN in the effluent water when released to streams (Fig. 8.2), and did have less crop *E. coli* content; however, the health risk was still significant.

Table 8.1 Relative system-wide positive benefits and negative costs for relevant tradeoffs

	Energy use/GHG emissions	Food produced	Groundwater used	Infrastructure cost	Pathogen indicator on crop
Groundwater	+	−	−	+	±
Treated effluent	±	+	+	−	±
Untreated surface water	−	+	+	+	−

8.11 Key Findings and Future Recommendations

As cities grow and domestic wastewater is either released to the environment without treatment or WWTPs are built and wastewater is treated, this study strives to quantify the holistic impacts of wastewater use for urban agriculture. The key findings are as follows:

1. Contrary to expectations, investments of energy and GHG emissions, in terms of constructing, operating, and maintaining WWTP infrastructure, actually reduce system-wide GHG emissions. This is because significant CH_4 and N_2O are generated from untreated wastewater in streams. Urban agriculture further reduces system-wide GHG emissions because CH_4 emissions are negligible when wastewater is reused as irrigation water.
2. Because the nutrients in wastewater effluent are dilute, a very large amount of urban agricultural land is needed to capture the water and nutrients. This limits the potential for wastewater reuse for irrigation water within city limits where large amounts of land are less available; however, peri-urban areas are often nearby and more open. Pumping and piping infrastructure would likely be needed to maximize the amount of land used.
3. Although the water quality in this study improved by several orders of magnitude due to WWTP treatment, crop quality did not improve when irrigated with higher-quality water. Both behavioral and environmental causes were found to contribute to contamination.
4. Although water was treated via the WWTP and subsequently utilized for crop irrigation, the treated water still posed a health risk to consumers. Therefore, precautions and education programs are important.

Overall, quantitative analysis of urban water contamination shows that investing in WWTP infrastructure offers the most benefits in the FEW-Health nexus; however, key environmental/behavioral factors need to be considered when evaluating wastewater reuse in urban agriculture. While the purpose of WWTP implementation is not specifically to provide irrigation water to urban farmers, farmers can benefit from WWTP-treated water for use on their crops. There is little guidance due to few published, quantitative studies on appropriate water quality standards in low-income countries for urban agriculture. Therefore, field studies that measure pathogens on crops in many locations, climates, and seasons could help to inform these parameters.

Benefits to urban agriculture may be better realized from other methods of wastewater treatment. Assessing the potential of natural treatment/vegetative buffer strips for megacities where the majority of wastewater is untreated, or alternatives to flush toilets leading to centralized WWTPs, could be more favorable from the perspective of water reuse for urban agriculture.

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