Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India

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Abstract

Nutrients and water found in domestic treated wastewater are valuable and can be reutilized in urban agriculture as a potential strategy to provide communities with access to fresh produce. In this paper, this proposition is examined by conducting a field study in the rapidly developing city of Hyderabad, India. Urban agriculture trade-offs in water use, energy use and GHG emissions, nutrient uptake, and crop pathogen quality are evaluated, and irrigation waters of varying qualities (treated wastewater, versus untreated water and groundwater) are compared. The results are counter-intuitive, and illustrate potential synergies and key constraints relating to the food–energy–water–health (FEW–health) nexus in developing cities. First, when the impact of GHG emissions from untreated wastewater diluted in surface streams is compared with the life cycle assessment of wastewater treatment with reuse in agriculture, the treatment-plus-reuse case yields a 33% reduction in life cycle system-wide GHG emissions. Second, despite water cycling benefits in urban agriculture, only <1% of the nutrients are able to be captured in urban agriculture, limited by the small proportion of effluent divertible to urban agriculture due to land constraints. Thus, water treatment plus reuse in urban farms can enhance GHG mitigation and also directly save groundwater; however, very large amounts of land are needed to extract nutrients from dilute effluents. Third, although energy use for wastewater treatment results in pathogen indicator organism concentrations in irrigation water to be reduced by 99.9% (three orders of magnitude) compared to the untreated case, crop pathogen content was reduced by much less, largely due to environmental contamination and farmer behavior and harvesting practices. The study uncovers key physical, environmental, and behavioral factors that constrain benefits achievable at the FEW-health nexus in urban areas.

1. Introduction

Reutilization of nutrients and water from domestic treated wastewater to urban agriculture is often considered as a potential food–energy–water–health (FEW–health) nexus strategy that may use energy and increase GHG emissions, while advancing water cycling and nutrient recovery, and also providing access to fresh/healthy foods (Hanjra et al 2015, Makoni et al 2016). The FEW nexus, a systems approach that evaluates trade-offs to promote successful project implementation (Hoff 2011, Bazilian et al 2011, Kurian 2017), is a key interdisciplinary strategy for sustainable infrastructure in cities (Walker et al 2014, Gondhalekar and Ramsauer 2017, Schlor et al 2017) In this paper, the above proposition is examined in the context of rapidly-developing cities that are beginning to install wastewater treatment and
where the practice of urban agriculture with urban domestic waters is quite ubiquitous. In developed 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, their use of land, water, and energy resources, as well as waste generation, also increases. Often in developing nations, cities displace surrounding agricultural land and appropriate water previously used for agriculture, forcing peri-urban agriculture downstream of urban riverine/wastewater discharges (Van Rooijen et al. 2005). This nutrient-rich wastewater is viewed as a valuable resource to urban farmers seeking a consistently available source of irrigation water. Worldwide, an estimated 200 million farmers irrigate at least 20 million hectares (ha) with raw or partially treated wastewater (Qadir et al. 2007, Raschid-Sally and Jayakody 2008), accounting for ~8% of total worldwide irrigated land, of which two-thirds lies in Asia (Howell 2001). Agriculture with wastewater represents livelihoods for approximately 15% of farmers worldwide (FAOSTAT 2009), although the proportion of rural versus urban farmers is not certain.

There are many advantages and disadvantages of irrigating urban farms with untreated or partially-treated wastewater. The advantages, particularly in developing countries, include water conservation (van der Hoek et al. 2002), nutrient recycling (Qadir et al. 2007), avoided fertilizer usage (Asano 1998, Pitterle and Ramaswami 2009, Corominas et al. 2013), land treatment of wastewater (Raschid-Sally and Jayakody 2008), spatial and temporal accessibility of irrigation water (Qadir et al. 2007), decreased need for expensive refrigerated transport or storage facilities (Qadir et al. 2008), improved nutrition for urban residents (Qadir et al. 2008), and better livelihoods (Kilelu 2004, Raschid-Sally and Jayakody 2008). The disadvantages include increased health risks and decreased environmental quality as water, soil, and crops become increasingly contaminated with pathogens, metals, etc. (Qadir et al. 2007, Ensink et al. 2008). Pathogens, e.g. bacteria, viruses, protozoa, and nematodes, can cause acute health affects (Ensink et al. 2008).

Engineered physical and biochemical treatment processes can help remove pathogens, thereby mitigating some of the health risks of urban wastewater agriculture (Asano 1998). The construction and operation of these centralized wastewater treatment plants (WWTPs) use energy and emit associated greenhouse gases (GHGs), which are considered an investment that can mitigate the health risks associated with resource reutilization when wastewater is treated and reused in agriculture. Indeed, this is often viewed as a key opportunity when exploring the FEW-health nexus from a city perspective. However, the interactions, trade-offs and co-benefits of WWTP energy use and urban wastewater agriculture risks have not been quantified in the field to confirm these expectations, primarily because wastewater agriculture is being practiced in developing world cities where WWTPs are only now being installed at a significant scale. As more and more cities in the developing world implement WWTP infrastructure to treat sewage-polluted water, the trade-offs between water, energy, and health in the context of food-borne disease must be evaluated at the intersection of urban agriculture and urban water systems (including groundwater, wastewater, and surface flows).

Work relating to the urban FEW-health nexus draws upon multiple strands of literature, emerging at three main fronts. First, regarding life cycle assessment (LCA) studies of WWTP technologies, many studies include embodied energy and GHGs along with avoided fertilizer (Corominas et al. 2013), and many have been studied in developing cities (Friedrich et al. 2009, Zhang et al. 2010, Fine and Hadas 2012, Cornejo et al. 2013, Li et al. 2013, Cornejo et al. 2014). However, only a few include the direct link with urban farming practices within the cities (Verbyla et al. 2013, Symonds et al. 2014). Additionally, key knowledge gaps remain. In particular, the biosolids pathway does not address the situation in developing cities where untreated or treated wastewater is directly being used in urban agriculture, which is the focus of this study. There are no LCA studies of WWTPs in developing countries that include a consequential analysis of the wastewater effluent beyond the WWTP fence-line in the context of direct application of nutrient-rich effluent in urban agriculture. Beyond a traditional WWTP LCA, methane (CH₄) and nitrous oxide (N₂O) are emitted from wastewater effluent in streams, and from farming, and the latter has not been modeled to date.

Second, concerning GHG emissions from agriculture, national studies have been done; however, vegetable crops that are common in urban agriculture are not included in these studies. The DAYCENT model, used in this study, quantifies GHG emissions from cropped lands (US EPA 2011), but has not been applied to urban agriculture crops (herbs, vegetables) grown with nutrient-rich wastewater.

Third, there have been many studies in developed countries establishing general water reclamation standards, including for urban agriculture, and the general guidelines in the United States are to treat to levels similar to drinking water standards; in developing countries, this is an area where there are few studies and guidance is sought to address the complex interactions that are the topic of this paper (e.g. equity, nutrition, etc.). The contribution of this work is in bringing these three strands of literature together in a urban farming field study conducted in a real city with the parameters of an operating WWTP, field parameters of wastewater agriculture, and an actual farmer.

Furthermore, there are a few field studies assessing pathogens on crops treated with irrigation water from...
diverse sources. For example, only one study has measured bacteria content of the crop (peppers) following irrigation with treated wastewater (Dagianta et al 2014); however, the entire system was not studied, including agriculture with untreated wastewater or the system impacts wherein the energy use and emissions from WWTP with agricultural impacts are linked to the crop quality. Integrated field studies are needed that connect systems analysis around WWTPs with actual field measurements and related health benefits of the resulting urban agriculture system. In recent years, a few studies have investigated WWTP effluent water quality and its suitability for reuse in agriculture (Norton-Brandão et al 2013, Trinh et al 2013, Becerra-Castro et al 2015, Bunani et al 2015, Kihila et al 2014, Mojid and Wyseure 2014, Myszograj et al 2014, Quist-Jensen et al 2015, Woltersdorf et al 2015). However, implications from WWTP effluent reuse in agriculture were not fully examined in the context of GHG emissions from such agriculture or crop pathogen quality.

An integrated case study of a city’s GHG emissions reductions from wastewater reuse in agriculture, and potential health benefits from WWTP effluent reuse in agriculture, are the focus of this paper. The objective of this study is to conduct a first field exploration in India to evaluate water–energy–health impacts at the nexus of urban agriculture and wastewater systems, and to reveal potentials and key constraints. A major contribution is that the field methodology must integrate multiple methods for each of the sub-systems at one site: WWTP LCA, surface water GHG emission estimations, a field study with different irrigation water scenarios, an agricultural system GHG emission model, and quantification of the microbiological quality of the harvested crop. The focus of the study is not on recovery of resources from wastewater, but on comparing the case of untreated sewage (partly reused in agriculture and the remainder released to the river) versus treated WWTP effluent (partly reused in agriculture and the remainder released to the river) in terms of water-energy-health impacts of urban agriculture. As reutilization of treated wastewater in urban agriculture is conceptually cited (Hanjra et al 2015, Makoni et al 2016) as a strategic opportunity at the FEW-health nexus, this paper compares expectations with field observations.

2. Methodology

2.1. Overview of field study

The field method quantifies the multiple impacts of implementing wastewater treatment with subsequent water reuse in urban agriculture in a case study of Hyderabad, India, to assess the FEW-health nexus. Small urban spinach farms were irrigated with three different qualities of water in this area and compared: untreated-diluted wastewater in a surface stream, WWTP effluent, and groundwater.

The parameters measured were: food production in the field, water used for irrigation, energy used in WWTP, and water quality. Based on these data the following impacts were modeled, energy use and GHG emissions in two cases including carbon dioxide (CO₂), CH₄, and N₂O, and crop quality in urban wastewater agriculture. Details of these are provided in the online supplementary information. Two phases of work were executed to assess these impacts:

1. An LCA was conducted to address the full system energy use and GHG emissions per liter for the combination of wastewater treatment and reuse in agriculture. Most studies end the LCA at the gate of the WWTP, i.e. when treated effluent is generated. This paper includes modeling of the conversion to GHG emissions in urban agriculture versus stream release.

2. An urban farming field study was conducted utilizing the three types of water to determine impacts at three farm plots (12 m² in size).

2.1.1. Site description

Hyderabad, India: Because many location-specific factors affect these impacts, a comprehensive case study approach was necessary. Hyderabad, India was chosen where a centralized WWTP (Nallacheruvu—N-WWTP, one of four WWTPs in Hyderabad) was newly implemented (2009) and located in close proximity to urban agriculture areas. Adjacent to the N-WWTP, farmers grow crops such as spinach, coriander, mint, chilies, papaya, amaranth, fenugreek, fennel, and others (figure 1).

WWTP Parameters: Like many WWTPs in India, N-WWTP uses upflow anaerobic sludge blanket (UASB) technology followed by oxidation and polishing ponds for secondary treatment. Some WWTPs in India use aerobic treatment processes like activated sludge (Miller et al 2013), which are thought to use more energy (USEPA and NREL 1995) and emit fewer GHGs (Heffernan et al 2012) than anaerobic treatment processes; however the differences in the effectiveness of these treatments in India are not well-quantified and are beyond the scope of this single case study. In this paper, the additional impacts of using treated wastewater in urban agriculture and/or releasing it to a stream are evaluated yielding an LCA of the combination of wastewater treatment and reuse in agriculture; biosolids are not included because they remained on-site at the time of the field study. The impacts of two core scenarios were evaluated:

- Uncontrolled release of wastewater to the riverine system without treatment at N-WWTP (untreated surface water scenario), and
Treatment at N-WWTP with partial reuse in urban agriculture with the remainder flowing into the riverine system downstream (treatment plus reuse scenario).

Field Study of Three Farm Plots: The urban farming field study included three farm plots, irrigated with treated wastewater, untreated surface water near the WWTP, and groundwater (figure 2). Spinach was grown in all three plots during the dry season (March–May 2010), when wastewater was the least diluted with stormwater. The plots were co-located with their water source and their soils had similar physical and chemical characteristics (Miller 2011). At the same time, the plots were hydrologically distinct in that irrigation water from one did not flow to the other. For example, the groundwater plot was far upstream of the WWTP effluent plot and the untreated water plot. The plot irrigated with WWTP treated effluent was at a higher elevation on one bank of the stream while the untreated plot was on the opposite bank where untreated surface water drained into the stream (figure 2). An experienced local farmer was recruited to farm the plots per his normal practice which included using furrows and small dams to divert irrigation water via gravity flows. The researchers instructed the farmer not to use any fertilizer in order to isolate water quality as the only major difference between the three farm plots. A researcher visited the farmer at least twice a week during irrigation events to collect water samples, crop samples, and to observe farmer practices. See schedule over one growing...
season in online supplementary table S1 available at stacks.iop.org/ERL/12/075005/mmedia.

The indicator microorganisms of interest in soil, water, and on the crop were *Escherichia coli* (*E. coli*; a coliform indicator) and nematode ova or eggs (roundworm *Ascaris lumbricoides* (*Ascaris*); and hookworm: no distinction was made between Old World, *Ancylostoma duodenale*, and New World *Necator americanus* hookworm). *E. coli* and nematode eggs are commonly used as indicators of wastewater contamination and associated health risks (Cifuentes 1998, An et al 2007, Mara et al 2007, Ensink et al 2008). Parameters, such as macronutrients, organics, microorganisms, and physical characteristics, were measured in the irrigation water, soil, soil water, and vegetable matter for each plot, and used in calculations and comparisons across plots; tests were carried out primarily at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) labs (methods detailed in table S1).

2.2 Method development

2.2.1. Assessment of GHG emissions from untreated wastewater

Uncontrolled release of untreated wastewater into nearby streams can result in release of N₂O and CH₄ (IPCC 2006), and anoxic stream conditions will increase CH₄ emissions. Methane-related GHG emissions from wastewater are estimated using IPCC methods as the product of the maximum CH₄ producing capacity for domestic wastewater (0.25 kgCH₄ kg⁻¹ COD) and a methane correction factor that is applied to represent the oxic (correction factor = 0) or anoxic status (correction factor = 0.2) of the receiving water body (IPCC 2006). At the time of this case study, despite four operating WWTPs in Hyderabad, only 40% of the city’s wastewater was collected and treated. The remaining untreated wastewater enters the Musi River, which flows through the center of Hyderabad. Average dissolved oxygen levels of 0.9 (range 0.2–3.9) mg l⁻¹ were measured in the Musi River by N-WWTP operators. Because of these low oxygen levels, a methane correction factor suited for anoxic conditions of 0.2 kgCH₄ kg⁻¹ COD, was used (IPCC 2006); this results in an emission factor of 0.05 (range 0–0.05) kgCH₄ kg⁻¹ COD discharged (see equation 1).

\[
\frac{\text{GHG}_{\text{CH}_4}}{\text{L}_{\text{Water}}} = C_{\text{COD}} \times (B_0 \times \text{MCF}) \times \text{GWF}_{\text{CH}_4}
\]  

(1)

where: GHG_{CH₄}/L_{Water} = greenhouse gas emissions attributed to methane per liter of water; C_{COD} = concentration of COD in water (mg l⁻¹); B₀ = maximum CH₄ producing capacity (mgCH₄/mg COD); MCF = methane correction factor for rivers, lakes, and streams.

N₂O emissions from rivers was based on a meta-analysis synthesizing the results from several stream N₂O field studies (Beaulieu et al 2011), which estimated that 0.0075 (range 0.001–0.05) kgN₂O/kg⁻¹ dissolved inorganic nitrogen discharged to rivers is converted via denitrification and nitrification. This meta-analysis estimation was about 50% higher, on average, than IPCC estimates (IPCC 2006), but is within the same range. A more detailed characterization of N₂O emissions (Ahn et al 2010) through on-site measurement is beyond the scope of this study, as it requires high access to the plant, and highly sophisticated N₂O measurements not readily available in local water quality labs. Both CH₄ and N₂O emissions were multiplied by the respective global warming potential (GWP) to yield GHG emissions from untreated wastewater discharges (see equation 2).

\[
\frac{\text{GHG}_{\text{N}_2\text{O}}}{\text{L}_{\text{Water}}} = C_{\text{DIN}} \times \text{EF}_{\text{N}_2\text{O}/\text{DIN}} \times \text{GWP}_{\text{N}_2\text{O}}
\]

(2)

where: GHG_{N₂O}/L_{Water} = greenhouse gas emissions attributed to nitrous oxide per liter water; C_{DIN} = concentration of dissolved inorganic nitrogen (DIN) in water (mg l⁻¹); EF_{N₂O/DIN} = emission factor (mgN₂O/mgDIN).

The COD and DIN concentrations in wastewater are variable. COD was measured by N-WWTP operators weekly for the year previous to this study. Because nutrients were not included in the weekly water quality measurements, DIN and other parameters were measured throughout the study at each irrigation event by the researchers. This field study was carried out in the height of the dry season, so stormwater did not dilute the irrigation waters.

2.2.2. Estimating GHG emissions from wastewater reuse for urban agriculture

The DAYCENT model, developed by the Natural Resource Ecology Laboratory at Colorado State University, is well-documented and widely used to estimate GHG emissions from cropped fields, usually major crops such as corn, soybean, wheat, alfalfa, and cotton in the United States (Del Grosso et al 2005, Iarecki et al 2007, Del Grosso et al 2009, US EPA 2011). This paper presents the first application of DAYCENT for wastewater agriculture, for vegetables, and for India.

The DAYCENT model is dependent on numerous input parameters such as 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. Therefore, the model is not linear and must be run to determine apparent emission factors.

In the DAYCENT model, the first growing cycle (about 4.5 weeks) was modeled after actual field parameters that were measured in the farm plots. For the rest of the year, irrigation and nitrogen inputs were
modeled to be repeated based on these measured farm parameters, and monthly variation in India’s riverine nitrogen (Green et al 2004, Bakkes et al 2008). Ten growing cycles (for spinach) were modeled per year, with each cycle at approximately one month and excluding two monsoon months, as agriculture is minimal at that time.

N$_2$O is the only GHG produced from agriculture, because the aerobic environment of agriculture does not facilitate biochemical oxygen demand (BOD) conversion to CH$_4$, and these are the processes modeled in the DAYCENT model. The N$_2$O and CH$_4$ fluxes could not be verified analytically due to the complexity of the methods; instead net primary productivity (NPP), or crop yield, determined by the DAYCENT model, was compared with that observed for the first crop cycle. When DAYCENT-modeled NPP values are similar to the observed values (table 1), it indicates that the net carbon uptake by plants is modeled correctly. DAYCENT practitioners typically use such agreement to indicate that the modeled agricultural system overall is satisfactorily representing how water inputs and other contributing factors are interacting (Lee et al 2012, Chang et al 2013, Necpalová et al 2015).

The land available for urban agriculture near N-WWTP was limited by terrain. While aerial photographs showed as much as 562 000 m$^2$ of open land around the N-WWTP effluent channel (from its exit from the N-WWTP boundary to its eventual outfall to the Musi river), the actual land under farming that was readily gravity-fed from the N-WWTP effluent channel was estimated to be only 1% (approximately 5500 m$^2$) (figure S1). This readily irrigable farmland area was modeled to be cropped with spinach, as in the farm plots, to conduct the LCA of the combination of wastewater treatment and reuse in agriculture. See the online supplementary information for assumptions and calculations made to estimate water use and GHGs attributed to avoided fertilizer use.

### 3. Results and discussion

**System-wide GHG emissions:** The modeling conducted in this paper, using field measured data on WWTP operations energy and on water quality measurements of treated and untreated water at the N-WWTP urban agriculture site, showed the following results for various scenarios in figure 3. On average, system-wide GHG emissions from the WWTP treatment case alone are 32% less than that from untreated release of wastewater into streams; much of this reduction is due to the reduction in CH$_4$ and N$_2$O due to 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 reduces overall GHG emissions because significant CH$_4$ and N$_2$O is generated from untreated wastewater.

The nutrient and organic matter content of the three irrigation waters differed consistently, and as expected, throughout the study. For example, average total nitrogen measured was at 3, 37, and 48 mg l$^{-1}$ for groundwater, treated effluent, and untreated surface water, respectively. Nitrogen levels are relatively high in the treated effluent because nitrogen is not one of the primary treatment targets of the WWTP; the treatment is focused on meeting the Indian disposal standards of BOD$_3$ below 30 mg l$^{-1}$ and fecal coliforms below 10 000 MPN/100 ml, among other parameters (Miller-Robbie et al 2013). These additions
provided nutrients to crops, with the treated effluent and untreated surface water plots producing the highest crop yields. As expected, the nutrient and organic matter levels in the irrigation water translated into crop productivity and the groundwater plot had lowest NPP (table 1(a)). The addition of nutrients via irrigation water also affected N2O fluxes from agriculture. The NPP results modeled by DAYCENT and that observed in the plots were similar (table 1(a)), confirming that the DAYCENT model effectively modeled the biophysical processes occurring at these sites. These results in conjunction with other field studies testing the DAYCENT model (Del Grosso et al 2005, Jarecki et al 2007) suggest that it may be suitable to model N2O as well as NPP in wastewater-irrigated agriculture. The total N2O flux for the untreated plot was lower than that of the treated plot (table 1(a)). The model suggests that the treated effluent plot has higher N2O fluxes due to the ratio of nitrate (NO3) to ammonia (NH3) in the irrigation water (2:1 NO3 to NH3 for the treated effluent plot, 1:2 for the untreated surface water plot, and 1:1 for the groundwater plot). Based on the treated effluent plot, the DAYCENT model yielded an apparent emission factor of 0.00070 gN2O-N flux/g DIN applied to agriculture. This is about ten-fold less than the river emission factor of 0.0075 gN2O-N/g DIN (explained earlier) (Beaulieu et al 2011). Thus, in general, the DAYCENT model shows that urban agriculture would be effective in removing carbon and reducing the production of CH4 and N2O (table 1(b)). This is an important and counter-intuitive result which indicates that both water and GHG benefits can arise due to applying treated wastewater to urban agriculture.

However, the potential for nutrient cycling is found to be very low. While nutrients in the water suffice for the crops, the limiting factor is the land; 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 is relatively small (reduction in GHG by less than 1% in this field study) (figure 3). Farmers indicated that gravity-driven irrigation with surface water was the methodology used by them. In the event that 100% of N-WWTP effluent could be reused in agriculture, the theoretical 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 some practical constraints.

**Crop Quality:** Although the water quality improved by several orders of magnitude due to treatment, crop quality did not improve significantly. As seen in the crop *E. coli* results (figure 4), 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; the groundwater crop had statistically significant less *E. coli* content than the crop irrigated with other waters (*p* < 0.1 for groundwater and treated; *p* < 0.01 for treated and untreated). However, the *E. coli* content on the spinach at harvest were not as different as in 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 to simulate real-world conditions. 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 (figure S3).

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) gunny-sack to prevent wilting. As a result of these observations during the study midpoint, the researcher collected samples alongside the farmer at final harvest. The researcher-harvesting included use of hand sanitizer between samples and care was taken to not touch anything except the crop and sterile sample bag.

The researcher-harvest yielded crop samples that were at least one order of magnitude less for *E. coli* content than the farmer-harvested samples (statistically significant at *p* < 0.1) (figure 4(b)). 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 (figure 4(b)). 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 measured 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* by several orders of magnitude (figure 4), but have a significantly smaller effect for crops produced from urban agriculture.

From table 2, it is evident that the use of groundwater for urban agriculture was least beneficial for food production and groundwater use, and had a minimal impact on energy use/GHG emissions and

### Table 2. Measured data from the farm field study.

|                      | Energy Use/GHG Emissions | Food Produced | Pathogen Indicator on Crop | Groundwater Used |
|----------------------|--------------------------|---------------|----------------------------|------------------|
|                      | mCO₂ e yr⁻¹ | g m⁻² yr⁻¹ | CFU/100 g | l m⁻³ yr⁻¹ |
| Groundwater          | 5 E−4    | 2118     | 47 733 | 355 |
| Treated Effluent     | 3686    | 19 555   | 135 940 | —  |
| Untreated Surface Water | 5449   | 22 968   | 325 200 | —  |

**Figure 4.** (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.
the lowest spinach pathogen indicator (E. coli) content. Use of treated effluent and untreated surface water for urban agriculture were more similar; they yielded higher food productivities, energy use/GHG emissions, and crop E. coli content, while avoiding groundwater extraction. Despite the added embodied energy and GHG emissions in WWTP infrastructure, the treated effluent case does emit fewer GHGs overall than the untreated surface water case due to reduced COD and DIN in the effluent water when released to streams.

4. Conclusions

This is a first multi-system study to quantify the impacts for a combination of wastewater treatment and reuse in urban agriculture by utilizing WWTP LCA, surface water GHG emission estimations, a field study with different irrigation water scenarios, an agricultural system GHG emission model, and evaluation of the microbiological quality of the harvested crop. Wastewater treatment does mitigate direct CH₄ and N₂O emissions (an average of 68%), and yield a 99% E. coli reduction and 81% BOD reduction, thereby meeting the wastewater effluent quality criteria in India. Further, the addition of WWTP infrastructure has a strong role in reducing overall GHG emissions substantially (average of 32%) when compared to untreated wastewater release, even after incorporating the embodied energy to build the WWTP infrastructure. Thus, implementing WWTP is a good for the environment both from a water quality and energy/GHG perspective.

When the presumed benefits to urban agriculture are evaluated, we find that although there is good potential for nutrient recycling and GHG reduction with wastewater reuse in urban agriculture, the modeling of farm plots show that high water flow rates and land constraints limit nutrient recycling. As described earlier, nutrient reuse in readily cultivable, gravity-fed urban farmland was relatively small in terms of the proportion of nutrients recycled versus the nutrients discharged to the stream. Consequently, WWTP-associated GHG emissions with and without urban agriculture are not much different due to physical typography. Dried biosolids, in contrast, could be a more successful avenue for nutrient recovery as it can be distributed easily. However, a market for the biosolids must first be established.

In terms of the expected health benefits of using treated effluent in agriculture, our studies showed an unexpected result and we found that farmer behavior and prior history of contamination to be important considerations in the FEW-health nexus. This points to a need for further field research of the urban FEW-health nexus in developing cities. Additionally, a limitation of this study is that it focused on a single crop and growing cycle; a longer study in different seasons could capture differences between the dry and wet seasons.

The study has a certain focus and limited scope on the case of direct wastewater reuse in urban agriculture in a developing city that has a mix of sewered and unsewered wastewater systems, exploring environmental benefits and presumed health benefits to urban agriculture. The study is among the first to quantitatively assess the linkages among water-wastewater reuse, energy, and urban agriculture in a developing world context. This case study reveals key leverage points and constraints, and develops a method for evaluating impacts at the nexus of water-energy-wastewater and food systems. These are significant findings needed to operationalize resource efficiency and health benefits at the food–energy–wastewater nexus in rapidly-developing cities.

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