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Can a Rice Field Ingest Untreated Municipal Waste Water Beneficially in Bangladesh?

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Abstract

Safe usages of untreated municipal waste water (WW) containing both plant nutrients and contaminants can reduce cost and clean the environment. This study investigated rice (Oryza sativa L.) traits and soil health under irrigation with municipal WW in combination with five fertilizer doses in two field experiments. The fertilizer treatments comprised no application of fertilizer (F_0, control) and application of 25%, 50%, 75% and 100% of recommended standard fertilizer dose (F_1, F_2, F_3, F_4, respectively) that were distributed in a Randomized Complete Block Design (RCBD) with three replications. Waste water contained N, P and K @ 17.5, 3.7 and 10.3 mg L^{-1}, respectively that correspondingly contributed 82%, 137% and 124% of recommended N, P and K for rice production in experiment 1 (Exp 1) and 96%, 163% and 148% in experiment 2 (Exp 2). Tiller density (tiller no. per unit area), plant height, panicle length and leaf area index (LAI) of rice improved significantly ($p \leq 0.05$) under F_4 compared to F_0 in most cases. These rice traits were however statistically similar under F_0, F_1 and F_2 fertility levels. F_3 produced significantly improved filled grains, grain dry matter and 1000-grain weight compared to the other fertilizer doses. However, all fertilizer treatments produced statistically similar grain yield, straw yield, biomass yield, harvest index and water productivity. Thus, WW alone supplied most of the nutrients required for rice production; additional fertilizers in excess of 25% of the recommended dose had no beneficial use, revealing that F_1 was the optimum fertilizer dose for maximizing rice production under WW irrigation. Irrigation with municipal WW and the applied fertilizers raised soil EC and pH, and augmented OC, N, P, K, S, Na, Ca and Mg contents of the soil. However, the variations in these soil quality parameters are significant for pH, K and Ca only. The information reported herein reveals good potential of rice fields to ingest untreated municipal waste water beneficially apart from hygienic aspects, which need to be investigated.

Keywords

Rice cultivation, Water reuse, Fertilizer saving, Soil health

Introduction

Approximately 70 percent of freshwater withdrawals are used for agriculture globally; some countries in the South Asia, Africa and Latin America use more than 90 percent of water withdrawals for agriculture, with the highest (96%) in Sudan [1]. Approximately 50% of worldwide irrigation water is used by rice cultivation [2]. In developing countries like Bangladesh, fast-growing urban populations are demanding more fresh water and food, while generating larger volumes of domestic waste water (WW). This WW is increasing over time although other water sources are decreasing both in quantity and quality. Generally, reusing waste water in irrigating crops is viewed as a harmful practice since it may introduce pollutants to the environment, spread waterborne diseases, generate odor problems and result in dislike to the crops. However, in the face of fresh water scarcity, usage of WW for irrigating crops is often viewed as one of the approaches to maximize the existing water resources. Farming communities in many regions in the world are increasingly utilizing municipal WW in agriculture [3,4] because of water scarcity, nutrient value of WW and environmental protection [5-7]. Irrigation with WW has now become a common practice in many countries and is considered as an alternative water resource in a changing agricultural environment [8,9]. This water is free of cost and always available, even during droughts, and being rich in nutrients.

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In spite of many advantages, inappropriate use of WW may adversely affect crop production and soil health since it may contain high concentrations of suspended and dissolved solids, including heavy metals and pathogens. Some of the risk factors are short term and vary in severity (e.g., microbial pathogens), whereas others have longer-term impacts that increase with the continued use of WW (e.g., heavy metals accumulation in soil). Results reported in the literature on the impacts of WW on soil are often contradictory. For example, reduced [10,11], raised [12] and also an inconsistent [13] pH of surface soil [14] was reported due to the impacts of WW. Some systematic observations were also reported, such as augmented salinity [12-14], organic carbon, nitrogen, phosphorus, potassium, and exchangeable Na, K, Ca and Mg [13-16] due to irrigation with untreated WW.

Irrigation of rice crop using treated or untreated WW was practiced and examined in several countries to investigate benefits [17-19] or drawbacks of the practices [20,21]. This irrigation practice is also common in several Asian countries [9,22,23]. However, in some countries like Bangladesh, although few studies have been done on irrigation of upland crops with untreated [24-26] or treated WW there have been only a few reports on WW reuse for rice cultivation [27].

Due to lack of a comprehensive WW management policy, vast majority of the WW (both municipal and industrial sources) in Bangladesh joins the natural water bodies causing their severe pollution. And, until now, only a few farmers at some peri-urban areas informally irrigate their crops with municipal WW [28]. Hence, there have been hardly any reports of practical WW reuse for rice production in Bangladesh. However, success in using municipal WW for crop production will largely depend on adopting appropriate strategies aimed at optimizing crop yields, maintaining soil productivity and safeguarding the environment. The objectives of this study were therefore (i) To investigate fertilizer contribution of untreated municipal WW irrigation on rice traits, and (ii) To evaluate the impacts of this irrigation practice on soil health. This information is required to clarify the potential effects and to develop the agricultural reuse technology for use with municipal WW before large-scale use of WW for rice production. However, the hygienic aspects arising from the possible biological pathogens must also be known beforehand.

Materials and Methods

Historical data of two rice experiments done during January-May of 2011 under irrigation with untreated municipal WW at farmers' fields in peri-urban area of Mymensingh (24.75 °N latitude and 90.50 °E longitude) in Bangladesh were analyzed. A 20-cm silty clay layer underlain by 40-cm clay layer in Exp 1 and a 60-cm clay layer in Exp 2 in the fields belong to the old Brahmaputra floodplain [29]. The fields within a medium low-lying area were suitable for single crop cultivation. Farmers used to cultivate only rice during January to May (almost rainless dry period) under irrigation with municipal WW in addition to standard fertilizer doses recommended for rice cultivation for the area. Farmers possessed hardly any knowledge of fertility value of the WW. Every year after harvesting rice in May, the fields received monsoon rainfall of about 200 cm and remained submerged in seasonal flood water during June through September. The climate in the area is sub-tropical with an average annual rainfall of 242 cm, which is concentrated over May to September. The summer is hot and humid, and the winter (November-February) is moderate with occasional small amount of rainfall in some years. The daily maximum temperature during April-May varies from 28.8 °C to 35.9 °C. January is the coldest month with a daily minimum temperature of 9.6 °C to 12.9 °C. The weather conditions were favorable for rice cultivation during the period of experiment with a total rainfall of 12.6 cm.

Experimental design

Five fertilizer doses were tested for rice cultivation under irrigation with untreated municipal WW at two sites, which were over 1 km apart. The treatments were F_0: no application of fertilizer (control) and F_1-F_4: Application of 25%, 50%, 75% and 100% of the recommended standard fertilizer dose, respectively. Both experiments were laid out in a Randomized Complete Block Design (RCBD) with three replications. The fields were plowed adequately with a power tiller. The plot size was 3 m × 4 m with a buffer space both between the adjacent plots and adjacent blocks/replicates of 1 m. A 10-cm high ridge was constructed around each plot to retain irrigation water. Recommended fertilizer dose for rice for the study area was 260 kg N, 75 kg P, 82 kg K, 60 kg S and 12 kg Zn ha^{-1} in the form of urea, triple super phosphate (TSP), muriate

Table 1: Applied fertilizer doses (urea; triple super phosphate, TSP; muriate of potash, MP; gypsum, and zinc sulphate, $ZnSO_4$) for rice cultivated under irrigation with untreated municipal waste water at Mymensingh in Bangladesh.

Fertilizer	Standard doses	Applied fertilizer doses				
		F_0 (kg ha^{-1})	F_1:25% (kg ha^{-1})	F_2:50% (kg ha^{-1})	F_3:75% (kg ha^{-1})	F_4:100% (kg ha^{-1})
Urea	260	0	65.0	130.0	195.0	260.0
TSP	75	0	18.8	37.5	56.3	75.0
MP	82	0	20.5	41.0	61.5	82.0
Gypsum	60	0	15.0	30.0	45.0	60.0
$ZnSO_4$	12	12.0	12.0	12.0	12.0	12.0

Note: The applied doses of urea, TSP, MP and gypsum were - F_0: No application of fertilizer (control) and F_1-F_4: Application of 25%, 50%, 75% and 100% of recommended fertilizer dose, respectively.

of potash (MP), gypsum and zinc sulphate, respectively [29]. Urea was applied in three equal splits: at 10, 30 and 60 days after transplanting (DAT). The other fertilizers were applied to the plots as a basal dose. The quantity of each fertilizer for a plot was determined based on the treatments (Table 1). Rice seedlings of age 45 days (variety BRRI dhan29, developed by Bangladesh Rice Research Institute) were transplanted manually in the plots of both experiments on 4 January 2011. Three to four seedlings per heel were transplanted, keeping both heal-to-heal and line-to-line spacing at 20 cm; so, there were 36 heels per square meter. One herbicide and an insecticide were applied at 5 DAT to control weed and cutworms, respectively. At the mid-growth stages, weeds were effectively controlled by uprooting manually.

Waste water quality and irrigation application

Three samples of municipal WW were collected once a month during the experiments at the point of the main sewage system of Mymensingh town from where WW was diverted for irrigating experimental rice. WW samplings were done following standard procedures as detailed in Mojid et al. [24]. The WW was mostly generated from water usages at households, restaurants, educational institutes, offices and hospitals; there was no notable industrial source of WW. The major chemical properties of the water samples were measured, mostly, with a DR/890 Colorimeter (Hach Co., USA). The concentrations of B, Fe, K, NO_3-N, PO_4-P, Na, Pb, Cu, Zn and Cd in the WW were below their threshold values set by WHO [30] for safe use in agriculture; only Mn exceeded the allowable limit. The electrical conductivity (EC) of WW (0.55-1.05 dS m^{-1}), which depends on sodium adsorption ratio (SAR), often exceeded the WHO-recommended threshold values. The WW was slightly alkaline with pH of 7.33. During irrigation period, properties of the WW remained practically unchanged. Due to dilution with rainfall and flood water during monsoon (June-September), the concentration of various chemical constituents in WW (not measured in this study) would be much smaller than those during the dry season. Details of WW quality parameters of Mymensingh sewage were reported in Mojid et al., Biswas et al. and Biswas et al. [26,28,31].

WW was pumped to the experimental rice fields and irrigation was applied in check basin. Irrigation started 2 days before transplanting of seedlings and ended 15 days before harvesting the matured rice. A standing water level of 2-8 cm above the soil surface was maintained except for a period of 2-3 days preceding top-dressing of urea during which no standing water was kept in the field. Total amount of irrigation during the crop period was 55.88 cm for Exp 1 and 66.04 cm for Exp 2. Including 12.6 cm rainfall, the total water used by the crop of the corresponding experiment was 68.48 and 78.64 cm. These water usages were significantly lower than the reported average water requirement of rice (120 cm) in Bangladesh. The reasons were the low percolation loss of water through the clay soil in the fields and low evaporative demand of atmosphere (≈ 2.4 mm d^{-1}) at the location of the experiments compared to the average evaporative demand of the country (3.1 mm d^{-1}).

Data recording

The rice plots were monitored intensively and tiller number, leaf area index (LAI) and biomass/above-ground dry matter (ADM) were measured at different growth stages. These attributes of rice for the plots in each replicate were measured by collecting samples of 5 randomly selected plants (main stems). Rice was harvested manually by using sickles on 16 May 2011 from a sampling area of one square meter at the middle of each plot. The harvested rice plants were transported immediately after harvesting to a laboratory for data recording. The plant height, tiller density (number of tillers per square meter), panicle length, and number filled and unfilled grains per panicle were counted/ measured. Grain and straw dry matters, and weight of 1000 grains were determined. The grain yield was calculated from weight of the harvested rice of one square meter after sun-dried at 14% moisture content.

Soil sampling and analysis

Soil samples were collected twice: one before land preparation for transplanting rice seedlings and the other at harvest. The samples were collected manually from each plot with a soil auger from 0-60 cm soil profile with a depth increment of 20 cm from soil surface. The samples were air-dried in the laboratory and sieved for chemical analysis by using standard laboratory methods. EC, pH, organic carbon (C), total Nitrogen (N), Phosphorus (P), Potassium (K), Sulphur (S), Sodium (Na), Calcium (Ca) and Magnesium (Mg) contents of the samples were determined in order to assess the effects of WW irrigation on soil properties. Details of analyzing the soil samples were reported in Biswas, et al. [26].

Statistical analysis

Analysis of variance (ANOVA) was done by using Statistix 10 software package of Analytical Software [32]. Comparisons of means of the rice traits and soil quality parameters among the five fertilizer treatments, three depths for soil quality parameters, and two experiments were done at 5% level of significance ($p \le 0.05$) by implementing Tukey's Honest Significant Difference (HSD) test.

Results

Fertilizer contribution of municipal WW

WW contained N, P and K @17.5, 3.7 and 10.3 mg L^{-1}, respectively. The amount of applied irrigation during the

Table 2: Nitrogen (N), phosphorus (P) and potassium (K) nutrients and their equivalent fertilizers (urea, TSP and MP) input to two rice fields from untreated municipal waste water of Mymensingh in Bangladesh.

Experiment	Nutrients		
	N (mg L^{-1})	P (mg L^{-1})	K (mg L^{-1})
1	98	21	58
2	116	24	68
	Equivalent fertilizers		
	Urea(kg ha^{-1})	TSP(kg ha^{-1})	MP(kg ha^{-1})
1	212	103	102
2	250	122	121

crop period was 55.88 cm in Exp 1 and 66.04 cm in Exp 2. Table 2 records the quantity of N, P and K along with their equivalent fertilizers (urea, TSP and MP) contributed by the applied WW to the rice crop. The quantities of N, P and K were estimated from their average concentrations in the WW and the quantity of applied irrigation. WW contributed 82%, 137% and 124% of the recommended N, P and K for rice production, respectively in Exp 1, and 96%, 163% and 148% of the recommended N, P and K, respectively in Exp 2. Note that the WW-contributed fertilizer was distributed over the growing season of rice with the progress of irrigation applications.

Growth attributes

Tiller density, plant height, panicle length and LAI of rice increased with the increasing doses of fertilizers except for tiller density and panicle length under F_2 (application of 50% of recommended fertilizer dose (Table 3). These rice traits were significantly ($p \le 0.05$) larger under recommended fertilizer dose (F_4) compared to non-fertilized (control) treatment (F_0) except for panicle length and tiller density at 65 DAT. Application of 75% of recommended fertilizer dose (F_3) produced significantly improved plant height, tiller density at 45 DAT and LAI at 77 DAT. Strikingly, all the growth traits of rice were statistically similar under F_0, F_1 and F_2 fertility levels. All the

Table 3: Average tiller density (T45, T55, T65 and T131), plant height, panicle length, and leaf area index (LAI40, LAI55 and LAI77) under municipal waste water irrigation with five fertility levels (F_0, F_1, F_2, F_3 and F_4) at two locations in Mymensingh peri-urban area in Bangladesh.

Treatment	T45 (m^{-l})	T55 (m^{-l})	T65 (m^{-l})	T131 (m^{-l})	Plant height (cm)	Panicle length (cm)	LAI40 (-)	LAI55 (-)	LAI77 (-)
Fertilizer									
F_0	103b	277b	418a	390b	64.5c	23.2ab	0.31b	2.78b	5.63b
F_1	114ab	311ab	480a	451ab	66.1c	23.4ab	0.31b	2.87b	5.79b
F_2	111ab	301ab	431a	412ab	67.0bc	23.1b	0.33b	3.26ab	6.72ab
F_3	124a	335ab	468a	461ab	71.8ab	23.4ab	0.37ab	3.44ab	7.46a
F_4	124a	361a	526a	487a	72.1a	24.5a	0.51a	3.71a	7.54a
Experiment									
Exp 1	139a	357a	444a	409b	65.1b	22.2b	0.21b	0.57b	5.60b
Exp 2	91b	277b	485a	472a	71.4a	24.9a	0.52a	5.85a	7.66a

Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \le 0.05$).

Note: The five fertility levels were: F_0: No fertilizer, F_1: 25% of recommended fertilizer dose, F_2: 50% of recommended fertilizer dose, F_3: 75% of recommended fertilizer dose, and F_4: Recommended fertilizer dose. The tiller density was measured at 45, 55, 65 and 131 days after transplanting and the leaf area index at 40, 55 and 75 days after transplanting.

Table 4: Average above ground dry matter (ADM40, ADM55 and ADM77), filled and unfilled grains per ear, grain and straw dry matter, and 1000-grain weight under municipal waste water irrigation with five fertility levels (F_0, F_1, F_2, F_3 and F_4) at two locations in Mymensingh peri-urban area in Bangladesh.

Treatment	ADM40 ($t\ ha^{-1}$)	ADM55 ($t\ ha^{-1}$)	ADM77 ($t\ ha^{-1}$)	Filled grains (no./ear)	Unfilled grains (no./ear)	Grain dry matter ($kg\ m^{-2}$)	Straw dry matter ($kg\ m^{-2}$)	1000-grain weight (g)
Fertilizer								
F_0	0.31b	1.77b	4.56c	120a	37b	1.01a	0.71b	21.2a
F_1	0.37ab	2.55ab	6.26bc	113a	40b	1.03a	0.74b	20.6a
F_2	0.38ab	3.24a	7.88ab	118a	45b	1.01a	0.73b	21.1a
F_3	0.41ab	3.25a	7.82ab	123a	37b	1.19a	0.86ab	21.3a
F_4	0.48a	3.41a	8.45a	1260a	63a	1.26a	0.91a	20.6a
Experiment								
Exp 1	0.58b	3.88b	0.58b	102b	26b	0.90b	0.63b	20.8a
Exp 2	5.11a	10.11a	5.11a	1382a	63a	1.30a	0.95a	21.1a

Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \le 0.05$).

Note: The five fertility levels were: F_0: No fertilizer, F_1: 25% of recommended fertilizer dose, F_2: 50% of recommended fertilizer dose, F_3: 75% of recommended fertilizer dose, and F_4: Recommended fertilizer dose. The above ground dry matter was measured at 40, 55 and 77 days after transplanting.

rice traits except tiller density at 65 DAT were significantly greater in Exp 2 than in Exp1 due to more fertile soil in Exp 2 than in Exp 1 (explained latter).

Yield attributes

The applied fertilizer doses did not cause variation in the number of filled grains, grain dry matter and 1000-grain weight (Table 4). The fertility levels F_0, F_1, F_2 and F_3 exerted invariant effect in producing the growth traits of rice except ADMs at 55 DAT and 77 DAT. F_3 produced significantly greater growth traits of rice compared to the other fertilizer doses in most cases. Although both experiments were done under same management practices, Exp 2, due to more fertile soil, provided significantly improved yield attributes of rice compared to Exp 1 except 1000-grain weight.

Yield and water productivity

Table 5 provides an attention-grabbing observation on yield, harvest index and water productivity of rice under the five fertilizer treatments, which produced statistically similar grain yield, straw yield, biomass yield, harvest index and water productivity, both for grain (WP_g) and biomass (WP_b) production. Only F_1 (application of 25% of recommended fertilizer) exerted, to some extent, noticeable contribution on these attributes of rice. These results reveal that WW alone supplemented most of the fertilizers required for optimum production of rice and that additional fertilizer in excess of 25% of the recommended dose had no beneficial use to the crop. Although the harvest indices of rice under the five fertilizer doses were statistically indifferent, the full dose of fertilizer (F_4) produced a greater fraction of grain than straw compared to the other fertilizer doses. Similar to the growth and yield attributes, Exp 2 provided more improved yields and water productivity of rice than Exp 1.

Soil chemical properties

EC, pH, OC, N, P, K, S, Na, Ca and Mg contents of soils of the two experimental rice fields, both at pre-planting and harvest, are compared in Table 6 for the five fertilizer treatments, three depth profiles of soil (D1: 0-20, D2: 20-40 and D3: 40-60 cm) and two experiments. The values of pre-planting soil quality parameters were significantly ($p \leq 0.05$) greater in the rice field of Exp 2 than in Exp 1 except for EC, Na and Mg. All pre-planting soil quality parameters in both rice fields were significantly greater than those at harvest under the control (F_0) except for N and Mg in Exp 1, and N and Ca in Exp 2. Irrigation with municipal WW and the applied fertilizers augmented the soil quality parameters; however, their variations are significant for pH, K and Ca only (Table 6). The magnitude of the soil quality parameters decreased with increasing depth of soil except pH and K, which increased with the increase in depth. EC, pH, OC, N and P varied significantly among the three soil profiles, with D1 and D2 profiles providing statistically alike values. EC, K and Na contents of the soil were significantly greater and pH, N and Ca contents were significantly smaller in Exp 1 than in Exp 2.

Discussion

Contribution of fertilizers and WW to growth attributes

Five fertilizer doses, including one control, were imposed to the rice plots in two experiments with the same quantity of municipal WW irrigation to each fertilizer doses (55.88 cm in Exp 1 and 66.04 cm in Exp 2). The applied WW contributed 212 kg urea ha^{-1} in Exp 1 and 250 kg urea ha^{-1} in Exp 2 (Table 2) against the recommended dose of 260 kg ha^{-1}. It added 37% and 33% more P and K, respectively in Exp 1, and 63% and 56% more P and K, respectively in Exp 2 than the recommended doses of these nutrients (Table 2). Although the quality of municipal WW can vary among different regions of the world depending on living style of the communities, all municipal WWs contain substantial quantities of plant nutrients. For example, Jiménez-Cisneros [33] estimated 16-62 kg of N, 4-24 kg of P and 269 kg K per 1000 m^3 of municipal WW in Mexico. So, the WW, when used for irrigation,

Table 5: Grain yield, straw yield, biomass yield, harvest index, and water productivity for grain (WP_g) and biomass (WP_b) production under municipal waste water irrigation with five fertility levels (F_0, F_1, F_2, F_3 and F_4) at two locations in Mymensingh peri-urban area in Bangladesh.

Treatment	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Biomass yield (t ha^{-1})	Harvest index (-)	WP_g (kg m^{-3})	WP_b (kg m^{-3})
Fertilizer						
F_0	9.64a	10.70a	20.35a	0.49a	1.26a	2.65a
F_1	10.69a	11.37a	22.05a	0.51a	1.41a	2.88a
F_2	9.91a	9.53a	19.44a	0.52a	1.30a	2.54a
F_3	9.26a	9.12a	18.39a	0.51a	1.23a	2.42a
F_4	10.11a	9.48a	19.59a	0.53a	1.34a	2.57a
Experiment						
Exp 1	8.25b	6.90b	15.15b	0.55a	1.20b	2.21b
Exp 2	11.60a	13.18a	24.78a	0.47b	1.41a	3.01a

Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \leq 0.05$).

Note: The five fertility levels were: F_0: No fertilizer, F_1: 25% of recommended fertilizer dose, F_2: 50% of recommended fertilizer dose, F_3: 75% of recommended fertilizer dose, and F_4: Recommended fertilizer dose.

can supply significant amount of nutrients that can improve soil fertility, plant growth and crop yield with reduced application of costly fertilizers [34]. The rice plants in our experiments grew more vigorously in the plots with applied fertilizers (F_1-F_4) compared to the control plots (F_0). Most growth attributes of rice however remained statistically similar under the five fertility levels. The three major nutrients (N, P and K) supplemented by WW irrigation, accumulated in the soil and became available to the plants after mineralization that eventually enhanced the growth of rice plants. The observed statistically similar growth attributes thus revealed that the applied fertilizers did not contribute significantly ($p \leq 0.05$) in the growth process of rice. These results are also supported by the observations of Phung et al. [35], who obtained high yields of protein-rich forage rice with continuous sub-irrigation with treated WW without the need for synthetic fertilizers. The huge fertilizer content of municipal WW can therefore make it a cash incentive to many farmers, who usually apply reduced quantity of inorganic fertilizers when irrigating with fresh water due to high cost, with a consequent low harvested yield. Papadopoulos et al. [36] reported obtaining up to 11.9% reduced production cost of rice by irrigating with municipal WW compared to irrigation with fresh water. Alternate sources for nutrient fertilizers will always remain important for cost-effective sustainable agricultural practices, and WW can become an unconventional resource for this in providing food for many communities [6] globally, especially in many water-scarce developed countries. However, it is most likely that due to rapid urbanization, agricultural use of WW will increase, bringing about many issues of unplanned reuse [8].

Contribution of fertilizers and WW to yield attributes and yield

Like growth attributes, the yield attributes of rice improved, mostly insignificantly, with the increase in fertilizer doses. Various yield attributes contributed to produce grain and biomass yields of rice. The major nutrient contents (N, P and K) of WW mostly satisfied the crop's requirements and the additional application of inorganic fertilizers did not appreciably contribute producing the grain and biomass yields. The highest grain and straw yields, obtained with application of 25% of recommended fertilizer (F_1), revealed that this fertilizer dose is optimum for maximizing rice production under WW irrigation in a most cost-effective way. The increased grain yield obtained under F_1 was an outcome of the complex interactions of the improved yield-causative attributes of rice. Several investigators [19,27] at different regions also reported obtaining significantly higher yield of rice with WW irrigation compared to fresh water irrigation. For example, Yoon et al. [37] obtained up to 50% greater yield of rice with WW irrigation compared to fresh water irrigation, while Thu [38] obtained 10-15% higher yield with such irrigation practice. Farmers of the two experimental fields used to irrigate rice crop recurrently with municipal WW, which caused accumulation of nutrients in the soils, now requiring no or only minimal amount of additional fertilizers. So, the present practice of the farmers' WW irrigation combined with the recommended fertilizer doses contributed non-profitably to both grain and straw production. With nitrogen level exceeding its recommended dose for optimal yields, rice growth is stimulated together with some degree of yield loss and delayed-ripening [39]. Maintaining optimum fertility levels is crucially important to obtain desired yield of rice when irrigating with WW. Nyomora [19] could obtain four times higher yield of rice with WW irrigation compared to tap water irrigation without application of inorganic fertilizers, but 3.2 times less yield with WW irrigation in combination with N, P and K fertilizers compared to WW irrigation without N, P and K fertilizer application.

Impacts of fertilizers and WW on water productivity

Statistically similar water productivities for grain (WP_b) and biomass (WP_b) production under the five fertility levels (Table 5) revealed that WW supplied adequate nutrients to rice crop for its optimum production. The highest water productivities obtained with the application of 25% of the recommended fertilizer dose (F_1) reaffirmed that this fertilizer dose is optimum for rice production under irrigation with untreated municipal WW. The current farmers' practice of applying the recommended fertilizer dose (F_4) for rice cultivation under irrigation with WW is therefore a gross misuse of costly inorganic fertilizers. Farmers' very poor knowledge on fertilizer contribution of WW and lack of policy on WW irrigation are to blame for this undesired practice.

Impacts of WW on soil chemical properties

Municipal WW is rich in organic matters and contains substantial amount of macronutrients and micronutrients. So, the nutrient levels of soils irrigated with WW are likely to increase, the magnitude of which depends on the nutrient contents of WW. In farmers' practice, the quantity of applied irrigation (not measured in this study) was typically similar to that applied in our experiments since the farmers also maintain similar depths of standing water in their rice fields as in the experiments. So, after the monsoon season the soil quality parameters would decrease to their magnitudes obtained at the pre-planting state. Generally, 6-7 soil pH is considered suitable for adequate availability of nutrients in soils. But, due to irrigation with WW, soil pH increased beyond this range, in most cases significantly (Table 6). It however reduced to the suitable range at the end of monsoon season. Thus, pH of the WW-irrigated soils remained optimum for availability of nutrients to maintain soil fertility and crop productivity. The OM content of a soil, often considered an index of soil fertility, influences the physical, chemical and biological properties of the soil. OM of the experimental soils was 0.21-0.48% (organic-C of 0.12-0.28%), but WW irrigation augmented it to 0.34-2.72% (organic-C of 0.2-1.0%) with resulting improvement in soil fertility as well as soil structure by enhancing soil humidity and microbial activity [40]. Improvement in soil organic carbon is regarded as a sustainable strategy for enhancing soil resilience and reducing greenhouse gas emissions in rice cropping system [41]. Nitrogen content in a soil below 0.075%, and P, K and S contents below 12, 78 and 12 ppm, respectively are considered insufficient for crop production in

Table 6: Comparison of chemical properties of the rice field soils under municipal waste water irrigation with five fertility levels (F_0, F_1, F_2, F_3 and F_4) at three soil profiles (D_1, D_2 and D_3) along with pre-planting soil properties (F_i) at two locations in Mymensingh peri-urban area in Bangladesh.

Treatment	EC (dS m^{-1})	pH	OC (%)	N (%)	P (ppm)	K (ppm)	S (ppm)	Na (ppm)	Ca (ppm)	Mg (ppm)
Pre-planting soil properties										
Exp 1	0.14a	6.66b	0.12b	2.57a	0.30b	6.6b	0.3b	16.9a	3.0b	83a
Exp 2	0.10a	7.16a	0.28a	1.68b	3.70a	32.7a	4.5a	20.0a	419a	37a
F_i (avg)	0.12	6.91	0.20	2.13	2.00	19.7	2.4	18.0	211	60
Fertilizer										
F_0	0.19b	7.26bc	0.65b	0.88a	5.84b	46.3b	7.3b	95b	359d	40a
F_1	0.22b	7.49ab	1.03b	4.76a	8.07b	67.9ab	9.5b	172a	496bcd	33a
F_2	0.21b	7.18bc	1.04b	5.11a	8.55b	78.4a	10.9b	179a	637ab	50a
F_3	0.22b	7.99a	0.96b	4.74a	7.93b	70.6ab	11.5b	183a	752a	65a
F_4	0.22b	7.46b	1.03b	4.81a	8.80b	72.6ab	13.7b	171a	553bc	67a
Depth										
D_1	0.26a	7.18b	1.62a	5.64a	13.75a	68.5a	17.6a	168a	529a	60a
D_2	0.23ab	7.51a	0.89b	2.76ab	11.86ab	66.8a	15.6a	162a	575a	56a
D_3	0.21b	7.45ab	0.78b	1.86b	10.75b	71.4a	12.9a	162a	508a	51a
Experiment										
Exp 1	0.26a	7.25b	1.16a	0.12b	11.95a	76.7a	14.8a	180a	440b	54a
Exp 2	0.20b	7.51a	1.04a	6.72a	12.29a	61.1b	15.9a	149b	635a	57a

Common letter(s) within the same column do not differ significantly at 5% level of significance ($p \leq 0.05$).

Note: The measured soil chemical properties were: Electrical conductivity, EC; pH; organic carbon, OC; total nitrogen, N; phosphorus, P; potassium, K; sulphur, S; sodium, Na; calcium, Ca; and magnesium, Mg. The five fertility levels were: F_0: No fertilizer; F_1: 25% of recommended fertilizer dose; F_2: 50% of recommended fertilizer dose; F_3: 75% of recommended fertilizer dose, and F_4: Recommended fertilizer dose. The three soil profiles were D_1: 0-20 cm; D_2: 20-40 cm and D_3: 40-60 cm.

Bangladesh [42]. The N, P, K and S contents in the soils of the two experimental fields were in the low range at pre-planting state, but irrigation with WW increased soil fertility by augmenting these nutrient elements (Table 6). Since there was no elevated level of heavy metals in the WW [28], no attention was focused in this study on soil contamination by them.

Nitrogen in WW comprises several chemical forms, such as nitrate, nitrite, ammonia and organic nitrogen. All of these forms are soluble and mobile in water. When WW is applied in the rice field, all forms of nitrogen except ammonia are easily washed out and may cause pollution of groundwater through leaching and surface water that receives runoff water from the field. Only ammonia in WW can attach to soil particles and is retained in rice fields. But, at the soil surface and root zone layer, with the presence of oxygen, ammonia is gradually converted to nitrite and finally nitrate due to bacterial activities. Xu et al. [43] reported that CH_4 and N_2O emissions from rice fields are closely associated with soil carbon and nitrogen availabilities and transformation processes, which are significantly dependent on soil properties, soil heavy metal contents and soil microbial communities. Consequently, Zou et al. [44] hypothesized that WW irrigation would significantly increase these gas emissions from rice fields. By contrast to ammonia, P can exist as a trivalent action and hence is stable in soil. In addition, since WW contains a smaller amount of P than that required by most crops, irrigation with WW hardly exerts any adverse impact on the water environment [41].

Hygienic safety of WW irrigation

While irrigation with municipal WW for rice cultivation can bring benefits to farmers by increasing yield with reduced fertilizer application, it also has potential to cause harm to human health and the environment [9]. Although microbial properties of WW used in irrigating the experimental rice fields were not measured in this study the risk of microbial pathogens is inarguably a major concern for health regulators, farmers and the general public when WW irrigation is concerned. Mojid and Wyseure [45] reported average total coliform (TC) and fecal coliform (FC) counts in WW of the same source (as used in our study) as 17.2×10^6 and 13.4×10^3 cfu/100 ml, respectively. As outlined by WHO [46], for the reuse of WW in crops TC must be < 100 colonies per 100 ml in 80% of the samples and no FC should be in 100 ml samples. With regard to health, the reuse criteria refer mainly to FC content, which according to Mara and Cairncross [47] should be less than 10^3 cfu/100 mL. So, the municipal WW used in this study did not meet these criteria. It has been reported that the practice of reuse of untreated or even treated WW for irrigation may cause epidemiological problems among nearby populations and consumers of uncooked agricultural products [48].

In the areas where rice cultivation is completely mechanized, the farmers do not need to come into contact with the WW. But, most cultivation practices in the study area and also in the whole of Bangladesh are done manually. The farmers use protective clothing, such as boots, shoes and gloves, to reduce the health risk. As for the safety of the product, rice has to be boiled before consumption, which would reduce pathogens (bacteria, protozoa and viruses) by 6-7 log units [30]. Moreover, the interval between the final irrigation to the crop and consumption would reduce pathogens in hot and dry weather [49]. In rice cultivation, the interval between final irrigation and harvesting the crop is usually 15 to 20 days in Bangladesh. During this period a hot (with average temp ≈ 28°C) and dry (with average relative humidity ≈ 75%) weather prevails, thus leaving no real risk for rice consumers. However, effective hygiene education and promotion programs are always needed to inform field workers, produce handlers, vendors and consumers about the source quality of water. WW irrigation can cause also adverse effects on groundwater resource; the crucial one is infiltration of nitrates from irrigated WW into groundwater.

Although WW irrigation has a potential to contaminate freshwater sources, it is expected that quality of the WW is improved by being used for irrigation. Suspended solids including pathogenic microorganisms are trapped and absorbed in the upper soil layers and removed from the WW. The efficiency of solid removal depends on sizes of soil pores and the solids [50]. Adsorption of microorganisms to soil particles is favored at low pH, high salt concentration in the WW and high relative concentrations of calcium and magnesium over monovalent cations, such as sodium and potassium in soil [39]. Organic matters in WW can be rapidly converted in soils to stable and nontoxic ones, such as humic and fulvic acids. In fact, biodegradation of a wider variety and greater amount of organic matters occur in soils than in water bodies. So, the organic matters in term of chemical oxygen demand (COD) and biological oxygen demand (BOD) in the irrigated WW are significantly reduced after percolation through soil layers. More significant reduction in nitrogen concentration is expected at rice fields with WW irrigation due to absorption by plants, release to the atmosphere due to nitrification and denitrification, and adsorption of ammonium to soil particles.

Conclusions

Nitrogen content in the municipal WW of Mymensingh town was almost sufficient while phosphorus and potassium contents were in excess to meet the requirement for rice production under WW irrigation. For other crops, the quantity of these nutrients to be supplied through irrigation will depend on the quantity of applied irrigation. The employed check basin method for rice irrigation rendered the WW as an important source of nutrients, which, in coincidence with high cost of inorganic fertilizer, could return considerable profit to the rice farmers and plausibly to farmers cultivating other crops through reduced fertilizer cost. WW-irrigated soils were enriched with the basic fertilization (N, P and K) and the residual nutrients could be used by subsequent crops, where possible to cultivate. WW being free of heavy metals caused no toxic/adverse effects on the irrigated soils. Apart from the hygienic aspects, which need to be taken into consideration, the municipal WW can be beneficially used as an alternative water source for irrigated rice production in many peri-urban areas of Bangladesh under prevailing scenario of limited fresh water availability for irrigation. The findings of this study provide applicable advice to farmers, agricultural researchers and policy makers, and municipal authorities for management and proper use of municipal WW.

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