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# Reuse of domestic wastewater treated in macrophyte ponds to irrigate tomato and eggplant in semi-arid West-Africa: Benefits and risks

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ABSTRACT

The scarcity of freshwater resources is a critical problem in semi-arid zones and marginal quality water is increasingly being used in agriculture. This paper aimed at evaluating the physico-chemical and biological risks on irrigated soils and fruits of macrophyte treated wastewater (TWW), the nutrients supply, and the effect on tomato and eggplant production in semi-arid Burkina Faso. During three years of experiments, treated wastewater was used, with fresh water as control, in combination with or without mineral fertilizer application at recommended rate (140 kg N/ha + 180 kg $P_2O_5$/ha + 180 kg $K_2O$/ha). The study revealed that the treated wastewater provided variable nutrients supply depending on year and element. The treated wastewater without mineral fertilizer improved eggplant yield (40% in average) compared to the freshwater. Both crops responded better to mineral fertilizer (52% for tomato and 82% for eggplant) and the effects of the treated wastewater and fertilizer were additive. As the N supply of TWW was very unsteady (8–227% of crop need), and $P_2O_5$ supply did not satisfy in whole crop need (3–58%) during any of the three years of experiment, we recommended that moderate N and $P_2O_5$ fertilizers be applied when irrigating with TWW in semi-arid West-Africa. On the contrary, the $K_2O$ supply was more steady and close to crop requirement (78–126%) over the three years of experiment and no addition of K fertilizer may be needed when irrigated with TWW. Faecal coliforms and helminth eggs were observed in treated wastewater and irrigated soils at rate over the FAO and WHO recommended limits for vegetable to be eaten uncooked. Tomato fruits were observed to be faecal coliform contaminated with the direct on-foliage irrigation with treated wastewater. Our results indicate that treated wastewater can effectively be used as both nutrients source and crop water supply in market gardening in the semi-arid Sub-Saharan West Africa (SSWA) where freshwater and farm income are limiting. Yet consumers should properly cook or disinfect treated-wastewater irrigated vegetables before eating, and market gardeners should also be careful manipulating treated wastewater to avoid direct health contamination in this environment.



## 1. Introduction

In semi-arid zones, the scarcity of freshwater resource is a critical problem and the reuse of marginal quality water in agriculture is increasing regularly (Cissé, 1997). In towns such as Ouagadougou (capital city of Burkina Faso), with a population estimated at more than 1.2 million people (2001) and a mean annual growth rate of 6.5% against 2.4% for the whole country, urban agriculture is rapidly developing. Urban agriculture cannot rely solely on the limiting freshwater resource, and calls for the use of secondary quality waters. According to the National Institute of Water and Sanitation (*Office National de l'Eau et de l'Assainissement* ONEA, Burkina Faso; Vezina, 2002) the total discharged wastewater represents more than 20,000 $m^3$/year of domestic wastewater and 600,000 $m^3$/year of industrial effluent. Until recently, and because of the absence of any sewerage system, raw wastewater from the central market, the main hotels, the hospitals, the brewery, the tanneries and the abattoir were discharged without any treatment into natural canals and mixed with run-off rainwater (Cissé et al., 2002). The surroundings of these canals were spontaneously invaded by market gardeners who use the water to irrigate their vegetables without any kind of treatment. Cissé (1997) identified 48 sites of market gardening between 1995 and 1996 with a total area of 174.35 ha in Ouagadougou. This extensive use of untreated wastewater for urban agriculture has led to various consequences on vegetable quality, population health and soil quality that have been reported by several studies. In Ouagadougou, soil, crop leaves and fruits (carrot, lettuce, tomato, etc.) were reported to be heavily contaminated by faecal coliforms and helminth eggs (Cissé, 1997; Cissé et al., 2002). The authors reported also frequent pathogen health effects

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on market gardener family members. Similar vegetable contamination was reported in other areas, such as in Ghana (Amoah et al., 2006), Turkey (Erdogrul and Sener, 2005), Morocco (Amahmid et al., 1999) and Mexico (Blumenthal et al., 2001). Moreover other problems may be caused to soils irrigated with raw wastewater. Suspended matters in untreated wastewater can accumulate and create clogging, reducing soil aeration and hydraulic conductivity (Viviani and Iovino, 2004; Toze, 2006), sodium and nitrate in excess may create salination and nitrate groundwater contamination (Ayers and Westcot, 1988; Oron et al., 1999). To alleviate the health risks of raw wastewater use on crop and soil quality and on consumers many research works, focusing on treatment possibilities through low cost lagoon systems, were performed with encouraging results in Ouagadougou at the pilot center for the semi-arid SSWA (Koné et al., 2002; Koné, 2002; Klutsé, 1995). Reuse of treated wastewater for agricultural irrigation may be beneficial for different reasons: (1) water scarcity can be alleviated by the large amount of wastewater that is available during the whole year, (2) pollution hazard from direct release to environment is diminished, (3) economic benefits attributed primarily to the nutrients content of the wastewater, which reduces fertilizer expenses to farmers (Lubello et al., 2004; Oron et al., 1999). In the semi-arid SSWA, lagoon treated wastewater was claimed to be biologically sound and has interesting nutrients content for vegetable cropping (Cissé, 1997; Koné, 2002; Koné et al., 2002). Because on-site experiments are still lacking to evaluate the remaining health risks, the nature and amount of nutrients supplied by treated wastewater, the aim of this study was to evaluate (1) the physico-chemical and biological risks to irrigated soil, (2) the pathogen health risks on fruit and consumers, (3) the nutrients supply, and (4) the effect on the yield of tomato and eggplant crops of lagoon (macrophytes) treated wastewater irrigation.

## 2. Materials and methods

### 2.1. Experimental site

The experimental site is located at the *Institut International d'Ingénierie de l'Eau et de l'Environnement* (2IE) in Ouagadougou (12°20–12°25 N and 1°27–1°35 E), Burkina Faso. The climate is tropical soudano-sahelian characterized by less than 800 mm mean annual rainfall and 25–30 °C mean monthly temperature. The rainy season extends from May–June to October. The evaporation rate is high with an average of more than 6 mm/day (Mermoud et al., 2005). The soil is ferruginous with a $pH_{(H_2O)}$ of 7.7, low organic matter content (0.66%) and cation exchange capacity CEC (6.6 meq/100 g), 79% of base saturation.

### 2.2. Experimental design, irrigation waters and crop material

Randomized complete block design (RCBD) was adopted on the basis of four treatments with three replicates each: irrigation with (1) freshwater of the Loumbila dam (FWL) alone, (2) FWL and mineral fertilizer application, (3) treated wastewater (TWW) alone, (4) TWW with mineral fertilizer application.

Treated wastewater was collected out from the macrophytes (*Pistia stratiotes* L.) ponds of the 2IE institute (treatment capacity: 6 $m^3$/day). Wastewater comes from the students' residence hall of the 2IE institute and was firstly submitted to a primary purification (decanter), and two levels of secondary treatment (macrophyte ponds) and a horizontal filter (Koné, 2002).

The freshwater from the Loumbila small dam (20 km from Ouagadougou) was collected from the canal between the dam and the treatment station and was not yet treated to be fit for direct human consumption.

The experiments took place during dry seasons and were initially carried out on tomato crop (*Lycopersicum esculentum* Mill., c.v Roma VF) from November 2000 to March 2001 (denoted as 2001 in the following). Due to a leaf shrinkage disease, of unknown origin, towards the end of the first year experiment, the crop was replaced by eggplant (*Solanum melongena* L.) for two other experimental campaigns from January to June 2002 and October 2002 to April 2003, denoted as 2002 and 2003, respectively. Eggplant cultivar was Black-beauty and Kalenda in 2002 and 2003, respectively. Plot size was 2.5 m × 2.5 m i.e. 6.25 $m^2$ for tomato and 3 m × 3 m i.e. 9 $m^2$ for eggplant with a planting density of 0.5 m × 0.5 m and 0.6 m × 0.6 m, respectively. One month old plants were replanted from nursery to experiment plots. All plots and treatments were treated against insects, nematods, acarina and fungi combining periodically carbofuran, cypermethrin, dimethoate and maneb.

### 2.3. Irrigation and mineral fertilizer application

The amount and frequency of irrigation were the same for every treatment and both crops.

Irrigation amount was 6 mm/day during the first month after transplanting and 9 mm/day afterwards. The irrigation amount was computed based on the average reference evapotranspiration of dry season months for Ouagadougou available in CLIMWAT 2.0 database (FAO, 2006) and crop coefficients of Solanaceae family (Allen et al., 1998). Watering-can (10 l) was used and side on-soil-surface watering was practiced in ditches to avoid direct water contact with crop foliage. We hypothesized that this side on-soil-surface watering may reduce possible fruit pathogen contamination as Cissé (1997) reported high contamination with direct on foliage watering. However, two weeks before the end of the experiments (during harvest period), this technique was replaced by direct watering on the foliage (as done by gardeners in the area) to compare the relative risks of the two irrigation techniques on fruit pathogen contamination.

For fertilized treatments (FWL + fertilizer and TWW + fertilizer), mineral fertilizers were applied according to the recommendation of the Institute for Environment and Agricultural Research (*Institut de l'Environnement et de la Recherche Agricole* – INERA, Burkina Faso): 140 kg N/ha + 180 kg $P_2O_5$/ha + 180 kg $K_2O$/ha as NPK (15–25–15) split in three equal amounts on 15, 30 and 50 days after transplanting for tomato. For eggplant (2002 and 2003), the fertilizer amount was the same as that of tomato and was applied as NPK (15–25–15) at planting time and as urea (46–0–0) split in two equal amounts during the fructification period.

### 2.4. Measurements and statistical analysis

During the experimental period, the quality of the two irrigation waters (FWL and TWW) was monitored every two weeks approximately. Physico-chemical characteristics (Biochemical Oxygen Demand $BOD_5$, Chemical Oxygen Demand COD, electrical conductivity EC, suspended matter SM, pH, nitrate $NO_3^-$ and other cations), and biological characteristics (faecal coliforms and helminth eggs) were assessed.

The irrigated soils (0.0–0.2 m depth) and fruits were also sampled every two weeks approximately for biological contamination in faecal coliforms and helminth eggs. Water, soil and fruit samples were collected and analyzed according to the recommendations of the American Public Health Association APHA (1998) and the French Standard Association AFNOR (1990) (Table 1).

Nutrients supply was estimated from average irrigation water content in related ions ($NH_4^+$, $NO_3^-$, $PO_4^{3-}$ and $K^+$) and total irrigation water supply during the growing cycle. This was done in terms of fertilizing elements: nitrogen (N), phosphoric anhydride ($P_2O_5$) and potassium oxide ($K_2O$). This study did not account for

**Table 1**
Methods used to analyze water, plant and soil.

| Parameters | Method | Reference |
|---|---|---|
| Water analysis | | |
| $BOD_5$ | 5-day BOD test | 5210-B[a] |
| COD | Closed reflux, colorimetric method | 5220-D[a] |
| SM | Total suspended solid dried at 103–105 °C | 2540-D[a] |
| pH | Electrometric method | 4500-$H^+$ B[a] |
| P total, $NO_3^-$, $NH_4^+$ | Ultraviolet spectrophotometric screening method | 4500-$NO^{3-}$ B[a] |
| $K^+$, $Na^+$ | Flame photometric method | 3500-K D[a], 3500-Na D[a] |
| $Ca^{2+}$, $Mg^{2+}$ | EDTA titrimetric, calculation method from hardness | 3500-Ca D[a], 3500-Mg E[a] |
| Turbidity | Nephelometric method | 2130 B[a] |
| EC | Electrical conductivity method | 2520 B[a] |
| Faecal coliforms | Fermentation technique | AFNOR[b] |
| Helminth eggs | SAF[c] method | AFNOR[b] |
| Plant and soil analysis | | |
| Faecal coliforms | Fermentation technique | AFNOR[b] |
| Helminth eggs | Adapted SAF[c] method | AFNOR[b] |

[a] APHA (1998).
[b] AFNOR (1990).
[c] Sodium acetate–acetic acid formalin.

organic N or P supply of TWW. Irrigation water nutrients supply was compared to tomato and eggplant requirements from INERA.

Yields of fresh fruit of tomato and eggplant were recorded and results were submitted to analysis of variance in R 2.7.0 software (R Development Core Team, 2008) using a randomized complete block structure with 2 factors (with 2 levels each) and 3 replications in which the two years of eggplant were considered at the split-plot level. Differences between treatments were regarded at error probabilities $p < 0.05$. Quadratic and linear regression analyses were performed to model crop response to total nutrient supply over the cropping season.

## 3. Results

### 3.1. Physico-chemical quality of irrigation waters

Table 2 shows the average physico-chemical characteristics of the two irrigation waters. Overall the load of most of the analyzed parameters was much higher for TWW than for the FWL. The physical characteristics (SM, EC, pH and turbidity) of both waters were in agreement with the recommendations of FAO (Pescod, 1992). In terms of chemical quality, high values (with high standard deviation SD) were observed in 2002 compared to 2001 and 2002 for TWW. FWL was in agreement with the normal ranges contrary to TWW (Pescod, 1992; Feigin et al., 1991). In 2002, BOD of TWW was in average higher than the 25 mg/l FAO limit (Pescod, 1992). Average nitrate ($NO_3^-$) content in TWW was above the limit of 10 mg/l in 2002 and 2003, and average ammonium ($NH_4^+$) was in the recommended range (Feigin et al., 1991). Average potassium ($K^+$) was also above the normal range. Sodium adsoption ration (SAR) was low, indicating that hazard of sodification is minimal.

### 3.2. Nutrients supply of irrigation waters

Nutrients supplied by Loumbila freshwater (FWL) was consistently much lower than that of treated wastewater (TWW) (Fig. 1). Nevertheless supply of FWL in $K_2O$ was not negligible (31% of tomato needs in 2001 and about 50% of eggplant requirements in 2002 and 2003).

Treated wastewater (TWW) nutrient supply varied much between years and were much higher in 2002 than in 2001 and 2003. TWW nutrients supply was 8–3–92% of tomato requirements (2001), 227–58–126% and 73–23–78% of eggplant requirements (in 2002 and 2003, respectively). TWW nutrients supply covered almost and even the whole crop requirement (tomato in the case of $K_2O$ in 2001, and eggplant for N and $K_2O$ in 2002 and 2003). It is important to highlight that $P_2O_5$ supply was always low and crop requirement was not satisfied totally during the three years of experiment (3, 58 and 23%, respectively).

### 3.3. Biological quality of irrigation water

The average load in faecal coliforms of FWL was conform to the WHO recommendation (Blumenthal et al., 2000; WHO, 2006) on irrigation water quality for crops susceptible to be eaten uncooked ($\leq 10^3$ faecal coliforms in 100 ml i.e. 3 decimal logarithmic units

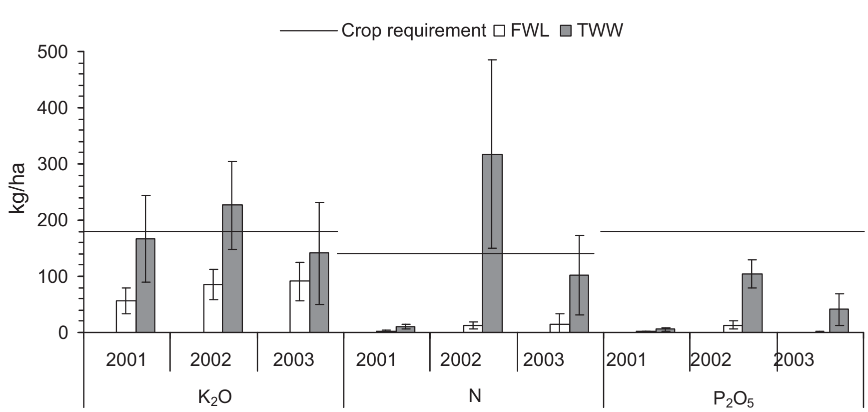


**Fig. 1.** Nutrients supply of freshwater from the Loumbila dam (FWL) and treated wastewater (TWW) compared to tomato (2001) and eggplant (2002, 2003) requirements. Error bars denote standard deviations.

**Table 2**
Average physico-chemical characteristics (± standard deviation) of freshwater of Loumbila (FWL) dam and treated wastewater (TWW) used to irrigate tomato (2001) and eggplant (2002, 2003) in Ouagadougou, Burkina Faso. Normal values are given after Feigin et al. (1991) and Pescod, 1992 (FAO).

| | Units | FWL (fresh water Loumbila) | | | TWW (treated waste water) | | | Normal range |
|---|---|---|---|---|---|---|---|---|
| | | 2001 ($n=5$) | 2002 ($n=10$) | 2003 ($n=15$) | 2001 ($n=5$) | 2002 ($n=10$) | 2003 ($n=15$) | |
| Physical characteristics | | | | | | | | |
| SM[a] | mg/l | 4.4 ± 1.4 | 8.8 ± 6.4 | 11.1 ± 5.9 | 21.4 ± 4.5 | 29.4 ± 10.5 | 27.9 ± 8.4 | 20–30[b] |
| EC[c] | mS/cm | 0.1 ± 0.0 | 0.1 ± 0.0 | 0.1 ± 0.0 | 0.3 ± 0.1 | 0.7 ± 0.2 | 0.4 ± 0.2 | 1–3[b] |
| pH | – | 6.6 ± 0.2 | 7.3 ± 0.4 | 7.6 ± 0.2 | 7.5 ± 0.4 | 7.4 ± 0.3 | 7.4 ± 0.4 | 6.5–8.5[b] |
| Turbidity | – | 1.6 ± 0.1 | 2.1 ± 0.9 | – | 10.7 ± 5.7 | 4.5 ± 2.2 | – | – |
| Chemical characteristics | | | | | | | | |
| $BOD_5$[d] | mg/l | 0.4 ± 0.8 | 14.9 ± 4.1 | 9.7 ± 1.3 | 23.2 ± 4.8 | 50.8 ± 14.2 | 25.6 ± 6.7 | <25[b] |
| COD[e] | mg/l | 1.2 ± 2.4 | 19 ± 7.1 | – | 77.3 ± 10.2 | 56.3 ± 12.4 | – | 30–160[f] |
| $NO_3^-$ | mg/l | 1.2 ± 1.4 | 4.9 ± 2.7 | 4.1 ± 5.9 | 6.8 ± 2.7 | 16 ± 6.4 | 24.2 ± 15.5 | <10[f] |
| $NH_4^+$ | mg/l | – | 0.1 ± 0.1 | 0.5 ± 0.3 | – | 38.5 ± 20.8 | 4.2 ± 3.3 | 1–40[f] |
| Total P | mg/l | 0.1 ± 0.0 | 0.6 ± 0.4 | 0.04 ± 0.0 | 0.3 ± 0.2 | 4.8 ± 1.1 | 0.8 ± 1 | – |
| $PO_4^{3-}$ | mg/l | – | 1.8 ± 1 | 0.1 ± 0.1 | – | 14.8 ± 3.5 | 2.3 ± 3.1 | – |
| $K^+$ | mg/l | 6.4 ± 2.6 | 7.5 ± 2.4 | 6.4 ± 2.5 | 19 ± 8.8 | 19.7 ± 6.8 | 10.0 ± 6.4 | 10–40[f] |
| $Na^+$ | mg/l | 4.7 ± 1.9 | 2.8 ± 0.9 | 5.0 ± 1.0 | 31.2 ± 7.3 | 39.3 ± 10.9 | 18.8 ± 12.1 | 50–250[f] |
| $Ca^{2+}$ | mg/l | 1.8 ± 0.6 | 10.3 ± 1.3 | 5.8 ± 1.5 | 4.6 ± 0.3 | 23.6 ± 4 | 14.5 ± 2.2 | 20–120[f] |
| $Mg^{2+}$ | mg/l | 0.5 ± 0.3 | 2.5 ± 0.9 | 1.5 ± 0.3 | 0.7 ± 0.6 | 3.8 ± 1.9 | 2.5 ± 0.7 | 10–50[f] |
| SAR[g] | $(mmol/l)^{0.55}$ | 0.8 ± 0.4 | 0.2 ± 0.1 | 0.5 ± 0.1 | 3.6 ± 0.7 | 2 ± 0.5 | 1.1 ± 0.7 | 4.5–7.9[f] |

[a] Suspended matters.
[b] Pescod, 1992 (FAO).
[c] Electric conductivity.
[d] Biochemical oxygen demand.
[e] Chemical oxygen demand.
[f] Feigin et al. (1991).
[g] Sodium adsorption ratio, $SAR = Na^+/[0.5(Ca^{2+} + Mg^{2+})]^{0.5}$; concentrations in meq/l.

per 100 ml or log(FCU/100 ml), but the average load of TWW was consistently higher than this standard (3.9 ± 0.3, 4.2 ± 0.4 and 3.3 ± 1.5 log FCU/100 ml in 2001, 2002 and 2003, respectively (Fig. 2).

Quantitative research of helminth eggs in irrigation water took place only during 2002 and 2003 experiments (Table 3). FWL was found to be free from helminth eggs but TWW showed helminth eggs concentrations of 9.3 ± 11.4 and 0.2 ± 0.9 eggs/l in 2002 and 2003, respectively. Such a concentration in helminth eggs is higher than the recommendations of the revised WHO standards (less than 0.1 egg/l) (Blumenthal et al., 2000; WHO, 2006) for crops likely to be eaten uncooked.

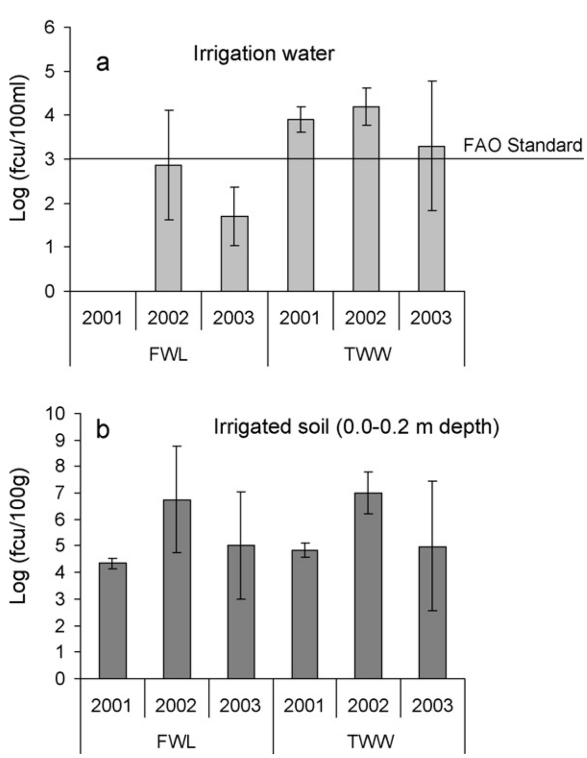


**Fig. 2.** Average rates of faecal coliforms in (a) freshwater of Loumbila (FWL) dam and treated wastewater (TWW) and (b) irrigated soil cropped with tomato (2001) and eggplant (2002, 2003). Error bars denote standard deviation.

### 3.4. Biological effect on irrigated plots and fruits

#### 3.4.1. Irrigated soils

Fig. 2 shows the rates of faecal coliforms and Table 3 the rates of helminth eggs in the irrigated soils. Both soils watered with FWL and TWW presented a contamination in faecal coliforms and helminth eggs. Regarding contamination in faecal coliform, soils of plots watered with FWL had 4.3 ± 0.2, 6.8 ± 2.0 and 5 ± 2.0 log(FCU/100 g) (average ± SD), those watered with TWW had 4.9 ± 0.3, 7 ± 0.8 and 5 ± 2.4 log(FCU/100 g) respectively in 2001, 2002 and 2003.

For contamination in helminth eggs, soils of plots watered with FWL had 3.8 ± 5.9 egg/100 g and those watered with TWW a higher concentration with 14 ± 16.9 egg/100 g during 2002.

#### 3.4.2. Fruits

Tomato fruits in 2001 showed contamination in faecal coliforms (not quantified) in case of direct TWW irrigation on foliage. In 2002

**Table 3**
Average number of helminth eggs in freshwater of Loumbila (FWL) dam and treated wastewater (TWW), and in soils irrigated with those waters in 2001 (tomato), 2002 and 2003 (eggplant). Standard comes from recommended revision of WHO standards (Blumenthal et al., 2000). Values in bracket denote standard deviation.

| | Water (egg/l) | Soil (egg/100 g) |
|---|---|---|
| FWL | | |
| 2001 ($n=4$) | – | – |
| 2002 ($n=9$) | 0 (0) | 3.8 (5.9) |
| 2003 ($n=15$) | 0 (0) | 0 (0) |
| TWW | | |
| 2001 ($n=4$) | – | – |
| 2002 ($n=9$) | 9.3 (11.4) | 13.6 (16.9) |
| 2003 ($n=15$) | 0.2 (0.9) | 0 (0) |
| WHO revised standard | <0.1 | – |

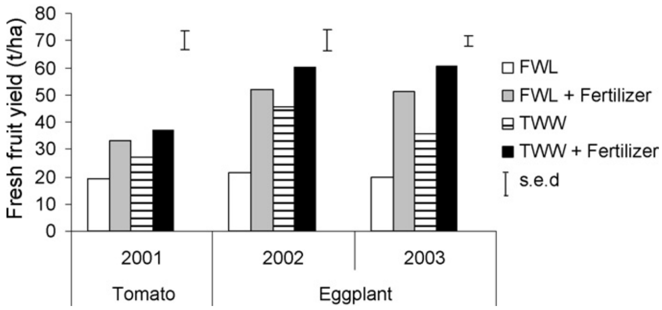


**Fig. 3.** Tomato and eggplant response to irrigation with freshwater of Loumbila (FWL) dam and treated wastewater (TWW) and chemical.

and 2003, neither faecal coliform, nor helminth eggs contamination was found on eggplant fruits regardless of the irrigation water and technique (on-soil surface or over crop foliage).

### 3.5. *Crop yield and response to nutrient supply*

The main effect of irrigation water was significant on eggplant yield in 2002 ($p = 0.025$) and 2003 ($p < 0.001$) contrary to tomato yield in 2001. Overall, irrigation with treated wastewater improved eggplant yield from 36.2 to 50.6 t/ha (s.e.d. = 2.8 t/ha) (40% compared to the irrigation with the freshwater of Loumbila).

The main effect of mineral fertilizer was significant all the years on tomato yield (2001, $p = 0.044$) and eggplant in 2002 ($p = 0.006$) and 2003 ($p < 0.001$). In 2001, tomato yield was improved by 52% i.e. from 23.1 to 35.2 t/ha (s.e.d. = 4.7 t/ha) by mineral fertilizer application compared to the no fertilizer treatment (Fig. 3). On average over the two years (2002 and 2003), mineral fertilizer improved eggplant yield from 30.7 to 56.0 t/ha (82% compared to the control) (s.e.d. = 2.8 t/ha). No significant interaction was detected between mineral fertilizer application and irrigation water for any cropping year indicating an additive effect of the two factors. We found that eggplant yield significantly responded to nutrient supply (N, $P_2O_5$ and $K_2O$ combined from water and mineral fertilizer) in quadratic models (Fig. 4a–c). Linear regression was considered for tomato yield response to nutrient because of limited data. The relation was only significant for $K_2O$.

## 4. Discussion

The reuse of treated wastewater in agriculture has become in the whole world and particularly in the semi-arid SSWA, a strategic mean to save and complement first quality water resource which is more and more limiting. We irrigated tomato and eggplant for three years (2001–2003) using TWW (and FWL as control), with the addition of mineral fertilizer or not, in order to evaluate the physico-chemical and biological risks for soil-fruit-consumer, the nutrient supply and crop yield response.

In this experiment we used 6 mm/day during the first month after transplanting and 9 mm/day afterwards. Using a similar irrigation schedule in 1998–1999 for onion which need a bit less water than tomato and eggplant (having higher crop coefficients, Allen et al., 1998), Mermoud et al. (2005) found that 13% (104 mm) of irrigation water was lost by drainage, when applying 8 mm/day for the whole season. We consider that drainage will likely occur during this experiment that applied 9 mm/day (mid-season) but its rate might be minimal and the consequence on nutrient lost of the same magnitude.

We found that the measured physical characteristics (SM, EC, pH and turbidity) of freshwater of Loumbila and treated wastewater was in agreement with FAO recommendations. Clogging (due to high organic content) and pH related risks could be considered low

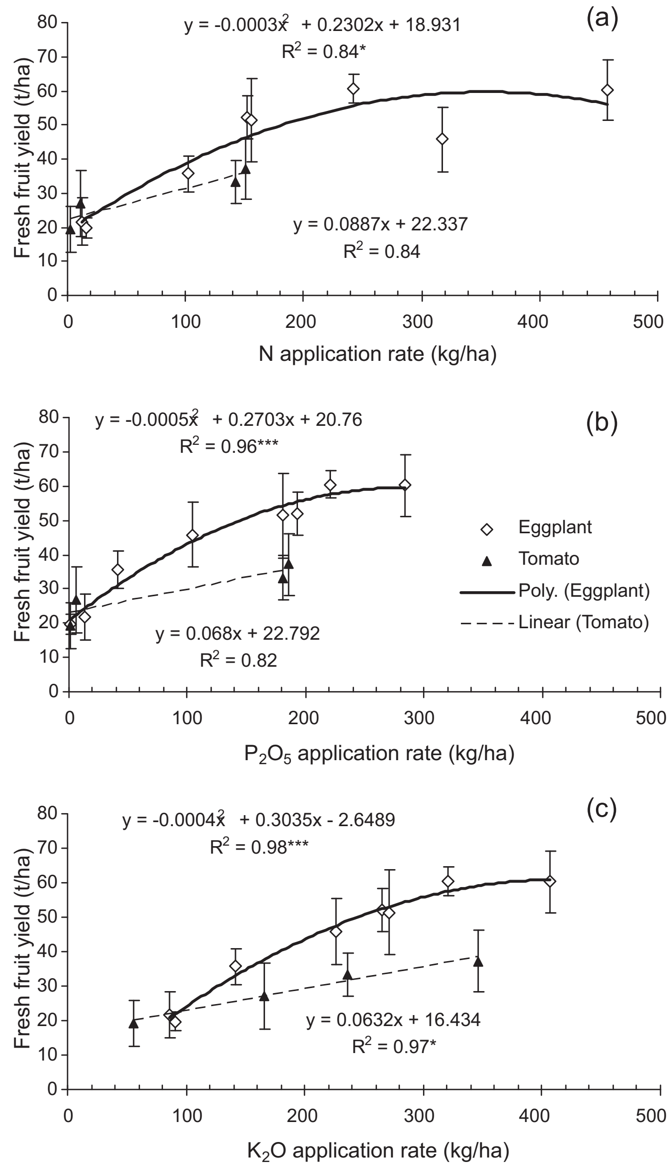


**Fig. 4.** Tomato and eggplant yield response to N (a), $P_2O_5$ (b) and $K_2O$ (c) input from combined irrigation water (FWL or TWW) and mineral fertilizer in 2001, 2002 and 2003 at 2IE experimental station, Ougadougou, Burkina Faso. Measured yields (dots) are yearly treatment average (with standard deviations as error bars) modeled by parabolic curves or linear trendlines (equation and $R^2$). *, ** or *** mean that model is significant at $p < 0.05$, 0.01 or 0.001 respectively.

for both water sources. Negative effect on infiltration and hydraulic conductivity could be considered low as well.

The content in most physico-chemical elements varied much between years. High contents of BOD and $NO_3^-$, compared to the literature recommended values for wastewater reuse in agriculture were recorded in 2002 and 2003 in TWW. This may be ascribed to the fact that the lagoon plant of 2IE was a pilot station under various treatment trials from year to year (various incoming loads, macrophyte density and residence time) which makes the quality of treated wastewater unsteady (Koné, 2002). The excess in nitrogen (2002) may be risky due to possible groundwater pollution. Lubello et al. (2004) reported that in many investigations, a negative effect of high concentrations of ammonia on crop root growth was observed. In the bulk of soil, ammonia goes through nitrification processes. Nitrates indeed migrate into the deep soil layers and can be hazardous for shallow groundwater. For our environment, Tamini and Mermoud (2002) and Mermoud et al. (2005)

showed in studies of nitrate dynamics in Kamboinsé (20 km from Ouagadougou) that the high evaporation of the region leads to high volatilization of nitrogen, which is expected to alleviate the risk of N excess in TWW.

We found a beneficial effect of TWW as nutrients source that can supply relatively high contribution of 8–3–92% to tomato requirement (2001); 227–58–126% and 73–23–78% to eggplant requirement (2002 and 2003 respectively) in N, $P_2O_5$ and $K_2O$, respectively. Many research works reported variable nutrient supply from TWW depending on element, areas and method and level of treatment. An extended review was done by Fonseca et al. (2007a), but little information still exists to our knowledge as far as market-gardening is concerned. Fonseca et al. (2007a) reported N input of about 200 kg N/ha in Israël (>100% of cotton need). Feigin et al. (1991) mentioned that TWW can supply up to 100% of K need for cotton. In the present study the N supply was very unsteady (8–227% of crop need). This indicates that N supply may be insufficient to meet crop need or may be in excess as well. As the consequence of the excess is minimal in our environment with high volatilization due to high evaporation, according to Mermoud et al. (2005), we can recommend moderate N fertilizer addition when irrigating with TWW in semi-arid West-Africa (Fig. 4a). The same recommendation should also apply for $P_2O_5$ as its requirement was not satisfied in whole during any of the three years of experiment (Fig. 4b). On the contrary, the $K_2O$ supply was more steady and close to crop requirement over the three years of experiment and no addition of K fertilizer should be needed when irrigated with TWW. Accounting for these recommendations may help reduce the amount and expenses of mineral fertilizer.

The TWW nutrients supply resulted in eggplant yield improvement of 40% compared to freshwater over two years. The same effect was found on several vegetables in Morocco by Bouhoum and Amahmid, 2002 with three water irrigation types (untreated wastewater, treated wastewater, surface water). They found that wastewater reuse increased yield of 13% for mint, 20.3% for coriander, 31.6% for radish and 35.1% for carrot. Similar results were also obtained in Soudan by Mirghani et al. (2002) on fodder crop irrigated with treated wastewater. They noticed a significant effect of wastewater irrigation on fodder crops growth, number of leaves, stem diameter, leaf area and above-ground biomass. Crop response to TWW may be ascribed to water and nutrient supplies but mainly because nutrient are provided and released continuously (e.g. Feigin et al., 1991; Fonseca et al., 2007b).

Although FWL was helminth egg free, the latter were found in related irrigated soils. The reason is unclear and may be due to a permanent contamination of the site. But fruit of tomato and eggplant were helminth egg free regardless of irrigation water and irrigation technique. Amahmid et al. (1999) and Bouhoum and Amahmid, 2002 indicated a strong contamination of the vegetables in parasites particularly the cysts of Giardia and eggs of helminths (Ascaris) with the irrigation with untreated wastewater whereas treated wastewater resulted in no contamination. They mentioned that the degree of contamination is a function of the type of vegetable and is higher for vegetables with dense foliage (coriander, mint) whose products of harvest are directly in contact with the contaminated soil (carrot, radish), contrary to sweet pepper and eggplant that were not contaminated neither by the cysts of Giardia nor by eggs of helminths.

Faecal coliform analyses on fruit were positive for tomato in the case of direct irrigation on foliage but negative for eggplant regardless of water types and irrigation technique. Cissé (1997) indicated an average level of pollution in faecal coliforms on lettuce and carrots of 8.9 and 6.5 log(UFC/100 g) respectively, on the site of market gardening of Tanghin (Ouagadougou) where the technique practiced by market-gardeners was a direct watering on foliage with untreated wastewater. Vegetables, in general are either directly contaminated by water or indirectly by contact with the polluted soil. Although both irrigated soils (with FWL and TWW) were observed to be permanently contaminated in faecal coliforms, the contamination of the tomato fruits was a direct and superficial contamination by the treated wastewater because watering directly on soil surface did not show any contamination. This was possible because tomato fruit surface is not very smooth compared to eggplant fruit that has a rather uniform and smooth surface leading to no contamination.

Presently, gardeners who reuse wastewater, in Ouagadougou and surroundings, do not practice this side on-soil-surface watering technique. The technique will necessitate just a little more precaution than the direct on foliage technique. The shower head of the watering can need to be removed, the can lowered and water be poured slowly in ditches (to avoid damage to soil surface). In order to minimize pathogen contamination risks, we expect that the side on-soil-surface watering technique can be adopted by gardeners with little additional effort if not any. Another successful option to minimize pathogen contamination risks is irrigation cessation prior to harvest (Drechsel et al., 2008). Yet precaution measures (good disinfection or good cooking) by the consumer is still necessary to eliminate any kind of remaining pathogen health risks of the TWW.

## 5. Conclusion and recommendations

During three years of experiments, we used treated wastewater, and fresh water as control, in combination with or without mineral fertilizer application to evaluate the physico-chemical and biological risks on irrigated soils and fruits of macrophyte TWW, the nutrients supply, and the effect on tomato and eggplant production in semi-arid Burkina Faso. We found that: 1) the physico-chemical quality of lagoon-treated wastewater was acceptable whereas bacteriological quality (faecal coliforms) and helminths quality were not satisfactory according to directives of FAO and WHO on the quality of the water intended for irrigation of crops to be consumed uncooked, 2) the reuse of TWW to irrigate tomato and eggplant significantly improved (less than fertilizer) eggplant yield compared to that of the freshwater of Loumbila dam and 3) the TWW provided variable nutrients supply depending on year and element. As the N supply was very unsteady (8–227% of crop need), and $P_2O_5$ (3–58%) supply did not satisfy in whole crop need during any of the three years of experiment, we recommended that moderate N and $P_2O_5$ fertilizer be applied when irrigating with TWW in semi-arid West-Africa. On the contrary, the $K_2O$ supply was more steady and close to crop requirement (78–126%) over the three years of experiment and no addition of K fertilizer should be needed when irrigated with TWW. Our results show clearly that treated wastewater can be used as both as nutrients source and crop water supply in market gardening in areas of freshwater shortage and low farm income in SSWA. However, vegetable consumers should properly cook or disinfect before eating, and market-gardeners should avoid the direct contact with treated wastewater because of the remaining biological risks.

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