Core Ideas

- Wheat biomass increased by 33% when poor quality compost and Fe-WTR were combined
- Combined amendments and control outperformed single amendments of compost and WTR
- Bioavailable metals measured after the pot trial did not increase
- Co-application of compost with WTR may counter the negative effects of P sorption

Better Together: Water Treatment Residual and Poor-Quality Compost Improves Sandy Soil Fertility

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Abstract

Water treatment residual (WTR) is an under-utilized clean water industry byproduct, generally disposed to landfill. This study assesses the benefits and risks of ferric-WTR as a soil amendment or co-amendment for plant growth in a nutrient-poor sandy soil. A 12-week pot trial tested the efficacy of WTR and a locally available, low-quality, municipal compost as single (1, 5, 12.5% dry mass) and co-amended treatments (1:1 WTR:compost ratio, at 2%, 10% and 25%) on wheat growth in a sandy soil. The low total N content of the compost and low WTR P and K contents resulted in significantly lower (up to 50% lower; $p<0.05$) plant biomass in single amendments compared to the control, while the highest co-amendment produced significantly higher plant biomass (33% higher; $p<0.05$) than the control. This positive co-amendment effect on plant growth is attributed to balanced nutrient provision, with P and K from the compost and N from the WTR. Foliar micronutrient and Al levels showed no toxic accumulation, and co-amended foliar Mn levels increased from near deficient (20 mg/kg) to sufficient (50 mg/kg). Total WTR metals were well below maximum land application concentrations (USDA). Trace element bioavailability remained the same (Ni, Cu, Hg) or significantly decreased (B, Al, Cr, Mn, Fe, Zn, As, Cd; $p < 0.05$) during the pot trial. These results suggest, within this context, that a WTR-compost co-amendment is a promising soil improvement technology for increasing crop yields in sandy soils.

Keywords: Fe-WTR, Waste Recycling, drinking water purification, Arenosol

1. Introduction

Water treatment residual (WTR) is a global byproduct of drinking water treatment which purifies raw water to produce drinking water for municipalities. Basibuyuk and Kalat (2004) reported that several million tons of WTR are produced in Europe every year, with production estimated to double within the next decade. In Africa, WTR production is also set to increase due to a growing population requiring increasing access to clean drinking water. WTR is most commonly disposed in landfill, both globally (Basta et al., 2000) and within South Africa (Herselman, 2013). Alternative uses of this waste byproduct are of global interest to water companies, many of which are looking towards zero waste strategies to reduce costs, and contribute to the United Nations Sustainable Development Goals (SDG 12, Responsible Production and Consumption; UN, 2016).

WTR consists of flocculating agents (ferric and aluminium oxyhydroxides), de-watering agents (polyelectrolytes), activated carbon, and flocculated material from the catchment dams, including clay particles, microbes and dissolved organic matter (Matilainen et al., 2010). Given the soil-like composition of WTR, land application is an important potential disposal option. The implications of land application have been well researched (Ippolito et al., 2011). A major limitation encountered with land application of WTR is the high P-fixation capacity of the Fe and Al-oxyhydroxides (Elliot and Dempsey, 1991; Ippolito et al., 2003; Norris and Titshall, 2012). Addition of WTR to soils results in yield loss and P-deficiency symptoms in maize (Rengasamy et al., 1980), lettuce (Elliott and Singer, 1988) and sorghum-Sudan grass (Heil and Barbarick, 1989). Another problematic factor is the high concentrations of bioavailable Al and Mn in WTR (Ippolito et al., 2011; Novak et al., 2007; Titshall and Hughes, 2005), which may result in phytotoxic conditions.

Compost is commonly used to improve both chemical (fertility and phytotoxicity) and physical (aggregation and water holding capacity) properties of soils. It is well-established that compost addition can reduce the P sorption capacity of Al and Fe oxides in soils (Havlin et al., 2005), yet the use of WTR and compost as a co-amendment is not well-researched. Hsu and Hseu (2011) looked at the co-addition of a good quality (C:N ratio = 20, total N = 3.9%) compost with Al-WTR. In contrast to the above-mentioned studies, they observed an increase in the growth of Bahia grass with Al-WTR added as a single amendment. Co-addition of the compost improved growth but not significantly. Compost increased plant available P in co-amended treatments, although plant tissue P was not significantly affected. In many small-scale farming systems in Africa, compost quality is often poor, with high C:N ratios and typically low total N contents (Vanlauwe and Giller, 2006). Our research findings showcase the first use of a ferric-WTR and poor quality compost co-amendment as a cost-effective soil improvement technology to improve crop productivity through balanced nutrient provision, in sandy soils from Southern Africa.

Sandy soils are ubiquitous throughout Africa, where despite their low fertility and low water holding capacity, they support crop production in small-scale dryland systems. Dryland farming in sandy soil has a high risk of crop failure due water stress, which is exacerbated in nutrient-deprived plants (Steynberg et al., 1989). Infertile soils affect both plant growth and human nutrition. For example, communities solely subsisting on crops grown in sandy soils in Maputuland, South Africa, had elevated incidences of dwarfism and endemic osteoarthritis due to nutrient deficiencies (Ceruti et al., 2003).

The Cape Flats region, just outside Cape Town, has nutrient poor, sandy soils of aeolian origin. The area is predominantly occupied by low-income communities and hosts the largest informal settlement in the Western Cape (Statistics South Africa, 2016). Residential urban agriculture is uncommon, mainly due to lack of space, but also due to the nutrient poor soils and restricted access to irrigation water. However, in a community where unemployment levels are over 30% (Western Cape Government, 2017), backyard vegetable gardens can provide fresh produce to supplement the common maize staple. Thus, any improvement to the soils in terms of increased water holding capacity and nutrient provision, could stimulate backyard gardening, impacting community health and wellbeing. The Faure raw water treatment works is the main supplier of potable water to the City of Cape Town, producing approximately 14 000 tons Fe-WTR per year (personal communication, City of Cape Town Municipality, 2018), and lies physically close to the Cape Flats region. Currently Faure WTR is transported approximately 50 km to a local landfill site. Therefore, if the Faure WTR could be used to improve the Cape Flats soil it would be beneficial for both the municipality and the local inhabitants. In this study we focus on the contamination risks and plant response of WTR amendments and compare the effect of WTR and a typical low quality compost both added separately and as co-amendments on plant yield, bioavailable metals and plant nutrient levels in typical sandy Cape flats soil.

2. Materials and methods

2.1 Sample collection and characterization

Water Treatment Residual was obtained from Faure water treatment works, outside Cape Town. The main storage dam, and the only reservoir supplying Faure at the time of sampling, is the Theewaterskloof dam. The plant uses $Fe_2(SO_4)_3$, $Ca(OH)_2$, a chemical coagulant (Praestol 2540, a copolymer of acrylamide and sodium acrylate) and varying amounts of activated carbon for odour control (Titshall and Hughes, 2005). The resulting WTR is a mixture of ferric hydroxides, reservoir sediments, flocculated organic acids, coagulant and activated carbon. Samples of WTR were collected on three dates - 28 February, 9 May and 15 May 2017. During this period the Western Cape was experiencing a severe drought, and turbidity and odour levels were elevated due to the increased microbial blooms. This increased coagulant and activated carbon use during water purification. The three individual samples were air-dried (30°C, 1 month) before being crushed to pass through a 2 mm sieve. The three individual samples were chemically analysed to assess elemental variation, before being thoroughly combined for re-analysis and subsequent application in incubations, chemical analyses, and plant trials.

The commercially available compost used in this study is made from municipal green waste (chipped garden refuse) and was used and analysed without sieving. The total C and N content of the compost was analysed on a milled subsample.

The sandy soil was collected from a fallow field outside Brackenfell (Western Cape). The Quartzipsamment soils of this region are typical acid variants of the Cape Flats sands. These sands are windblown marine deposits, that have been leached of all carbonates, have an inherently low nutrient status and are mildly acidic (Schloms et al., 1983). The top 30 cm of soil was collected, air-dried and passed through a 2 mm sieve before analysis. Details of the basic characterization methods and statistical analysis are provided in the Supporting Information.

2.1.1 Trace element content and availability

Trace elements (TE) were measured in i) aqua regia (USEPA method 3015a), and ii) NH_4NO_3 (representing bioavailable fraction) following the DIN 19730 procedure (Herselman, 2013). Extracts, prepared in triplicate, were analysed for metals using ICP-MS with an Agilent 8800 QQQ ICP-MS.

2.2 Pre-Trial Incubation Analyses

Incubation profiles of pH, EC, Mn and P were assessed, to inform application rates. Six application levels (0, 10, 25, 50, 75 and 100%) of (a) WTR and (b) a 1:1 WTR-Compost mixture were added on a dry weight % basis to the soil. Each air-dried sample (50 g) was wet to field water capacity, covered in parafilm to prevent moisture loss and incubated at room temperature (± 25°C) in duplicate for two weeks. Samples were regularly weighed to confirm moisture retention. Samples were analyzed post-incubation for pH, EC, Mn and P as described in Supplementary Materials.

2.3 Pot Trials

Pot trials were set up to assess the impact of increasing application rates of WTR, compost and the WTR-Compost (WTR-Comp) co-amendment on wheat growth and elemental accumulation in nutrient-poor sandy soils. The application rates used were 0 (control), 1, 5 and 12.5% (w/w) for the single compost or WTR treatments and 0, 2, 10 and 25% (w/w) for the 1:1 WTR-Comp co-amendment. All treatments were prepared in triplicate. Pots (5 L) were packed to a bulk density of 1500 kg/m^3. Six wheat seeds (*Triticum aestivum L.*) per pot were planted and thinned to 3 plants per pot after germination. Pots were weighed and watered twice a week, maintaining field water capacity. Greenhouse pot placement was randomized and randomly re-organized twice during the 3-month trial. Pots were fertilized using the wheat recommendation of the Fertilizer Society of South Africa (FSSA, 2007) for Western Cape sandy soils (N = 130, P = 50, K = 75, Ca = 40, Mg = 13 and S = 40 kg/ha). The 500 mL fertilizer concentrate was added as three applications over the 3 month trial period.

2.4 Post-Trial Analyses

After 3 months of growth, the pot trial was terminated. The above-ground plant material was harvested by cutting the plant at soil level. Roots were weighed after soil material was removed. Plant material was oven-dried (60°C) overnight and weighed per pot. Total macro- and micronutrients of the dried above-ground plant material were determined using the Kjeldahl method (N), and acid digestion and ICP-MS (P, Ca, Mg, K, Na, Fe, B, Zn, Mn, Cu and Al; Elsenberg Plant Laboratory).

Soil from the pots was sieved (2 mm) to remove roots and air-dried. The NH_4NO_3 extractable metals (see Section 2.1), were measured on the pre- and post-trial soil mixtures.

3 Results and Discussion

3.1 WTR, Compost and Soil Characterization

The properties of the sandy soil, WTR and compost are given in Supplemental Table S1. The soil is mildly acid (pH_{water} = 6.5), with very low EC (64 µS/cm), total C (0.6%) and N (0.04%). The P level in the soil (52 mg/kg) is above the 33 mg/kg recommended for most crops (Mehlich, 1985). Bray II K levels in the soil are extremely low (9 mg/kg), falling well below the recommended 50 mg/kg for winter wheat production (FSSA, 2007). The WTR has a neutral pH in water (6.8) and low EC (319 µS/cm). The total C is 17%, which includes flocculated dissolved organic C and the added activated carbon. The total N content of the WTR is 0.35%, which is in the typical range for South African WTRs (0.02 – 0.52%), but lower than reported for Faure WTR in 2005 (0.52%; Titshall and Hughes, (2005)). Thus, the severe drought had not significantly increased the total N content of the WTR. The mineral N content (165 mg/kg) of the WTR falls within the range of typical WTRs in South Africa (Titshall and Hughes, 2005) and those reviewed by Ippolito et al. (2011). The Mehlich III P concentration in the WTR is within the lower region of the range reported by Dayton and Basta (2001), between 1.6 and 54.4 mg/kg.

The compost has a slightly alkaline pH_{water} (7.8), very high EC (5410 µS/cm) and a relatively low total C content (9.6%) for a compost. Despite an acceptable C:N ratio (25), the total N content of the compost (0.38%) falls well below the 1% threshold recommended in composts intended for fertilizer use (Barker, 1997). The mineral N content (7 mg/kg) of the compost is also very low, falling short of that required to support crop growth (50-200 mg/kg; (Mulvaney, 1996)). On the other hand, the compost has ample plant available K and P (145 and 2944 mg/kg, respectively).

The aqua regia metal concentrations of the three Faure WTR samples collected at different times are shown in Supplemental Table S2. Iron is the dominant metal (14-19%), with substantial Al concentrations (5.3- 7.7%). Manganese is variable (0.05 – 0.29%) but lower than the values reported by Titshall and Hughes (2005) for Faure WTR in 2005 (0.7 and 1.8%). The source of Mn in the Faure WTR is anticipated to be from impurities in the ferric sulphate or lime used during the water treatment process (Titshall and Hughes, 2005). The lower Mn values measured in this study suggests that purer sources or lower quantities of these additives are currently being used. With the exception of Mn, Zn and Ni, which were higher in summer (February), the trace elements in the WTR do not differ substantially between sampling dates. The metal concentrations of all samples are well below both the United States Environmental Protection Agency (USEPA, 2000) and the more conservative South African guidelines (Herselman, 2013) for the maximum allowable limits for land application.

The bioavailable metals (NH_4NO_3 extract) for the soil, composite WTR and compost are given in Table 1. Prior to WTR land application in South Africa, receiving soils must be analysed for bioavailable metals to assess the soils' suitability for receiving waste (Herselman, 2013). The Cape Flats sand has metal concentrations far below the maximum limit permitted for soils that will receive WTR (Herselman, 2013). The pure WTR had slightly elevated bioavailable Mn concentrations (17 mg/kg). There are no plant micronutrient thresholds for NH_4NO_3 extracts, so Mehlich III extracts of the soil, compost and WTR were analyzed. The Mn concentrations in the Mehlich III extracts were 2.2 (±0.2), 22.9 (±0.7) and 124.0 (±2.6) mg/kg for the soil, compost and WTR, respectively. The available Mn in the soil is well below the critical minimum level required for crop growth (10 mg/kg; (Sims and Johnson, 1991)) and Mn deficiencies could be expected. There are no clear guidelines for phytotoxic Mn levels in soils, but application of the WTR in the Cape Flats sand up to rates of 10% (w/w) would bring the Mn concentrations close to the minimum critical level. The compost contained a very high bioavailable As concentration (141 µg/kg), which may be due to pesticide residues in municipal green waste or inclusion of treated wood in the composted material (Adriano, 2001). This compost was selected for its low C and N content. The elevated As was an unexpected property of the widely used compost, and although it adds an interesting aspect to the study, the emphasis is on metals in the WTR, rather than metals in an inherently variable compost stream.

3.2 Pre-Trial incubation studies

Prior to the pot trial design, 14-day incubations were performed at field water capacity with i) WTR and ii) a 1:1 WTR-Compost co-amendment added to the sandy soil, at 6 application rates between 0 and 100% (dry w/w). The results of the incubation studies (Figure 1) provide insights into the effects extreme loadings of WTR and WTR-Compost co-amendments might have on important soil parameters. Both WTR and the co-amendment increased pH (Figure 1a), which would benefit acid soils, although increasing the pH above 7.5 is undesirable as it can result in trace element deficiencies (Havlin et al., 2005). The higher pH readings in the incubation studies, compared to the initial characterization (Supplemental Table S1) is assigned to longer equilibrium times during the incubation. At higher loadings the 1:1 WTR-Compost co-amendment exceeded 500 µS/cm (Figure 1b) which is considered the critical EC level (in a 1:5 water extract) where plant growth is affected negatively (Sonmez et al., 2008). The compost is likely to be the main contributor to salinity with an EC > 5000 µS/cm (Supplemental Table S1). To keep EC within tolerable levels, the 1:1 WTR-Compost co-amendment loadings should be below 25%. The high P-sorption potential of the WTR is evident from the incubations (Figure 1c) and increases with WTR application rate in the single amendment. However, compost co-addition increases plant-available P suggesting that the compost might alleviate this limitation to a degree. Bioavailable Mn concentrations increase linearly with increasing loading rates (Figure 1d). These incubation results suggest that maximal application rates should be kept below 25% WTR to prevent phytotoxic Mn conditions developing in the soil. Based on these incubation studies the maximum WTR application rate was set at 12.5% and the WTR-Comp co-amendment was set at 25%.

Figure 1 Pre-trial incubations, investigating the effect of increasing application rates of WTR and a 1:1 WTR-Compost (WTR:Comp) co-amendment on (a) pH, (b) EC (c) P (Mehlich III) and d) Mn (Mehlich III). Average of duplicate incubations shown.

3.3 Pot Trial: Post-Harvest Plant Physiology and Chemistry

The above- and below-ground biomass of the treatments are shown in Figure 2a and b, respectively. The WTR-Comp co-amendment resulted in significantly higher (up to 33%; $p<0.05$) above-ground biomass than the control at the two highest application rates (10 and 25% WTR-Comp). The individual compost and WTR treatments had a significant negative effect on above-ground biomass (up to 50% lower), with biomass concomitantly decreasing with increasing amendment rates (Figure 2a). The below-ground biomass for the highest amendment loadings showed a similar pattern, significantly lower root biomass in the single amendments than the control, while the co-amended treatment showed no significant difference to the control (Figure 2b).

Figure 2 The effect of single WTR (W) and compost (C) amendments, and co-amendments (WC), on plant growth parameters, (a) total above-ground biomass and (b) root biomass. Bars that do not differ significantly ($p<0.05$) contain the same letter.

At the end of the trial, plants in all treatments except for the 12.5% WTR started to show N – deficiency symptoms through older leaf yellowing and senescence despite fertilizer application. Plants in the 12.5% WTR treatment did not show deficiency symptoms, due to the fact that this treatment was significantly stunted (Figure 2a) and thus utilized less of the applied N, which was confirmed by the leaf N-levels (Figure 3a). Although plants from all treatments were well below the critical N-level (3%) for wheat (Plank and Donohue, 2000), the 12.5% WTR treatment had the highest N weight percent, followed by the 5% WTR treatment. The highest co-amendment (25% WTR-Comp) showed significantly higher (30%; $p<0.05$) leaf N-levels than the control, despite these plants being 33% larger. The compost amended treatments all showed similar leaf N-levels to the control, although plants in the higher loadings were severely stunted (Figure 2a).

Figure 3 Foliar macronutrient contents of harvested wheat plants as a weight percentage a)-c) and as absolute accumulation in grams d)-f) for WTR (W), compost (C) and WTR+Compost (WC). Critical macronutrient levels for wheat (Plank and Donohue, 2000) shown by red lines. Bars that do not differ significantly ($p<0.05$) contain the same letter.

The leaf P-levels showed the opposite trend to the N-levels, with the two lowest single WTR amendments having significantly lower leaf P-levels than the control while all single amendment compost treatments had significantly higher P-levels than the control (Figure 3b). The two highest co-amended treatments did not show a significant difference to the control in terms of P content. All treatments were above the 0.15% critical level for P in wheat (Plank and Donohue, 2000), except for the two lowest WTR treatments. The slightly higher P content of the 12.5% WTR treatment is attributed to smaller plant size. Potassium levels are generally below the critical level of 2% (Plank and Donohue, 2000) but all treatments significantly increased the K level compared to the control (Figure 3c).

The poor plant response to the compost is not surprising, considering the low total and mineral N content of this material (Supplemental Table S1). The fact that the compost treatments performed worse than the control suggests that N-immobilization is taking place in these treatments. This is also illustrated by the total grams of N taken up by the plants (Figure 3d), which shows the plants in the compost treatment assimilated the lowest amount of nitrogen into their leaves. In contrast, the two highest co-amendments took up significantly more N than the control or the single WTR treatments. The same trend is observed with the absolute amount of P in the leaves (Figure 3e). While the single compost treatments showed the highest weight % P (Figure 3b), the co-amendment treatments showed higher absolute P-levels, because the biomass of these plants was greater. The same was true for K accumulation (Figure 3f).

When interpreting these growth response results in light of the nutrient contents in the compost and WTR it is clear that both amendments are providing different macronutrients, with the WTR adding mineral N while the compost contributes P and K. Although total provision of nutrients by the co-amendment is likely to be the main cause of improved growth, there is also the potential for the organic matter from the compost to sorb to the WTR surface and prevent the fixation of added P to the oxide surfaces (Havlin et al., 2005).

The foliar micronutrient and Al levels of the wheat plants are given in Figure 4. Foliar Mn in the control is at the lowest critical limit for wheat growth (Figure 4b). Addition of compost with WTR at 25% had the largest effect on foliar Mn, raising the concentration to sufficiency levels (20-150 mg/kg). This increase was significantly greater than addition of WTR alone, indicating a synergistic effect on plant uptake of Mn in the co-amendment. Possible reasons for this synergy include lowering of the redox potential in the soil and addition of Mn-associated microbiomes, which may aid in Mn mobilization in the rhizosphere (Rengel, 2015). Manganese is often flagged as a possible problematic metal in WTR (Novak et al., 2007; Titshall and Hughes, 2005). The incubation experiments also indicate that Mn phytoxicity might be an issue at higher loadings (Figure 1d). The foliar analysis shows that even at the highest levels of WTR application (12.5%), the foliar Mn concentrations were only at sufficient levels and far below the toxicity threshold (380 mg/kg) for small grains (Keisling et al., 1984). Thus, for nutrient poor soils, such as the Cape Flats sands, WTR-Compost co-amendments could constitute an important source of Mn plant nutrition although careful monitoring under field conditions would be required if repeated WTR additions were made to such a sandy soil.

Figure 4 Foliar micronutrient and Al concentrations provided with critical values for wheat production (Plank and Donohue, 2000) and Al toxicity threshold (Pais and Benton Jones, 1997) for WTR (W), compost (C) and WTR+Compost (WC). Bars that do not differ significantly ($p<0.05$) contain the same letter.

Aluminium constitutes up to 7.7% of the WTR used in this study (Supplemental Table 2), thus Al toxicity in plants was considered a potential risk when applying the material to an acid soil. Only treatments with the highest loading of WTR (12.5% WTR and 25% WTR-Comp) showed a significant increase in foliar concentrations (Figure 4f) and these were well below (less than half) the Al toxicity level for crops (Pais and Benton Jones, 1997).

3.4 Pot Trial: Bioavailable trace elements

Bioavailable TE were measured before and after the pot trial on selected treatments (Table 2). Before the trial B, Mn, Fe, Ni, Cu and As concentrations were significantly higher ($p < 0.05$) in the 25% WTR-Comp treatment while Al, Zn and Cd concentrations were significantly lower ($p < 0.05$) compared to the Before-trial control. Before-trial WTR and WTR-Comp treatments had significantly lower Pb, while compost on its own had significantly higher Pb ($p<0.05$) than the Before-trial control. The higher TE bioavailability before the trial is attributed to the higher TE content of the amendments (Table 1), while the lower Al, Zn and Cd availability is most likely due to an increased pH in the soil system (Figure 1a).

When adding a waste to a soil, it is important to consider any mobilizing effects plant growth might have on the bioavailability of metals, thus before and after trial comparisons were made. The TE either showed no change or significantly decreased in bioavailability after the trial (Table 2). For all the compost- and WTR-treated soils, extractable Mn concentrations were significantly lower after the pot trial. Importantly, phytotoxic Al was not mobilized and either showed little change or decreased during the trial.

Plant available As levels were elevated in the compost (Table 1) and, for the 12.5% compost treatment, levels were beyond the threshold for soils to receive additional WTR (Herselman, 2013), both before and after the pot trial. Pre-trial As concentrations (11.7 µg/kg) in the 25% WTR-Comp were significantly lower ($p<0.05$) than in the pre -trial 12.5% compost treatment (29.3 µg/kg). This is attributed to the capacity of WTR to strongly chemisorb As (McCann et al., 2018; Sarkar et al., 2007) and suggests WTR addition to an As-rich compost could reduce bioavailable As content.

With the exception of As in the compost treatment, the bioavailable TE measured after the trial were substantially below the maximum extractable threshold for receiving soils (Table 2). In addition, all TE concentrations are far below the soil screening guidelines for the protection of water sources (Table 2) thus the risks of trace metal contamination of ground- and surface water, even at very high WTR application rates, measured under pot trial conditions, appears low. The maximum rates applied in this trial are unrealistically high (375 tons WTR + 375 tons compost/ha), but suggest multiple applications of WTR at lower rates would keep TE levels within guideline levels. Further work is required to establish responsible application rates for WTR-Compost amendments. In addition, elevated As in the compost, highlights the importance of screening the compost used as a co-amendment for known contaminants.

3.5 Implications for WTR-Compost co-amendments

In African small-scale farming systems, organic residues are often available but are of poor quality with high C:N ratios and/or low total N (Vanlauwe and Giller, 2006). The compost used in this study was of extremely poor quality, with low total C and N contents, high salinity and unacceptably high As levels. Addition of WTR to this compost provided mineral N, increased certain deficient trace elements and decreased the bioavailable As content, creating a more favorable growth medium than compost on its own. The compost, in turn, provided K and countered or reduced P-sorption tendencies of the WTR.

The mildly acidic sandy soils used in this study are ubiquitous in Africa (Jones et al., 2013) and communities relying solely on these soils for food are at greater risk of malnutrition due to insufficient soil micronutrients (Ceruti et al., 2003). Our results suggest that WTR-Compost co-amendments show potential to improve crop productivity where the two materials are abundantly available and within the context of considering transport costs versus economic and social benefits of improved soil function.

The potential risks associated with land application of wastes are contamination of soil and groundwater resources (Pritchard et al., 2010). Sandy soils lack clays and sesquioxides, which sequester contaminants and often buffer the soil and underlying groundwater against contamination. Sandy soils, especially the acid variants, are considered high risk for land application of wastes (Pritchard et al., 2010). Provided that the sandy soils are well drained to maintain aerobic conditions, addition of sesquioxide-rich WTR could in fact increase the buffer capacity of such soils. The results obtained here suggest that even at extreme loadings (375 ton WTR/ha), contamination risks from heavy metals are low, although these need to be verified under field conditions using multiple WTR applications.

Wheat was used in this study as an indicator crop, however, in subsistence agriculture leafy greens are frequently grown to supplement the maize staple. Leaf nutrition and metal uptake in edible leaves needs to be determined in assessing the safety of WTR land application. In addition, there are other potential toxicity risks of WTR land application, which are seldom addressed. These include microbial contamination from polluted water sources, phyto-uptake and toxicity of micropollutants (e.g. pharmaceuticals, pesticides, plasticizers), as well as the toxicity of the chemical additives used in coagulation and flocculation. All of these risks should be investigated before large-scale land applications of WTR are permitted on susceptible sandy soils.

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Supplementary Material includes description of basic characterization methods, statistical methods and characterization data for materials used

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Figure Captions

Figure 5 Pre-trial incubations, investigating the effect of increasing application rates of WTR and a 1:1 WTR-Compost (WTR:Comp) co-amendment on (a) pH, (b) EC (c) P (Mehlich III) and d) Mn (Mehlich III). Average of duplicate incubations shown.

Figure 6 The effect of single WTR (W) and compost (C) amendments, and co-amendments (WC), on plant growth parameters, (a) total above-ground biomass and (b) root biomass. Bars that do not differ significantly ($p<0.05$) contain the same letter.

Figure 7 Foliar macronutrient contents of harvested wheat plants as a weight percentage a)-c) and as absolute accumulation in grams d)-f) for WTR (W), compost (C) and WTR+Compost (WC). Critical macronutrient levels for wheat (Plank and Donohue, 2000) shown by red lines. Bars that do not differ significantly ($p<0.05$) contain the same letter.

Figure 8 Foliar micronutrient and Al concentrations provided with critical values for wheat production (Plank and Donohue, 2000) and Al toxicity threshold (Pais and Benton Jones, 1997) for WTR (W), compost (C) and WTR+Compost (WC). Bars that do not differ significantly ($p<0.05$) contain the same letter.

Tables

Table 1 Bioavailable trace element concentrations (μg/kg) in the pot trial materials, together with threshold limits for metal concentrations in the soil where WTR will be applied (Herselman, 2013)

Element	Receiving soil limit	Soil	WTR	Compost
B		31.5	188.7	659.0
Al		208.7	60.3	2473.1
Mn		194	17000	343
Fe		126.8	130.8	1534.2
Ni	1200	3.3	94.7	19.5
Cu	1200	9.8	363.6	113.9
Zn	5000	57.6	100.0	96.3
As	14	1.7	30.1	141.3
Cd	100	0.2	0.5	0.3
Hg	7	0.03	<0.05	0.06
Pb	3500	1.0	1.4	5.1

Table 2 Trace element concentrations in 1M NH_4NO_3 extracts of selected soil treatments analyzed before and after the wheat pot trial.

Element	Receiving soil limit[a]	Soil Screening values[b]	Control		12.5% Compost		12.5% WTR		25% WTR+Comp	
			μg/kg							
	μg/kg	mg/kg	Before	After	Before	After	Before	After	Before	After
B			31.5	32.5	215.3	176.7	26.0	26.6	152.7*	100.8
Al			208.7	191.6	146.4*	111.6	28.3	23.9	67.5*	44.3
Mn			194.3	173.8	283.2*	101.9	3931.6*	404.8	2292.6*	473.9
Fe			126.8	110.3	371.8*	309.2	52.7	32.5	252.2*	133.2
Ni	1200	91	3.3	3.4	5.8*	4.7	8.4	7.6	9.9	9.4
Cu	1200	200	9.8	20.1	60.2	57.9	29.5	29.6	37.2	34.3
Zn	5000	3700	57.6	51.3	44.6*	33.0	19.4*	10.2	23.2*	13.6
As	14	5.8	1.7	1.9	29.3	17.4	4.8*	1.7	11.7*	4.1
Cd	100	7.5	0.16	0.18	0.13*	0.08	0.08	0.04	0.09	0.06
Hg	7	1	0.03	0.03	0.04	0.05	0.02	0.01	0.03	0.02
Pb	3500	20	1.02	1.29	1.89*	1.24	0.11	0.11	0.14	0.13

[a.] According to (Herselman, 2013); [b] South African Soil screening values for the protection of water sources using a dilution factor of 20 (DEA, 2010)

*Marks significance between Before and After concentrations at a 95% confidence limit, for comparisons made between treatments p values are provided in the text.