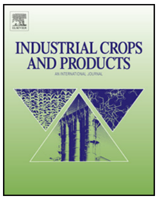
Industrial Crops and Products xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Industrial Crops and Products

journal homepage: www.elsevier.com/locate/indcrop



Wastewater reuse for fiber crops cultivation as a strategy to mitigate desertification

Bruno Barbosa[a], Jorge Costa[a], Ana Luisa Fernando[a,*], Eleni G. Papazoglou[b]

[a] *UBIA, Departamento de Ciências e Tecnologia da Biomassa, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, Campus de Caparica, 2829-516 Caparica, Portugal*
[b] *Agricultural University of Athens, Laboratory of Systematic Botany, Department of Crop Science, 75 Iera Odos, 11855, Athens, Greece*

ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form 29 June 2014
Accepted 2 July 2014
Available online xxx

Keywords:
Fiber crops
Wastewater reuse
Water resources
Desertification
Biodiversity loss
Soil conservation
Sustainable management
Sustainable irrigation

ABSTRACT

Combating desertification, a marked problem in arid, semi-arid and other desertification-affected areas of the world, encompasses the management of water resources and the conservation of soil properties. Establishing vegetation on land and reuse of wastewaters in irrigation may be advantageous as a strategy to mitigate desertification and biodiversity loss. In this context, fiber crop production under wastewater irrigation is reviewed, with the aim of identifying prospects and limitations. Reports of laboratory, pilot and field research indicate that bast and grass fiber crops show potential simultaneously to deliver high yields, restore soil properties and promote water quality improvement. Their production in water-scarce regions could provide environmental benefits and social and economic opportunities, safeguarding freshwater resources. Nevertheless, this practice has environmental and social concerns due to the presence of harmful substances in wastewater. Several technical and economic barriers should also be considered when designing and managing a system, such as wastewater quality, and the quantity and quality of biomass produced. In order to promote the sustainable reuse of wastewater for irrigation of fiber crops, further research is needed, factoring in issues such as yields, inputs and costs, as well as potential environmental and socio-economic impacts. It is recommended that site-specific factors should be accurately assessed to evaluate the adequacy among crop, location and wastewater irrigation, in order to overcome negative impacts and public rejection.

1. Introduction

Desertification is the process that leads to the loss of ecosystem services in arid, semi-arid and dry sub humid areas caused by climatic variation and by anthropogenic activities, affecting one-quarter of the world's land surface, containing one-fifth of the world's population (UNCCD, 1994). This process involves the loss of biological or economic productivity and biodiversity, and has political and socio-economic implications (Barbero-Sierra et al., 2013; Yang et al., 2005). The rapid spread of desertification is mainly due to non-sustainable anthropogenic activities, such as overcultivation and overgrazing, fuel gathering, deforestation and ineffective irrigation and land management practices. In areas suffering from desertification, the main environmental consequences are a permanent imbalance in water availability, damage to soil, increased flash flooding, loss of riparian ecosystems, changes in vegetation pattern and structure, and deterioration of the ecosystem's carrying capacity (Millennium Ecosystem Assessment, 2005; Pereira et al., 2002; Li et al., 2006).

More specifically, regions disturbed by desertification are characterized by an imbalance between water needs and water reserves, resulting in the frequent reuse of non-conventional waters. Wastewater is any water that has been adversely affected in quality by anthropogenic influence, and it has been used as a source of irrigation water for centuries. Irrigation with treated wastewater in agriculture combines several advantages, such as: offering a low cost water source, eliminating part of the demand for synthetic fertilizers by its fertilizing properties (fertirrigation), increasing the available agricultural water resources and eliminating the need for expensive tertiary treatment (Angelakis et al., 1999). Nevertheless, its utilization may involve many risks and in some cases public acceptance is difficult. Wastewater quality should satisfy agronomic and public health protection requisites and should not be a vehicle for harmful substances, especially if these substances exacerbate desertification. According to Monte and Albuquerque (2010), salinity and dissolved inorganic salts, suspended solids, biodegradable organic matter, refractory organic

---

* Corresponding author. Tel.: +351 212948543; fax: +351 212948543.
E-mail addresses: ala@fct.unl.pt (A.L. Fernando), elpapazo@aua.gr (E.G. Papazoglou).

http://dx.doi.org/10.1016/j.indcrop.2014.07.007
0926-6690/© 2014 Elsevier B.V. All rights reserved.

compounds, heavy metals, nutrients, pH, residual chlorine and pathogenic microorganisms, are the most important characteristics of wastewaters to be controlled since they are associated with most of the water quality problems derived from its reuse in agriculture.

One of the options to mitigate desertification is the introduction of alternative livelihoods that may have less negative impacts on dryland resources, or the creation of economic opportunities in these lands by introducing a vegetative cover that might restore soil properties and increase biodiversity (Chiaramonti et al., 2000; Cortina et al., 2011; Hooke and Sandercock, 2012; Millennium Ecosystem Assessment, 2005; Mohammad and Adam, 2010; Qadir et al., 2007).

The demand for natural fibers has increased sharply due to their diverse uses and industrial applications, such as textiles, papers, woven clothes, mats, hats, ropes and cordage material, as well as in composite applications for the automotive and construction industries (Akil et al., 2011; Ardente et al., 2008; Faruk et al., 2012; Pandey and Gupta, 2003). Even though production of fiber crops sustains employment and income in many regions, the intensive use of land may lead to soil nutrient and water depletion, as well as to degradation and pollution. These impacts are very important, especially in water-scarce regions, where the competition for land and water among agriculture, industry and urbanization are leading to environmental desertification (Barbero-Sierra et al., 2013; Portnov and Safriel, 2004). Therefore, fiber crop production in desertified areas should be established in a sustainable multiple-crop rotation system.

Additionally, water and land resources must be included in an integrated management strategy in order to ensure food and water security, as well as biological and landscape diversity. In this context, the use of non-conventional water, such as domestic and agro-industry wastewaters, in the irrigation of fiber crops could reduce the cost of their cultivation, meet their growing water demands, preserve freshwater supplies and reduce the contamination of water bodies (Cirelli et al., 2012; Norton-Brandão et al., 2013; Qadir et al., 2007; Zema et al., 2012). In order to be sustainable and to conserve, mitigate or reverse desertification, the established species should display low water and nutrient demands, present commercial value for a specific region, have few environmental constraints, no competition with food crops, and be integrated with waste management (Laraus, 2004; Kassam et al., 2012; Norton-Brandão et al., 2013).

This article reviews the potential of fiber crops to mitigate, control and reverse the desertification process in susceptible areas through re-utilization of non-conventional sources of water. In the discussion, benefits and constraints of wastewater reuse in the irrigation of fiber crops are highlighted and prospects and recommendations are presented.

2. Production of fiber crops irrigated with wastewaters: case studies

There has been a growing interest in crops from which natural fibers are taken, resulting in a growing market for biodegradable and recyclable materials. In order for their cultivation to be sustainable and economically viable, suitable fiber crops with low input requirements should be selected.

Crops such as jute, hemp, kenaf and sisal are cultivated mainly for their fiber content, while from other plants, such as pineapple, palm and coir, fibers are produced as by-products (Faruk et al., 2012). There are different types of natural fibers: (a) bast fibers made from the phloem of plants such as jute, flax, hemp, ramie and kenaf; (b) leaf fibers such as from abaca, sisal and pineapple; (c) fibers from seeds of plants, such as coir, cotton and kapok; (d) core fibers such as from kenaf, hemp and jute; (e) grass and reed fibers, such as from wheat, corn and rice, and (f) all other wood and roots crops (Faruk et al., 2012).

In this work, the production of bast and grass fiber crops when irrigated with wastewater is reviewed.

2.1. Wastewater reuse on bast fiber crops

Bast fiber crops are generally annual crops and when cultivated in marginal, desertified and degraded lands can enhance soil fertility and structure, increase soil organic matter content, help in controlling erosion and increase biological and landscape diversity (Fazio and Monti, 2011; Fernando et al., 2010; Finnan and Styles, 2013; Zegada-Lizarazu and Monti, 2011). Generally, they have low establishment cost and can be cultivated under rotation systems with other food or economically valuable non-food crops. Their insertion into a crop rotation can improve yield and profitability over time, control diseases and weeds, limit insect and other pest infestations, provide an alternative source of nitrogen and increase soil organic matter, reduce soil erosion and runoff of nutrients and chemicals, and the potential for contamination of surface water. An additional benefit is gained if the selected crop is simultaneously a source of biomass for both fiber and bioenergy.

The effects of wastewater reuse on kenaf (*Hibiscus cannabinus* L.), hemp (*Cannabis sativa* L.) and nettle (*Urtica dioica* L.) have been reported (*e.g.*, Adler et al., 2008; Fernando et al., 2011; Sinha et al., 2006). These works focus mainly on the capacity of these crops to remove contaminants from wastewaters, with information on growth and yield responses. Especially in water-scarce regions, the potential to reuse wastewaters in the irrigation of bast fiber crops seems promising and will contribute to preserving freshwater supplies.

The growth responses and the biomass quality and productivity of kenaf irrigated with wastewater with different ammonium, nitrate and phosphate concentrations were studied (Fernando et al., 2011, 2012, 2013). The results showed that irrigation with wastewater enriched with nitrates (up to $100\,\mathrm{mg\,dm^{-3}}$ NO_3) or phosphates (up to $2.4\,\mathrm{mg\,dm^{-3}}$ P) did not affect the growth and productivity of kenaf (with an average yield of *ca.* $700\,\mathrm{g\,m^{-2}}$ (dry weight) for the aerial tissues). Wastewater with increased levels of ammonium up to $30\,\mathrm{mg\,dm^{-3}}$ NH_4^+, did not affect the biomass productivity either. In contrast, application of a higher amount of ammonium ion, $60\,\mathrm{mg\,dm^{-3}}$ NH_4^+, negatively affected plant biomass productivity. The bulk supply of ammonium ion and its concomitant absorption by the plants may lead to acidification of the rhizosphere, affecting the availability of other nutrients, and the enzymes of the cytosol. Concerning the biomass quality, irrigation with wastewater correlated with an increased uptake of minerals, nitrogen and phosphorus by the crop, a fact that may penalize its use for combustion purposes but not for biomaterials, since the total fiber content is not affected. These studies also suggested that excess nitrates, phosphates and ammonium ion in wastewater are easily trapped and accumulated by the kenaf root system, avoiding contamination of groundwater resources. These findings are consistent with those of Abe and Ozaki (1998, 2007) and Davison et al. (2006), who also indicated that kenaf is a good candidate plant for nutrient removal from wastewater in constructed wetland systems. However, Abe and Ozaki (2007) stated that low dissolved oxygen affects the rate of nutrient removal by kenaf. Moreover, kenaf is described as opportunistic in relation to water availability, with a high rate of stomatal conductance and transpiration rate when water is not limited, and a markedly reduced stomatal conductance and transpiration rate when water availability is restricted (Fernando, 2013; Patanè and Sortino, 2010; Scordia et al., 2013). This is a relevant trait of this crop to be explored in water-scarce regions when wastewater availability (in terms of volume) is low.

Please cite this article in press as: Barbosa, B., et al., Wastewater reuse for fiber crops cultivation as a strategy to mitigate desertification. Ind. Crops Prod. (2014), http://dx.doi.org/10.1016/j.indcrop.2014.07.007

Hemp was also tested for wastewater remediation purposes. In constructed wetland systems, Davison et al. (2006) reported an uptake of up to 239 kg N ha^{-1}, and Nivala et al. (2007) described the effective treatment of landfill leachates through nutrient removal. Sinha et al. (2006) also specified the ability of this crop to remove heavy metals from tannery wastewater (presenting 3.2 mg dm^{-3} Cr among other heavy metals).

Some studies reported nettle as a potential species for developing a low cost and energy-saving wastewater treatment technique in combination with resource recycling and amenity functions. Nivala et al. (2007) utilized nettle in a constructed wetland system to treat landfill leachates for nutrient removal and Izydorczyk et al. (2013) employed nettle in a vegetable buffer zone to reduce diffuse phosphorus pollution (>3.0 mg PO_4 dm^{-3}) in the Sulejow Reservoir of the Pilica River (Poland). In the Polish study, yield was 134 g m^{-2} (dry weight) for the aerial tissues and the plants removed 32 kg ha^{-1} N and 8.8 kg ha^{-1} P during one growing season. Teuchies et al. (2013) registered a productivity of 0.267 Mg ha^{-1} in nettle biomass in the Schelde estuary, a eutrophic area in Belgium and the Netherlands, characterized by high heavy metal concentrations, suspended solids and sediments. Simultaneously, nettle was capable of extracting the heavy metals and reducing the suspended solids, thus improving water quality.

Adler et al. (2008) investigated the suitability of nettle in the purification of nutrient-enriched wastewater and when exposed to landfill leachates, and compared its response to other plant species. The experimental treatments strongly affected plant growth. Compared to the control (irrigation with a balanced nutrient solution), total plant growth was reduced by 77% when plants were irrigated with municipal wastewater, and by 85% when exposed to landfill leachates. Nettle had the lowest growth rate among the tested species (*Salix* spp., *Populus* spp. and *Phragmites australis*).

In spite of the promising results obtained with annual fiber crops, due to their short growing season and the need to replant annually, it has been suggested that perennial crops are better candidates for both nutrient removal and biomass production purposes (Davison et al., 2006; Fernando et al., 2010).

2.2. *Wastewater reuse on grass fiber crops*

Halting soil degradation and desertification with cultivation of grass fiber crops has been argued as a promising solution (Dauber et al., 2012; Pidlisnyuk et al., 2014). Compared to annual bast fiber crops, perennial crops offer additional environmental advantages and provide a wider range of ecosystem services such as: higher ground cover, longer permanence in the soil, limit erosion, lower susceptibility to diseases, reducing pesticides needs, and due to their extensive rooting system they have high nutrient and water efficiencies, thus minimizing nutrient and contaminant leaching (Fernando, 2005; Fernando et al., 2010; Zhang et al., 2011). Combining these traits with wastewater recycling provides an efficient low-cost alternative to treating effluents and ensures economically viable fiber production for industrial uses, especially in regions where irrigation is required and freshwater supplies are limited.

Giant reed (*Arundo donax* L.) is highlighted by several authors as a suitable crop for combining biomass production with wastewater treatment. Literature refers to experiments with saline winery wastewater (9 dS m^{-1}) in saline soils (Williams et al., 2008), wastewaters contaminated with Zn (10 and 20 mg dm^{-3}) or Cu (1 and 2 mg dm^{-3}) (Costa et al., 2013), water containing Cd and Ni (5–100 mg dm^{-3}) (Papazoglou, 2007; Papazoglou et al., 2005, 2007), synthetic wastewaters contaminated with As (100 μg dm^{-3}) (Mirza et al., 2010), swine effluents in a closed gravel hydroponic system (Mavrogianopoulos et al., 2002), dairy processing factory wastewater with a median electrical conductivity of 8.9 mS cm^{-1} (Idris et al., 2012), domestic treated wastewater (Barbagallo et al., 2011), pre-treated wastewater (Tzanakakis et al., 2009), high salinity tannery wastewater in a wetland system (Calheiros et al., 2012), *etc.* All these works indicate the high crop adaptability and tolerance to different levels and types of pollution. Contamination was efficiently reduced and the biomass produced represented an additional opportunity for secondary income through its utilization. Moreover, although giant reed is commonly associated with riparian and wetland systems, this crop adapts well to a wide variety of ecological conditions, including water-stressed environments under semi-arid climates (El Bassam, 2010).

Other grass fiber crops have shown potential simultaneously to deliver high biomass yields, with high content of hemicellulose and cellulose, remove nutrients from wastewater and act as a carbon sink. Miscanthus (*Miscanthus spp.*), bamboo (*Bamboo sp.*), soft rush (*Juncus effusus* L.), and papyrus (*Cyperus papyrus* L.) are some candidate grasses, but they have been mostly used in constructed wetlands for contamination removal and less for water-scarce and semi-arid regions.

Bandarra et al. (2013) tested irrigation of Miscanthus (*M. sinensis*, *M. giganteus* and *M. floridulus*) with wastewater contaminated with Zn (10 mg dm^{-3}) or Cu (1 mg dm^{-3}). Additionally, Zhao et al. (2012) tested *Miscanthus sinensis* Anderss. in hypereutrophic water. In both studies, growth and productivity were not affected and pollutants were removed efficiently by the deep and extensive rooting system of plants.

Miscanthus violaceus (K. Schum.) and *Cyperus papyrus* were studied by Mugisha et al. (2007) in Nakivubo and Kirinya wetlands in Uganda. The Nakivubo wetland is dominated by both species and has been receiving wastewater from Kampala city for more than 30 years; Kirinya wetland is dominated by papyrus. Both plants were periodically harvested from both wetlands in order to obtain nutrient removal, water quality improvement and biomass for fiber purposes. Concerning the Nakivubo wetland, the re-introduction of papyrus reversed the eutrophication that resulted from the replacement of native papyrus by cocoyam and sugarcane cultivations (Kansiime et al., 2005). This emphasizes the importance of the ecological functions of papyrus, especially in environments where it is native.

The capacity of papyrus to store nutrients in its tissues, particularly when it is grown in nutrient-rich environments, seems to be higher than that of other macrophytes (Chale, 1987). According to Kyambadde et al. (2004), the root structure of *C. papyrus* provides high microbial shelter, sufficient wastewater residence times, traps suspended particles, provides adequate surface area for pollutant adsorption and assimilation in plant tissues, and oxygen for organic and inorganic matter oxidation in the rhizosphere. Papyrus is a crop with an enormous potential for producing high quality fiber products under different types of wastewaters, providing improvement of water quality, and high nutrient removal from domestic wastewaters, as well as from contaminated natural water bodies, swamps and wetlands (Abe and Ozaki, 1998; Chale, 1987; Kyambadde et al., 2004; Perbangkhem and Polprasert, 2010; Theophile et al., 2011).

Similar findings were described for bamboo and soft rush. Arfi et al. (2009) reported efficient removal of organic matter (99%) and nutrients (98%) by *Semiarundinaria fastuosa*, *Phyllostachys viridis* and *Phyllostachys viridis* "sulfurea", in a two-year experiment in a constructed wetland receiving winery wastewaters (8.7 g dm^{-3}, COD and 6.4 g dm^{-3}, BOD_5) in France. Sharma et al. (2005) also stated efficient removal of NPK by two-year old agroforestry plantations of bamboo developed in Australia, and irrigated with wastewaters. Tanner (1996) tested the growth and nutrient uptake of *Juncus effusus* in wetland systems enriched with ammonium organic wastewaters. Although the harvestable biomass was low, *J. effusus* biomass removed NP and K. Rahman et al. (2011) demonstrated the potential of *J. effusus* in the removal of As by testing a constructed wetland system under laboratory-scale horizontal-flow to treat synthetic wastewater, obtaining high As retention capacity (59–61%) of the total As inflow. These studies demonstrate the potential of these crops as an efficient treatment technique for contaminated wastewaters, combined with biomass production and water and nutrient resources savings.

3. Benefits and constraints of reuse of wastewater for fiber crop cultivation

In water-scarce regions, marginal-quality waters will become an increasingly important component of agricultural water supplies (Angelakis and Durham, 2008; Qadir et al., 2007; Trinh et al., 2013). Wastewater reuse for irrigation purposes counterbalances the scarcity or seasonality of rainfall, ensures groundwater recharge, allows the conservation of water resources (Kfir et al., 2012; Pereira et al., 2002; Plappally and Lienhard, 2012; Portnov and Safriel, 2004; Rebhun, 2004), reduces contamination of water bodies (Zema et al., 2012) and may also contribute to reducing the need for fertilizers due to the presence of nutrients in the effluent, with both environmental and economic revenues.

Furthermore, increased plant growth and yields due to wastewater reuse for irrigation may contribute to increase the amplitude of the energy balance, carbon sequestration, reduction of greenhouse gases, and net profit (Barbosa et al., 2013). The presence of a vegetative cover and the incorporation of crop residues into soils may restore soil properties (fertility, structure, organic matter), control erosion and increase biological and landscape diversity (Fernando et al., 2010). In addition, accumulated organic carbon represents an option for carbon credit programs (Williams et al., 2008).

Nevertheless, the reuse of wastewaters still involves much controversy, and does not always have public and stakeholders' acceptance. This is a fundamental precondition as support from local authorities depends largely on the dedication and commitment of local players. On the other hand, the production of fiber crops in rural areas could be a way to combat rural exodus, being a means of new employment and new opportunities (Barbosa et al., 2013). Additionally, wastewater recycling is gaining significance both in developing and developed countries, since these water sources can contribute to maintaining current agricultural activities, highlighting environmental and socio-economic opportunities for these areas. In many regions, the reuse of wastewater in agriculture is the only way to face eminent disaster induced by desertification, and associated biodiversity loss and poverty (Habib et al., 2013; Kharraz et al., 2012). This is particularly true in semi-arid areas which are likely to be affected by severe drought and possible extreme weather events (*e.g.*, prolonged heat waves, hail and storms), as recognized by Cosentino et al. (2012) for southern Europe, in view of forecasted climate change.

However, the reuse of wastewaters in the irrigation of fiber crops can also present some technical and environmental obstacles. These systems require management practices in order to approximate the nutrient load and its potential assimilation by the crop (Tzanakakis et al., 2009). Reclaimed water can serve as a reservoir of nutrients essential for plant growth, but when applied to the soil in excessive amounts may cause many problems, such as nutrient imbalances in surface and groundwater, excessive runoff and eutrophication (Jampeetong and Brix, 2009; Rittmann et al., 2011; Rivett et al., 2008). The rise of the water table should also be controlled by means of appropriate drainage when water load is excessive. Reuse of wastewaters may also result in an accumulation of contaminants in the soil, as observed by Bandarra et al. (2013). At the same time, effluents should be applied at rates capable of satisfying crop evapotranspiration in the tested region. Matching hydraulic loading and nutrient uptake in order simultaneously to treat water and produce economically viable biomass can be complex. Crops with high water-use efficiency should be used with wastewaters of high nutrient load, if pre-application treatment schemes to reduce nutrient concentration in the effluent is not an option, or the adjustment of nutrient application rates is difficult (Tzanakakis et al., 2009). Constructed wetlands comprising fiber crops could be used as an additional treatment to reduce nutrient loads, being introduced after secondary treatment in wastewater treatment plants. Implementing this strategy could improve water quality and reduce risks in the irrigation of fields, as well as produce fiber crops in both systems (Tzanakakis et al., 2009).

Effluent availability in terms of volume, especially of domestic wastewater from rural areas with low population, may not match the crop's water needs. To adequately respond to this problem, Barbagallo et al. (2011) and Costa et al. (2013) tested *A. donax* under different irrigation regimes to evaluate the ratio of yield reduction to wastewater load reduction. The variability of effluent production and quality over time may also be a barrier. In the Mediterranean area, for example, there may be an excess of water load in the rainy season, from precipitation and pluvial waters from treatment plants, with a shortage of water in the summer. Adjustment of the growing season to the total yearly wastewater production is also mandatory, especially for annual fiber crops, or when irrigation is required on a supplementary basis only. Storage facilities may be needed during the non-growing period/non-irrigation period either at the farm or near the wastewater treatment plant.

In order to reuse wastewaters in the irrigation of fiber crops, land should also be available for the crop's cultivation, and land use changes should be monitored to avoid negative environmental and socio-economic impacts (Dauber et al., 2012; Fritsche et al., 2010). The distance between the wastewater treatment plant and the field is also a key point in systems design; the greater the distance, the higher the costs associated with effluent transport. According to Malveiro (2013) for the cultivation of *A. donax* and Miscanthus in Portugal, the distance between the field and treatment plant should be less than 3.82 km in order to cover the maintenance costs with the biomass being produced.

Wastewater should satisfy the agronomic and public health quality legislation and should not carry harmful substances. To address these concerns, the World Health Organization (WHO) developed guidelines for safe use of wastewater (WHO, 2006). Many countries adopted WHO guidelines or developed their own policy and water management strategies which are closely dependent on their own crop systems needs and available technologies.

High concentrations of total suspended solids can cause blockages in watering systems (Monte and Albuquerque, 2010) and affect soil hydraulic properties, such as by blocking water-conducting pores (Lado and Ben-Hur, 2009). High salinity in wastewater hampers the proper development of many plants. Sodium, boron and chlorine can be toxic to plants, and, in particular, sodium can induce soil pore blockage, and reduce soil permeability, leading to waterlogging, poor plant performance, salinization and decreased leaching (Muyen et al., 2011). Selection of more tolerant crops, irrigation methods that reduce salt levels or crop exposure to salts, or increase leaching (to prevent excess of salts in the root zone), and other management practices, *e.g.*, application of calcium-supplying amendments, are some of the options to relieve salinity toxicity (FAO, 1992). Desalination of reclaimed wastewater using membrane processes may prevent salinization of soils and groundwater, but this process remains very expensive and does not represent an appropriate option (Rebhun, 2004). pH is also important, since it may affect metal solubility and soil alkalinity. The presence of pathogens can also represent a barrier to the use of the wastewater due to the risk of disease transmission.

The presence of persistent organic compounds, heavy metals, chloride and excess nutrients, such as nitrogen, may also limit the

Please cite this article in press as: Barbosa, B., et al., Wastewater reuse for fiber crops cultivation as a strategy to mitigate desertification. Ind. Crops Prod. (2014), http://dx.doi.org/10.1016/j.indcrop.2014.07.007

Table 1
Overview of the main benefits and constraints related to the use of wastewater in the irrigation of fiber crops.

Benefits	Constraints
• Fulfillment of growing water demands	• Low effluent availability in terms of volume to match crop needs
• Scarcity/seasonality of rainfall is counterbalanced	• Matching hydraulic loading and contaminant remediation by the crop
• Preservation of freshwater supplies	
• Groundwater recharge	• Variability of effluent production and quality over time
• Minimization of fertilizer needs	
• Reduced energy use and chemical pollution from wastewater treatment	• Distance between wastewater treatment plant and fields
• Restoration of soil properties	• Availability of land
• Biological and landscape diversity increment	• Land use change
• Reduced contamination of water bodies	• Matching effluent production with crop-growing season
• Nutrient and water resource recycling	• Need for a storage facility for wastewater
• Increased plant growth and productivity	• Leaching and runoff of contaminants to water bodies
• Increased carbon sequestration	
• Increased energy savings	• Accumulation of contaminants in the soil
• Reduction of GHG emissions	
• Creation of economic opportunities in water-scarce regions	• Wastewater quality may limit its application
• Economically viable use of biomass	• Yields can be affected
• Reduction of cultivation costs	• Biomass quality may limit its industrial use
• Reduction of water treatment costs	
• Prevention of rural exodus	• Reduced public and stakeholders' acceptance
• Creation of employment	

use of effluent for irrigation (FAO, 1992; Monte and Albuquerque, 2010). In fact, the presence of toxic compounds, *e.g.*, heavy metals, in wastewater may give rise to elevated levels in the soil and groundwater, and lead to undesirable accumulation in plant tissue and reduction of crop growth. Furthermore, increased ash, metal or nitrogen content in the biomass due to irrigation with wastewater may limit or dictate options for its industrial use.

Table 1 gives an overview of the main benefits and constraints related to the use of wastewater in the irrigation of fiber crops.

4. Conclusions and recommendations

This study provides a scientific background in support of wastewater reuse for fiber crop cultivation as a strategy to mitigate desertification. Review of the pilot and field work indicates that the establishment of fiber crops in degraded lands, combined with wastewater irrigation, represents an opportunity to produce sustainable biomass in water-scarce regions. Protection of freshwater resources, with improvement of soil properties and of rural development, are some of the environmental and socio-economic benefits that were identified. With extensive root systems, grass fibers (and to a lesser extent, bast fibers) are associated with control of soil erosion, minimization of nutrient leaching and carbon sequestration. These features have considerable importance in desertified areas, controlling and reversing the main drivers of desertification. As part of an integrated management strategy to reverse desertification, fiber crops can improve wastewater and soil quality, produce high quality biomass for industrial uses, guarantee biological and landscape diversity and indirectly ensure food and water security.

Nevertheless, this study also indicates that constraints and their implications should be properly assessed and accounted for in order to avoid intensification of desertification. The challenges of the sustainable reuse of wastewater for irrigation of fiber crops require use of existing knowledge and should be based on scientific understanding of the effects of the options undertaken on different scales and their socio-economic and environmental trade-offs. It is therefore recommended that site-specific factors should be properly assessed to evaluate the adequacy among crop, location and wastewater irrigation. Besides removal efficiency of the system and yields, information regarding biomass quality, soil quality, and effects on hydrology, is needed, in order to integrate knowledge concerning environmental appraisals. As part of active planning, bench-scale treatability studies should be conducted prior to field implementation. These studies represent a cost–effective tool for simultaneously evaluating multiple variables, optimizing performance and ultimately reducing environmental, social and economic costs.

In addition, development of future options requires preparation for uncertainty. It will become increasingly important to identify species and varieties which can tolerate the changes likely to come as a result of climate change, as well as to breed plants for stress tolerance. As various stakeholders are involved in the planning and establishment of fiber crop plantations, proper communication of potential environmental and socio-economic impacts (positive and negative) might be of equal importance to overcome public rejection and to boost the sustainable production of fiber crops irrigated with wastewaters.

Acknowledgements

The authors would like to acknowledge the European Union for financially supporting this work through the FIBRA project: Fiber Crops as a Sustainable Source of Bio-based Materials for Industrial Products in Europe and China, Grant Agreement No.: 311965, Coordination and support action, FP7-KBBE.2012.3.1-03).

References

Abe, K., Ozaki, Y., 1998. Comparison of the useful terrestrial and aquatic plant species for removal of nitrogen and phosphorus from domestic wastewater. Soil Sci. Plant Nutr. 44, 599–607.

Abe, K., Ozaki, Y., 2007. Wastewater treatment by using kenaf in paddy soil and effect of dissolved oxygen concentration on efficiency. Ecol. Eng. 29, 125–132.

Adler, A., Karacic, A., Weih, M., 2008. Biomass allocation and nutrient use in fast-growing woody and herbaceous perennials used for phytoremediation. Plant Soil 305, 189–206.

Akil, H.M., Omar, M.F., Mazuki, A.A., Safiee, S., Ishak, Z.A.M., Abu Bakar, A., 2011. Kenaf fiber reinforced composites: a review. Mater. Des. 32, 4107–4121.

Angelakis, A.N., Marecos Do Monte, M.H.F., Bontoux, L., Asano, T., 1999. The status of wastewater reuse practice in the Mediterranean basin: need for guidelines. Water Res. 33, 2201–2217.

Angelakis, A.N., Durham, B., 2008. Water recycling and reuse in EUREAU countries: trends and challenges. Desalination 218, 3–12.

Ardente, F., Beccali, M., Cellura, M., Mistretta, M., 2008. Building energy performance: a LCA case study of kenaf-fibers insulation bord. Energy Build. 40, 1–10.

Arfi, V., Bagoudou, D., Korboulewsky, N., Bois, G., 2009. Initial efficiency of a bamboo grove-based treatment system for winery wastewater. Desalination 246, 69–77.

Bandarra, V., Fernando, A.L., Boléo, S., Barbosa, B., Costa, J., Sidella, S., Duarte, M.P., Mendes, B., 2013. Growth, productivity and biomass quality of three miscanthus genotypes irrigated with Zn and Cu contaminated wastewaters. In: Eldrup, A., Baxter, D., Grassi, A., Helm, P. (Eds.), Proceedings of the 21th European Biomass Conference and Exhibition, Setting the course for a Biobased Economy. 3–7 June, Copenhagen, Denmark, pp. 147–150.

Please cite this article in press as: Barbosa, B., et al., Wastewater reuse for fiber crops cultivation as a strategy to mitigate desertification. Ind. Crops Prod. (2014), http://dx.doi.org/10.1016/j.indcrop.2014.07.007

Barbagallo, S., Cirelli, G.L., Consoli, S., Milani, M., Toscano, A., 2011. Utilizzo di acque reflue per l'irrigazione di biomasse erbacee a scopi energetici. Convegno Nazionale di medio termine dell'Associazione Italiana di Ingegneria Agraria, Gestione e controllo dei sistemi agrari e forestali, Belgirate, 22–24 Settembre.

Barbero-Sierra, C., Marques, M.J., Ruíz-Perez, M., 2013. The case of urban sprawl in Spain as an active and irreversible driving force for desertification. J. Arid Environ. 90, 95–102.

Barbosa, B., Fernando, A.L., Mendes, B., 2013. Environmental and socio-economic impact assessment of the production of kenaf (*Hibiscus cannabinus* L.) when irrigated with treated wastewaters. In: Castro, F., Vilarinho, C., Carvalho, J., Castro, A., Araújo, J., Pedro, A. (Eds.), Proceedings of the 2nd International Conference: wastes: solutions, treatments and opportunities. Braga, Portugal, 11–13 September, pp. 643–648.

Calheiros, C.S.C., Quitério, P.V.B., Silva, G., Crispim, L.F.C., Brix, H., Moura, S.C., Castro, P.M.L., 2012. Use of constructed wetland systems with Arundo and Sarcocornia for polishing high salinity tannery wastewater. J. Environ. Manage. 95, 66–71.

Chale, F.M.M., 1987. Plant biomass and nutrient levels of a tropical macrophyte (*Cyperus papyrus* L.) receiving domestic wastewater. Hydrobiol. Bull. 21, 167–170.

Chiaramonti, D., Grimm, H., El Bassam, N., Cendagorta, M., 2000. Energy crops and bioenergy for rescuing deserting coastal area by desalination: feasibly study. Bioresour. Technol. 72, 131–146.

Cirelli, G.L., Consoli, S., Licciardello, F., Aiello, R., Giuffrida, F., Leonardi, C., 2012. Treatment municipal wastewater reuse in vegetable production. Agric. Water Manage. 104, 163–170.

Cortina, J., Amat, B., Castillo, V., Fuentes, D., Maestre, F., Padilla, F., Rojo, L., 2011. The restoration of vegetation cover in the semi-arid Iberian southeast. J. Arid Environ. 75, 1377–1384.

Cosentino, S.L., Testa, G., Scordia, D., Alexopoulou, E., 2012. Future yields assessment of bioenergy crops in relation to climate change and technological development in Europe. Ital. J. Agron. 7, 154–166.

Costa, J., Fernando, A.L., Coutinho, M., Barbosa, B., Sidella, S., Boléo, S., Bandarra, V., Duarte, M.P., Mendes, B., 2013. Growth, productivity and biomass quality of arundo irrigated with Zn and Cu contaminated wastewaters. In: Eldrup, A., Baxter, D., Grassi, A., Helm, P. (Eds.), Proceedings of the 21st European Biomass Conference and Exhibition, Setting the course for a Biobased Economy. 3–7 June, Copenhagen, Denmark, pp. 308–310.

Dauber, J., Brown, C., Fernando, A.L., Finnan, J., Krasuska, E., Ponitka, J., Styles, D., Thrän, D., Groenigen, K.J.V., Weih, M., Zah, R., 2012. Bioenergy from "surplus" land: environmental and social-economic implications. BioRisk 7, 5–50.

Davison, L., Pont, D., Bolton, K., Headley, T., 2006. Dealing with nitrogen in subtropical Australia: seven case studies in the diffusion of ecotechnological innovation. Ecol. Eng. 28, 213–223.

El Bassam, N., 2010. Handbook of Bioenergy crops – a complete reference to species, development and applications. Earthscan, Ltd., London.

FAO, 1992. Wastewater Treatment and Use in Agriculture, Series: FAO Irrigation and Drainage Papers, http://www.fao.org/docrep/T0551E/T0551E00.htm (accessed February 2014).

Faruk, O., Bledzki, A.K., Fink, H., Sain, M., 2012. Biocomposites reinforced with natural fibers: 2000–2010. Prog. Polym. Sci. 37, 1552–1596.

Fazio, S., Monti, A., 2011. Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass Bioenergy 35, 4868–4878.

Fernando, A.L., 2013. Environmental aspects of Kenaf production and use. In: Monti, A., Alexopoulou, E. (Eds.), Kenaf: A Multi-Purpose Crop for Several Industrial Applications. Series: Green Energy and Technology, VII. Springer-Verlag, London, pp. 83–104.

Fernando, A.L., Barbosa, B., Boléo, S., Mendes, B., 2011. Growth, productivity and biomass quality of kenaf irrigated with wastewaters – the effect of ammonium ion. In: Faulstich, M., Ossenbrink, H., Dallemand, J.F., Baxter, D., Grassi, A., Helm, P. (Eds.), Proceedings of the 19th European Biomass Conference and Exhibition, From Research to Industry and Markets. 6–10 June, Berlin, Germany, pp. 68–71.

Fernando, A.L., Duarte, M.P., Almeida, J., Boléo, S., Mendes, B., 2010. Environmental impact assessment of energy crops cultivation in Europe. Biofuel Bioprod. Bioref. 4, 594–604.

Fernando, A.L., Ferreira, M., Boléo, S., Mendes, B., 2012. Growth, productivity and biomass quality of kenaf irrigated with wastewaters – the effect of nitrate ion. In: Krautkremer, B., Ossenbrink, H., Baxter, D., Dallemand, J.F., Grassi, A., Helm, P. (Eds.), Proceedings of the 20th European Biomass Conference and Exhibition. 18–22 June, Milano, Italy, pp. 179–182.

Fernando, A.L., Lopes, S.P., Mendes, B., Alexopoulou, E., 2013. Growth, productivity and biomass quality of kenaf irrigated with wastewaters – the effect of phosphate ion. In: Eldrup, A., Baxter, D., Grassi, A., Helm, P. (Eds.), Proceedings of the 21st European Biomass Conference and Exhibition, Setting the course for a Biobased Economy. 3–7 June, Copenhagen, Denmark, pp. 381–384.

Fernando, A.L., (PhD Thesis) 2005. Fitorremediação por *Miscanthus* x *giganteus* de Solos Contaminados Com Metais Pesados. Universidade Nova de Lisboa, Lisbon, Portugal.

Finnan, J., Styles, D., 2013. Hemp: a more sustainable annual energy crop for climate and energy policy. Energy Policy 58, 152–162.

Fritsche, U.R., Sims, R.E.H., Monti, A., 2010. Direct and indirect land-use competition issues for energy crops and their sustainable production – an overview. Biofuel Bioprod. Bioref. 4, 692–704.

Habib, H., Anceno, A.J., Fiddes, J., Beekma, J., Ilyushenko, M., Nitivattananon, V., Shipin, O.V., 2013. Jumpstarting post-conflict strategic water resources protection from a changing global perspective: gaps and prospects in Afghanistan. J. Environ. Manage. 129, 244–259.

Hooke, J., Sandercock, P., 2012. Use of vegetation to combat desertification and land degradation: recommendations and guidelines for spatial strategies in Mediterranean lands. Landscape Urban Plan 107, 389–400.

Idris, S.M., Jones, P.L., Salzman, S.A., Croatto, G., Allinson, G., 2012. Evaluation of the giant reed (*Arundo donax*) in horizontal subsurface flow wetlands for the treatment of dairy processing factory wastewater. Environ. Sci. Pollut. R. 19, 3525–3537.

Izydorczyk, K., Frątczak, W., Drobniewska, A., Cichowicz, E., Michalska-Hejduk, D., Gross, R., Zalewski, M., 2013. A biogeochemical barrier to enhance a buffer zone for reducing diffuse phosphorus pollution – preliminary results. Ecohydrol. Hydrobiol. 13, 104–112.

Jampeetong, A., Brix, H., 2009. Effects of NH_4^+ concentration on growth, morphology and NH_4^+ uptake kinetics of Salvia natans. Ecol. Eng. 35, 695–702.

Kansiime, F., Oryem-Origa, H., Rukwago, S., 2005. Comparative assessment of the value of papyrus and cocoyams for the restoration of the Nakivubo wetland in Kampala. Uganda. Phys. Chem. Earth 30, 698–705.

Kassam, A., Friedrich, T., Derpsch, R., Lahmar, R., Mrabet, R., Basch, G., Gonzále-Sánchez, E., Serraj, R., 2012. Conservation agriculture in the dry Mediterranean climate. Field Crop Res. 132, 7–17.

Kfir, O., Tal, A., Gross, A., Adar, E., 2012. The effect of reservoir operational features on recycled wastewater quality. Resour. Conserv. Recy. 68, 76–87.

Kharraz, J., El-Sadek, A., Ghaffour, N., Mino, E., 2012. Water scarcity and drought in WANA countries. Procedia Eng. 33, 14–29.

Kyambadde, J., Kansiime, F., Gumaelius, L., Dalhammar, G., 2004. A comparative study of *Cyperus papyrus* and *Miscanthidium violaceum* – based constructed wetlands for wastewater treatment in a tropical climate. Water Res. 38, 475–485.

Lado, M., Ben-Hur, M., 2009. Treated domestic sewage irrigation effects on soil hydraulic properties in arid and semiarid zones: a review. Soil Till. Res. 106, 152–163.

Laraus, J., 2004. The problems of sustainable water use in the Mediterranean and research requirements for agriculture. Ann. Appl. Biol. 144, 259–272.

Li, X.R., Jia, X.H., Dong, G.R., 2006. Influence of desertification on vegetation pattern variations in the cold semi-arid grasslands of Qinghai-Tibet Plateau, North-west China. J. Arid Environ. 64, 505–522.

Malveiro, D.C., (MSc Thesis) 2013. Avaliação do Potencial em Portugal de Reutilização de Águas Residuais para irrigação de culturas energéticas. Universidade Nova de Lisboa, Lisbon, Portugal.

Mavrogianopoulos, G., Vogli, V., Kyritsis, S., 2002. Use of wastewaters as a nutrient solution in a closed gravel hydroponic cultures of giant reed (*Arundo donax*). Bioresour. Technol. 82, 103–107.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Desertification Synthesis. World Resource Institute, Washington DC.

Mirza, N., Mahmood, Q., Pervez, A., Ahmad, R., Farooq, R., Shah, M.M., Azim, M.R., 2010. Phytoremediation potencial of *Arundo donax* in arsenic-contaminated synthetic wastewater. Bioresour. Technol. 101, 5815–5819.

Mohammad, A., Adam, M., 2010. The impact of vegetation cover type on runoff and soil erosion under different land uses. Catena 81, 97–103.

Monte, H.M., Albuquerque, A., 2010. Reutilização de Águas Residuais. Série Guias Técnicos 14, Entidade Reguladora dos Serviços de Águas e Resíduos e Instituto Superior de Engenharia de Lisboa., pp. 339.

Mugisha, P., Kansiime, F., Mucunguzi, P., Kateyo, E., 2007. Wetland vegetation and nutrient retention in Nakivubo and Kirinya wetlands in Lake Victoria basin of Uganda. Phys. Chem. Earth 32, 1359–1365.

Muyen, Z., Moore, G.A., Wrigley, R.J., 2011. Soil salinity and sodicity effects of wastewater irrigation in South East Australia. Agric. Water Manage. 99, 33–41.

Nivala, J., Hoos, M.B., Cross, C., Wallace, S., Parkin, G., 2007. Treatment of landfill leachate using an aerated, horizontal subsurface-flow constructed wetland. Sci. Total Environ. 380, 19–27.

Norton-Brandão, D., Scherrenberg, S.M., van Lier, J.B., 2013. Reclamation of used urban waters for irrigation purposes – a review of treatment technologies. J. Environ. Manage. 122, 85–98.

Pandey, A., Gupta, R., 2003. Fiber yielding plants of India, genetic resources, perspective for collection and utilization. Nat. Prod. Rad. 2 (4), 194–204.

Papazoglou, E.G., 2007. *Arundo donax* L. stress tolerance under irrigation with heavy metal aqueous solutions. Desalination 211, 304–313.

Papazoglou, E.G., Karantounias, G.A., Vemmos, S.N., Bouranis, D.L., 2005. Photosynthesis and growth responses of giant reed (*Arundo donax* L.) to the heavy metals Cd and Ni. Environ. Int. 31, 243–249.

Papazoglou, E.G., Serelis, K.G., Bouranis, D.L., 2007. Impact of high cadmium and nickel soil concentration on selected physiological parameters of *Arundo donax* L. Eur. J. Soil Biol. 43, 207–215.

Patanè, C., Sortino, O., 2010. Seed yield in kenaf (*Hibiscus cannabinus* L.) as affected by sowing time in South Italy. Ind. Crop Prod. 32, 381–388.

Perbangkhem, T., Polprasert, C., 2010. Biomass production of papyrus (*Cyperus papyrus*) in constructed wetland treating low-strength domestic wastewater. Bioresour. Technol. 101, 833–835.

Pereira, L., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. Agric. Water Manage. 57, 175–206.

Pidlisnyuk, V., Stefanovska, T., Lewis, E.E., Erickson, L.E., Davis, L.C., 2014. Miscanthus as a productive biofuel crop for phytoremediation. Crit. Rev. Plant Sci. 33, 1–19.

Plappally, A., Lienhard, J., 2012. Energy requirements for water production, treatment, end use, reclamation, and disposal. Renew Sust. Energy Rev. 16, 4818–4848.

Please cite this article in press as: Barbosa, B., et al., Wastewater reuse for fiber crops cultivation as a strategy to mitigate desertification. Ind. Crops Prod. (2014), http://dx.doi.org/10.1016/j.indcrop.2014.07.007

Portnov, B.A., Safriel, U.N., 2004. Combating desertification in the Negev: dryland agriculture vs. dryland urbanization. J. Arid Environ. 56, 659–680.

Qadir, M., Sharma, B.R., Bruggeman, A., Choukr-Allah, R., Karajeh, F., 2007. Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. Agric. Water Manage. 87, 2–22.

Rahman, K.Z., Wiessner, A., Kuschk, P., van Afferden, M., Mattusch, J., Müller, R.A., 2011. Fate and distribution of arsenic in laboratory-scale subsurface horizontal-flow constructed wetlands treating an artificial wastewater. Ecol. Eng. 37, 1214–1224.

Rebhun, M., 2004. Desalination of reclaimed wastewater to prevent salinization of soils and groundwater. Desalination 160, 143–149.

Rittmann, B., Mayer, B., Westerhoff, P., Edwards, M., 2011. Capturing the lost phosphorus. Chemosphere 84, 846–853.

Rivett, M., Buss, S., Morgan, P., Smith, W., Bemment, C., 2008. Nitrate attenuation in groundwater: a review of biogeochemical controlling processes. Water Res. 42, 4215–4232.

Scordia, D., Testa, G., Cosentino, S.L., 2013. Crop physiology in relation to agronomic management practices. In: Monti, A., Alexopoulou, E. (Eds.), Kenaf: A Multi-Purpose Crop for Several Industrial Applications. Springer-Verlang, London, pp. 17–43.

Sharma, A., Ashwath, N., Podberscek, M., Toon, D., Wees, B.V., Efferey, R., 2005. Extending Sustainable Use of Effluent Disposal Sites: Some Field Lessons. ICT Society, http://www.ictcsociety.org/LinkClick.aspx?fileticket=Fa3A0jsk1X0%3D&ta (accessed February 2014).

Sinha, S., Gupta, A.K., Bhatt, K., Pandey, K., Rai, U.N., Singh, K.P., 2006. Distribution of metals in the edible plants grown at Jajmau, Kanpur (India) receiving treated tannery wastewater: relation with physico-chemical properties of the soil. Environ. Monit. Assess. 115, 1–22.

Tanner, C.C., 1996. Plants for constructed wetland systems – a comparison of the growth and nutrient uptake of eight emergent species. Ecol. Eng. 7, 59–83.

Teuchies, J., Jacobs, S., Oosterlee, L., Bervoets, L., Meire, P., 2013. Role of plants in metal cycling in a tidal wetland: implications for phytoremediation. Sci. Total Environ. 445–446, 146–154.

Theophile, F., Sako, I.B., Martin, L., Fabrice, M.T., Akoa, A., 2011. Potential of *Cyperus papyrus* in yard-scale horizontal flow constructed wetlands for wastewater treatment in cameroon. Universal J. Environ. Res. Technol. 1, 160–168.

Trinh, L.T., Duong, C.C., Van Der Steen, P., Lens, P.N.L., 2013. Exploring the potential for wastewater reuse in agriculture as a climate change adaptation measure for Can Tho City, Vietnam. Agric. Water Manage. 128, 43–54.

Tzanakakis, V.A., Paranychianakis, N.V., Angelakis, A.N., 2009. Nutrient removal and biomass production in land treatment systems receiving domestic effluent. Ecol. Eng. 35, 1485–1492.

UNCCD, United Nations Convention to Combat Desertification, 1994. Intergovernmental Negotiating Committee For a Convention to Combat Desertification. In: Elaboration of an International Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa. U.N. Doc. A/AC.241/27, 33 I.L.M. 1328. United Nations, New York.

WHO, 2006. Guidelines for the Safe Use of Wastewater, Excreta and Greywater. World Health Organization, Geneva, Switzerland.

Williams, C.M.J., Biswas, T.K., Schrale, G., Virtue, J.G., Heading, S., 2008. Use of saline land and wastewater for growing a potential biofuel crop (*Arundo donax* L.) irrigation. In: Irrigation Australia 2008, Conference May 20, South Australian Research and Development Institute, Melbourne.

Yang, X., Zhang, K., Jia, B., Ci, L., 2005. Desertification assessment in China: an overview. J. Arid Environ. 63, 517–531.

Zegada-Lizarazu, W., Monti, A., 2011. Energy crops in rotation. A review. Biomass Bioenergy 35, 12–25.

Zema, D., Bombino, G., Andiloro, S., Zimbone, S.M., 2012. Irrigation of energy crops with urban wastewater: effects on biomass yields, soils and heating values. Agric. Water Manage. 115, 55–65.

Zhang, Y., Li, Y., Jiang, L., Tian, C., Li, J., Xiao, Z., 2011. Potential of perennial crop on environmental sustainability of agriculture. Procedia Environ. Sci. 10, 1141–1147.

Zhao, F., Yang, W., Zheng, Z., Li, H., Yang, X., He, Z., Gu, B., Rafiq, M.T., Peng, H., 2012. Nutrient removal efficiency and biomass production of different bioenergy plants in hypereutrophic water. Biomass Bioenergy 42, 212–218.

Please cite this article in press as: Barbosa, B., et al., Wastewater reuse for fiber crops cultivation as a strategy to mitigate desertification. Ind. Crops Prod. (2014), http://dx.doi.org/10.1016/j.indcrop.2014.07.007