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Use of (partially) treated municipal wastewater in irrigated agriculture; potentials and constraints for sub-Saharan Africa

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ABSTRACT

This review identifies the potentials and constraints of using (partially) treated or blended wastewater for irrigation in order to assess the potentials in the context of cities in sub-Saharan Africa, specifically Maputo, the capital of Mozambique. Less than 5% of the wastewater produced in the region is being treated. Nonetheless, untreated, partially treated, and/or blended wastewater is extensively being used for agricultural purposes. Despite the last updated WHO 2006 guidelines for 'wastewater use in agriculture', authorities only consider the different water quality parameters at the point of use. Other aspects such as irrigation type, crop management and post harvesting practices, which clearly influence the contaminant log reduction, are simply ignored. Those parameters, however, are considered alternatives to a classic contaminant log reduction, which may be very beneficial for developing countries. In a more holistic approach, trade-off is favoured between the required water quality for irrigation, use of affordable treatment technologies, and adequate post-harvest strategies to reduce the current health risks to acceptable levels. Such a trade-off makes use of multiple barrier approach, whereby wastewater treatment and critical point barriers throughout the supply chain are combined. Thus, there is a long way ahead to achieve proper water reclamation for productive use; the current paradigm has to change. Current restrictive guidelines are unrealistic given current practices, and approaches more appropriate to the location's situation still need to be developed. A multiple barrier approach in combination with master planning is recommended to consider wastewater treatment and critical point barriers throughout the supply chain.

1. Introduction

The global population is increasing, and projections indicate that it will continue to increase to around 9 billion in the year 2050 (Angelakis and Gikas, 2014). Whereas in 1950 only 20% of the world's population was living in cities, in 2016, this proportion had already reached 50% (Orsini et al., 2013; World Bank, 2016). It is predicted that this fraction will raise to around 70% in 2050 (Moir et al., 2014; Orsini et al., 2013; Vairavamoorthy et al., 2008). A commonly referenced implication of urban population increase is the need for more food production in urban areas (Bryld, 2003; de Fraiture and Wichelns, 2010; Orsini et al., 2013; Whittinghill and Rowe, 2011). Urban agriculture is believed to play an important role, to both i) address population increase in the forthcoming century (de Zeeuw et al., 2011; Duran et al., 2003; Orsini et al., 2013) and ii) to provide a reliable source of income for the poor farmers who migrate towards cities (Bryld, 2003; Whittinghill and Rowe, 2011). However, in many locations, water is the major limiting factor for agriculture, which is particularly true for urban agriculture (Orsini et al., 2013). Urban areas typically have high population densities, which translates into high land prices and high water demands. Moreover, urban agriculture must compete for land with other activities such as housing, industry and recreational activities (Zasada, 2011), making it difficult to maintain current urban farms, particularly when it is not part of the city master planning (Aubry et al., 2012). In addition, competitive water claims are common and may result from the fact that the water often has to be pumped from distant areas (Roon, 2007; Vairavamoorthy et al., 2008). As a result, urban farmers often struggle to obtain high quality irrigation water because of competition with potable uses (Moglia, 2014). However, in urban areas, alternative (low-grade) water sources are generally available, such as wastewater originating from households, industries, and storm water (Toze, 2006; van Lier and Huibers, 2010). These alternative sources have frequently been studied for use in agricultural irrigation (Roon, 2007; Srinivasan and Reddy, 2009; van Rooijen et al., 2010; Villamar et al., 2018).

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If appropriate safety measures are followed, treated or partially treated wastewater can be used safely, which is referred to as reclaimed water. Therefore, wastewater can be viewed as an alternative and reliable water source with the ability to increase urban water availability, especially during dry periods (Dorta-Santos et al., 2015; Huibers and van Lier, 2005; Jiménez and Asano, 2008b). In addition, the available wastewater quantity is in direct relation to the supply coverage, sewerage coverage, and population size of the urban areas (Huibers and van Lier, 2005). Furthermore, irrigation with adequately treated wastewater will also protect freshwater sources and the environment (Aiello et al., 2007; Qadir et al., 2010a). Reclaimed water is also a source of macro- and micro-nutrients that are important for plant development, soil pH, soil buffer capacity and cation exchange capacity (CEC) (Chen et al., 2013; Mohammad et al., 2007). Therefore, the use of reclaimed water could eventually lead to the reduced usage of commercial fertilizers (Jiménez-Cisneros, 2014a; Qadir et al., 2010a; Srinivasan et al., 2013). This is of particular importance for the case of phosphorous, due to limited available quantities of high-quality phosphorus rock in the world and predicted price increases of artificial fertilisers (Elser and Bennett, 2011; Woltersdorf et al., 2016). Furthermore, water reclamation leads to revenue generation (Jiménez-Cisneros, 2014b), which has the potential to support the improvement of sanitation services, as wastewater works can become revenue sources instead of simply being costly services.

In Africa, an estimated 40% of urban dwellers are involved in some sort of agricultural activity, and this percentage increases to 50% in South America (Zezza and Tasciotti, 2010). In these continents, water reclamation for irrigation is of special importance as it sometimes is the only water source available (Norton-Brandão et al., 2013). Water reclamation in Africa and South America typically involves the use of partially treated or untreated wastewater (Huibers and van Lier, 2005), a practice that is unsafe for farmers, consumers, and the environment alike (Fatta et al., 2005; Norton-Brandão et al., 2013; Weldesilassie et al., 2011). With regard to sanitation, Nansubuga et al. (2016) reported that in 2012 more than 800 million urban dwellers in developing countries live in slum areas that generally fail to provide inhabitants with inclusive, affordable, and appropriate sanitation services. It can thus be argued that water reclamation has the potential to address pivotal challenges that developing countries face, specifically providing safe water for an increasing urban agriculture production, while supporting the improvement of lacking sanitation services. Therefore, this paper aimed at identifying the potentials and constraints of using (partially) treated wastewater in irrigated agriculture for sub-Saharan Africa. The specific aims were to review the current worldwide trends for water reclamation in agriculture, to identify the required water quality of reclaimed water for irrigation and to identify the status of water reclamation in sub-Saharan countries. Special attention is given to the possible translation of global examples into the context of sub-Saharan African cities, particularly Maputo, the capital of Mozambique.

2. Methodology

A literature review is conducted on the use of (partially) treated municipal wastewater in irrigated agriculture, reviewing its potentials, and constraints for sub-Saharan Africa. The study considered peer-reviewed international literature, as well as projects dealing with water reclamation linked to agricultural irrigation, conference proceedings, and technical reports. The purpose of this review was to find examples, trends, potentials, and constraints of water reclamation for irrigation that could be further applied in the SSA region. In addition to searches on 'global trends for water reclamation in agriculture' and 'water quality of reclaimed water for irrigation', we also considered the various international guidelines for irrigation with ((partially) treated) wastewater. Wastewater treatment options with examples were reviewed, grouped and classified in regulated and non-regulated water reclamation , as well as irrigation and post-harvesting practices. In addition to peer reviewed scientific papers, also practical water reclamation examples, with an irrigation component were include, with special attention for projects concerning sub-Saharan Africa. The variety of project examples and literature hampered a thorough meta-analysis. However, a conclusive state of the art and way forward recommendation is provided regarding the potentials of water reclamation for agricultural reuse in sub-Saharan Africa.

3. Results and discussions

3.1. Global trends for water reclamation in agriculture

The amount of wastewater produced around the world is an indicator for potential (peri-) urban water reclamation. Globally, the daily volume of wastewater production varies from 680 to 960 million m^3 with a current maximum treatment capacity of 32 million m^3, representing less than 5% of the amount produced (Lautze et al., 2014). This means that there is a huge need for increasing the collection and treatment capacity and thus increasing the water availability for reclamation. Several authors argue that the main reasons for this gap are obsolete, inappropriate, and/or mismanaged sanitation infrastructure (Scott et al., 2004), lack of inclusion in urban planning (Bahri, 2012), limited financial resources (Raschid-sally and Jayakody, 2008), and lack of capacity to enforce regulations (Qadir et al., 2010b).

As discussed, water reclamation is regarded an affordable alternative for many water-scarce regions (Saldías et al., 2016) and a reliable provision of a consistent nutrient source (Akponikpè et al., 2011; Miller--Robbie et al., 2017; Scott et al., 2004). Given the aforementioned accessibility to wastewater streams, irrigation tends to be an important endpoint for untreated or (partially) treated wastewater in many developing countries (Al-Hamaiedeh and Bino, 2010; Jaramillo and Restrepo, 2017; Keraita et al., 2008; Raschid-Sally et al., 2005; Scott et al., 2004). At the eve of the 21st century, it was estimated that about 10% of the global population consumed crops irrigated with raw, partially treated, or blended wastewater (Smit and Nasr, 1992) coming from over 20 million hectares of arable land in about 50 countries (Hussain et al., 2001; Malik et al., 2015; van der Hoek, 2004). Other estimates indicated that worldwide, the total area irrigated with raw, (partially) treated, or blended wastewater is about 1.5–6.6% of a total irrigated area of 301 million hectares (Sato et al., 2013); and it is predicted that water reclamation for irrigation will have the largest increase compared to other uses such as industrial and domestic (Jiménez-Cisneros, 2014b).

Within Europe, water reclamation for agricultural use is typically practiced in the semi-arid regions, which includes most coastal areas, and on the islands in the South of the continent (Angelakis and Gikas, 2014; Bixio et al., 2006; Sato et al., 2013). The amount of reclaimed water predicted for Europe will exceed 3 million km^3 per year by 2025 (Angelakis and Gikas, 2014; Raso, 2013). In non-European Mediterranean countries, the situation is very similar to their European counterparts, namely using the reclaimed water mainly for agricultural purposes (Bedbabis et al., 2010). Water reclamation is highest in Israel, reclaiming almost 90% of the produced wastewater (Powley et al., 2016). Similarly, in western North America and Australia, water reclamation is mostly used for irrigation (Sato et al., 2013). In areas where wastewater treatment is scarcely implemented, farmers use non-treated or diluted wastewater for irrigation. China, India and Mexico are the countries with the largest areas irrigated with untreated or diluted wastewater (Jaramillo and Restrepo, 2017; Keraita et al., 2008; Lautze et al., 2014), covering areas of about 3.5 million hectares in China and more than 1 million hectares in both India and Mexico (Lautze et al., 2014). In Chinese water reclamation programs, the main irrigated crops are vegetables, such as spinach, cabbage, parsley, and cauliflower; and cereals, typically maize, wheat, rice, and brown rice (Zhang et al., 2015). For the case of India, examples include sugar cane fields irrigated with industrial effluents (Pandey et al., 2016) and vegetables irrigated with municipal wastewater (Gupta et al., 2008; Sharma et al., 2007). In Mexico, untreated or partially treated wastewater is even used to irrigate vegetable crops consumed raw such as radish, spinach, lettuce, parsley, and celery (Castro-Rosas et al., 2012), but also maize, alfalfa, and other forage crops (Chávez et al., 2011).

The potential role of water reclamation for irrigation in Africa is more closely linked to the localized value in the (peri-)urban setting than to the absolute quantitative amounts relative to the national water budgets. (Peri-)urban agriculture is an important economic activity in African cities since it provides agricultural goods at limited distances from the consumers (Raschid-Sally et al., 2005). In some cities such as Accra, Ghana, over 60–70% of the consumed agricultural goods that are consumed in the urban area are also produced there (Agodzo et al., 2003). Water withdrawals for different uses in different regions of Africa show large differences between agricultural water abstractions and urban water uses. In most regions of Africa, the majority of water abstractions are used for irrigation, which comprises 70–90% of the total abstractions on the continent (FAO, 2005). Agriculture contributes to 35% of the GDP in sub-Saharan Africa, and food production is required to double by the year 2050 (Diao et al., 2010; FAO, 2009; Rockström et al., 2010). The average water demand for agriculture is 1300 m^3 per capita per year, and it is expected to increase to a total value of 8, 500–11,000 km^3 per year by 2050 (Rockström et al., 2010). Also, the quantity and quality of water is rapidly reducing across countries in sub-Saharan Africa (Freitas, 2013), resulting in growing water shortages due to increasing water demands for food production as well as industrial and domestic use (Rockström et al., 2010). The agriculture sector is by far the largest freshwater user, and thus, water reclamation for irrigation is an alternative that might reduce pressure on freshwater resources, particularly near and in urban areas, while also preventing non-controlled wastewater discharges to the environment (Pedrero et al., 2010; van Lier and Huibers, 2010). In addition, urban water reclamation is an opportunity to reduce the use of artificial fertilizers, which can serve as an economic benefit to (poor) farmers and help to improve their livelihood. Therefore, it is argued that if the produced wastewater in Africa could be collected, treated and reclaimed for safe irrigation, it could help to ensure food production and to overcome the pronounced cases of water shortages near and in (peri-)urban areas, while also contributing to environmental protection.

3.2. Water quality of reclaimed water for irrigation

3.2.1. Health and environmental impact of irrigating with untreated or partially treated wastewater

Wastewater sources include municipal wastewater, which consists of water from households, industries, and storm water. Wastewater characteristics differ from community to community regarding (in)organic matter content, nutrients, salts, heavy metals, toxic chemicals, and pathogens (Capra and Scicolone, 2007; Hussain et al., 2002; Popa et al., 2012). Urban agriculture in developing countries is often practiced by a population living at a low socioeconomic level (Orsini et al., 2013). Frequently, these farmers cannot afford to have safe water sources other than untreated or partially treated wastewater (Qadir et al., 2010b), a practice that might have detrimental impacts to soil, groundwater, crops and the health of farmers and consumers alike (Becerra-Castro et al., 2015; Christou et al., 2017).

Soils continuously irrigated with non-treated or partially treated wastewater display soil quality modifications as a result of both structure deterioration (e.g., salinization of clays) and mineral, organic, and bacteriological pollution (Bauder et al., 2007; Jaramillo and Restrepo, 2017; Klay et al., 2010). For example, a soil in the Zaouit Sousse perimeter in Tunisia was irrigated with treated wastewater for a period of four years and demonstrated that irrigation with wastewater of high salinity content for long period affects its geochemical properties such as soil salinization and accumulation of heavy metals (Klay et al., 2010). However, the level of deterioration of soils after receiving wastewater for a prolonged period of times varies depending on infiltration capacity, permeability, cation exchange capacities, phosphorus adsorption capacity, water holding capacity, soil texture and structure, and type of clay mineral (Emongor and Ramolemana, 2004). In addition, long-term irrigation with untreated or partially treated wastewater led to the increase in sodium, chlorine, and nitrate concentrations in groundwater (Chen et al., 2013).

When wastewater is contaminated with heavy metals, the concentrations in plant tissue tend to increase in a process known as bioaccumulation (Li et al., 2016; Qadir et al., 2010b) and has been shown to lead to phytotoxicity in dependence to plant species (Bedbabis et al., 2010). Heavy metals uptake by plants can occur either via roots or foliar surfaces (Chauhan and Chauhan, 2014). Leafy vegetables, in particular, are prone to accumulate metals (Parvin et al., 2014). Zinc, cadmium, lead and copper are some of the common metals found in vegetables (Chaoua et al., 2018; Qadir et al., 2010b), and the metals uptake may increase with time, depending on soil concentration (Shakir et al., 2016).

Consumers are the final link in the supply chain and might be severely affected by these unsafe practices. In addition to heavy metals, wastewater is also a vector in spreading pathogens (Uyttendaele et al., 2015). In the United States, a *Salmonella* outbreak (2008) was caused by contaminated peppers. In Sweden, an *E. coli* outbreak (2013) was caused by contaminated lettuce. Both outbreaks were attributed to irrigation with untreated or partially treated wastewater (Uyttendaele et al., 2015). The use of untreated or partially treated wastewater for irrigation is also often linked to the community presence of gastrointestinal and skin diseases (Naidoo and Olaniran, 2013). Furthermore, the concentration of chemicals in wastewater may pose a serious threat to human health (Shakir et al., 2016). For instance, the effects of the previously mentioned heavy metals on human health can be quite severe but vary per element. Cadmium and lead have carcinogenic effects to humans; copper and zinc, although essential elements, can be toxic in high concentrations; and a copper surplus can cause acute stomach and intestinal aches (Chaoua et al., 2018). Therefore, to minimize the negative environmental and human health impacts, it is thus important to analyse the quality of the available wastewater and the necessary level of treatment to create adequate and location-specific regulatory frameworks so that the treated wastewater can be safely used for irrigation. However, considering the risks of post-harvest contamination, the control of the water quality at the treatment plant is not enough to ensure the consumers safety, since the produce might be contaminated due to handling management or unsafe washing practices at the market and household levels (Amoah et al., 2005).

Therefore, guidelines have been developed worldwide that define wastewater treatment levels, accurate effluent management practices, restricted agricultural practices related to crops choices, and safe irrigation and harvesting methods (Aiello et al., 2007).

3.2.2. Guidelines for irrigation with wastewater

There are several guidelines around the world to regulate water reclamation for agricultural use (Table 1). The most commonly used guidelines were developed by the US Environmental Protection Agency (USEPA) and the World Health Organization (WHO) with the exception of the American state of California, which developed its own guidelines. The USEPA developed guidelines in order to ensure safe use of reclaimed water in irrigated agriculture (Angelakis and Gikas, 2014; Lazarova, 2004; Lazarova and Bahri, 2004). The WHO initially developed its guidelines in 1989 with an updated version in 2006. The WHO guidelines have been widely adopted or used as reference by many countries such as in Latin America (Mateo-Sagasta et al., 2013) and Europe (Lazarova and Bahri, 2004). However, whereas some southern European countries have encouraged water reclamation through the creation of specific regulations (Angelakis and Durham, 2008), other countries such as Italy have established stricter regulations for water reclamation,

Table 1
Wastewater guidelines for irrigation in agriculture and treatment options.

Guidelines	Unrestricted irrigation		Restricted Irrigation		Reference(s)
	Water quality	Treatment option	Water quality	Treatment option	
USEPA (2004)	• pH = 6-9 • ≤ 10 mg/l BOD7 • ≤ 2 NTU[a] • No detectable fecal coliforms/100 ml • 1 mg/l Cl_2 residual (minimum)	Secondary treatment, Filtration, Disinfection	≤30 mg/l BOD[d] ≤30 mg/l SS ≤200 fecal coliforms/100 ml 1 mg/l Cl_2 residual (min.)	Secondary treatment, Filtration	Blumenthal et al. (2000)
WHO (1989)	Intestinal Nematodes <1 eggs/l Faecal coliforms <1000/100 ml		Intestinal Nematodes <1 eggs/l N.A for faecal coliforms		WHO (1989)
WHO (2006)	$<10^{-6}$ DALY[b] (pathogen reduction 1–4 logs from 10^7-10^8 to 10^3-10^4 per 100 ml)	Secondary treatment, filtration, and disinfection	$<10^{-6}$DALY (pathogen reduction 3–4 logs from 10^7-10^8 to 10^3-10^4 per 100 ml)	Stabilization ponds for 8–10 days	(Lazarova and Bahri, 2004; WHO, 2006)
California (2014)	≤2.2/100 ml TC[c] ≤23/100 ml in more than one sample in any 30 day period (maximum)	Secondary treatment, Coagulation, Filtration, Disinfection	≤23/100 ml TC ≤240/100 ml in more than one sample in any 30 day period	Secondary treatment, Coagulation	(California Department of Public Health, 2014; Lazarova and Bahri, 2004)

[a] NTU: Nephelometric Turbidity Unit.
[b] DALY: Disability Adjusted Life Years corresponds to the sum of years of potential life lost due to premature mortality and the years of productive life lost due to disability.
[c] TC: Total coliforms.
[d] BOD: Biochemical oxygen demand.

essentially discouraging its practice (Angelakis and Gikas, 2014).

In the USEPA, WHO, and the California guidelines for the use of treated wastewater for restricted and unrestricted irrigation, various parameters are considered, particularly with respect to microbial parameters (Lazarova et al., 2001). Restricted irrigation includes the use of treated wastewater for the irrigation of industrial crops, animal fodder, trees, and crops that are not consumed raw, whereas unrestricted irrigation includes all crops. The mentioned guidelines (California Department of Public Health, 2014) focus on the presence of limited concentrations of specific components such as total coliforms for both restricted and unrestricted irrigation (Blumenthal et al., 2000; Lazarova and Bahri, 2004). Furthermore, both the USEPA and California guidelines include a disinfection step as a required condition for unrestricted use, which is not mentioned in the 2006 WHO guidelines. In fact, the USEPA and California guidelines only focus on the water quality parameters at the point of use, i.e. the water quality at the supply point that it is available for crop irrigation. These guidelines do not take into consideration other aspects of the supply chain from production to consumer site, such as the type of irrigation system, crop management, handling, and domestic disinfection. It can be argued that the application of non-debatable restrictive quality parameters makes the USEPA guidelines stricter, requiring extensive treatment under all conditions. However, the newer WHO guidelines (2006) consider Disability Adjusted Life Years (DALYs) as a metric based on the regional conditions and supported by quantitative microbial risk assessment (QMRA) models (Lazarova and Bahri, 2004). The tolerable risk framed in terms of DALYs is an approach that represents a level of risks that can be approximated and measured based on the lost years due to premature death and/or disability caused by a disease (Busgang et al., 2018; Carr et al., 2004). This metric helps to quantify the population health burden of diseases and to prioritise and evaluate the impact of specific public health interventions (Gibney et al., 2013). Additionally, the 2006 WHO guidelines consider health based targets for the whole supply chain, from production to consumption of wastewater irrigated products, making adjustments relevant to local conditions (Drechsel et al., 2008). As such, the 2006 WHO guidelines better include the reality of a given country as its approach ensures the realistic measure of waterborne diseases on human life, while protecting human health and including a cost effective approach for the wastewater use chain (Blumenthal et al., 2000). Furthermore, various authors and contributors to the 2006 WHO guidelines argue that irrigation water does not have to necessarily meet the quality standards as defined in the guidelines in order to ensure human health protection (Carr et al., 2004; Ensink et al., 2007). The 2006 WHO guidelines include opportunities to use a multi-barrier approach, which might be much more cost-effective in ensuring environmental and human health. In such approach, critical components are addressed throughout the production and supply chain including, but not limited to, the quality of the water source (Huibers and van Lier, 2005). This alternative includes a combined approach for selecting wastewater treatment options followed by post-treatment health protection and control measures, which are comprised of pre-farm, on-farm and post-farm barriers such as, when possible, wastewater treatment to improve water quality parameters, crop restrictions, and post-harvest handling (Huibers and van Lier, 2005; Keraita et al., 2014; Scheierling et al., 2011). In effect, it is only in industrialised countries, where efficient collection and treatment of wastewater is available, that wastewater treatment alone guarantees risks reduction to the defined levels and therefore restrictive effluent guidelines are applied (Angelakis and Gikas, 2014). However, as previously stated, in developing countries, there is a general lack of wastewater collection and treatment (Miller-Robbie et al., 2017) and thus a need to use restrictive effluent guidelines where adequate wastewater treatment exists and a multiple barrier approach where non-treated or partially treated water is utilised (Amponsah et al., 2016; Keraita et al., 2010). Ideally, it can be argued that a combination of these two approaches should be considered. In addition, official water reclamation projects are site-specific and typically motivated by a lack of water to irrigate crops, supplying nutrients to the crops, and protecting the environment from uncontrolled discharges. Moreover, a variety of wastewater sources are being used to irrigate horticultural crops and pastures, with the implementation depending on the specific need in the region (Haering et al., 2009; Martijn, 2005). Finally, it can be concluded that at most locations where wastewater treatment is crucial in the reclamation step, there are efforts to meet the restrictive guidelines in order not to pose risks to the environment and humans. However, in developing countries, water reclamation is still unplanned and uncontrolled, which can often be related to the costs linked to wastewater treatment, lack of institutional frameworks, and the lack of available physical infrastructure.

3.2.3. Wastewater treatment options

To date, many different wastewater treatment techniques have been developed, leading to incremental levels of treatment: primary, secondary, tertiary, and quaternary. Secondary or biological treatment can be implemented as a compact mechanised treatment system or as an engineered system in nature, making use of lagoons or wetlands (Kalbar et al., 2012). Examples of secondary treatment technologies are activated sludge, trickling filters, biotowers, upflow anaerobic sludge blanket (UASB) reactors, rotating biological contractors (RBC), sequential batch reactors, aerated lagoons, waste stabilization ponds, duckweed ponds, and constructed wetlands (CWs) amongst other treatment techniques (Kalbar et al., 2012).

Selecting the most appropriate wastewater treatment technology is a complex process and includes many technological and socio-economic parameters. As such, the decision making process can be regarded as contextual and situational (Kalbar et al., 2012; Muga and Mihelcic, 2008) and includes capital costs, operational and maintenance cost, land requirements, and sustainability issues (Kalbar et al., 2012). In industrialised countries, the most important selection criteria for wastewater treatment technologies are efficiency, reliability, sludge disposal, and land requirements (von Sperling, 1996). In addition, Massoud et al. (2009) noted that the selection of the most appropriate wastewater treatment technology is based on criteria such as economic affordability, environmental sustainability, and social acceptability. In developing countries, the most critical parameters for the selection of a wastewater treatment technology are construction and operational costs, sustainability, and simplicity (von Sperling, 1996).

Current wastewater treatment facilities of major cities in industrialised countries are connected to centralized conveyance systems and are commonly linked to high investment and operational costs that are prohibitive and not feasible for many developing countries (Zhang et al., 2014). In the latter countries, the number of wastewater treatment facilities are limited due to high costs and a lack of laws for environmental pollution and/or its enforcement (Kivaisi, 2001). Furthermore, existing treatment facilities often are poorly operated and maintained (Wang et al., 2014), which hampers adequate wastewater management and treatment in many developing countries.

Increasing wastewater treatment levels generally reduces environmental and human health risks but is correlated with an increase in treatment costs (VO et al., 2014). Particularly in developing countries, there is a significant need for cost-effective technologies to treat wastewater to a desirable level. In this context, the most common wastewater treatment technologies are stabilization ponds (Kivaisi, 2001), with up-flow anaerobic sludge blanket (UASB) reactors being common in South America and India (Chernicharo et al., 2015; Noyola et al., 2012; van Lier et al., 2010). Stabilization ponds are characterised by the lowest investment and operation costs, provided that the large required areas of land are cheap (WHO, 2001). However, in the vicinity of large cities, the latter is generally not the case. This means that large conveyance systems are required, leading to high investment costs (van Lier and Lettinga, 1999). Moreover, land-based systems are not easily adaptable to accommodate population growth, so treatment performance may deteriorate with time.

When the final use is for irrigation, the selection of wastewater treatment technologies for irrigation should be in accordance with agrotechnological, sanitary, and environmental requirements that also include the protection of human health (Norton-Brandão et al., 2013). Different technologies for wastewater treatment are applied when the effluent is used in a planned agricultural irrigation setting (Table 2). In most of these examples, the wastewater is treated before its application to crops. Various methods including (advanced) disinfection are implemented in industrialised countries, such as Australia, Israel, and the US, for unrestricted irrigation. However, some examples of wastewater treatment in developing countries include solely secondary treatment, with the effluent being used to irrigate crops in an unplanned agricultural irrigation scheme (Table 3). The obtained water quality does not always meet the restrictive regulatory standards.

3.2.4. Irrigation and post-harvesting practices

Irrigation methods and post-harvesting practices are crucial for the reduction of contamination risks associated with the consumption of wastewater irrigated produce (Keraita et al., 2007a, b). Contamination can occur at several levels in the supply chain such as at the production site, transportation, crop handling, and market display (Faour-Klingbeil et al., 2016; Gil et al., 2015). Contamination at the production site can originate from the farm leading up to the harvest when unsafe water sources are used for irrigation, manure is handled inappropriately, and sanitation practices are unsuitable at farm level (Faour-Klingbeil et al., 2016; Gil et al., 2015). During transportation, contamination may occur when a proper cooling system is not available along the supply chain, or when the containers are not or improperly sanitized that are either used to transport the products, or to pile the produce at the market entrance after distribution (Faour-Klingbeil et al., 2016; Gil et al., 2015). Contamination during crop handling at the market occurs due to inadequate market structural facilities or during the washing process, when there is an inability to maintain a clean water supply, while washing large volumes of fresh produces (Faour-Klingbeil et al., 2016; Gil et al., 2015). At the consumer level, contamination occurs when consumers

Table 2
Worldwide examples on planned water reclamation for irrigation.

Scope	Treatments	Crops irrigated	Reference(s)
Municipal wastewater	Trickling filter plant, activated sludge plant, dissolved air flotation filtration, multi-media filtering and chlorination, anaerobic pond, aerated pond, and network of reservoirs, waste stabilization ponds, aerated pond, activated sludge or attached growth processes or a combination of both, flocculation, dissolved air flotation, rapid sand filtration, granular activated carbon filtration, and chlorine disinfection	Horticultural, pasture sugar cane , tea tree plantations, sporting fields, a turf farm, citrus, , bananas, grapes and certain stone fruits	(Ammary, 2007; Bixio et al., 2005; Boake, 2006; Elimelech, 2006; Friedler, 1999; Haruvy, 1997; Indian Institute of Technology (IIT), 2011; Institute for Sustainable Futures (ISF), 2013; Lahnsteiner and Lempert, 2007; Po et al., 2003; Radcliffe, 2010; Woltersdorf et al., 2016)
Domestic + Industrial wastewater	Grit removal, activated sludge process, aeration tanks comprised of an anoxic zone (denitrification) and aerobic zone, maturation ponds, secondary treatment, aerobic-biological	Horticultural, olive trees	(Bedbabis et al., 2010; Emongor and Ramolemana, 2004)
Domestic wastewater	Synthetic sponge, sedimentation baffled/graded settlement tank, filtration using gravel and sand roughing filtration, aeration and chlorination	irrigating the food crops, olive trees and vegetable crops, lawns, plants, shrubs and trees and lettuce	(Al-Hamaiedeh and Bino, 2010; Indian Institute of Technology (IIT), 2011)
Industrial and municipal wastewater	Activated sludge	Fish farming	(Indian Institute of Technology (IIT), 2011)

Table 3
Worldwide examples of unplanned water reclamation for irrigation.

Location	Drivers	Treatments	Scope	Crops irrigated	Findings	Reference(s)
Bolivia: Cochabamba	poverty and lack of planning and management capacity, uncontrolled use of wastewater	Diluted or partly treated, limited treatment, wastewater with high contamination of pathogens, heavy metals, and salts	Municipal and industrial sewage wastewater	Fodder crops, including fodder maize alfalfa, and vegetables for farmers' own consumption	Farmers not confronted with specific health problems related to the use of polluted water, contradicting reports from local health workers.	Huibers et al. (2004)
Burkina Faso		On-farm technologies	Municipal	Eggplant, tomatoes		(Akponikpè et al., 2011; Keraita et al., 2014)
Cameroon: Nomayos-Yaonde city	Unplanned discharge of sludge	Comprises individual wastewater systems (septic tanks and latrines) and collective wastewater (sewer and treatment plants	Urban sludge	Lettuce	Existing wastewater treatment facilities are not adequately structured and will require further planning	(Mafuta et al., 2011; Tsama et al., 2015)
Eritrea		Untreated		Lettuce cabbage, tomato, carrots		Srikanth and Naik (2004)
Etiopia: Kality and Kotebe	Polluted water, economic drivers	Untreated	Municipal	lettuce, Swiss chard, cabbage, carrot, beet root and potatoes	perceived illness prevalence is significantly higher for household members working on wastewater irrigation farms than for those working with freshwater.	(Teklu, 2007; Weldesilassie et al., 2011)
Ghana: Kumasi	Freshwater pollution and water scarcity in dry season, the need to cultivate vegetable all year round wherever irrigation water is available	Septic tanks, biological treatments	Informal irrigation with untreated or partially treated domestic/municipal wastewater	cereals as maize in the rainy seasons and vegetables in the dry seasons.	Sanitation infrastructure in Ghana has been outpaced by population increases, making the management of urban wastewater ineffective	(Agodzo et al., 2003; Buechler et al., 2006; Keraita and Drechsel, 2004; Sato et al., 2013)
India: Ahmedabad, New Delhi, Hyderabad, Kanpur and Kolkata	Population growth and food security	Partial treatment	Municipal wastewater	Horticultural crops, cereals, paddies, flowers	Wastewater management and treatment cannot be planned in isolation	Amerasinghe et al. (2013)
India: Vadodara, Gujarat	Lack of freshwater sources	Little treatment; none of the three sewage treatment plant is fully functional	Municipal sewage	Vegetables, fruits, cereals, flowers and fodder	Uncertainty associated with water use for marginalised farmers would be overcome with a planned.	Bhamoriya (2004)
Kenya: Nairobi		Untreated or partially treated, stabilization ponds or system comprises of discrete units of barrels that allows for filtration, flocculation, sedimentation and disinfection.	Municipal wastewater	mixed vegetable farming	Heavy metals were recorded mostly in the stem and leaves farming and non-farming households are predisposed to infection from these contaminants,	(Hide et al., 2001; Karanja et al., 2010; Kariuki et al., 2011; Mafuta et al., 2011)
Mexico: Tula Valley in The Mezquital Valley	Lack of water	Activated sludge systems/ stabilization ponds	Municipal	alfalfa and maize (60%), but oats, barley, wheat, beans and some vegetables (chilli, Italian squash and tomatoes)	Wastewater must be treated and managed wisely	Jiménez (2008)
Nepal: Kathmandu Valley (Kirtipur and Bhaktapur)	Water scarcity	Lagoon system	Bhaktapur: direct utilization of wastewater; Kirtipur: indirectly by gravity flow from polluted rivers	Rice, wheat and vegetables	Quality of wastewater used varies from diluted wastewater to raw sewage. Wastewater use in agriculture is not regulated	Rutkowski et al. (2007)
Pakistan: Haroonabad and Faisalabad-	Absence of a suitable alternative water source, high nutrient value obtained from wastewater,	Untreated wastewater (80% of wastewater irrigated schemes)	Municipal wastewater in two cases (Haroonabad: small town without major industry) and	Haroonabad: Vegetables (cauliflower), cotton and fodder Faisalabad: fodder,	Untreated wastewater irrigation poses serious health risks. For the case of Pakistan, there are some benefits. It is unlikely that	Ensink et al. (2004)

(continued on next page)

Table 3 (*continued*)

Location	Drivers	Treatments	Scope	Crops irrigated	Findings	Reference(s)
	reliability proximity to urban markets		(Faisalabad: large and industrialised city)	wheat, cotton and vegetables (cauliflower, spinach, and aubergine).	Pakistan will be able to treat all wastewater currently used by farmers up to WHO guidelines standards	
Vietnam	Unplanned discharge of wastewater into natural water courses, drainage canals or irrigation canals	Stabilization ponds	Municipal wastewaters	Paddy rice	Wastewater agriculture provides a primary or secondary source of income to 1% of the urban population although there is need for a typology to effectively capture characteristics	Raschid-Sally et al. (2004)
Harare-Zimbabwe		Secondary - trickling filter and modified activated sludge	Greywater	Vegetable and pasture irrigation	Regulations for use of wastewater exists, but proper enforcement is lacking and there is need for comprehensive guidelines specifically addressing the safe use of wastewater in agriculture	(Jiménez and Asano, 2008b; Muchuweti et al., 2006; Nansubuga et al., 2016; Thebe and Mangore, 2015)

fail to wash the produce before eating (Gil et al., 2015).

In a situation where conventional wastewater treatment is not available, irrigation and post-harvesting practices should be considered as complementary and are of practical importance in the context of developing countries to reduce the risk of contamination (Amoah et al., 2007; Drechsel et al., 2008; Keraita et al., 2007a). Irrigation methods can have an impact on the reduction of produce contamination and can be used to control the level of contamination by wastewater (Choi et al., 2004). Three irrigation categories can be grouped as i) flood and furrow, where water is applied at the soil surface ii) spray and sprinkler, where water is applied on top of the crop and iii) localized, which refers to drip and trickle irrigation in which water is directly applied to the crop in a localized manner (Keraita et al., 2007a; WHO, 2006). The irrigation method and nature of the crop to be grown (e.g., to be eaten raw or cooked) can be changed according to the prevailing water quality in order to reduce the risk of contamination (Drechsel et al., 2008; Gil et al., 2015). This means that for crops to be eaten raw, an irrigation method that makes a direct contact with the produce (e.g., spray irrigation in the case of leafy vegetables to be eaten raw) should be avoided (Gil et al., 2015). Furrow and spray irrigation generally leads to 1 log reduction in microbial contamination, whereas a 2–4 log reduction can be expected with localized irrigation, leading to lower risks for the farmers and minimal contamination transfer to the crop surface (Keraita et al., 2008). The lower contamination risk is due to the fact that irrigation water is applied to the root zone of the crop, resulting in minimal direct contact between wastewater and crops (Drechsel et al., 2008; Keraita et al., 2007a). However, localized irrigation methods can be considered an advanced technology that is too expensive for most farmers in developing countries and are characterized by high maintenance cost due to clogging problems (Carr et al., 2011; Martijn, 2005). Sprinklers have medium to high cost, and the water use efficiency is medium (Qadir et al., 2010b). Furrow irrigation is commonly used in peri-urban and rural agriculture, and watering cans are widely used for urban wastewater irrigation, especially in sub-Saharan Africa (Martijn, 2005). Few studies are available regarding the effects of using watering cans in wastewater irrigation, which is a common practice in developing countries (Martijn, 2005). However, Keraita et al. (2007a) showed that using watering cans in wastewater irrigation can reduce contamination by thermotolerant coliforms (bacteria group) up to 2.5 log units.

Post-harvesting practices such as washing and handling before consumption can also influence the final concentrations of contaminants (Qadir et al., 2010a). Simple washing leads to a 1 log reduction, with 2 log reduction is achieved with the use of domestic disinfection solutions, such as a weak disinfectant dissolved in washing water (Keraita et al., 2008). Finally, cooking leads to a 6–7 log reduction (Keraita et al., 2008). Therefore, considering the potential log reduction in pathogenic organisms, the appropriate irrigation methods, post-harvesting practices, and crop selection should be considered as an alternative for, or a complement to, wastewater treatment for the case of developing countries.

3.3. *Water reclamation for irrigation in sub-Saharan Africa (SSA)*

3.3.1. *Potentials and constraints of water reclamation for irrigation in sub-Saharan Africa*

Wide-scale proper implementation of water reclamation for agricultural irrigation in SSA will positively address various aspects of the sustainable development goals as outlined by the United Nations (UN General Assembly, 2015). The main advantages are: 1) wastewater is a secure available water source promoting food production in the (peri-) urban areas; 2) water reclamation promotes better sanitation, protecting human and environmental health; (3) water reclamation improves the famers' quality of life and livelihood. In the below paragraph, these advantages are further discussed in the SSA context.

1) *Increased water availability.* Decreasing freshwater availability with increasing water demand makes wastewater a reliably available alternative water source for irrigation in most (peri-)urban areas of sub-Saharan Africa (Adewumi et al., 2010; WorldBank, 2013). Examples of wastewater being used untreated or partially treated for irrigation are available in Ghana, Kenya and Mozambique, simply because this water is available in (peri-)urban areas (Alade, 2019; Hide et al., 2001; Karanja et al., 2010). The rapid population increase in SSA cities at a rate of 3.5% per annum, will lead to 1.26 billion people living in African cities by 2050 (Bougnom et al., 2019; Werner et al., 2019). This will increase the need for water reclamation in the SSA urban regions, particularly for (peri-)urban agricultural uses (Qadir et al., 2020). Other studies researched the potentials for water reclamation in non-agricultural applications, such as landscaping and industrial uses in some areas of Western Cape, in South Africa (Adewumi et al., 2010).
2) *Improved sanitation and health.* The design of water reclamation schemes concomitantly offers opportunities to improve sanitation in African cities, thus protecting human and environmental health. In sub-Saharan Africa, wastewater is limitedly collected and typically disposed into the environment without treatment (Nansubuga et al.,

2016). In most cases, the implementation of infrastructure for proper wastewater collection and further management is constrained by limited financial resources in a large number of African countries (Jiménez and Asano, 2008b). Therefore, most of the population in the continent rely on on-site sanitation, typically latrines (Nansubuga et al., 2016), with local discharge of the produced wastewater to the environment. The huge difference between actual water supply and wastewater collection also limits the available information regarding the quantity of wastewater produced, collected, treated, and reclaimed (Sato et al., 2013).

3) *Improved livelihood.* Application of proper water reclamation schemes will improve the living conditions of local farmers in peri-urban settings. At present, in most SSA countries, (diluted) urban wastewater is commonly used for irrigation without any treatment, creating great risks for microbial contamination and the exposure to other types of contaminants (Dickin et al., 2016). This current practice can have deleterious impacts to the public health, groundwater quality, soil and waterways. Therefore, reclaiming wastewater in a safe manner will improve the working and living conditions for farmers. Moreover, it will contribute to safety in wastewater handling and will improve the quality of the produce. In addition, it has social benefits as it generates employment for most of the (peri-) urban farmers (de Bon et al., 2010).

The major challenge for implementation of regulated water reclamation schemes in SSA region is costs. Capital exploitation costs are derived from the installation of conveyance and sewerage systems, siphons and pumping stations, and wastewater treatment facilities, whereas operational exploitation costs comprise costs for personnel, energy, chemicals and repair (Kihila, 2015, 2014; Kivaisi, 2001). The application of conventional centralized wastewater treatments schemes comes with exorbitant costs associated with the construction, operation and maintenance for both the transportation and treatment of wastewater (Amoah et al., 2018; Qadir et al., 2020). Those schemes are difficult to maintain in many of the less prosperous countries (Akhtar et al., 2018). In fact, the lack of financial and technical facilities undermines the ability of the countries to even supply water that can be reclaimed (Ashraf et al., 2017; Massoud et al., 2009; Wilderer et al., 2000). The poor management of wastewater treatment facilities and insufficient funds that are allocated to these facilities, result in many of them failing (Edokpayi et al., 2015). Furthermore, in many sub-Saharan African countries, there is a lack of regulatory measures to promote water reclamation, coupled to environmental and public health protection. The most striking negatives impacts of non-controlled use of wastewater are deterioration of soil, health hazards, deterioration of groundwater quality (Ashraf et al., 2017). As a result of lacking infrastructure for wastewater management, SSA cities produce the lowest amount of wastewater per capita, which is around 46 m^3 and is half of the global average of 95 m^3 (Qadir et al., 2020). This situation limits the capacity for water reclamation for agricultural reuse in SSA (peri-) urban agriculture. Therefore, reclaiming water will contribute to revenue generation covering its costs and sustaining wastewater treatment.

3.3.2. Water reclamation for agricultural irrigation in sub-Saharan Africa: current status and way forward

Typically, wastewater treatment in sub-Saharan Africa consists of pond systems (Kivaisi, 2001) with some examples of activated sludge processes in countries such as Botswana, Ghana, Namibia and South Africa (Adonadaga, 2014; Emongor and Ramolemana, 2004; Lahnsteiner and Lempert, 2007; Nikiema et al., 2013; Salaudeen et al., 2018).

There are few available examples of controlled wastewater treatment for irrigated agriculture (Tables 2 and 3) located in Namibia, Mauritius and South Africa. In Namibia, treated wastewater is used for potable water preparation and irrigation (Lahnsteiner and Lempert, 2007; Woltersdorf et al., 2016). In Mauritius, treated wastewater is used to irrigate sugar cane plantations (Joysury et al., 2012). Some of the many non-regulated examples using uncontrolled untreated, blended, or partially treated wastewater are documented in the literature and can be found in Cameroon, Kenya, Ghana and Mozambique. In the city of Yaoundé (Cameroon), partially treated wastewater is used for irrigation of lettuce (Tsama et al., 2015), whereas in Nairobi (Kenya), lettuce is irrigated with untreated wastewater (Githuku, 2009). Some studies addressed in-situ treatment options in Burkina Faso, Togo and Ghana (Keraita et al., 2014). Water reclamation for irrigation in Maputo is performed unplanned in peri-urban areas. This practice is driven by water scarcity (Rietveld et al., 2016) and, likely, the availability of nutritional water (Agodzo et al., 2003; Huibers and van Lier, 2005), using the partially treated water from the nearby wastewater treatment plant in Maputo (Arsénio et al., 2018; Tauzene et al., 2017). In addition, some examples of on-farm/on-site treatment can be found in Ghana and South Africa. In Ghana, on-farm wastewater treatment options are used for irrigation to produce vegetables (Agodzo et al., 2003; Antwi-agyei, 2015; Keraita et al., 2014). Another example is in South Africa, where the Lynedoch Eco Village uses extensive on-site water reclamation for irrigation (Adewumi et al., 2010).

The many non-controlled uses of blended, non-treated, and partially-treated wastewater in sub-Saharan Africa reveal that there is a significant need for infrastructure that is appropriate for the local conditions. Experiences from Zimbabwe, where centralised treatment systems were implemented, show that adopted wastewater technologies were too sophisticated such that the country could not continue utilising them (Nhapi and Gijzen, 2004). Authors conclude that in such cases, natural treatment methods, such as pond systems, are preferred since they are cheaper and easier to maintain and operate (Nhapi and Gijzen, 2004). However, it is important to note that natural treatment systems have surface-based dimensions and can thus only be implemented where land is available and affordable, requiring large conveyance pipes to outside the urbanised areas.

Considering the points above, it can be concluded that in Sub-Saharan Africa, there is a very large potential for water reclamation, particularly for agricultural purposes. Wastewater is an alternative water supply resource that is reliably available and coupled with several benefits (e.g. presence of nutrients). However, a more proper balance between required water quality and level of required technology for wastewater treatment should be searched for, to cost-effectively reduce current risks using a multiple barrier approach (Amponsah et al., 2016; Keraita et al., 2010). According to Norton-Brandão et al. (2013), a proper reclamation technology for improving the water quality addresses the removal of pathogenic organisms as well as heavy metals, whereas salinity levels are taken into account when adopting technologies for irrigated agriculture. Restricted crops irrigation would be unrealistic under the prevailing societal conditions, but barriers should be placed in critical points throughout the supply chain, combining barriers to reduce the risk in total terms (Keraita et al., 2010). The multiple barrier approach would combine the required water quality for irrigation, use of affordable treatment technologies, and adequate post-harvest approaches and management throughout the supply chain to reduce current health risks to acceptable levels. In addition, guidelines that only take into consideration the water quality at the point of use are unrealistic for the current situation of many African cities and countries. On the long term, there is a need to balance the treatment level with the required water quality level (van Lier and Huibers, 2010). Within this approach, the required water quality at the farmer's level would set the boundary conditions for the treatment system, while combining the use of treated wastewater with other protective measures and master planning. The protective measures would consider the irrigation and post-harvest practices to help pathogen reduction. Master planning may require a division of wastewater irrigated areas according to water quality requirements and respective crops to be produced. Such division is in place in several South-Mediterranean countries such as Jordan and Tunisia (Boom et al., 2008; Chenini et al., 2003). The feasibility of this approach will depend on the actual conditions of the country where the protective measures can be applied. Following this approach will likely contribute to sustaining the livelihood of farmers, while improving health conditions for farmers, handlers, consumers, and the environment.

4. Conclusions

Urban agriculture is a very relevant activity in many developing countries because it serves as a means for cost-effective food provision to local people in addition to nutrition improvement, economic development, job creation, and food security. In urban areas, water is scarce and expensive, but water reclamation for agricultural use has several benefits that range from alleviation of pressure on freshwater resources, to nutrient recovery and environmental protection benefits. Examples of water reclamation are widespread in the world, and the literature reveals that there is a great opportunity for sub-Saharan Africa to implement water reclamation in a planned manner. The benefits from water reclamation will be an increased water availability, an improved sanitation, health and livelihood for sub-Saharan Africa. In addition, it also serves as an opportunity for developing countries to offer better sanitation services through revenue generation. However, there are also risks associated to water reclamation for agricultural use, such as soil degradation and seepage infiltration, leading to microbial and heavy metal contamination to water, soil and crops, impacting human and environmental health. Therefore, the water quality at the point of use must be considered an important issue.

Informally, water reclamation is widely practiced in many sub-Saharan Africa countries. Some planned and formal examples are available, but mostly untreated reclaimed wastewater is used for agricultural purposes. Currently, there are no country-specific guidelines to control the quality of wastewater to be used, so the WHO guidelines are generally used. Since the 2006 WHO guidelines are more difficult to implement, most countries still use the 1989 WHO guidelines, which are based on restrictive effluent criteria. However, restrictive guidelines are unrealistic given current farmer practices. Most guidelines consider the water quality at the point of use, which is a limitation because developing countries have inefficient or inexistent wastewater treatment facilities and institutional capacity. Thus, contamination is prone to occur throughout the supply chain. In order to achieve the quality requirements for safe water reclamation, the current paradigm for development has to change. Although there is potential for water reclamation in African countries, exploiting these potentials requires leap-frogging developments by planning the future water and sanitation infrastructure to provide support for the proposed approaches. The multiple barrier approach proposed in the article in combination with master planning is recommended, which combines wastewater treatment and critical point barriers in order to reduce health risks, throughout the supply chain. In addition, for the long term, an approach needs to be developed that considers the required water quality at the point of use to design affordable wastewater treatment systems and reduce risks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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