UNIVERSITY OF HOHENHEIM

Potential of waste water hydroponics to advance urban vegetable production in Accra, Ghana:

An assessment of water quality, economic profitability, and social acceptance of lettuce

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Abstract

Waste water is a health burden but also a critical resource for urban vegetable production in the Global South. Therefore, new ways must be found to sustainably use urban water and nutrient flows. Simplified hydroponic systems are one such solution for harvesting wastewater nutrients while avoiding the contamination of edible plant parts. This study investigated the potential of rolling-out a wastewater hydroponic system as an alternative to soil-based lettuce production in Accra, Ghana.

The current status of irrigated vegetable production in Accra was examined to establish a baseline against which the new technology was compared. A simplified hydroponic system was designed based on information from surface water quality analysis; surveys of farmers, vendors, and consumers; and economic analyses. Finally, an investment analysis was performed and potential environmental benefits of the proposed system were estimated.

The results indicate that waste water irrigated vegetable production plays an important role in income generation and sustaining the city's food supply. However, lingering threats include reduced planting area, salinity, and disease. The widely used irrigation methods likely promote pathogen transfer while frequent use of agrochemicals threatens human and environmental health. Still, surface water in Accra could be used as a nutrient solution for hydroponic lettuce production. Surveys of farmers, vendors, and consumers indicated a keen interest in the system, while investment analysis suggested selling prices as the key hurdle.

The proposed hydroponic system could be profitable at self-marketing price that triple farmer's income. If widely adopted, expected environmental benefits may include improvement of surface and groundwater quality, reduction of phytosanitary products, and containment of soil degradation.

This study from Ghana suggests that simplified hydroponics may be a socially accepted technology for using urban water and nutrient flows to produce food, raise incomes, and protect human health.

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List of abbreviations

CBA	Cost-benefit analysis
CFA	Continuous flow analysis
CSIR	Council for Scientific and Industrial Research
CVAAS	Cold-vapor atomic absorption spectrometry
EC	Electrical conductivity
GAMA	Greater Accra Metropolitan Area
GHS	Ghanaian cedi
HTH	High Technology Hydroponics
ICP-MS	Inductively coupled plasma mass spectrometry
ICP-OES	Inductively coupled plasma optical emission spectrometry
IN	Inorganic nitrogen
IRR	Internal rate of return
NFT	Nutrient flow technique
NH4-N	Ammonium nitrogen
NO3-N	Nitrate nitrogen
NPV	Net present value
PP	Payback period
QGIS	QuantumGIS
RMC	Recommended maximum concentrations
SAR	Sodium adsorption ratio
SH	Simplified Hydroponics
SS	Suspended solids
TDS	Total dissolved solids
TS	Total solid

1. Introduction

In 2007, a remarkable demographic event occurred. It was the first time the world population became was urban than rural. Twelve years later, in 2019, more than 55% of people lived in cities (UN 2018). This trend is projected to continue until in 2050 when ~ 67% of the estimated 9.8 billion people will live in urban areas. Close to 90% of the increase in urban populations is expected to happen in Asia and Africa (UN 2018). Compared with the Global North where urbanization – or the increasing proportion of a population living in cities, is associated with better access to public services (Davis 1965), nearly half of city dwellers in the Global South have inadequate living space, insecure land tenure, and poor access to water and sanitation infrastructure (Cohen 2006; Arimah 2010). The lack of sanitation infrastructure including sewer systems and water treatment plants causes disposal of wastewater via cities surface waters (Xu et al. 2019). Also, the growing number of the "urban poor" spend most of their income on food, which leaves them at the brink of being food and nutrition insecure (Nelson 2017; Tacoli 2017).

Urban agriculture, more specifically urban crop production can contribute to solving the challenges of urban food and nutrition insecurity and unsafe wastewater disposal prevalent in many cities of the Global South. It is estimated that ~ 250 million households worldwide participate in urban agriculture, with 29 million in Africa (Hamilton et al. 2014). At the household level, this practice provides direct access to nutritious food, creates resilience against price fluctuations, and generates valuable income (Zezza and Tasciotti 2010). Furthermore, urban crop production makes fresh and healthy food available at affordable prices and creates jobs along the supply chain (Orsini et al. 2013). Irrigated urban vegetable production is a particularly profitable branch of urban agriculture. Benefits include multiple cropping cycles that provide immediate and continuous returns, and close market proximity for perishables goods (De Zeeuw et al. 2011; Raschid-Sally 2013; Orsini et al. 2013). However, the gap between population growth and investment in sanitation in many cities of the Global South has resulted in inadequate wastewater collection and treatment, which causes urban vegetable farmers to rely on contaminated water sources (Drechsel et al. 2010b).

Wastewater irrigation is practiced on ~ 5 – 20 million hectares globally (Drechsel et al. 2010b; Raschid-Sally 2013). In many African cities, ~ 60 – 90% of leafy vegetables are irrigated with wastewater (Drechsel et al. 2006; Raschid-Sally 2013). Farmers benefit from free nutrients already diluted in surface water, which has potential to cutting costs for fertilizer (Corcoran et al. 2010; Kurian et al. 2013). However, excreta-related pathogens (e.g., bacteria, helminths, protozoa, viruses), skin irritants and infections, vector-borne pathogens and chemicals threaten the health of farm workers and consumers (WHO 2006; Bos et al. 2010). Yet, given the contribution urban agricultural makes towards alleviating poverty and food insecurity, a solution must be found to use freely available surface water and at the same time assure hygienic produce.

Hydroponics offers a solution for using urban wastewater for irrigation in a way that effectively harvests nutrients while safeguarding farmers and consumer health. For example, using pre-treated municipal wastewater as a water source, Bliedung et al. (2020) demonstrated that lettuce removed all measurable nitrogen and potassium from the water. Considerable reductions in microbial contamination in produce are also realised because only the roots instead of edible plant parts are submerged in the wastewater nutrient solution (Magwaza et al. 2020). Thus, the potential of hydroponics for purifying wastewater and producing vegetables has been documented in several studies in the last three decades (e.g. Neuray 1988; Boyden and Rababah 1996; Vaillant et al. 2003; Albert 2015; Da Silva et al. 2018; Bliedung et al. 2020).

However, two recent reviews on wastewater hydroponics for crop production by Cifuentes-Torres et al. (2020) and Magwaza et al. (2020) show that research on the topic has primarily relied on laboratory settings. The existing full-scale studies focus on the wastewater treatment aspect, i.e. the use of plants for removing nutrients without considering suitability for consumption. To date, no study has looked specifically at how a low-cost hydroponic system may advance urban agriculture in the Global South. Previous studies overlooked the issue of profitability and investment financing. Thus, to the best of my knowledge, there has only been one estimation of the income that can be generated with a low-cost wastewater based hydroponic system used in urban agriculture in the Global South (UNDP 1996).

Accra, the capital of the Republic of Ghana is a good test case to assess the potential of a wastewater hydroponic system to advance irrigated urban agriculture in the Global South. The Greater Accra Metropolitan Area (GAMA) is one of the fastest growing city regions in West Africa (The World Bank Group 2017). The sanitation sector has been outpaced by rapid growth of the urban population. Less than one-fifth of the Metropolitan Area is connected to a sewer system and none of the public sludge or wastewater treatment plants are fully functional (UNICEF 2016; ADF 2018). Thus, nearly all of the city's wastewater is disposed directly into the ocean or joins the urban surface waters (Adank et al. 2011). These surface waters are the main source of irrigation water for an estimated 800 – 1,000 urban vegetable farmers that daily supply more than 200,000 of Accra's dwellers with fresh produce (Amoah et al. 2007; Danso et al. 2014). Efforts to reduce the well-documented health risks associated with wastewater irrigation have failed to lessen pathogen contamination of vegetables (Keraita et al. 2003; Amoah et al. 2006, 2007; Seidu et al. 2008; Amoah et al. 2011; Lente et al. 2012; Silverman et al. 2013; Drechsel and Keraita 2014).

This study seeks to assess the potential of a simplified hydroponic system as an alternative to the soil-based irrigated vegetable production in Accra. Lettuce was chosen as a target crop. The theoretical framework underpinning this study is the three-pillar concept of sustainability (Purvis et al. 2019) that demands that an innovation be environmentally beneficial, economically viable, and socially acceptable. The design of the hydroponic system and the exploration of whether it is a sustainable alternative to the soil-based production system is guided by the following objectives: a) To describe and evaluate agronomic and socio-economic characteristics of the current soil-based production system; b) To analyse the quality of the surface water as a hydroponic nutrient solution; c) To assess the interest and concern of farmers, vendors and consumers regarding a wastewater based hydroponic system; d) To design a low-cost hydroponic system and evaluate its economic profitability and potential environmental impact.

The rest of the thesis includes a literature review on wastewater management, wastewater use in crop production, and wastewater hydroponics (Chap. 2); a description of materials and methods (Chap. 3); a presentation of the results (Chap. 4). The work concludes by discussing the most important findings (Chap. 5), the limitations, and an outlook for future research (Chap. 6).

2. Literature review

Amid lack of wastewater collection and treatment infrastructure, innovative use of wastewater provides a sustainable solution to food security, public and environmental health in cities of the Global South. In this chapter, challenges of urban wastewater management are reviewed along with scale, benefits, and risks of wastewater use for crop production. Advantages and disadvantages of hydroponics over soil-based farming and state-of-the-art of hydroponic systems are assessed. Finally, the adequacy of wastewater for hydroponic lettuce production is discussed.

2.1 Challenges of urban waste water management

2.1.1 Urban water scarcity and water quality

Human impact on the natural water cycle has become more negative (Oki and Kanae 2006). Changes related to population growth, economic development, improved living standards, and consumption patterns have increased water demand. Water supply has become inadequate because of competition among users, rising levels of pollution, and overuse (Jacobsen et al. 2013; Schewe et al. 2014; WWAP 2017). Water scarcity is rising in countries of the Global South according to the Falkenmark indicator, i.e., less than 1,000 m^3 per capita per year of renewable water are available (Falkenmark 1991; Oki and Kanae 2006). Also, 'economic water scarcity' is now a common feature of cities in the Global South because of limited institutional and financial means to use available water (IWMI 2007). A key contributor to economic water scarcity is lack of wastewater collection and treatment infrastructure that leads to pollution of available water. Cities in the Global South are hotspots of untreated wastewater because of poor water treatment infrastructure failing to cater for high population densities (Corcoran et al. 2010; WWAP 2017).

2.1.2 Defining waste water

The definition of "waste water" or wastewater is not agreed upon. Amoatey and Bani's (2011) attempt at a broad definition suggests that it is water whose physical, chemical or biological properties have been changed as a result of contamination by certain substances which make it unsafe for certain uses such drinking. For urban wastewater, a popular definition is that by Raschid-Sally and Jayakody (2008) who describe it as any combination of domestic effluent, water from commercial establishments and institutions, industrial effluent, storm water, and other urban runoff. They further distinguish between wastewater in its raw form and diluted wastewater, i.e., where raw wastewater is mixed with water from other sources like streams. Therefore, urban wastewater can be separated into runoff, industrial, and domestic/institutional (Fig.01; Amoatey and Bani 2011;WWAP 2017).

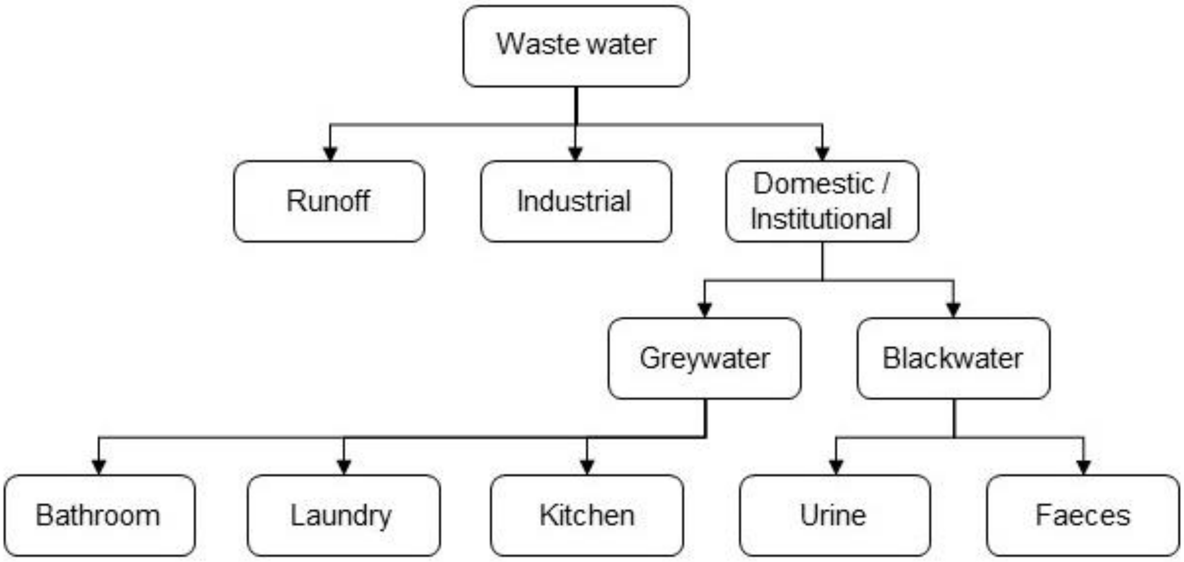

Fig.01: Types of urban wastewater (based on Amoatey and Bani 2011).

Urban runoff consists not only of rain water, but it carries solid wastes and other surface pollutants (e.g., rubber and motor oil from roads, or fertilizer and pesticides from lawns) that flush into drainage systems or often directly into surface waters (WWAP 2017). On the other hand, industrial wastewater composition is determined by the type of industry. For example, automobile manufacture, petroleum refining, beverage production, and meat processing produce different waste streams (Muralikrishna and Manickam 2017). However, typical components of industrial wastewater include solids, oil and grease, organic compounds, and metals (Abaidoo et al. 2007; Vymazal 2009; Muralikrishna and Manickam 2017; WWAP 2017).

In comparison, domestic or institutional wastewater contains human excreta carrying pathogenic microorganisms and nutrients, organic matter, and sometimes emerging pollutants like pharmaceuticals (WWAP 2017). This waste is also classified as blackwater and greywater. Blackwater contains faecal matter and/or urine, and greywater originates from sinks, showers, kitchen, laundry, and is free from faecal contamination (Adank et al. 2011). However, the distinction of wastewater is blurred by the common term “municipal wastewater”, which combines domestic, institutional, and industrial wastewater within settlements or communities (WWAP 2017).

A set of physical, chemical, and biological indicators are useful for indicating wastewater quality (Appendix A). Physical indicators include salt content (salinity) and solid particles. Salinity has the potential to harm plant growth and soil permeability when discharged untreated while suspended solid particles can act as absorption surfaces for pollutants and protection for pathogens (Rhoades et al. 1992; von Sperling 2007; Kasper et al. 2018). Relevant biological characteristics include the amount of organic matter represented by dissolved solids, biological and chemical oxygen demand that indicate increased oxygen consumption (von Sperling 2007; Amoatey and Bani 2011). Negative effects of increased oxygen consumption are septic and anaerobic conditions that kill aquatic life. Also, the amount of potentially harmful microorganisms is important as some cause water-borne diseases such as intestinal worm infections and diarrhoea (von Sperling 2007; Corcoran et al. 2010). Finally, chemical characterisation relates to concentration levels of nutrients and heavy metals. High nutrient concentrations (e.g., of phosphorus or nitrogen) cause excessive algal growth, toxicity to fish, and ground water pollution. Similarly, heavy metals can cause various toxic effects leading to soil and ground water contamination (von Sperling 2007; WWAP 2017).

2.1.3 Urban waste water treatment

Treatment of wastewater in urban areas evolved as a reaction to wastewater pollutants and their adverse effects on human health, environment, and economic activities (Amoatey and Bani 2011; WWAP 2017). For example, agricultural production was affected when the capacity of water bodies to assimilate the polluted waters was exceeded. The conventional approach to wastewater treatment in major towns and cities includes several stages that separate solid (sludge) from liquid (effluent) waste (Fig.02).

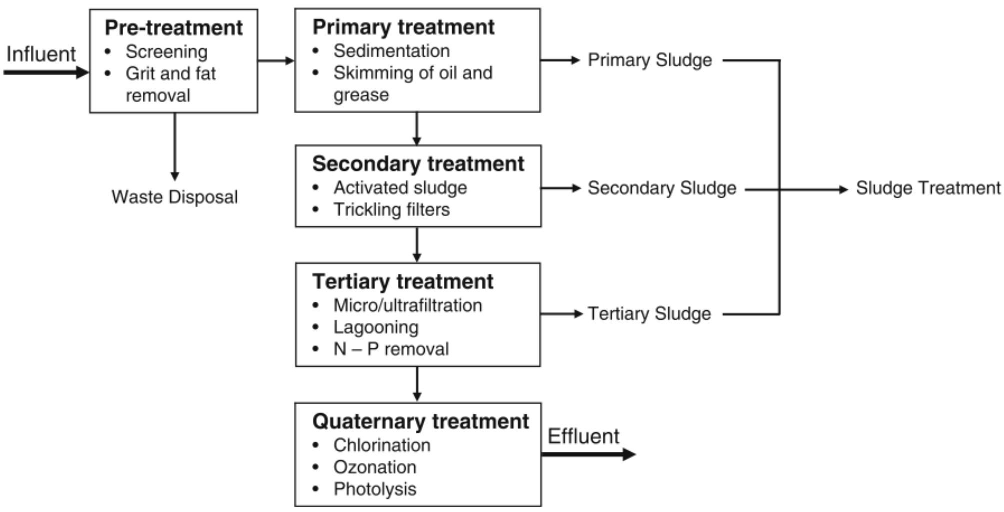

Fig.02: Treatment steps of a conventional wastewater treatment plant (adopted from Kestemont and Depiereux 2013).

However, many cities in the Global South do not conduct adequate conventional wastewater treatment. Often, the treatment process is hindered already by poor infrastructure for collection as is discussed for Ghana in the following section.

2.1.4 Waste water management in Ghana

Wastewater management in Ghana is similar to that of many sub-Sahara African countries. While water availability in the country is estimated to be around 2,033 m^3 per capita per year (Schuol et al. 2008), which is clearly above the threshold of the Falkenmark indicator for water stress, still Ghana has economic water scarcity (IWMI 2007). This undersupply is linked to shortcomings in the sanitation sector: lack of sufficient coverage of freshwater and failure to collect and treat wastewater that results in water pollution (Keraita and Drechsel 2004; Bahri et al. 2008; Nikiema et al. 2011). While the availability of safe drinking water is better in urban compared to rural areas, with significant improvements in the last decade (WHO/UNICEF JMP. Drinking water 2020), however, increased water supply to cities has raised wastewater amounts and overwhelmed the collection and treatment infrastructure (Bahri et al. 2008; Adank et al. 2011; Padi 2016).

Ghana already struggles with the collection of wastewater, a pre-requisite for safe treatment. Wastewater suitable for collection and treatment in the country is mostly from domestic sources and surface run-off because industries situated by the coast directly discharge wastewater into the ocean (Keraita and Drechsel 2004; Adu-Ahyiah and Anku 2007). About 4.5% of households are connected to a water-borne sewer system (UNICEF 2016), and only Akosombo in the Eastern Region and Tema in the Great Accra Region have adequate sewerage cover (Awuah et al. 2009). Much of the excreta is collected at household level or from public toilets in septic tanks from where it needs to be regularly pumped and driven to a faecal sludge treatment plant (Awuah et al. 2009; Murray and Drechsel 2011). However, the hiring of companies to collect faecal sludge is the responsibility of households, communities and institutions. Thus, waste disposal is often delayed and septic tank contents spill into surrounding environments (MLGRDE 2008; Keraita et al. 2014). As 17% of Ghanaians have no access to adequate toilet facilities (WHO/UNICEF JMP 2020), many poor urban dwellers defecate in the open (ADF. 2017) and the waste ends up in nearby water bodies (Murray and Drechsel 2011). Even greywater is directly dumped into open areas and storm-water gutters or surface waters (GSS 2014). As a result, channels carrying black- and greywater pollute streams and rivers (Adu-Ahyiah and Anku 2007; Padi 2016).

Wastewater treatment in Ghana remains a major challenge. The majority of treatment plants are decentralized, serving discrete populations such as hotels, schools, hospitals, military camps or single communities (Murray and Drechsel 2011; UNICEF 2016). Public treatment plants are frequently stabilization ponds, which leaves the water treatment process at primary level (Nikiema et al. 2011; UNICEF 2016). In 2011, several of the ten regions lacked any public facilities for wastewater or sludge treatment. There were only three operational wastewater treatment plants for residential areas in the country (Murray and Drechsel 2011; Nikiema et al. 2011). A key factor causing the break-down of operational plants was that most public plants were built with foreign funds or by companies from abroad. After being handed over to local authorities, many suffered because of the lack of local technical expertise and poor maintenance (Amoatey and Bani 2011; Awuah et al. 2014; UNICEF 2016). Other significant issues compromising treatment services included erratic electricity supply and lack of accountability of operators, leading to over or underutilisation of treatment plants (Adu-Ahyiah and Anku 2007; Murray and Drechsel 2011). Thus, less than 8% of Ghana's wastewater is estimated to undergo any form of treatment (Nikiema et al. 2011; Gyampo 2012).

2.1.5 Waste water collection and treatment in Accra

The infrastructure for wastewater collection and treatment in Accra is better than in the rest of the country. Nevertheless, most of the wastewater and faecal sludge in the city enters surface waters or the ocean untreated because of poor collection and treatment infrastructure.

Blackwater collection and treatment in the capital is provided by the municipality, private enterprises or certain communities, with sensitive businesses such as hotels providing their own collection and treatment on-site (Fig.03). The Accra central sewerage system was built in 1972 as part of the municipal service provision with support from the World Bank and the capacity to serve 1,500 buildings (Bahri et al. 2008; Adank et al. 2011). It was extended by 63 km during a recent African Development Fund Project and now covers approximately 18% of the Greater Accra Metropolitan Area (GAMA) (ADF 2018). The sewer system is the only connection to a wastewater treatment plant, therefore only the wastewater from few buildings connected to the central sewer system can access a public treatment plant (Fig.03). The vast majority of Accra's blackwater is collected by municipal or private septic collectors, or in transfer stations from where it is pumped to faecal sludge treatment plants (FSTP) (Adank et al. 2011). However, according to a 2016 assessment (UNICEF 2016), all public wastewater and faecal sludge treatment plants in Accra are dysfunctional. The only functional treatment facilities are two plants at hotels and one faecal sludge treatment plant serving a small community. Therefore, the only blackwater that is treated is from self-supplied communities or businesses that collect it in sewers and transfer it to a wastewater treatment plant (WWTP) (Fig.03). The rest of the self-supplied areas have latrines or Kumasi Ventilated Improved Pits (KVIPs) that do not require emptying (Adank et al. 2011). All other blackwater eventually seeps into surface waters, or enters the ocean (Bahri et al. 2008; Murray and Drechsel 2011).

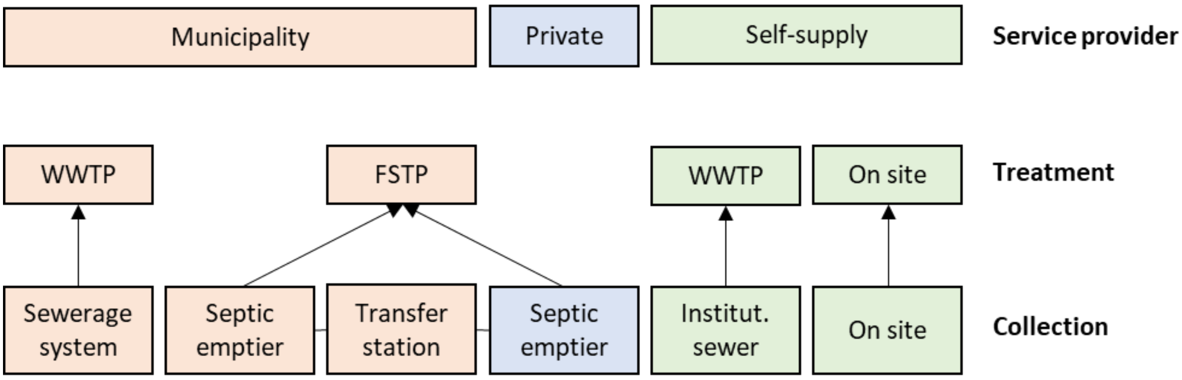

Fig.03: Infrastructure for black water collection and treatment in Accra. WWTP = waste water treatment plant and FSTP = faecal sludge treatment plant (adopted from Adank et al. 2011).

Greywater in Accra is mostly disposed into storm water drains or surface waters, or dumped onto streets (Adank et al. 2011). It ends up in Accra's streams and rivers that function as drains (Fig.04). Thus, Accra's poor wastewater collection and treatment infrastructure makes its rivers conveyors of runoff, greywater, and blackwater (Bahri et al. 2008; MLGRDE 2008; Padi 2016).

Fig.04: Direct disposal of greywater into the Kordjor River (left) and state of the Odaw River (right), two streams in the Accra Metropolitan District taken in 2018 (*Photo credits*, Johanna Volk).

2.2 Waste water use in crop production

The irrigation of crops with wastewater dates back to pre-historic times. As human societies transitioned from nomadic hunter-gatherer lifestyles to permanent settlements, systems for transporting wastewater evolved out of the need to remove human and other waste from settlements (Angelakis et al. 2018). The productive use of wastewater was first documented 5,000 years ago when the Minoans channelled wastewater onto agricultural land for irrigation and fertilization purposes (Angelakis et al. 2018). Centuries later, the use of wastewater for irrigation became widespread (Drechsel et al. 2010a; Liebe and Ardakanian 2013). Although global numbers on wastewater irrigation are fragmentary, it is estimated that annually, 5 – 20 million hectares are irrigated with untreated or partially treated wastewater (Drechsel et al. 2010c, a; Liebe and Ardakanian 2013). Furthermore, it is estimated that the area irrigated with untreated wastewater is over eight times higher than that irrigated with treated wastewater (Drechsel et al. 2010c). Therefore, approximately 10% or up to one billion people rely on food grown with wastewater, with many of these people living in cities of the Global South (WHO and UNEP 2006; Drechsel et al. 2010a).

2.2.1 Waste water irrigated urban vegetable production

Vegetables are the most common crops irrigated with wastewater in cities of the Global South (Raschid-Sally and Jayakody 2008; Raschid-Sally 2013). Raschid-Sally and Jayakody (2008) concluded from their global assessment of wastewater agriculture that in four out of five cities of the Global South, farmers used wastewater for irrigation. The key drivers of wastewater use in urban areas were the pollution of traditional irrigation water sources and demand for agricultural products (Drechsel et al. 2010a; Raschid-Sally 2013). Absence of cold transport systems and increased demand for exotic vegetables has given rise to urban vegetable production (Raschid-Sally 2013). For example, it is estimated that 60 – 90% of vegetables consumed by urban dwellers across West Africa are produced within or close to cities (Drechsel et al. 2006; Raschid-Sally 2013). Although urban vegetable production relying on wastewater irrigation has several economic, social, and environmental benefits, however, it also presents environmental and human health risks.

We associate several benefits with the irrigation of vegetables with wastewater. Urban wastewater is a low-cost or often free resource available all-year round (Corcoran et al. 2010; Raschid-Sally 2013). Frequently being the only available water resource to farmers, wastewater irrigation allows for multiple cropping periods per year especially in semi-arid or arid regions (Liebe and Ardakanian 2013; Raschid-Sally 2013). Plant nutrients dissolved in wastewater may increase yields while cutting expenditure for fertilizer, which makes urban vegetable production profitable (Corcoran et al. 2010; Kurian et al. 2013). Many urban farmers escape the poverty line of US$1 per day (Raschid-Sally 2013). From a societal perspective, next to the provisioning of income, wastewater irrigated vegetable production has positive health impacts by increasing availability of nutritious food (Liebe and Ardakanian 2013). In terms of environmental benefits, wastewater use in crop production contributes in closing the urban water and nutrient cycle as water and nutrients from domestic or municipal waste are re-used. For example, Qadir et al. (2010) estimated that ~ 1,000 m^3 of municipal wastewater contains up to 62 kg of nitrogen, 24 kg of phosphorus, and 69 kg of potassium. Thus, uptake of these nutrients by plants limits eutrophication risk by reducing wastewater nutrient loads (Bahri 2009). Also, wastewater use conserves fresh water resources (Kurian et al. 2013). Yet, severe environmental and human health risks are associated with wastewater irrigated vegetable production.

The environmental risks of wastewater irrigated vegetable production depend on its composition, irrigation practices, and type of vegetable. Depending on where it is sourced, urban wastewater may contain different levels of chemical contaminants, undesirable salts, metals, and metalloids (Liebe and Ardakanian 2013). When wastewater is frequently used, contaminants accumulate in the soil (Hamilton et al. 2007). Nonetheless, for most situations in the Global South, the risk of chemical contamination is higher through direct on-site application, e.g., from pesticides, than from wastewater (Liebe and Ardakanian 2013). Meanwhile, contamination by heavy metals is generally low in cities of the Global South and metals like chromium, mercury, and lead are quickly absorbed by the soil, reducing the risk of toxicity to plants (Abaidoo et al. 2010). However, salinity and sodicity are major concerns because of their negative environmental impact. Salinity and sodicity can cause specific ion toxicity, interfere with nutrient uptake via antagonistic effects or change in the osmotic pressure of the root zone, and negatively affect soil structure and permeability (Stevens 2006; Hamilton et al. 2007; Abaidoo et al. 2010; Qadir et al. 2010). Besides accumulating in soil, salts of chloride, sodium, and boron among others dissolved in wastewater may drain or leach from irrigated fields and contaminate groundwater (Ensink et al. 2002; Abaidoo et al. 2010).

Wastewater irrigation and agricultural produce grown from it poses a threat to human health. The main concern of wastewater irrigation in the Global South is pathogenic microorganisms (Hamilton et al. 2007; Liebe and Ardakanian 2013; Shakir et al. 2017). Most microbial pathogens found in wastewater are enteric in origin, i.e., they enter the environment from faeces of infected hosts, and this microorganisms load depend on the health status of the population producing wastewater (Santamaría and Toranzos 2003; García-Aljaro et al. 2019). Thus, municipal wastewater can contain a wide variety of microorganisms that are harmful to human health including bacteria (e.g. *Salmonella* spp., *Escherichia coli*), viruses (e.g. poliovirus, hepatitis A virus or rotavirus), protozoans (e.g. *Cryptosporidium* or *Giardia intestinalis*), and parasitic helminth worms (e.g. *Ascaris lumbricoides* or *Schistosoma spp*)

(Hamilton et al. 2007; Bos et al. 2010). Some of the more resistant microorganisms accumulate in soil (Santamaría and Toranzos 2003). Infection by these pathogens can cause several diseases and conditions including typhoid, dysentery, gastroenteritis, diarrhoea, vomiting, malabsorption, cholera, ascariasis, and anaemia (Shakir et al. 2017). Farm workers have high risk of infection from wastewater irrigation because of the duration of exposure and intensity of contact with wastewater and contaminated soils, especially from high exposure irrigation methods such as watering cans and sprinklers (Blumenthal and Peasey 2002; Amoah et al. 2011). Furthermore, consumers of raw vegetables grown close to the ground such as lettuce are also at high risk of infections (Harris et al. 2003; Liebe and Ardakanian 2013).

2.2.2 Waste water irrigated vegetable production in Accra

In Ghanaian cities, an estimated 40,000 hectares of agricultural land is seasonally irrigated with raw or diluted wastewater (Danso et al. 2014). This is more than double the 10,000 – 19,000 hectares under formal irrigation in the country (Gumma et al. 2011; FAO 2013). In the capital Accra, the total area irrigated with wastewater is close to 160 hectares (Antwi-Agyei et al. 2016). Wastewater vegetable production in Accra takes place at seven major sites, each hosting 60 to 200 agricultural workers (Antwi-Agyei et al. 2016). Of the estimated 800 – 1,000 vegetable farmers, 60% grow exotic vegetables such as lettuce, cabbage, spring onion or cauliflower while 40% produce local or traditional vegetables like tomatoes, okra, ayoyo (*Corchorus* sp.), aubergines, and hot pepper (Danso et al. 2014).

Public health risks linked to wastewater irrigated vegetable production in Accra are well-documented (Amoah et al. 2005, 2006, 2007; Seidu et al. 2008; Donkor et al. 2010; Lente et al. 2012; Silverman et al. 2013; Keraita et al. 2014; Lente et al. 2014). Water used for irrigated vegetable production in Accra mostly originates from storm water drains or streams, and less often from pipes and wells (Amoah et al. 2005; Donkor et al. 2010). Amoah et al. (2005, 2007a) and Silverman et al. (2013) found faecal coliforms and helminth egg contamination of drains, streams, and wells throughout the year that significantly exceeded WHO recommended levels for unrestricted irrigation. Stream water was found to have up to 6 helminth eggs per litre, far exceeding the recommended level of <1 egg per litre (WHO 1989). Silverman et al. (2013) also found human viruses (adenovirus and norovirus) in 16 of 20 water samples. On the other hand, heavy metal concentrations of wastewater were found to be below the recommended levels (Lente et al. 2012, 2014). Thus, Keraita et al. (2014) and Lente et al. (2014) concluded that the highest health risk from using surface and drain water for irrigation comes from faecal contamination, human adenovirus and norovirus stemming from inadequate sanitation infrastructure and wastewater management.

Harmful pathogens in wastewater find their way from farms to markets and then consumers. Amoah et al. (2005, 2007a) reported that faecal coliform levels on lettuce were above recommended thresholds for food quality. Interestingly, while piped water contained fewer pathogens, there were considerable coliform counts found on pipe-irrigated vegetables on the farm. We can attribute this to the fact that soils may already be contaminated from the application of manure and long-term wastewater irrigation. Pathogen transfer from soil to plants occurs via splashes from overhead irrigation (Keraita et al. 2007a; Seidu et al. 2008), which was confirmed by Donkor et al. (2010) who found comparable levels of faecal coliform counts in soil samples and stream water samples. Amoah et al. (2006) also found an average of 1.1, 0.4, and 2.7 helminth eggs per gram of lettuce, cabbage and spring onion, respectively, in market samples.

As a reaction to health risks, a multi-tier approach was suggested with interventions at different levels of the supply chain (Amoah et al. 2006, 2007). Washing of vegetables before consumption and alternative low-cost irrigation methods were frequently touted (Amoah et al. 2006, 2007; Keraita et al. 2007a, b). However, it has been shown that post-harvest handling does not increase the farm-gate contamination levels; and that the internalisation of microbes in vegetables renders washing unsatisfactory (Amoah et al. 2007; Donkor et al. 2010). However, swapping mainly used watering cans with drip irrigation kits and cessation of irrigation before harvest has been shown to reduce the levels of contamination (Keraita et al. 2007a, b). Nevertheless, drip emitters often get clogged with particles found in untreated waste water and require lower crop densities which may restrict other farm activities. On the other hand, dispensing with wastewater irrigation altogether cuts yields and is ineffective in the rain season because of pathogen survival and re-contamination from the soil (Keraita et al. 2007a, b).

2.3 Waste water hydroponics

2.3.1 Hydroponic systems and advantages over soil-based crop production

Hydroponics is an agricultural technique that uses a nutrient solution, i.e., water with elements essential for plant growth instead of soil (Jensen 1997). The technique is old, Aztecs used it from 1400 – 1600 to grow vegetables on floating islands (González Carmona and Torres Valladares 2014). Almost any plant species can be grown in a hydroponic system. However, commercial hydroponic systems are used for high-value crops like flowers, leafy vegetables (e.g. lettuce and spinach), strawberries, and other types of vegetables like tomato and pepper (Sharma et al. 2018; Magwaza et al. 2020). It is estimated that ~ 3.5% of vegetable cultivation area under greenhouses uses hydroponics or 95,000 hectares globally (Hickman 2011 cited in Sabir and Singh 2013; Hickman 2016 cited in Sambo et al. 2019). Today, there are several methods used to grow plants hydroponically.

Hydroponics systems are classified according to whether the nutrient solution is recycled or not (i.e., an open versus closed system); the regularity of the water supply (i.e., continuous versus periodical); and the method of supplying the nutrient solution to plant roots (i.e., solution culture versus solid media culture versus aeroponics) (Hussain et al. 2014; Maucieri et al. 2019). Furthermore, a distinction is made according to the level of technology and investment costs (i.e., High Technology Hydroponics (HTH) versus Simplified Hydroponics (SH) (Stajano et al. 2003).

Hydroponic agriculture has many benefits. Hydroponic production of crops makes productive use of degraded land, has high water and nutrient use efficiency, and allows for year-round high quality production at reduced environmental impact. With the replacement of soil with water as the growth medium, plant growth and yields become independent of soil quality, thus crop production can occur on infertile or degraded land (Maucieri et al. 2019; Sambo et al. 2019). Water consumption is low due to lack of drainage and runoff, reduced evaporation, and the possibility of water recycling (Olympios 1999). For example, lettuce grown hydroponically requires 1.6 litres of water per kg versus 76 litres in a soil cultivation system (Barbosa et al. 2015; Sambo et al. 2019). Delivering water and nutrients directly to roots ensures that all nutrients are plant available and uniformly distributed; water and nutrient stress are eliminated when pH and electrical conductivity are managed, and plants grow at high densities (Olympios 1999; dos Santos et al. 2013; Sardare and Admane 2013; El-Kazzaz 2017). Hydroponic systems can be set-up in greenhouses or indoors, which makes plant growth and development independent of weather. It also reduces pest pressure, and allows for the control of environmental factors like light, temperature and CO_2 concentration (Vox et al. 2010). Controlling nutrient uptake creates uniform plant growth, promotes high nutritional values, and gives excellent conditions for biofortification (Olympios 1999; Sambo et al. 2019). The elimination of weeds and soil-borne diseases makes weedicides unnecessary and reduces pesticide use (Sardare and Admane 2013; Sharma et al. 2018). Also, leaching of nutrients and pesticides into groundwater can be avoided by recycling water or through controlled waste disposal (Olympios 1999; Maucieri et al. 2019). Last, fossil fuel intensive activities like tilling are replaced with the opportunity to use renewable energy for technical equipment such as pumps, aerators or lights (Khan 2018).

Shortcomings of hydroponic crop production can be compensated by choosing the appropriate system. The most cited downsides are high initial investment, requirement of energy supply, technical knowledge, and risk of pathogens spreading among plants via the nutrition solution (Ikeda et al. 2002; Sardare and Admane 2013; Hasan et al. 2018; Sharma et al. 2018). Besides the pathogen contamination, which can be addressed with various physical, cultural, chemical, and biological methods (Ikeda et al. 2002), high investment cost and the need for technical knowledge and power can be attenuated by choosing a simplified hydroponic system and mitigated in using renewable energy.

2.3.2 Waste water and hydroponics

For a long time, wastewater has been a productive resource for irrigated agriculture, especially in urban areas where water demand and wastewater supply co-occur (Boyden and Rababah 1996, Rana and Roosta in da silva carvalho 2018). However, as discussed earlier, use of untreated wastewater comes with certain environmental and health risk for producers and consumers. In view of the above discussed advantages of hydroponics and its potential to separate the edible plant parts from wastewater, it is not surprising that the idea of using hydroponics for wastewater treatment and wastewater based crop production has been explored by various (e.g. Neuray 1988; Boyden and Rababah 1996; Vaillant et al. 2004; Haddad and Mizyed 2011; Lopez-Galvez et al. 2016; da Silva Cuba Carvalho et al. 2018; Bliedung et al. 2020).

2.3.2.1 Waste water hydroponics for crop production

Studies on wastewater use and hydroponics accelerated in the last 40 years (Neuray 1988; Ayaz and Saygin 1996; Boyden and Rababah 1996). For example, Boyden and Rababah (1996) explored the possibility of using primary domestic wastewater to produce lettuce in Australia while Ayaz and Saygin (1996) investigated whether hydroponically grown aquatic plants are useful as a tertiary treatment step in Turkey. Follow-up studies focused on the wastewater treatment aspect of hydroponics where plant biomass is used for removing nutrients from industrial effluents or municipal wastewater, i.e., a process called phytoremediation (Ayaz and Saygin 1996; Norström et al. 2003; Vaillant et al. 2003, 2004; Ottoson et al. 2005; Haddad and Mizyed 2011; Krishnasamy et al. 2012; Yeboah et al. 2015; Gebeyehu et al. 2018; Worku et al. 2018; Ndulini et al. 2018). Other studies targeted the use of wastewater to produce biomass such as giant reeds or flowers (Mavrogianopoulos et al.

2002; de Andrade et al. 2012; Santos Júnior et al. 2014). Because of high nutrient concentrations, several studies have investigated the potential of wastewater and brackish water to produce crops like barley (Al-karaki 2011; Adrover et al. 2013); water spinach (Cui et al. 2006); pepper (Lopez-Galvez et al. 2016); and lettuce (Boyden and Rababah 1996; Rababah and Ashbolt 2000; Cui et al. 2006; Keller et al. 2008; Soares et al. 2015; da Silva Cuba Carvalho et al. 2018; da Silva et al. 2018; Kim et al. 2019; Bliedung et al. 2020).

A key question for crop production using wastewater has been whether plants can access nutrients at concentrations much lower than those found in commercial nutrient solutions. For lettuce, this question has been answered to some extent. For example, Table 01 shows that previous wastewater hydroponic systems for lettuce production used water with initial nitrogen, phosphorus and potassium concentrations below 2 mg l^{-1}. Additionally, Swiader and Freiji (1996) showed that lettuce grew healthy and uniformly at a nitrate concentration of 6.2 mg l^{-1} and that the nitrogen level in the hydroponic solution was reduced to below 0.3 mg l^{-1}. Similarly, Chen et al. (1997) observed that reducing the nitrate concentration by a 100-fold from 595 mg l^{-1} to 6 mg l^{-1} had no significant effect on lettuce shoot biomass or shoot nitrogen concentration.

Tab.01: Concentrations of nitrogen, phosphorus and potassium in mg l^{-1} in waste water used for experiments to grow lettuce hydroponically.

Authors	Nitrogen mg l^{-1}	Phosphorus mg l^{-1}	Potassium mg l^{-1}
Bliedung et al. (2020)	1.8 – 40	2.5 – 10	22 – 25
Boyden and Rababah (1996)	64	6.5	NA
Cui et al. (2006)	10 – 50	1.5 – 12	NA
da Silva Cuba Carvalho et al. (2018)	24 – 45	5 – 15	15 – 19
Da Silva et al. (2018)	0.7 *	NA	6 – 88
Keller et al. (2008)	24 **	24 – 41	NA
Kim et al. (2019)	1.9	0.7	1.3
Rababah and Ashbolt (2000)	56	4.4	31

*only information on nitrogen (N) in form of nitrate **only information on N in form of ammonium

2.3.2.2 Waste water hydroponics for lettuce production

It is generally agreed that healthy lettuce plants may be grown in wastewater while successfully removing nutrients from the water. Using a closed hydroponic system with settled primary sewage, Boyden and Rababah (1996) found that lettuce removed 80% of nitrogen and 77% of the phosphorus. Phosphorus removal rates were similarly high with 67 – 72% for primary municipal wastewater at a treatment plant in Sydney circulated in a nutrient flow technique (NFT) system (Rababah and Ashbolt 2000). In a recent trial at a wastewater treatment plant in Germany using an open hydroponic system, nitrogen, phosphorus and potassium loads of pre-treated municipal wastewater were reduced by 100%, 67 – 89% and 100%, respectively (Bliedung et al. 2020).

However, there is less consensus on whether wastewater grown lettuce can achieve similar biomass compared to lettuce grown in commercial nutrient solutions. Boyden and Rababah (1996) found that lettuce grown using wastewater had up to 50% less biomass. When compared with lettuce grown in half-strength Hoagland solution, the biomass reduction was ~ 38% (Bliedung et al. 2020). But Keller et al. (2008) found no difference in biomass of lettuce grown in a wastewater-fed closed hydroponic system compared to lettuce grown with a commercial nutrient solution. Also, Kim et al. (2019) did not find differences in root and leaf growth until day 21 compared to lettuce grown in a nutrient solution when they used micro-algae treated effluent. Still, it has also been observed that lettuce grown in wastewater has different growth behaviour. Boyden and Rababah (1996) observed that lettuce plants growing in the nutrient solution followed a three-phase growth cycle with a lag phase, exponential growth and transition to stationary phase, while lettuce plants grown in wastewater followed an exponential curve. This shows that potentially lower biomass accumulation could be controlled for by modifying length of the growing period.

Debate is ongoing about issues of nutrient content, and microbial and heavy metal contamination of hydroponic lettuce grown in wastewater compared to lettuce grown in commercial nutrient solutions. On one hand, Cui et al. (2006) found lower nitrate concentrations, an important index for vegetable quality, and Da Silva et al. (2018) observed lower foliar accumulation of nutrients. The latter was accompanied by visual symptoms of nutrient deficiency linked to lack of micronutrients in wastewater (da Silva et al. 2018). However, Bliedung et al. (2020) found similar nitrogen, phosphorus, and potassium content in their wastewater-fed hydroponic lettuce to lettuce grown in a reference nutrient solution. Cui et al. (2006) registered similar levels of vitamin C, coarse protein, and soluble sugar content in wastewater-grown lettuce compared to nutrient solution grown lettuce.

For heavy metal accumulation, Rababah and Ashbolt (2000) observed accumulation in lettuce leaves above recommended levels for food. However, concentrations were below threshold values in the municipal wastewater fed system in Bliedung et al. (2020). Considering the microbial contamination of lettuce, Rababah and Ashbolt (2000) found no uptake of bacteriophages but uptake of spores of a faecal bacterium. Keller et al. (2008) found low levels of *E. coli*, thermotolerant coliforms and total coliforms; *Salmonella* spp. and helminth eggs were not detected at all.

Taken together, the mixed results of biomass accumulation, nutrient content, microbial and heavy metal contamination of hydroponic lettuce grown in wastewater compared to commercial nutrient solution show that wastewater is a highly variable resource whose impact on plant growth is difficult to generalize. Nevertheless, the balance of positive human and environmental health impacts appear more when using wastewater hydroponic for lettuce production compared with the conventional soil-based approach.

2.3.2.3 Quality parameters for water to be used as a nutrient solution

An important step before recommending the use of wastewater for commercial vegetable production is to assess its suitability as a nutrient medium. This process involves the assessment of absolute concentrations of essential and beneficial elements, relative nutrient concentrations, pH, electrical conductivity, temperature, solid load, heavy metals and aluminium, and salinity are indicators of such components influencing crop growth and development.

An element is considered essential when a lack makes it impossible for the plant to complete its life cycle, and the deficiency is specific to the element in question and can be prevented or corrected only by supplying this element, and when the element is directly involved in the plant's metabolism (Arnon and Stout 1939). Essential nutrients are divided into macronutrients and micronutrients (Schilling 2000). Macronutrients are required and present in the plant in relatively high concentrations (>1,000 mg kg^{-1} dry weight) and include nine elements: carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). Micronutrients are equally essential but required in lower amounts (<100 mg kg^{-1} dry weight) and comprise eight elements: boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl) and nickel (Ni) (Kirkby 2011; Kaur et al. 2016). Besides carbon and oxygen that are mainly taken up by the leafy canopy from the air, most essential nutrients are absorbed by the roots as cations and anions – except for boron which is absorbed as boric acid or borate ion, depending on the pH (Silber and Bar-Tal 2008). Following the strict definition of essentiality by Arnon and Stout (1939) an element easing toxic effects of another element (e.g. silicon (Si) for manganese (Mn) toxicity) or replacing another element (e.g. sodium (Na) for potassium (K)) are not essential for plant growth (Kirkby 2011). Still, such elements are required in certain plants for optimal growth and development and can play a vital role in the plants responses against biotic and abiotic stresses. These elements are termed beneficial or functional and include aluminium (Al), cobalt (Co), sodium (Na), selenium (Se) and silicon (Si) (Kaur et al. 2016).

Absolute and relative concentrations of essential and beneficial nutrients modify plant growth and development through nutrient deficiencies or toxicity. Plants have a limited ability for selective uptake of elements, leading to "luxury consumption" of essential elements and uptake of elements that may be toxic (Kirkby 2011). Therefore, absolute concentrations of single nutrients play a role in their potential to harm plant growth and development directly through deficiency or toxicity (Jones 2012). On the other hand, relative concentrations or ionic balances are important for considering interactions between nutrients in the solution, at the root surface or inside the plant. These interactions may induce deficiencies, toxicities, modified growth response or altered nutrient composition in the plant (Fageria 2001; Maucieri et al. 2019; Sambo et al. 2019).

Osmotic potential, pH, and water temperature are important characteristics of nutrient solutions. The osmotic potential is built-up by mineral salts and can be measured via the electrical conductivity (EC). It influences plant growth and development by affecting water uptake (Trejo-Téllez and Gómez-Merino 2012). pH is relevant as very low pH values in the root environment are toxic to plants, and because of its influence on the availability of plant nutrients (Sonneveld and Voogt 2009). Temperature of the nutrient solution affects nutrient and oxygen solubility and the capacity of the roots to take them up (Trejo-Téllez and Gómez-Merino 2012; Cortella et al. 2014).

Solid loads have the potential to harm plant growth and development by affecting nutrient uptake, root respiration, virus survival and water uptake. Solids consist of total dissolved solids (TDS) and suspended solids (SS). Suspended solids are composed of organic and inorganic matter held in suspension by turbulence and can include bacteria, inorganic particles and algae and metals and nutrients that are attached to particles (Bilotta and Brazier 2008; Kasper et al. 2018). Nutrient uptake and root respiration can be hindered by the presence of suspended solids and virus survival enhanced as solids serve as an adsorption surface (Westcot 1997; Sikawa and Yakupitiyage 2010). Knowledge of suspended solids load also allows for the implementation of an appropriate hydroponic filtering system to reduce clogging incidents (Pescod 1992; Sikawa and Yakupitiyage 2010). In comparison, TDS consist of small amounts of organic matter and inorganic salts, mainly calcium (Ca), magnesium (Mg), sodium (Na), carbonate (CO_3^{2-}), chloride (Cl), sulphate (SO_4^{2-}), nitrate anions ($NO3^-$) and potassium cations (K^+), that are in solution (WHO 2003). TDS are an indicator of salinity, risk of ion toxicity, and enhance the osmotic potential of water that increases biological and chemical oxygen demand and raises the amount of energy necessary for plants to take up water (Pescod 1992; Jonnalagadda and Mhere 2001; Norton-Brandão et al. 2013).

Heavy metals like cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), and lead (Pb) above certain concentration can be toxic to plants (Lente et al. 2012). They typically come from municipal and industrial wastes, vehicle emissions, phosphate-based fertilizers, pesticides, sewage sludge application or wastewater (Sridhara Chary et al. 2008; Luo et al. 2009; Abdu et al. 2011; Mahmood et al. 2020). They harm the growth and development of plants through oxidative stress (Mithöfer et al. 2004). Aluminium, derived mostly from mining and acid precipitation is toxic to plants at elevated concentrations as it reduces root growth by altered root architecture and elongation (Pilon-Smits et al. 2009).

Salinity adversely affects plants in causing water stress, disturbed mineral nutrition, and toxicity. Salinity occurs in the two major forms of salinity and sodicity. While salinity refers to the concentration of salts in the water, sodicity is concerned with salt composition (Läuchli and Grattan 2011). Salinity occurs where salt concentration in waters are sufficiently high to diminish crop yields or quality via osmotic effects in the solution leading to higher energy expenditure for water uptake, or by toxicity of specific ions (Pescod 1992). Sodicity is driven by a high concentration of Na^{+} in relation to Ca^{2+} and Mg^{2+}, not leading to strictly osmotic effects but still hindering plant growth and development via disturbed mineral nutrition or toxicity (Rhoades et al. 1992; Läuchli and Grattan 2011).

Summary

The above literature review makes it clear that wastewater is a broad term representing a resource that varies widely in composition. In cities of the Global South like Accra, diluted wastewater is used for irrigation as a result of structural problems in the wastewater collection and treatment system. Health risks resulting from crop irrigation with wastewater are well-documented for the Ghanaian capital. Yet, interventions have not been successful in reducing pathogen contamination to vegetables because of transfer from irrigation water and soil cannot be prevented using suggested measures. Nevertheless, there is a growing number of experiments successfully demonstrating the use of wastewater at various nutrient concentrations for hydroponic crop production. For lettuce, there are ongoing discussions on details of growth and quality, but still sufficient evidence suggesting use in a hydroponic system instead of irrigation can provide a safer and environmentally safer way of producing the crop. However, irrigation with waste water is a long-standing practices with a range of economic, environmental and societal benefits. Thus, the potential of accessing benefits of hydroponics for waste water based crop production cannot be determined alone by evaluating water quality parameters relevant for crop growth and development, but must be analysed holistically considering the economic, social and environmental dimension.

3. Material and methods

A workflow diagram was used to guide the evaluation of the economic, social, and environmental potential of a wastewater hydroponic system for lettuce production in Accra, Ghana (Fig.05). The analysis included a baseline study of the current irrigated vegetable production to evaluate costs and benefits, socio-economic characteristics, and environmental impacts against which a proposed hydroponic production system could be assessed.

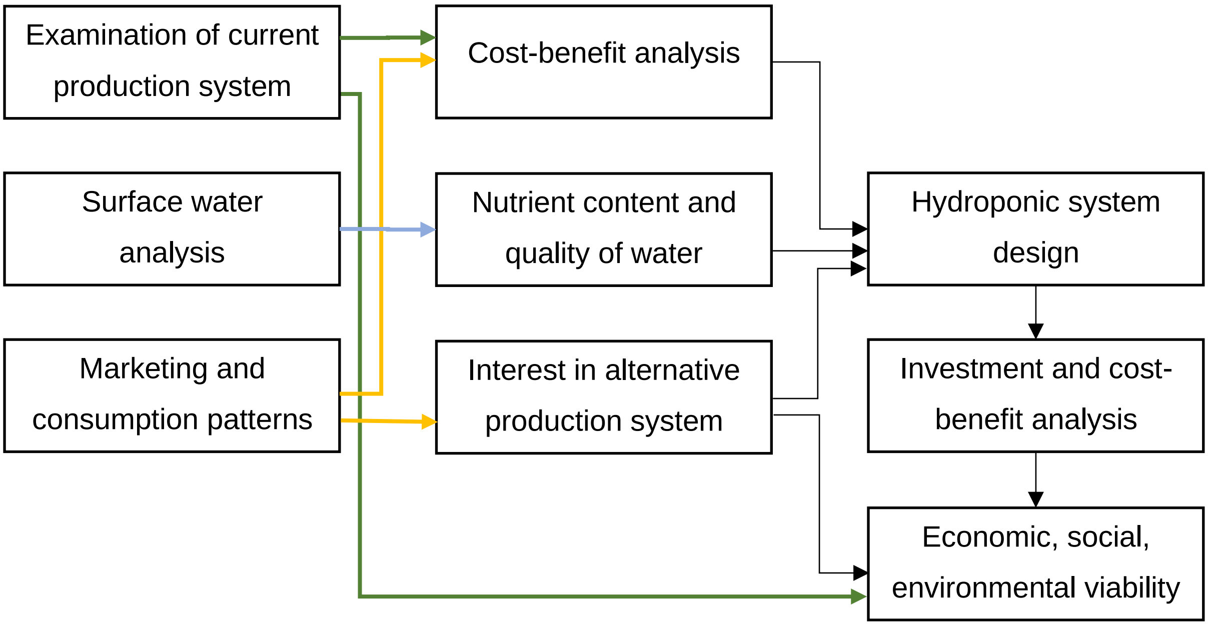

Fig.05: Workflow diagram used to assess the social, economic, and environmental potential of a wastewater hydroponic system for lettuce production in Accra.

3.1 Study area

The study area was the Accra Metropolitan District (5°33’ North and 0°13’ West), one of the 26 districts of the Greater Accra Region, Ghana (Fig.06). This district is the administrative boundary of the City of Accra, Ghana’s capital. Accra is in the coastal savanna agro-ecological zone where mean annual rainfall is 1,171 mm and mean annual temperature 26.7 °C (Fig.07). Rainfall distribution is bimodal, giving rise to a minor growing season of ~ 50 days from September to October and a major growing season of ~ 100-110 days between March and July (FAO 2005a, b). August has the lowest monthly minimum temperature of 21.9°C and the maximum monthly temperature of 32.4 °C occurs in February. The daily average minimum and maximum temperatures are 18.2 °C and 36.5 °C (NASA 2020).

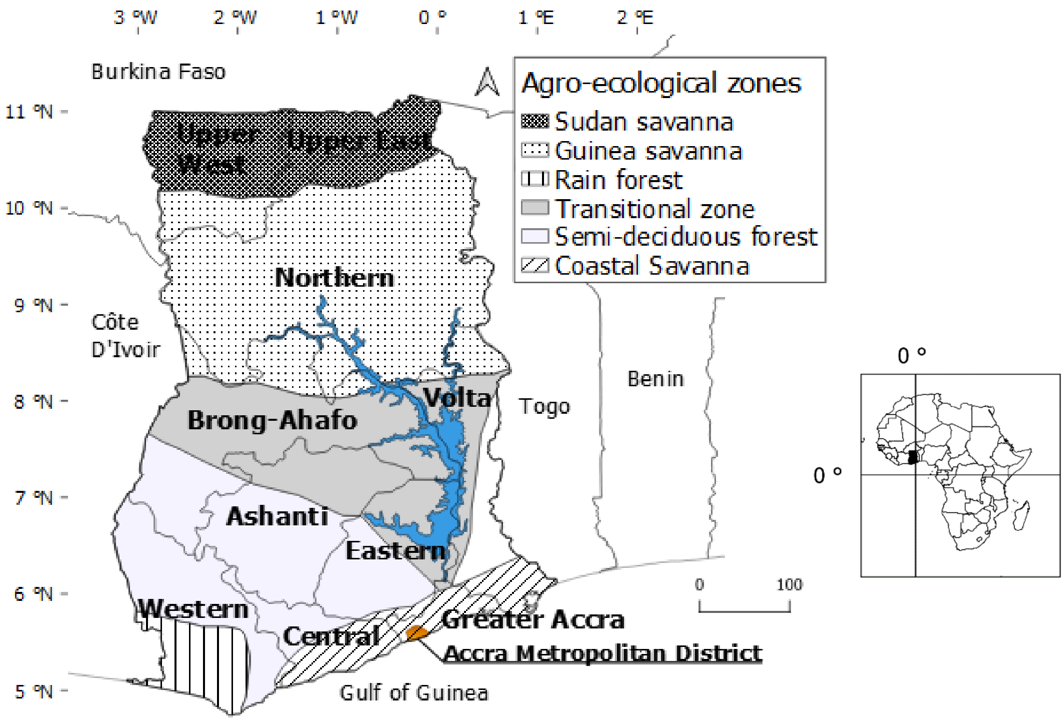

Fig.06: Location of the Accra study area within the African continent and Ghana (Date source: Map Maker (2007); Antwi-Agyei et al. (2012); GADM (2018)).

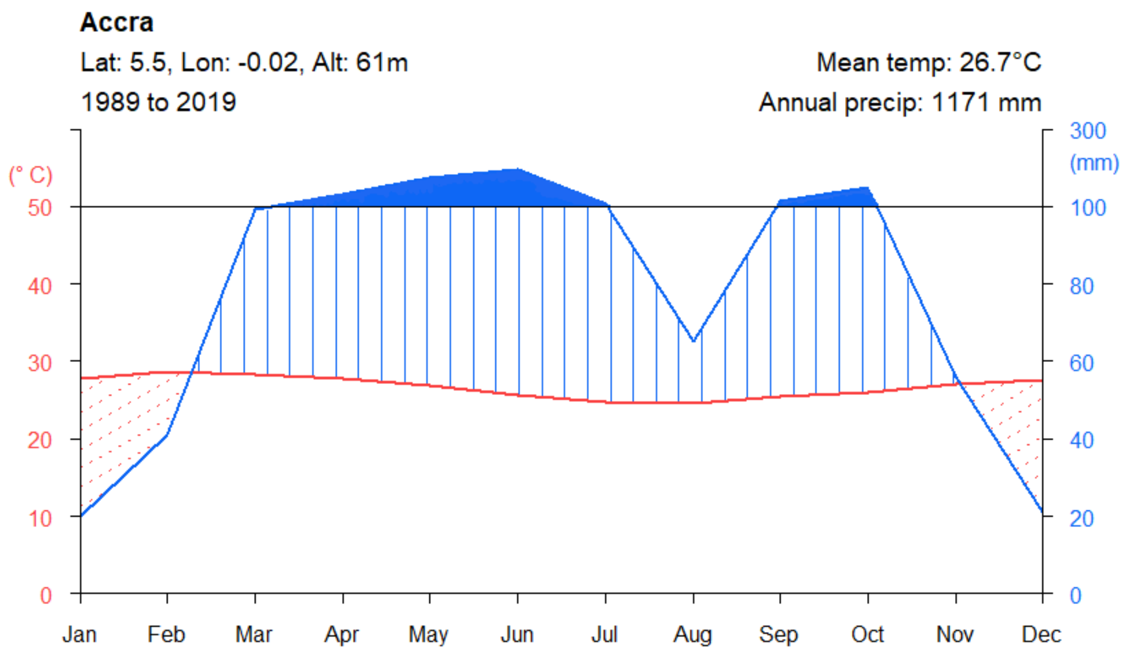

Fig.07: Climate diagram Accra, Ghana for 1989-2019; red-dotted area represents arid period, blue-striped area humid period; blue area represent wet period (rainfall >100mm) (Walter and Lieth 1967) (Data source: NASA (2020)).

The Volta River basin, including the artificially created Lake Volta, dominates Ghana's drainage system (Bharati et al. 2008). A network of rivers and streams that drain into the Gulf of Guinea dissect the Accra Metropolitan District (Fig.08). The longest waterways in the district are the Kordjor River entering the Kpeshie Lagoon, and the Odaw River issuing into the Korle Lagoon.

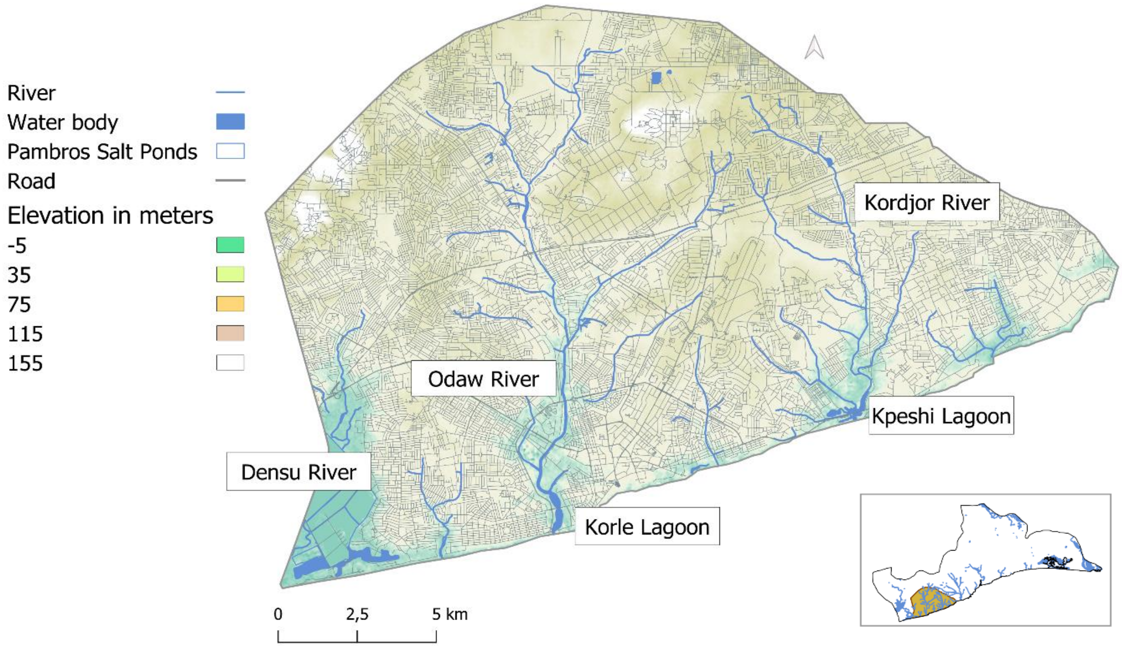

Fig.08: Major surface waters in the Accra Metropolitan District (Data source: GADM (2018); OSM (2018); Gov.Gh. (2020); Google (2020); LPDAAC (2020)) with an overview map of the district within the Greater Accra Region.

3.2 Current irrigated vegetable production in Accra

3.2.1 Location and size of farming sites

Spatial trends in irrigated vegetable production in the city-, i.e., size and location of irrigated vegetable production sites in the Accra Metropolitan district were compared with those documented in 2010. The 2010 map of farming activities by Drechsel and Keraita (2014) was georeferenced in QuantumGIS (QGIS). Locations and sizes of farming areas were compared using time series analysis with satellite images obtained from Google Earth® (Google Earth V7.3.3 2020). Officials from the Ministry of Agriculture and researchers at the International Water Management Institute (IWMI) in Accra were consulted about the location and status of old and new irrigated vegetable production sites within the city's boundaries. Ten major farming sites were visited to confirm the accuracy of map and satellite image data on farmed areas. In addition, plot or patch size per farmer, average growth bed size, and distance to water source were measured on-site using a GPS tracking phone application (myTrack Version 7.1.1). This spatial data was used to update the map of irrigated vegetable production sites in Accra. The most significant changes in irrigated vegetable production sites were analysed in detail with Google Earth® time series (Google Earth V7.3.3 2020) and on-site documentation.

3.2.2 Agronomic and socio-economic production characteristics

Detailed information on agronomic management including cropping pattern, soil preparation, irrigation, fertilization and pest management were collected together with socio-economic parameters like land tenure, energy supply, labour, and support structures to estimate the environmental, and socio-economic impact of the current production system. Two farmers from each of the ten major farming sites were met for questionnaire guided interviews (Appendix B) with the assistance of a translator when necessary. The marketing pathways of vegetable produce were reconstructed and data necessary to compute the net revenue and benefit-cost ratio were assembled for one crop per interviewed farmer. For each of seven target crops, two farmers were interviewed about the area on which the crop was cultivated.

3.2.3 Cost-benefit analysis of crops and crop rotations

A cost-benefit analysis (CBA) (Boardman et al. 2017) was used to assess seven target crops using crop-specific information collected during the farmer interviews (Tab.02). The goal of this CBA was to determine the conditions under which the hydroponic production of vegetables could economically compete with the current production system. The CBA included the systematic cataloguing of impacts as benefits and costs valued in Ghanaian cedis (GHS) and Euros (EUR) for a defined timeframe (Sain et al. 2017), and is therefore valuable for comparing the profitability of alternative investments (Boardman et al. 2017). Often referred to as a social cost-benefit analysis, a CBA includes all types of benefits and costs of investments, i.e., direct, indirect, public, and private (Brent 2006). However, in this analysis, an “economic” CBA (Daujanov et al. 2016) was performed. Non-monetary elements such as those derived from environmental impacts (Bumbescu and Voiculescu 2014) were not valued in cash.

Tab.02: Seven target crops selected for cost-benefit analysis.

Generic name	Scientific name
Cabbage	*Brassica oleracea [var. capitata] L.*
Chilli	*Capsicum chinense JACQ.*
Herbs (mint and parsley)	*Mentha spicata L., Petroselinum crispum M. F.*
Lettuce	*Lactuca sativa [var. longifolia] L.*
Spring onion	*Allium cepa L.*
Sweet pepper	*Capsicum annuum L.*
Tomato	*Solanum lycopersicum L.*

For the CBA, a crop was chosen if it is usually eaten raw and thus carries a high health risk when contaminated with polluted irrigation water (Liebe and Ardakanian 2013), and/or if it was often grown or can be grown hydroponically. For each crop, CBA was done twice with information obtained from two different farming sites. The mean of these two samples was calculated for each of the CBA indicators, e.g., total costs, or net revenue. An area of 200 m^2 was taken as a reference to compare the CBA indicators for different crops and crop rotations because this is the typical cultivation area of one crop (Danso and Drechsel 2003; own data).

3.2.3.1 Cost estimation

The cost of vegetable production was calculated by estimating fixed, variable, and total costs per target crop. Fixed costs are those associated with owning a fixed input. They do not change relative to the level of production in the short term (Kay et al. 2016a). In this analysis, fixed costs included lease for land, tools, and machinery. Fixed costs for each asset were estimated by multiplying the monthly depreciation of the asset with the time from transplanting to harvest, and the proportion of total land used for cultivating target crops (Kay et al. 2016a):

$$FC = (MD_P * t) * (A_C / A_T) \quad (1)$$

where FC = fixed cost of an asset [GHS/EUR]

MD_P = monthly depreciation [GHS/EUR]

t = time that target crop is in the field [months]

A_C = area used for cultivating target crop [m^2]

A_T = total farming area [m^2]

For land, monthly depreciation was set to equal the monthly lease. For equipment like sprinklers that were exclusively used for the target crop during the cultivation period, no ratio for the cultivated land was used. It was further assumed that no interest and no insurance must be paid for the fixed assets. The depreciation of fixed inputs was therefore calculated using the straight-line method (Kay et al. 2016a), assuming a salvage value of zero. In other words, it was assumed that equipment and tools are used until they are not functional and thus cannot be sold as “scrap”:

$$MD_P = \frac{\text{Purchase price [GHS]}}{\text{Useful life [months]}} \quad (2)$$

Total fixed cost per target crop was calculated by adding all its fixed costs (Kay et al. 2016a):

$$TFC = \sum_{i=1}^{n} FC_i \quad (3)$$

where TFC = total fixed cost [GHS/EUR]

FC_i = cost of the ‘ith’ fixed asset used for the target crop

In contrast, variable costs are not incurred unless production occurs. Variable costs therefore change in relation to production levels (Kay et al. 2016a). Costs for seeds, fertilizers, crop protection, irrigation water, and labour were included in this analysis as variable costs and estimated by multiplying the used quantity of an asset by its price per unit (Kay et al. 2016a):

$$VC = Q * C \quad (4)$$

where VC = variable cost of the asset [GHS/EUR]

Q = quantity used

C = cost per unit [GHS/EUR]

Total variable costs per target crop was calculated by adding all its variable costs (Kay et al. 2016a):

$$TVC = \sum_{j=1}^{n} VC_j \quad (5)$$

where TVC = total variable cost [GHS/EUR]

VCj = cost of the ‘jth’ variable asset used for the target crop

Total cost per target crop was calculated by adding total fixed costs and total variable costs (Kay et al. 2016a):

$$\mathrm{TC} = \mathrm{TFC} + \mathrm{TVC} \quad (6)$$

where TC = total cost [GHS/EUR]

To calculate the contribution of the two types of costs to the total costs, a ratio of variable to total costs was expressed as a percentage.

$$\mathrm{CVT} = \left(\frac{TVC}{TC}\right) * 100 \quad (7)$$

where CVT = contribution of variable costs to total costs [%]

3.2.3.2 Benefit estimation

The benefit of producing a target crop was estimated by calculating total revenue. Total revenue, or revenue, was defined for this analysis as the total value of products and services produced by a farmer in the form of cash (Kay et al. 2016b). Total revenue equals the money generated by selling a target crop and was calculated by multiplying the quantity sold by the unit price (Kay et al. 2016b):

$$\mathrm{TR} = \mathrm{Q_S} * \mathrm{P} \quad (8)$$

where TR = total revenue [GHS/EUR]

Q_s = quantity sold

P = price per unit [GHS/EUR]

3.2.3.3 Estimation of profit and efficiency

Net revenue, or profit, was estimated by subtracting total costs from the total revenue (Kay et al. 2016b):

$$\mathrm{NR} = \mathrm{TR} - \mathrm{TC} \quad (9)$$

where NR = net revenue [GHS/EUR]

As an estimate of efficiency, the benefit-cost ratio was calculated by dividing total revenue by the total cost (Boardman et al. 2017):

$$\mathrm{B/C} = {}^{\mathrm{TR}}/_{\mathrm{TC}} \quad \text{......} \quad (10)$$

where B/C = benefit-cost ratio

3.3 Marketing of irrigated urban vegetables and vegetable consumption patterns

To estimate the contribution of vegetables produced within the city to the markets, market prices, and consumption patterns of vegetables in Accra, questionnaire-guided interviews were conducted with 50 vegetable sellers and 43 consumers (Appendix B). The 50 vendors chosen were evenly distributed over the nine most frequented open vegetable markets (Fig.09). Due to time constraints, most of the 43 consumers were approached near the open vegetable markets and the Accra Mall.

Questionnaire guided interviews were conducted with 50 vegetable sellers to trace crop origins, learn about their assortment, criteria for quality, and knowledge on production. Also, produce availability and pricing of the seven target crops were assessed. To compare prices at open vegetable markets to those at supermarkets, prices of the seven target crops were sampled at Game® and Shoprite® (the two main retailers). Also, prices of vegetables were compared at the local vegetable retailer Farmer's Market® and the Labone Green Market (a small weekly market at the Labone district where sellers said they produce according to organic standards).

Consumer buying and consumption behaviour was analysed using questionnaire guided interviews on vegetable consumption frequency, budget allocation to different vegetables, quality criteria, and preferred market type.

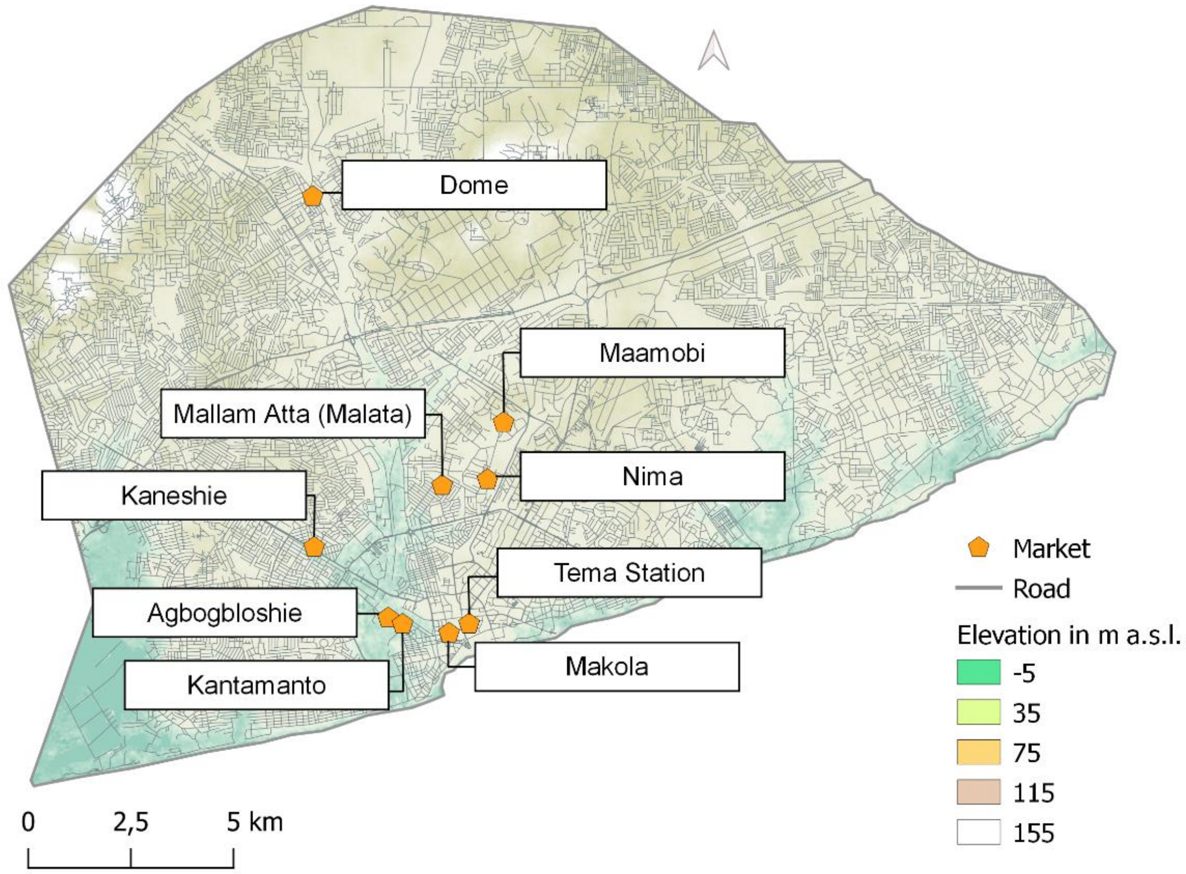

Fig.09: Markets visited for interviews (Data source: GADM (2018); Gov.Gh. (2020); Google (2020); LPDAAC (2020)) with overview map of the district within the Greater Accra Region.

3.4 Interest of farmers, vendors and consumers in a waste water hydroponic system

The structured farmer and consumer interviews were also used to assess knowledge of hydroponics, conditions for its adoption, market gaps, and concerns about it.

3.5 Data analysis for questionnaire-guided interviews

Data gather with the farmers, vendors and consumer questionnaires were processed in Microsoft Access and exported to Microsoft Excel for analysis. Simple descriptive statistic parameters of arithmetic mean, standard deviation and relative frequency were calculated (Beintema and Casper 2013).

3.6 Sampling and analysis of surface water

3.6.1 Surface water sampling

Surface water from streams in Accra (Fig.10) was sampled to determine parameters considered important for nutrient solutions in a hydroponic system. Forty-seven 100 ml water samples were collected with an extended sampler at 40 – 60 % of water depth and roughly at half-width of the water body (FUSEPA 2013). At one site, Korle-Bu, a sample was taken from an open drain used for irrigation. The other grab samples were taken at single points along streams (Martin et al. 1992). Along the 13 km stretch of the Kordjor River, a sample was taken every kilometre. Sampling was repeated four weeks later, resulting in 26 samples. At CSIR, thirteen samples were taken during one day from 6 am to 6 pm.

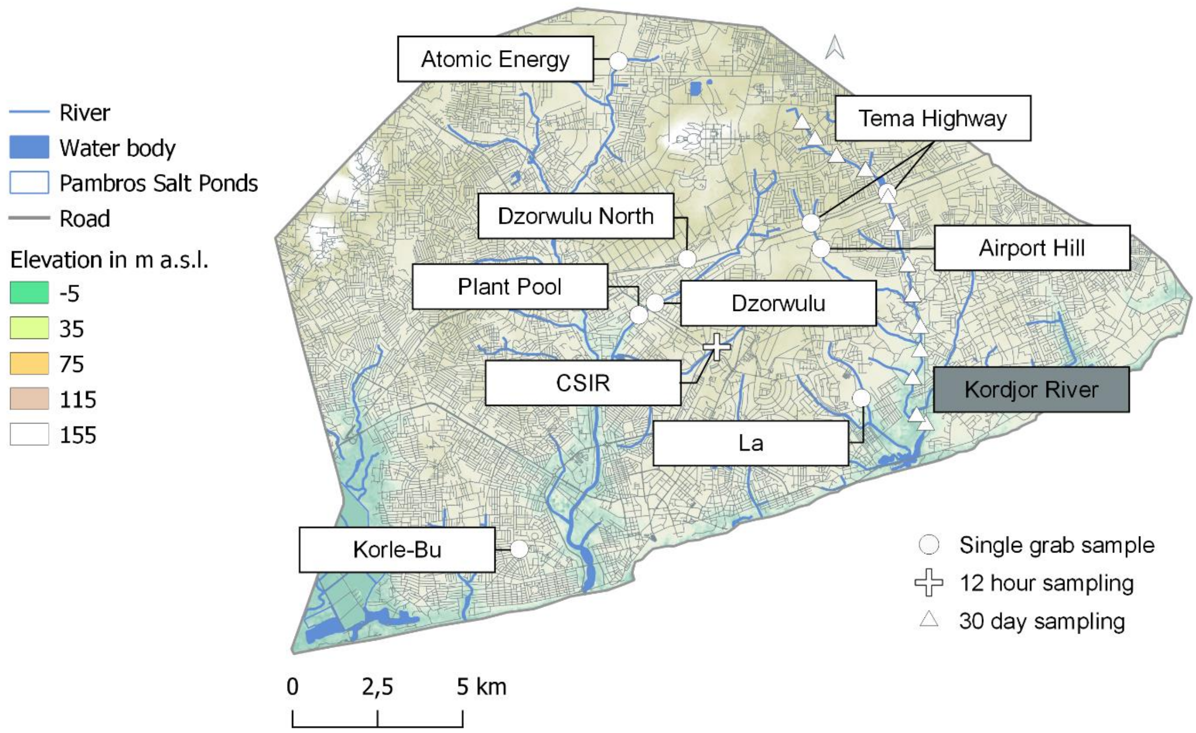

Fig.10: Locations of surface water sampling points on farming sites (white labels) and along Kordjor River (Data source: GADM (2018); OSM (2018); Gov.Gh. (2020); Google (2020); LPDAAC (2020)).

3.6.2 In-situ surface water analyses

In-situ testing of nitrate, nitrite, ammonia, chloride, pH was done for all 47 samples as first indicators of the plant nutrient content, and growth restrictions (chloride for salinity) (Rhoades et al. 1992). Specifically, 5 ml subsamples from 100 ml collected samples were pipetted into five containers to use QUANTOFIX® test strip and pH paper. Water temperatures were recorded for 35 samples at Kordjor River and CSIR using a digital water thermometer. Temperatures were measured between 6 am and 6 pm. About 50 ml of the original 100 ml samples were pipetted into Eppendorf™ tubes and transferred to a cooler box for storage at 7 °C.

Based on the in-situ test results, 14 samples were selected for laboratory analysis (Appendix, Tab. 2). As more sample was required for solids analyses, 11 additional samples were used from Plant Pool, Dzorwulu, Kordjor River and CSIR for total solids (TS) determination. Total dissolved and total soluble solids (TDS and TSS) were determined for three composites of four samples each. These 12 samples were from Kordjor River and CSIR.

3.6.3 Ex-situ surface water analyses

Ex-situ analyses of water parameters (i.e., electrical conductivity, solids, heavy metals, salinity, and sodicity) were done at the University of Hohenheim. Electrical conductivity (EC) was determined using a flow-through EC meter (Trejo-Téllez and Gómez-Merino 2012). For total solids (TS), i.e., the material left in a container after the evaporation of a sample and its subsequent drying in the oven, a sample volume of 5 – 10 ml – to fulfil the requirement of residue yield between 2.5 and 200 mg, was weighed in with a heat clean, desiccated and net weight porcelain crucible (APHA 1998, method 2540). The crucible with the sample was then dried to constant weight at 103 – 105 °C and cooled in a desiccator to balance temperature and weight, before being weighted to obtain the solid weight (11). Each sample had five replicates.

$$\text{mg total solids per L} = \frac{(\text{A}-\text{B})\ x\ 1000}{\text{sample volume,ml}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where A = weight of dried residue + dish in mg

B = weight of dish in mg

Total dissolved solids (TDS) and total soluble solids (TSS) were determined for three composites of four samples. Composites were divided into two replicates. Known volumes (between 93 – 96 ml) of composite samples were filtered at 2 µm, after the dry filter was weighed. To determine the concentration of TDS, crucibles with filtered water were dried at 180 °C before being cooled in a desiccator and weighed. Concentrations of TDS were calculated in the same way as total solids (11, APHA 1998, method 2540). Filters with the residue were dried at 103-105 °C, cooled and weighed to obtain TSS (12).

$$\text{mg total suspended solids per L} = \frac{(\mathrm{A-B})\ x\ 1000}{\text{sample volume,ml}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

where A = weight of filter + dried residue in mg

B = weight filter in mg

Concentrations of heavy metals and aluminium were analysed to assess how they compare with recommended maximum concentrations for irrigation water (Ayers and Westcot 1985). The concentrations of heavy metals cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), and lead (Pb) were analysed using inductively coupled plasma mass spectrometry (ICP-MS) and mercury (Hg) with cold-vapor atomic absorption spectrometry (CVAAS) (APHA 1998, method 3125 and 3112). In comparison, aluminium concentrations were determined with inductively coupled plasma optical emission spectrometry (ICP-OES) (Lyon et al. 1995).

Sodicity and salinity were determined by analysing Cl^- concentrations with the autoanalyzer method (Dawborn et al. 1965) and Na^+ using ICP-OES. Sodicity was indicated by the sodium adsorption ratio (SAR) (13, Rhoades et al. 1992). For each sample, the chloride concentrations were measured thrice to calculate the mean.

$$\text{Sodium adsorption ratio (SAR)} = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(13)$$

3.6.4 Assessment of essential and beneficial plant nutrients

Macronutrient and micronutrient contents of surface water were measured to assess how they compared with commercial nutrient solutions for growing lettuce. Concentrations of phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) were measured using ICP-OES; ammonium nitrogen (NH4-N) and nitrate nitrogen (NO3-N) were determined with continuous flow analysis (CFA) (APHA 1998, method 4120). Total inorganic nitrogen content was estimated by adding NH4-N and NO3-N. Sulphur (S) content could not be analysed due to constraints in laboratory capacity. For micronutrient contents, boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo) and nickel (Ni) concentrations were determined using ICP-MS while the autoanalyzer method (Dawborn et al. 1965) was used for chloride (Cl). As a reference for the nutrient load of the surface waters, the absolute and relative concentrations of essential and beneficial nutrients were compared with two commercially used nutrient solutions, i.e., the modified Hoagland solution (Epstein and Bloom 2005) and the modified Sonneveld solution (Mattson and Peters 2014). For lettuce specifically, the relative nutrient concentration in water samples was compared to desired values derived from the nutrient composition of lettuce leaves by Hartz et al. (2007) (Hansen 1978). As nitrogen was used as the indicator element to determine the cycling intervals of the water in the hypothetical hydroponic system (see 3.7.2), concentrations of all other nutrients were calculated in relation to nitrogen loads in the water.

To gain insight into the temporal variations of nutrient content in the surface waters, deviations from the daily mean of nitrate nitrogen (NO3-N), ammonium nitrogen (NH4-N) and total inorganic nitrogen were calculated for four times (6 am, 10 am, 2 pm and 6 pm) in the 12 hourly CSIR samples. For the Kordjor River samples taken 4 weeks apart, changes in NO3-N, NH4-N and total inorganic nitrogen concentrations were based on changes along the river and between the two sampling intervals.

3.7 Hydroponic system design

3.7.1 Scale and system components

Based on findings of the nutrient content of surface water, the cost-benefit analysis of the current production system, and the interest shown by farmers, vendors and consumers, a layout for a simplified low-cost hydroponic system was developed by incorporating materials likely to be found in Accra, Ghana. Like similar designs (e.g., Fecondini et al. 2009; Grewal et al. 2011), it would not contain any precision control of internal climate or nutrient parameters but instead be suitable for on-site maintenance by semi- to unskilled labour. The hydroponic system with all its components was designed to fit into a 200 m^2 greenhouse, an area used to produce one crop at the irrigated vegetable production sites in Accra. Lettuce was chosen as the crop to be hypothetically produced as it had the highest cost-benefit ratio among the analysed vegetables growing in the irrigated urban fields, is relatively easy to handle and is well-researched for hydroponic production (e.g. Brechner and Both 2013).

3.7.2 Nutrient solution cycling

To calculate the water cycling intervals within the hydroponic system, nitrogen was used as the indictor element because of its high demand for proteins, nucleic acids, chlorophyll, co-enzymes, phytohormones, and secondary metabolites (Hawkesford et al. 2011). Daily nitrogen requirements of lettuce plants were calculated by multiplying the expected nitrogen content of each lettuce plant, which depends on its growth stage, with the number of plants of each growth stage present in the hydroponic system (Hansen 1978). The total daily requirement of the lettuce plants was then compared to the nitrogen loads of the water source to calculate the number of times the water needs to be exchanged per day to deliver sufficient nitrogen. Water from CSIR, La, and from the North of the Korjor River (Upper Kordjor) were taken as hypothetical water sources due to their relatively high nutrient concentrations, and because the sites could be suitable locations for a hydroponic system.

3.7.3 Investment and cost-benefit analysis

An investment is a sacrifice of current money, or other resources such as time, for future benefits (Chandra 2017). Therefore, it should be assessed before the investment is made, whether it is justifiable in terms of the expected future benefits. Here, three methods were used to analyse the profitability of investing in a hydroponic system (Kay et al. 2016c): the payback period (PP), net present value (NPV), and internal rate of return (IRR).

To calculate these measurements of investment profitability, the initial cost of the investment must be known as well as the annual net cash revenue, the salvage value and the discount rate (Kay et al. 2016c).

The initial cost was the actual total payment for the purchase of the parts needed to set up the hydroponic system while the net cash revenue equalled the expected annual cash receipts from selling lettuce produce less the cash expenses used to cover the total annual cost. This total annual cost was calculated by adding the annual variable cost and the yearly total payment for the investment. The annual total payment of the investment was composed of the principal of the respective investment scenario, and an interests rate of 6% (Kay et al. 2016c). Prices for the hydroponic system components were researched online, assuming that a similar product might be available in Ghana. Unfortunately, no suppliers from Ghana could be successfully contacted regarding component costs. For variable costs, the expense for the lettuce production (e.g. seeds, plant protection) and labour requirement were estimated based on the values obtained for the current production system. Marketing expenses were assumed to equal 10% of the initial investment, while maintenance was set at 2% of the investment. An equal cash revenue was expected to be achieved each year by selling the same quantity of lettuce at a constant market price. The proportion of produce fit to sell was estimated at 95%.

The salvage value was set to zero. The opportunity cost of capital, i.e., the discount rate was set to equal the cost of capital borrowed to make the investment. An interest rate of 6% was assumed based on recent values from neighbouring countries (The World Bank Group 2020). To establish a credit repayment plan, it was further assumed that the investment will be for a period of 10 years and paid back in equal total payments (Kay et al. 2016c).

Thus, the payback period (PP) was calculated by dividing the initial cost of the investment by the expected annual cash revenue (Kay et al. 2016c):

$$\text{PP} = \frac{\text{initial cost [€]}}{\text{expected annual cash revenue [€]}} \quad \text{(14)}$$

The net present value (NPV) was computed using the following equation (Kay et al. 2016c):

$$\text{NPV} = -\text{ initial cost} + \frac{\text{P1}}{(1+\text{i})^1} + \frac{\text{P2}}{(1+\text{i})^2} + \cdots + \frac{\text{Pn}}{(1+\text{i})^\text{n}} \quad \text{(15)}$$

where: Pn = the annual net cash revenue in the nth year in €

i = $(1+i)^n$ = one plus the discount factor to the power of the nth year

Lastly, the internal rate of return was calculated by solving the following equation for “i” (Kay et al. 2016c):

$$\text{Initial cost} = \frac{\text{P1}}{(1+\text{i})^1} + \frac{\text{P2}}{(1+\text{i})^2} + \cdots + \frac{\text{Pn}}{(1+\text{i})^\text{n}} \quad \text{(16)}$$

Following the ex. post cost-benefit-analysis (CBA) of the currently practised irrigated vegetable farming (see 3.2.3), an ex. ante CBA analysis (Boardman et al. 2017) of the vegetable production in the hydroponic production system was computed to decide how and whether resources should be allocated to this alternative of the status quo. Cost and benefits were calculated in the same manner as for the ex. post CBA. However, fixed costs were assumed to equal the annual total payment (principal and interest) for the amortization of the money borrowed to make the initial investment.

3.7.4 Scenarios of investment financing

To simulate a sensitivity analysis (Kay et al. 2016c), two different scenarios were assumed for financing the initial investment. For scenario I, it was assumed that the total sum is borrowed and paid back with an equal total payment plan over ten years, at a 6% interest rate. On the other hand, scenario II assumed that half of the investment can be covered by subsidies or donations, whereby only half of the total investment needs to be amortized under the same conditions. Additionally, two different selling prices for the lettuce were assumed. One was similar to what an urban vegetable farmer in Accra is getting under current production and market conditions (€0.03) (Appendix E), and the other price was a “self-marketing price” of €0.29 derived from the prices in the supermarkets and the “organic market”. If the first price caused a loss, a break-even price was calculated necessary to cover the costs.

Break-even price = $\frac{\text{total cost [€]}}{\text{expected yield}}$……………………………………………………………………..(17)

where expected yield = number of lettuce heads harvested

4. Results

4.1 Status of irrigated vegetable production in Accra

4.1.1 Location and sizes of farming sites

The ten major irrigated vegetable farming sites within the Accra Metropolitan District had a total area of 285 hectares in 2018 (Appendix C, Fig.02). By far the single largest area was the 210-hectare farming site at the grounds of the Atomic Energy Commission (Fig.12). The other nine farming sites ranged between 2.3 hectares close to the Ghana Broadcasting Corporation (GBC) and 13.6 hectares at Dzorwulu, with an average of 8.2 hectares (Fig.12, Appendix C, Fig.02). Plot size per farmer ranged from 0.01 to 0.72 hectares and the average was 0.26 hectares. Except for the Atomic Energy site where plots included idle land, farmers growing irrigated vegetables in Accra had on average 0.15 hectares distributed over several growing beds averaging 29 m^2 each.

4.1.2 Changes in production area between 2010 and 2018

Compared to 2010 (Fig.12), the area of irrigated vegetable production within the Accra Metropolitan district in 2018 had shrunk by 59% from 702 hectares in 2010 to 285 hectares in 2018. Most crop patches were lost in the east of the airport (Airport Hill), at the northern section of Dzorwulu North, and on the grounds of the University of Ghana (Fig.12). While there were still irrigated fields at the University, the site visit showed that only a small area was planted for private or commercial vegetable production and the rest used for research. The marine drive site of four hectares in 2010 vanished completely, which was also evident from satellite imagery (Fig.11). The satellite image time-series showed that the fields were replaced by bare sandy soil between the 1st of April 2017 and the 23rd of December 2018.

12.01.2010 31.01.2018

Fig.11: Development of the Marine Drive farming site from being cultivated in 2010 to bare soil in 2018 (Data source: Google earth V7.3.3 (2020)).

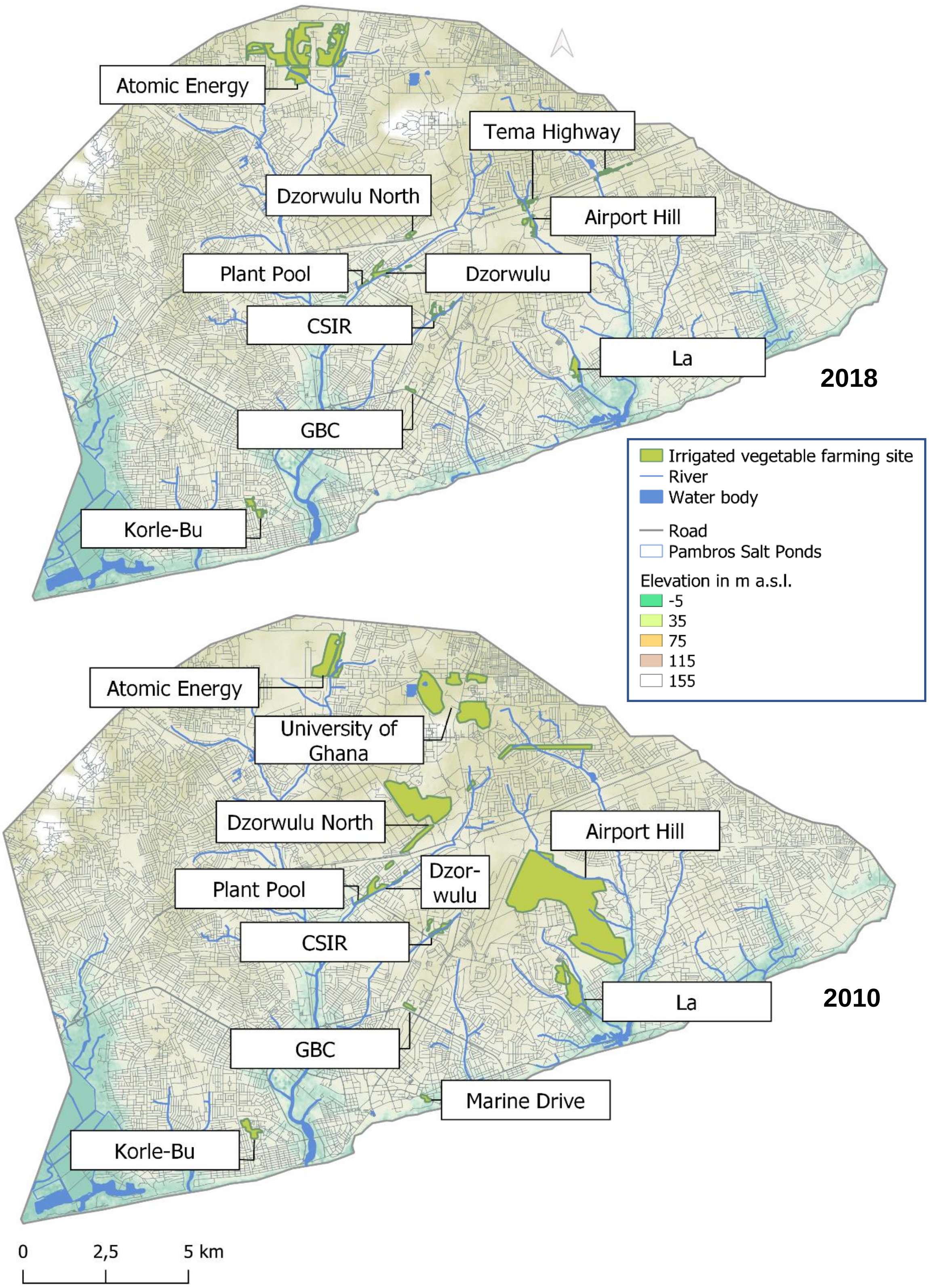

Fig.12: Irrigated vegetable production sites within Accra Metropolitan Area in 2018 (top) and 2010 (bottom). The map of 2010 is mainly based on that published by Drechsel and Keraita (2014); only half of the area at Atomic Energy, Dzorwulu North, La and Airport Hill was assumed to be under irrigation in 2010; (Data source: GADM (2018); OSM (2018); Gov.Gh. (2020); Google (2020); Google earth V7.3.3 (2020); LPDAAC (2020)).

Significant farmland was also lost at the La farming site, shrinking from ~ 58 hectares in 2010 to ~ 13 hectares in 2018 (Fig.13). Areas lost east of the Kordjor River and the northern parts were replaced by housing developments. However, the loss of the wetland opened up new cultivation area around its former edges (Fig.13).

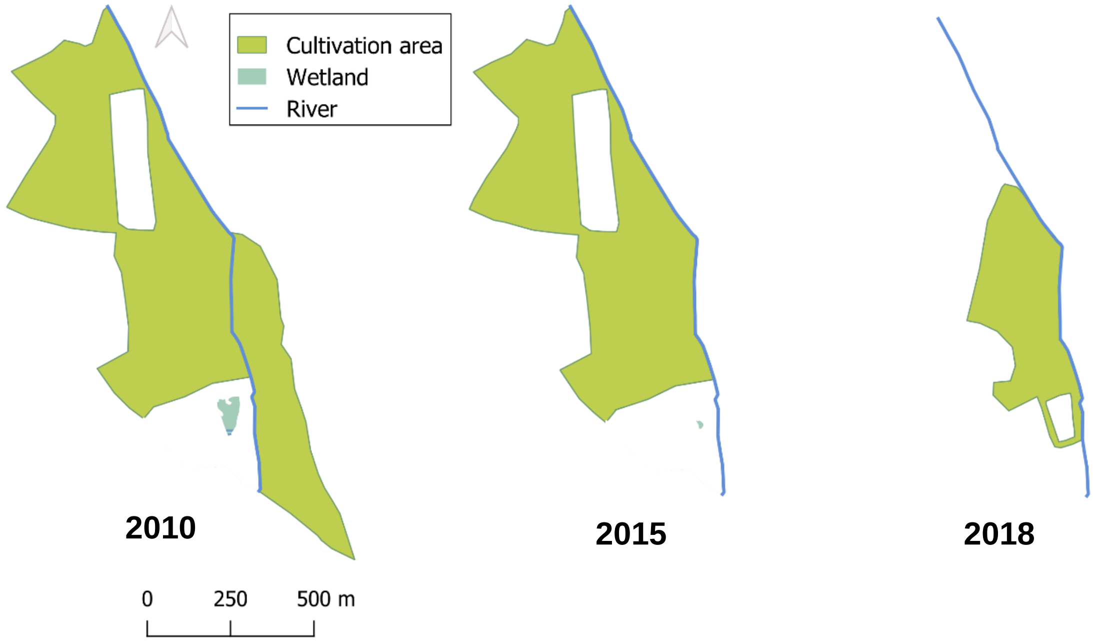

Fig.13: Development of the La farming site with its wetland from 2010 to 2018 (Data source: Google earth V7.3.3 (2020)).

4.1.3 Agronomic characteristics of the current production system

Urban vegetable farmers grew on average six different crops on their land. The crops were grown throughout the year in rotations averaging four crops. Two examples of crop rotations are (1) green pepper – lettuce or cabbage – lettuce – spring onion, and (2) cabbage – cucumber or lettuce and parsley – green pepper – chilli. Intercropping was seldom practised, whereas the most prominent combination was lettuce grown on the same bed as cabbage, pepper or spring onion. Lettuce was commonly found on farmers' fields with cabbage and cucumber, followed by various herbs (e.g., parsley, mint, coriander, amaranth leaves, ayoyo (*Chorchorus*), green pepper and cauliflower. Vegetables were sown directly or transplanted from an on-farm seedling bed.

Soil-fertility challenges were widely reported by farmers leading to the use of manure, fertilizer, and herbicides. The most frequently mentioned problems were salinity (15% of all farmers) and soil-borne plant diseases (15%), followed by high soil temperature (10%), alkalinity (5%)

and high sand content (5%). In terms of general soil management, the two most applied routines were spraying a herbicide before loosening the soil with a hoe, followed by the broadcasting or spaying a synthetic fertilizer after the seedlings have been transplanted; or spraying a herbicide after loosening the soil, followed by the broadcasting of manure, seedling transplantation and spraying of broadcasting of synthetic fertilizer. Farmers used on average two herbicides (active ingredient: imazethapyr, imazamox, paraquat, glyphosate, pendimethalin), and three different fertilizers (Appendix D, Tab.01-03).

The presence of different pests and pathogens was reported despite farmers using a range of insecticides and fungicides. The most-reported pests and pathogens were aphids (superfamily *Aphidoidea*) and caterpillars, followed by the diamondback moth (*Plutella xylostella*), unspecified fungal disease, maggots, whiteflies (family *Aleyrodidae*), mites (subclass *Acari*) and thrips (order *Thysanoptera*) (Appendix D, Tab.04). To avoid insect damage to crops, farmers used on average three different insecticides and typically applied them once per week. The most popular insecticides were Attack (with the active ingredients pirimiphos-methly and permethrin), Mektin (abamectin) and Golan (acetamiprid). Also, Bacillus thuringiensis based bacterial insecticides such as Agoo or Bypel were used while one farmer reported to used DDT (dichlordiphenyltrichlorethan) (Appendix D, Tab.05). For fungi control, a single fungicide was used once per week. The most applied fungicide (20% of farmers) was Benco with the active ingredient mancozeb. A major concern was that insecticides, fungicides, and weedicides were usually applied using a manually operated knapsack sprayer without the use of protective equipment.

Most farmers (56%) reported irrigating their fields at least every second day throughout the year while irrigation intervals ranged from twice per day to every two weeks. Streams were the major source of irrigation water (55% of farmers) follow by pipe and stream water (20%), pipe water only (10%), pipe and drain water (5%) and stream, pipe and groundwater (5%) (Appendix D, Tab.06). The average distance from a farmer’s field to the irrigation water source was 217 m, but ranged from 0.5-1,160 m. Popular irrigation set-ups were pump and pipes delivering water from a stream to sprinklers or piped water fetched from a ditch using a water can. As application method, 53% of farmers used sprinkler hoses, 21% watering cans, 11% furrows, 5% hosepipes, 5% sprinkler hoses and watering cans, and 5% hosepipes and watering cans (Appendix D, Tab.07).

4.1.4 Socio-economic characteristics of the current production system

Only one of the twenty interviewed farmers was a woman. Although none of the farmers owned the land they used, some had cultivated the same patches for more than a decade. Local authorities, companies, and institutions like the Ghana Grid Company or the Volta River Authority who rightfully owned the land tolerated its use (Appendix C, Tab.03). There was no legal agreement for using the land with the exception of the farming site at the Atomic Energy Commission where farmers had a one-year lease contract and paid GHS120 per acre.

The majority of respondents (55%) said farming was their full-time occupation. A typical farmer spent 9.8 hours per day on the farm. Watering or irrigation was reported as the most time consuming task followed by transplanting, bed preparation, weeding, loosening the soil and spraying pesticides. Half of all of farmers hired either several full-time or part-time workers, or a combination of both, with some 5% relying on family labour. About 25% of farmers had either one part time worker or seasonal employee while the other quarter did not hire additional labour. Hired workers earned on average GHS254 per month (~ €37 ±14.5).

About 85% of farmers used energy on farm in the form of petrol to power water pumps for irrigation. Energy costs were estimated at GHS13 per hour (~ €1.9) of using a pump or between GHS0.01 and 0.14 per irrigated square metre (~ €0.002-0.02).

In terms of support structures, all but three farmers were members of a farmer's association and 60% claimed they received government support. The support mostly came in form of subsidized fertilizer. However, only one farmer had regular contact with an extension service officer. There was also no report of NGO activity.

4.1.5 Cost-benefit analysis of crops and crop rotations

Of the seven crops analysed, sweet pepper produced the highest net revenue averaging GHS1,061 per 200 m^2 (~ €155), followed by chilli, tomato, herbs, cabbage, lettuce and finally spring onion with GHS 220 (~ €32) (Tab.03). Variable costs accounted for 82 – 99% of total costs, being lowest for spring onion and highest for cabbage. The average benefit-cost ratio was smallest for cabbage with 1.6 and highest for lettuce with 4.1 (Tab.03).

Considering a full twelve-month crop rotation, farmers were able to earn GHS1,751 to GHS1,885 on average per 200 m^2 of cultivation area (Tab.04). This amounted to GHS 13,134-14,134, or ~ EUR1,918 – 2,064 per 0.15 hectare, the average cultivation area per farmer. Per month, farmers earned an average monthly revenue of ~ EUR160 – 172.

Tab.03: Net revenue (NR), contribution of variable to total cost (CVT) and benefit-cost ratio (B/C) for a 200 m^2 cultivation area of lettuce, cabbage, parsley (herb), sweet pepper, spring onion, chilli and tomato.

	Unit	Lettuce	Cabbage	Herb	Sweet pepper	Spring Onion	Chilli	Tomato
NR	GHS	229	242	353	1,061	220	1,034	886
CVT	%	92	99	97	87	82	89	95
B/C	ratio	4.1	1.6	2.0	2.3	3.9	2.4	3.9

Tab.04: Net revenue for two examples of a twelve-month crop rotation calculated for a cultivation area of 200 m^2 and 0.15 hectare in Ghanaian cedi (GHS), and for 0.15 hectares and per month in Euros (EUR).

Crop rotation	GHS per 200m^2	GHS per 0.15ha	EUR per 0.15ha	EUR per month
Green pepper – lettuce – cabbage – lettuce – spring onion	1,751	13,134	1,918	160
Cabbage – lettuce – herb – green pepper	1,885	14,134	2,064	172

Of the total cost farmers spent to produce irrigated vegetables, fixed costs accounted for 8% while variable cost contributed 92% (Fig.14). Fixed costs were comprised solely of tools since on average farmer spent less than 0.5% of fixed costs on land. The majority of variable costs were for insecticides (30%), followed by seeds (20%), fertilizer (19%), and energy (14%). While water accounted for 7% of the average cost for production, only those farmers using piped water paid for irrigation water. Costs for herbicides and fungicides were at 5% and 4% respectively.

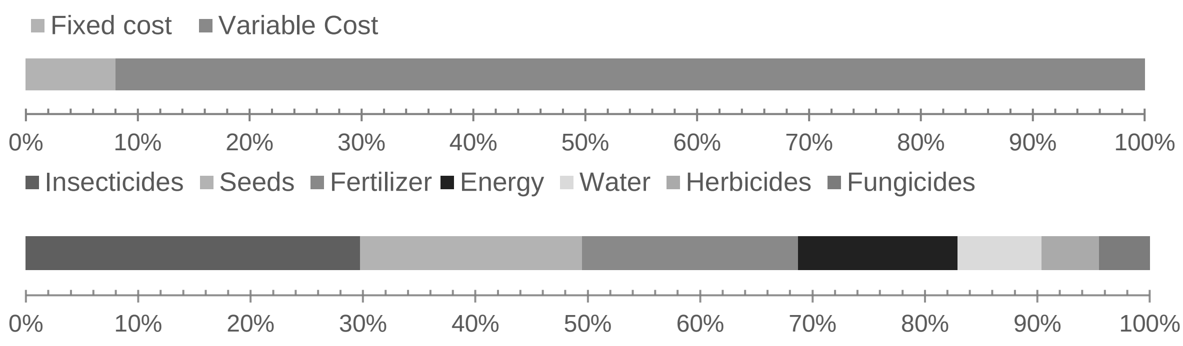

Fig.14: Mean production cost composition across the seven target crops of farmers in Accra.

4.2 Vegetable marketing, availability, and pricing structure

Once harvested, vegetables produced on the urban farms were sold to open wholesalers or smaller markets, with only 5% of farmers reporting to have directly produced food for vendors. Slightly more than half of all farmers had informal contracts with buyers, with only one farmer having a written form. The decision of what to cultivate in fields was mostly influenced by buyers (50% of farmers) and market demand (30%).

All of the 50 vegetable sellers were women. At the open vegetable markets, most-reported buying their vegetables from other markets (88%, mostly from Agbogbloshie market), while 8% purchased from another market and on farm and 4% only directly from farmers. Concerning the origin of vegetables, most sellers had a mixture of vegetables from locations within Ghana and abroad. Most sellers had vegetables from rural areas of Ghana (62%), followed by other cities in Ghana (56%), and other countries (44%). About 24% of all interviewees sold vegetables grown in urban areas of Accra. The percentages do not add up because multiple responses were allowed. Rural production sites were mostly located in the Volta Region followed by the Eastern and the Northern Region (Appendix F). Vegetables coming from other cities were from Kumasi. However, it was not clear whether the vegetables were grown in Kumasi or purchased from its markets. Vegetables coming from outside Ghana were mostly from Togo followed by the Netherlands, Burkina Faso, the United Kingdom, and Ivory Coast.

Vendors at the open vegetable markets sold on average 7 ± 3 different vegetables. An overview of the place-of-origin per type of vegetable is given in Table 05. Nine of the nineteen vegetables surveyed were grown in urban Accra. Vegetables mostly originating from urban Accra were lettuce, herbs, sweet pepper, and cauliflower.

Tab.05: Vegetables sold at open markets in Accra and their place-of-origin; order of places of origin represents frequency of denomination.

Vegetable	Place of origin
Aubergine	Kumasi, Ashanti Region, Volta Region
Beans	Eastern Region, Togo, Kumasi
Beetroot	Togo, Kumasi, Volta Region
Cabbage	Kumasi, Eastern Region, Accra urban,
Carrot	Kumasi, Netherlands, Togo, Eastern Region
Cauliflower	Accra urban, Eastern Region, Volta Region
Chilli	Kumasi, Northern Region, Accra urban, Eastern Region

Vegetable	Place of origin
Courgette	Kumasi
Cucumber	Togo, Kumasi, Accra urban, Central Region
Garlic	China
Herb	Accra urban, Kumasi, Togo, Western Region
Lettuce	Accra urban, Togo, Kumasi
Onion	Netherlands, Burkina Faso, Egypt, Ivory Coast, Niger, Northern Region, United Kingdom, Volta Region
Potato	Netherlands, UK, Egypt
Radish	Kumasi
Spring Onion	Togo, Volta Region, Accra urban, Kumasi, Eastern Region
Squash	Eastern Region, Kumasi
Sweet pepper	Accra urban, Kumasi, Eastern Region, Burkina Faso, Central Region, Ashanti Region, Togo
Tomato	Burkina Faso, Kumasi, Accra urban, Ashanti Region, Upper-East Region

Concerning availability, most vendors (85%) said they could source all types of vegetables throughout the year. Those mentioning inter-annual fluctuations in availability did not agree on the effect of rainy or dry seasons. Few vendors mentioned periods within the year when certain vegetables were more or less abundant or originated from certain locations. However, concerning vegetable prices, respondents agreed that there were inter-annual fluctuations. The most prominent reason given for the fluctuations were the rainy and dry seasons (36%). Lower prices were reported in the rainy season and higher ones in the dry season. The exception was crop spoilage by heavy rain that raised prices in the rainy season. Also, price hikes in the Christmas season were driven by increased demand.

Price differences for vegetables at open markets between the rainy and dry season were reflected in price assessments (Tab.06). The seven vegetables were on average 2.6 times more expensive in the dry season. Spring onion showed the least variation with a 1.3-fold price increase from the rainy to dry season, while lettuce was four times more expensive. Compared with the open vegetable markets, to purchase the same quantity of vegetables one had to pay on average 2.4 times more at the Farmer's Market, 3.9 times more at Game® store, 4.1 more at Shoprite® store, and 7.6 times more at the Labone 'organic' market. The highest relative price increase from the open markets to the other markets was found for lettuce, which was up to 25 times more expensive.

Tab.06: Average prices of seven target crops in Ghanaian Cedi* (GHS) at the open vegetable markets in Accra during the rainy and dry season and at the supermarkets Game®, Shoprite® and Farmer's Market, and the Labone 'organic' Market between September-November 2018 (*n* = 8 on average for open market, 1 for other markets); NA=vegetable was not available. * GHS 1 ≈ EUR 0.15.

Crop	Unit	Open market rainy season	Open market dry season	*Game®*	*Shoprite®*	*Farmer's Market*	*Labone Green Market*
Cabbage	Head	2.0	5.1	6.5	9	NA	5
Chilli	500g	2.4	8.2	8.3	9.9	8	NA
Herbs	Bunch	2.0	NA	3	5	3.9	5
Lettuce	Head	0.4	1.6	3.8	4	3	10
Spring Onion	Bunch	1	1.3	3	3.5	NA	5
Sweet pepper	Piece	0.3	0.7	1.3	0.3	1.8	NA
Tomato	Piece	0.4	0.8	1	1.3	0.9	1.2

4.3 Vegetable consumption patterns

Demographic information of interviews, i.e., age, education level, and sex are listed in appendix G. The majority of interviewees ate vegetables daily, with 23% reporting to having them in their diet at least thrice per week; 16% 4-5 times per week; 2% once per week. People allocated ~ 44% of the total budget spent on vegetables on leafy vegetables (lettuce, cabbage, spring onion, etc.), 29% on roots and tubers (cassava, yam, potato, carrots, etc.), and 27% on non-leafy vegetables (tomato, cucumber, pepper, etc.). Vegetables were most often bought from open vegetables markets (81%), followed by supermarkets (15%), and wholesale markets (4%). When asked about the quality criteria used to buy vegetables, the most important were freshness (42%), outward appearance (36%), place of origin (9%), and storage life (7%). Other criteria were the assumption that the produce was free from disease (2%), the quality of packaging (2%), and cleanliness (2%).

4.4 Water quality and nutrient content

4.4.1 General quality parameters

All sampled surface waters had a pH of 7 while the electrical conductivity was on average 0.99 dS m^{-1} (Tab.07). The mean load of total solids was 677 mg l^{-1}, composed mostly of total dissolved solids of averagely 666 mg l^{-1}, and to a lesser extent of total soluble solids averaging 79 mg l^{-1}. Water temperature was 30.9 °C on average (Tab.07).

Tab.07: Mean pH, electrical conductivity (EC), total solids (TS), total dissolved solids (TDS), total soluble solids (TSS) and temperature (Temp) of surface water. Standard deviations are given in brackets.

Parameter	Surface water	Unit	*n*
pH	7 (0)		14
EC	0.99 (2.4)	dS m^{-1}	14
TS	677 (172)	mg l^{-1}	11
TDS	666 (13)	mg l^{-1}	12
TSS	79 (3)	mg l^{-1}	12
Temp	30.9 (1.4)	°C	35

4.4.2 Heavy metals and aluminium concentrations in surface water

Concentrations of heavy metals and aluminium were found either below the recommended maximum concentrations for irrigation water (RMC) or below the individual detection limit (Tab.08). The highest metal concentrations were found for chromium at 35.5 µg l^{-1} near the Tema Highway (Fig.12; Tema Highway Western sampling point). However, mean chromium concentrations of 13.9 µg l^{-1} were well below the RMC.

Tab.08: Mean heavy metals and aluminium concentrations in comparison to threshold values for irrigation water (n = 14). Standard deviations are indicated in parentheses.

Element	Surface water mg l^{-1} or µg l^{-1}	RMC mg l^{-1} or µg l^{-1}
Al	BDL	5
Cd	BDL	10
Co	0.47 (0.19)	50
Cr	13.9 (9.8)	100
Cu	6.3 (2.5)	200
Hg	BDL	NA
Pb	BDL	5,000

Units for metals: µg l^{-1} , except for Al; RMC = Recommended maximum concentrations for irrigation water, according to FAO (Ayers and Westcot 1985); BDL = Below detection limit of <0.1 mg l^{-1} (Al), <0.05 µg l^{-1} (Cd), <0.5 µg l^{-1} (Hg) and <0.05 µg l^{-1} (Pb); NA = reference value not available

4.4.3 Salinity and sodicity

Concentrations of chloride (Cl) and sodium (Na) representing salinity were 238 mg l^{-1} and 103 mg l^{-1} on average, respectively. The average sodium adsorption ratio was 19 (Tab.09).

Tab.09: Mean chloride (Cl) and sodium (Na) concentrations and the sodium adsorption ratio (SAR) (n = 14). Standard deviations are indicated in parentheses.

Element or parameter	Surface water	Unit
Cl	238 (59.6)	mg l^{-1}
Na	103 (23.8)	mg l^{-1}
SAR	19 (2.7)	

4.4.4 Essential and beneficial plant nutrients

4.4.4.1 Absolute nutrient concentrations

Mean concentrations of essential and beneficial nutrients are shown in Table 10. For nitrogen, phosphorus, and potassium mean concentrations were 12.8 mg l^{-1}, 2.2 mg l^{-1}, and 16.1 mg l^{-1}, respectively. The CSIR site had the highest nitrogen concentration of 42.1 mg l^{-1}. Considering the form that nitrogen was present in water, nitrate nitrogen concentrations were on average nearly double the ammonium nitrogen concentrations (8.4 mg l^{-1} and 4.3 mg l^{-1}). Among the macronutrients, calcium had the highest average concentration with 42.2 mg l^{-1}, followed by magnesium with averagely 18.6 mg l^{-1}, and potassium with 16.1 mg l^{-1}. Silicon (Si) was present on average at 8.3 mg l^{-1}. Compared with the two commercial hydroponic nutrient solutions, macronutrient concentrations in surface waters were lower. Only magnesium (Mg) was present at relatively high concentrations compared with the nutrient solutions.

Micronutrient concentrations in the surface water were also below those of commercial nutrient solutions. Chloride and sodium however exceeded concentrations of the commercial nutrient solutions, averaging 237.6 mg l^{-1} and 103.4 mg l^{-1}, respectively. This was followed by boron (B) with 98.6 µg l^{-1}, manganese (Mn) with 35.2 µg l^{-1}, and iron (Fe) with 18.3 µg l^{-1}. Molybdenum (Mo) and nickel (Mo) had the lowest concentrations with 1.8 µg l^{-1} and 2.1 µg l^{-1} on average.

Tab.10: Mean concentrations (n = 14) of essential and beneficial plant nutrients in comparison with nutrient concentrations in modified Hoagland (Epstein and Bloom 2005) and modified Sonneveld nutrient solution (Mattson and Peters 2014). Standard deviations in brackets; macronutrients, Na, and Cl in mg l^{-1}, other micronutrients in µg l^{-1}; NA = value not measured (for surface water) or not available (for nutrient solution).

	Element / Parameter	Surface water (mg l^{-1} or µg l^{-1})	Mod. Hoagland (mg l^{-1} or µg l^{-1})	Mod. Sonneveld (mg l^{-1} or µg l^{-1})
Macronutrients	N	12.8 (9.6)	224	150
	P	2.2 (1.6)	62	31
	K	16.1 (4)	235	210
	Ca	42.2 (6)	160	90
	Mg	18.6 (8.1)	24	24
	S	NA	32	NA
	Si	8.3 (1.3)	28	NA
Micronutrients	B	98.6 (19.1)	270	160
	Cu	6.3 (2.5)	30	23
	Fe	18.3 (12.2)	1500	1000
	Mn	35.2 (48.1)	110	250
	Mo	1.8 (1.1)	50	24
	Ni	2.1 (0.5)	30	NA
	Zn	8.2 (8.8)	130	130
	Cl	238 (59.6)	1.77	NA
	Na	103 (23.8)	NA	NA

The CSIR site showed that nitrogen concentrations and composition during the day varied. Concentrations of nitrate nitrogen, ammonium nitrogen, and total inorganic nitrogen changed throughout the day (Fig.15). Compared with mean inorganic nitrogen concentrations of 27.6 mg l^{-1} for the day, total inorganic nitrogen concentrations (total IN) were higher at 10 am but lower in the early morning, afternoon and evening. Concentrations of nitrogen in the form of ammonium (NH4-N) followed a similar pattern, peaking at 10 am with a positive deviation of 22 mg l^{-1} from the 14.2 mg l^{-1} average. Nitrate nitrogen (NH3-N) on the other hand was present at higher than average amounts in the early morning, afternoon and evening. Expressed in percentage terms, the deviations from the day's mean ranged from 7–59% for NO3-N, from 37–157% for NH4-N, and from 7–53% for the total inorganic nitrogen.

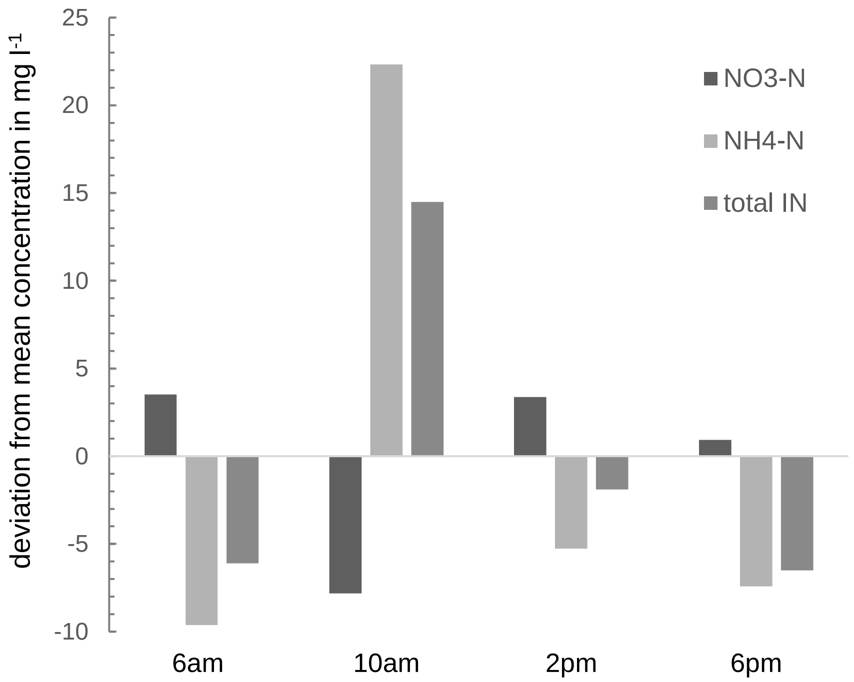

Fig.15: Concentrations of nitrate nitrogen (NO3-N), ammonium nitrogen (NH4-N) and total inorganic nitrogen (total IN) at the CSIR site measured at 6 am, 10 am, 2 pm and 6 pm, and expressed as deviations from the days mean (13.4 mg l^{-1} for NO3-N, 14.2 mg l^{-1} for NH4-N, and 27.6 mg l^{-1} for total IN.

Along the Kordjor River, total nitrogen concentrations increased from the mouth up to 13 km inland (Fig.16). Ammonium nitrogen (NH4-N) followed the same pattern with starting from 0 mg l^{-1} at 1 km and 7 km distance and peaking at 13 km. However, nitrate nitrogen concentrations increased slightly from 1 km distance to 7 km, before dropping close to zero at 13 km. Between the two measurements taken four weeks apart, the deviation from the calculated average were in the range of 2–23% for NO3-N, of 0–17% for NH4-N and 11–16% for the total inorganic nitrogen.

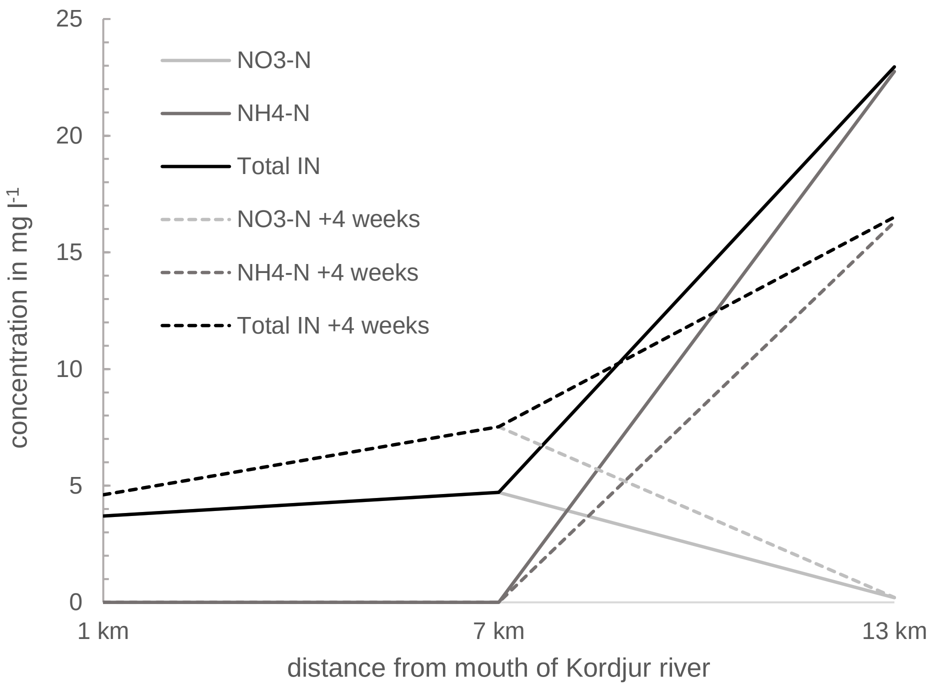

Fig.16: Concentrations of nitrate (NO3-N), ammonium (NH4-N), and total inorganic nitrogen (total IN) in mg l^{-1} along the Kordjor River at a distance of 1 km, 7 km and 13 km from its mouth. Measurements were taken four weeks apart (second measurements labelled with +4 weeks with dashed lines).

4.4.4.2 Relative nutrient concentrations

Considering the ratio of essential and beneficial concentrations in the surface water compared with the modified Sonneveld nutrient solution (Mattson and Peters 2014) – and in relation to nitrogen concentration, there was 5.5 times more calcium and ~ 9 times more magnesium present (Fig.17). On the other hand, phosphorus and potassium were 0.8 and 0.9 times the concentration of the reference solution. For micronutrients, concentrations of boron, manganese, and copper were 7, 2, and 3 times higher, respectively. However, nickel, molybdenum, zinc, and iron concentrations were too low. Iron had the lowest relative concentration with only 0.2 times the concentration found in the modified Sonneveld solution.

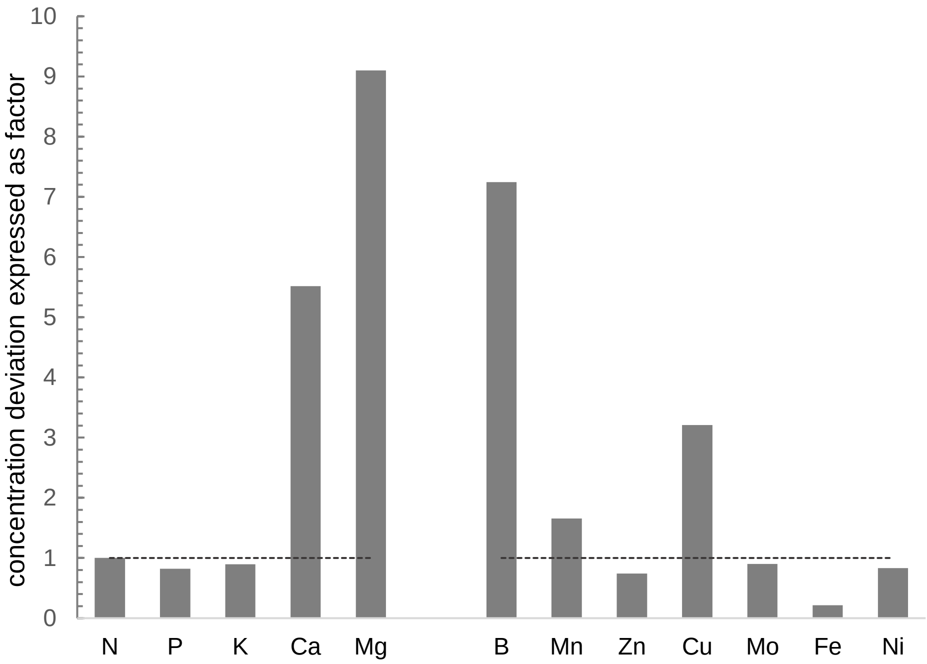

Fig.17: The ratio of essential nutrients concentrations in relation to the ratio in the modified Sonneveld solution (Mattson and Peters 2014) and expressed as a factor (i.e. there is 5.5 times as much calcium (Ca) in the surface water compared to its relative content in the commercial nutrient solution); the average nitrogen content of 12.67 mg l^{-1} was set to have the value one.

Nutrient concentrations in Accra's surface water relative to mean, upper and lower recommended concentrations for lettuce (Hartz et al. 2007) showed the same pattern of relative high or low concentrations than did the comparison with the two commercial nutrient solutions. Calcium, magnesium, boron, manages and copper exceed the mean recommended limit by a factor of 28, 22, 16, 3, and 4, respectively, surpassing the upper recommended limits (Fig.18). In contrast, zinc and iron were present in surface water at concentrations lower than the recommended mean for lettuce. Nevertheless, the measured zinc concentrations were still above the lower recommended limit. Concentrations of phosphorus and potassium exceeded the mean recommended concentrations for lettuce (Fig.18), while being in relative undersupply when compared to the relative concentrations in the commercial nutrient solutions (Fig.17). However, the measured values were only slightly above the maximum recommended limit.

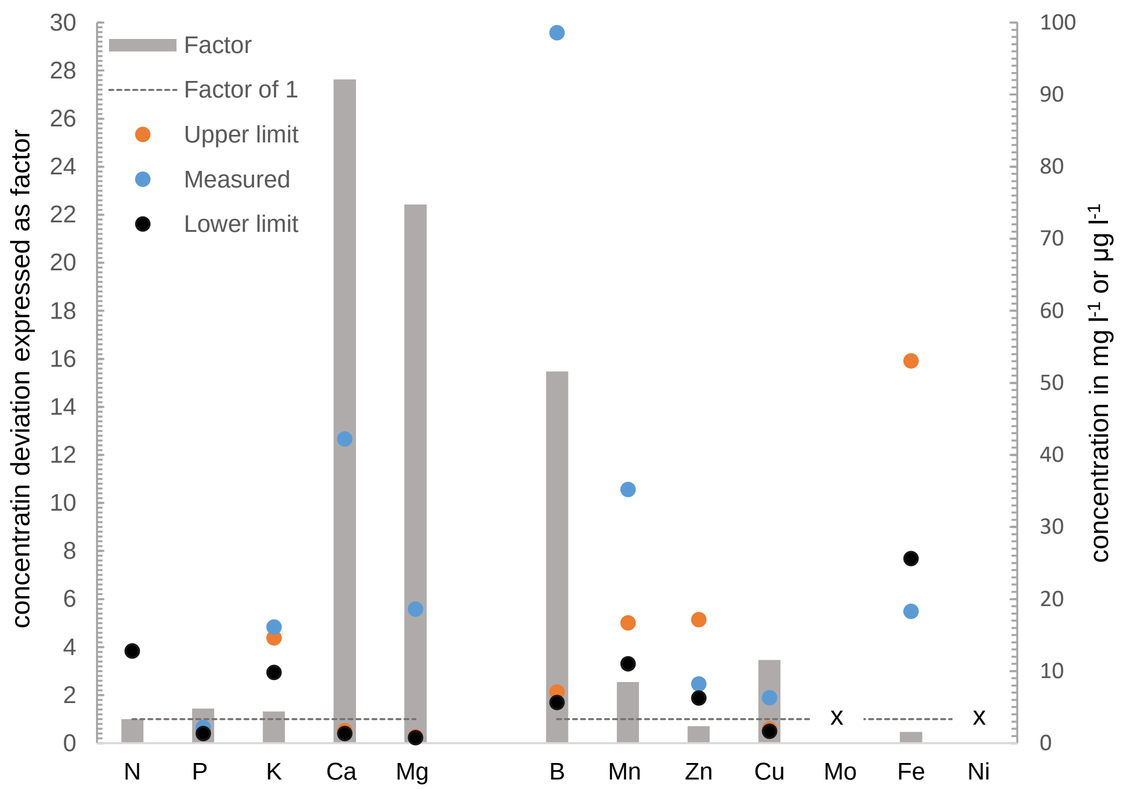

Fig.18: The ratio of mean essential nutrients concentrations in relation to the ratio in leaf nutrient concentrations of lettuce (Hartz et al. 2007) and expressed as a factor (i.e. there is 28 times as much calcium (Ca) in the surface water compared to its relative concentration in the lettuce leaf); the average nitrogen content of 12.67 mg l^{-1} was set to have the value one; orange and black dots represent upper and lower limit of the optimum range as established by Hartz et al. (2007), blue dots represent mean concentration in the surface water samples; x represents no reference value for leaf concentrations.

Nutrient compositions of surface water at the CSIR, La, and Upper Kordjor (Northern section of the Kordjor River) were similar to those described for the average surface water (Fig.19). Marked differences in composition from the mean were found for potassium, manganese, and zinc concentrations. While the mean potassium concentration remains below the target value, i.e., factor of 1, the Upper Kordjor site had 1.5 times the desired concentration. The same was true for the zinc concentration where the mean is below the reference value, but the concentration at the CSIR site is slightly above 1. In contrast, the manganese concentration at La is below the reference value, while the concentration of the surface water mean was above.

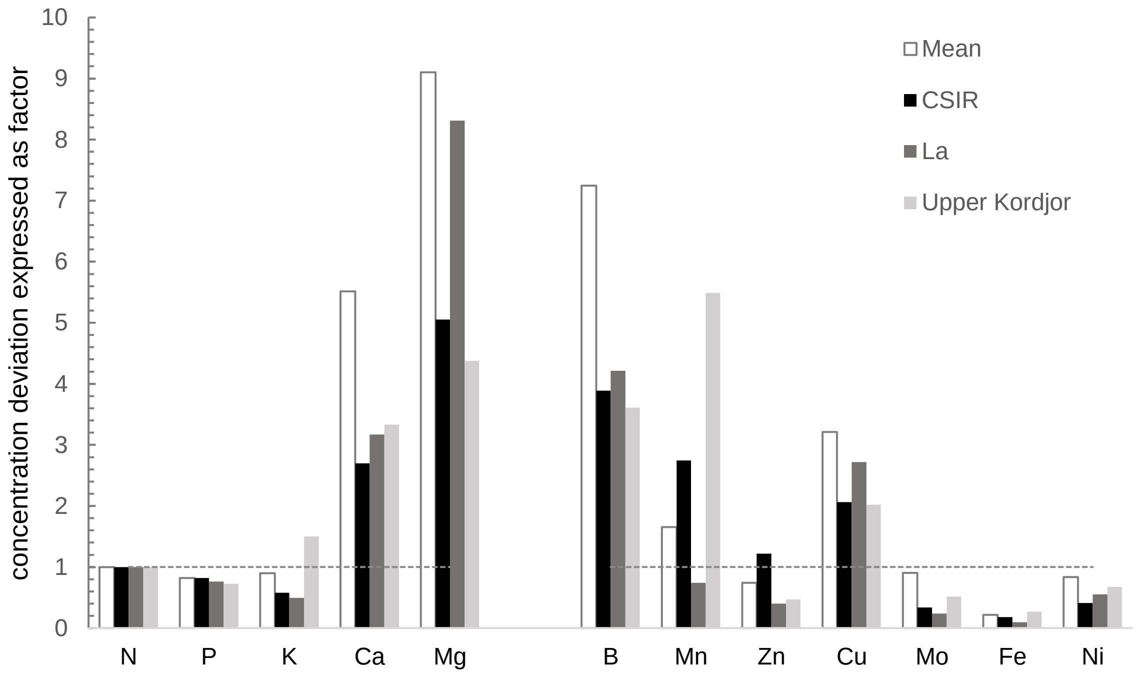

Fig.19: The ratio of essential nutrients concentrations for the mean across all samples, for CSIR, La and Upper Kordjor, set in relation to the ratio in the modified Sonneveld solution (Mattson and Peters 2014) and expressed as a factor (i.e. there is 5.5 times as much calcium (Ca) in the mean surface water compared to its content in the commercial nutrient solution); the total nitrogen content of 12.7 mg l^{-1} (mean), 27.6 mg l^{-1} (CSIR), 27.4 mg l^{-1} (La), 19.8 mg l^{-1} (Upper Kordjor), was set to have the value one.

4.5 Design of the hydroponic system

4.5.1 Interest of farmers, vendors, and consumers in waste water hydroponics

Less than a handful of farmers (three out of twenty) had heard about hydroponics. However, once this cultivation technique was explained including the use of wastewater, twelve said they would be willing to adopt it on at least some of their cultivation area on conditions that it was affordable. They wanted the initial investment costs covered and that crops grown are sold at a higher price. Farmers who lacked interest in the system cited the lack of tenure security and a potentially high financial investment as major concerns.

None of the vegetable vendors had heard about a hydroponic system before. The vast majority (88%) though said that they would sell vegetables produced in wastewater-based hydroponics after it was explained how such a system works. Forty of the fifty vendors thought there was a market for hydroponically grown vegetables. As market gaps, hygienic vegetables were mentioned alongside lettuce to avoid disease caused by producing it in the field after onion. Furthermore, tomatoes were seen as suitable crops as they often are delivered only once per week. It was also mentioned that hydroponically grown vegetables would help to increase the abundance of local vegetables on the market, especially during the dry season. For the preconditions for selling hydroponically grown vegetables, vendors recommended either that the price should be the same as at the current ones or still low enough to sustain accessibility. Vegetables should moreover look and taste similar to the once grown in the soil, and customers would need to be informed about the system. Concerns for marketing of hydroponic vegetables were that generally only few customers ask how and where vegetables are produced, so vendors must be able to explain the advantages of the hydroponics system should there be a difference in price or appearance.

Lastly, more than 90% of the consumers would buy vegetables grown in a wastewater-based hydroponic system after they were made familiar with such as system. About 84% were willing to pay a higher price for hygienically produced vegetables. The accepted increase in price was between 5 – 50% of current prices. Most of the interviewees also indicated that they would be interested in home-delivery of hydroponically produced vegetables.

4.5.2 Hydroponic system prototype

A layout for a simplified hydroponic system for lettuce production in Accra is presented (Fig.20). This system would contain four hydroponic growth units, two circulation tanks with a pump, two water storage tanks, and an area for seedling production. It would be covered by a greenhouse 20 m long and 10 m wide. A close up of two growth units with a circulation tank and a storage tank is shown in Figure 21.

	Area (m^2)	Water volume ($10^{-3}m^3$)
Seedling production	7.5	
Hydroponic growth unit	129	313
Circulation tank with pump	1.5	626
Water storage tank	0.8	1,252

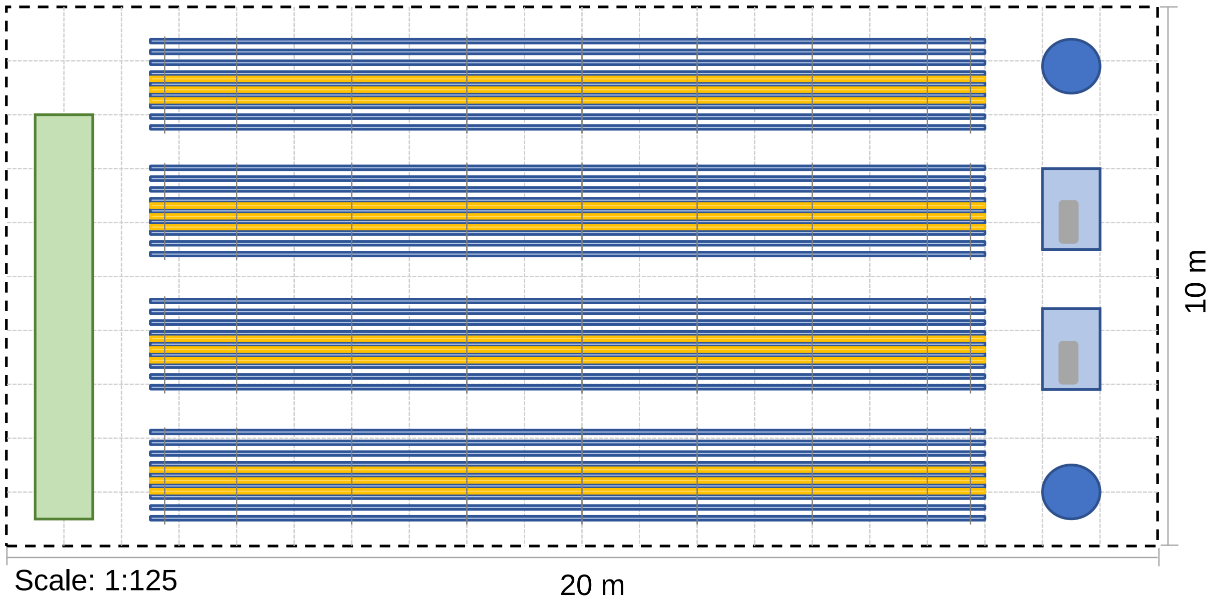

Fig.20: Layout of the proposed hydroponic system for a 200 m^2 greenhouse.

The hydroponic system was designed for lettuce production and will be likely operated in the following manner. First, the two water storage tanks are filled up with water from a stream. This water will be used to fill the circulation tanks. Meanwhile, lettuce seeds will be sown in the seedling production area. When ready for transplanting, the seedlings will be transferred into net pots placed in holes along the pipes of the hydroponic growth units. Water from the circulation tanks will then be pumped to the upper pipes (orange) of each hydroponic unit. Once the upper pipes are filled, water will overflow into the connectors and fill up the lower pipes (blue) (Fig.20,21). Once the nutrients in the water are depleted (see following section 4.5.3), water will be discharged back into the stream or collected for irrigation. Circulation tanks will be refilled by gravity with water stored in tanks. Measurements of the different parts of the hydroponic growth units, the circulation tank and the water storage tank are indicated in Figure 20 and listed in detail in the appendices (Appendix H, Tab.01-04).

About 6,960 lettuces are expected to be produced simultaneously in the hydroponic system. Each 14 m long pipe will support 145 plants spaced 9.7 cm apart. To produce continuous output and keep nutrient demand stable, there will always be the same amount of lettuce plants at different growth stages in the system. As lettuce in the fields in Accra were reported to take four weeks to harvest after being transplanted, three pipes of each growth unit will be devoted to freshly transplanted plants, and those that grew in the system for one, two and three weeks respectively. Fresh seedlings will replace ripe lettuce. The seedlings will be put in the three upper pipes (Fig.21) because these are slightly smaller in diameter and thus receive lower amount of nutrients. This means that lettuce plants will be rotated after every week within each growth unit to create space in the upper pipes for the transplanted seedlings.

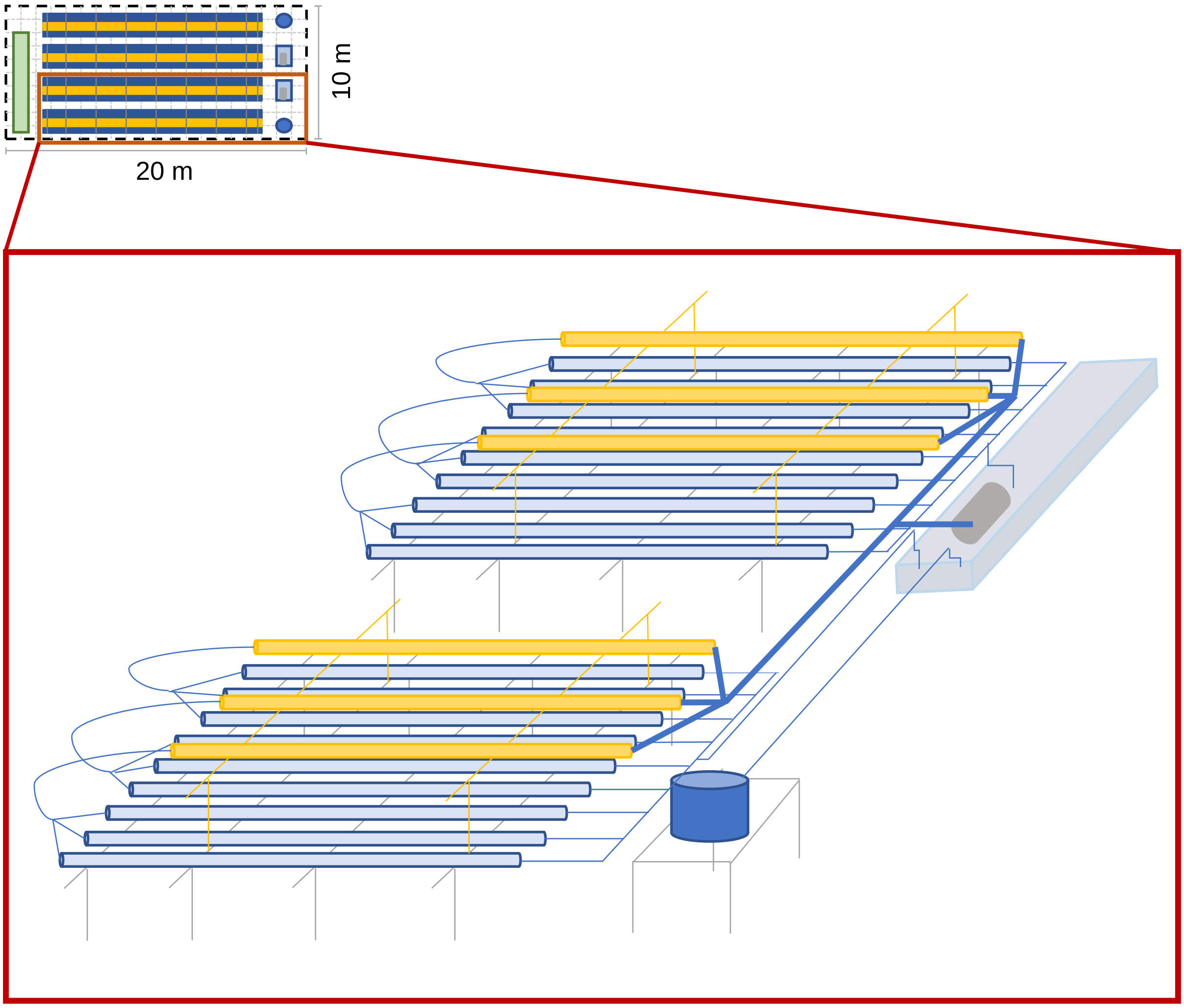

Fig.21: Layout of two growth units of the proposed hydroponic system including water storage tank and water circulation tank with pump.

4.5.3 Water cycling according to wastewater nitrogen concentrations

How often water in the hydroponic system will need to be exchanged depends on the concentration of nutrients in the water, but also on lettuce nutrient demands. As nitrogen was selected as the trigger element, the water exchange intervals were calculated according to nitrogen concentrations similar to those measured in surface water at CSIR, La and Upper Kordjor, and the amount of nitrogen that would be demanded by the lettuce plants in the system.

Nitrogen requirements of lettuce plants vary with age of the plant (Tab.11). Assuming a nitrogen content of 3.75% of the dry plant weight (Fontes et al. 1997; El-Shinawy and Gawish 2006; Søberg 2016; Anderson et al. 2017), and a fixed growth rate (Walker et al. 2001), each lettuce plant requires ~ 10.7 mg of nitrogen per day during the first week after transplanting, 16.1 mg per day in the second week, 5.4 mg in the third week, and 10.7 mg during the week before harvest. Therefore, each lettuce plant requires a total of ~ 300 mg of nitrogen during four weeks in the hydroponic system from transplanting to harvest.

Tab.11: Nitrogen (N) requirement of individual lettuce plants at nitrogen content of 3.75% of dry weight (DW) (Fontes et al. 1997; El-Shinawy and Gawish 2006; Søberg 2016; Anderson et al. 2017) for four growth stages of week four, week three, week two and week one before harvest; weekly increase in dry weight was adapted from Walker et al. (2001); total DW at harvest=10g; total fresh weight (FW) at harvest=200g (96% water (Mou 2009)).

Week 4	Week 3	Week 2	Week 1		
2	3	1	2	g DW plant^{-1} week^{-1}	Plant growth
75	113	38	75	mg N plant^{-1} week^{-1}	Additional N content
10.7	16.1	5.4	10.7	mg N plant^{-1} day^{-1}	N demand
			300	mg N plant^{-1}	Total N demand

With 435 plants at each of the four growth stages in each of the four hydroponic growth units (Fig.20), the total nitrogen demand would be 18,643 mg per hydroponic sub-unit per 28 days. The entire hydroponic system hosting 1,740 plants of each growth stage would require 74,571 mg of nitrogen for 28 days (Tab.12).

Tab.12: Nitrogen (N) requirement of one hydroponic plant growth unit, and the entire hydroponic system growing lettuce plants at nitrogen content of 3.75% of dry weight (DW) (Fontes et al. 1997; El-Shinawy and Gawish 2006; Søberg 2016; Anderson et al. 2017). Weekly increase in dry weight was adapted from Walker et al. (2001).

Week before harvest	N demand mg day^{-1} $plant^{-1}$	N demand mg day^{-1} 435 $plants^{-1}$	N demand mg day^{-1} 1,740 $plants^{-1}$
4	10.7	4,661	18,643
3	16.1	6,991	27,964
2	5.4	2,330	9,321
1	10.7	4,661	18,643
Total mg N 28 days:		18,643	74,571

The nitrogen content of surface water likely to be used in the proposed hydroponic system based on data from key sites in Accra is presented below (Tab.13). One hydroponic sub-unit is expected to have 8,628 mg of nitrogen when water from the CSIR stream is used, 8,565 mg with water from La and 6,190 mg with the Upper Kordjor River as the water source. Thus, nitrogen contents of the entire hydroponic system are expected to be ~34,512 mg, ~34,262 mg, and ~24,759 mg for water from the three potential sources respectively.

Tab.13: Nitrogen (N) content per hydroponic plant growth units (1 unit = 9 big lower pipes and 3 small upper pipes, half filled with water) for CSIR at 27.6 mg l^{-1} N, 27.4 mg l^{-1} N at La, and 19.8 mg l^{-1} N at Upper Kordjor (13 km from river mouth)).

	Volume 1 unit	Volume 2 units	Volume 4 units
Litres	312.6	625.2	1250.4
	N content of water mg	N content of water mg	N content of water mg
CSIR	8,628	17,256	34,512
La	8,565	17,131	34,262
Upper Kordjor	6,190	12,379	24,759

Finally, for the expected nitrogen content in the hydroponic system to meet the hypothetical nitrogen demand of lettuce (Tab.12,13), the 1,250 litres of water in the hydroponic system would need to be exchanged every eleven hours at CSIR and La, and every eight hours when water from the Upper Kordjor would be used (Tab.14).

Tab.14: Number of times the 1,250 litres of water in the proposed hydroponic system needs to be exchanged according to nitrogen content of surface water (N supply) at CSIR, La and Upper Kordjor, and the nitrogen requirement of 6,960 lettuce plants at different growth stages.

N supply mg unit^{-1}	N demand mg day^{-1}	No of exchanges in 24 h	Exchange intervals every x hours	Location
34,512	74,572	2	11	CSIR
34,262	74,572	2	11	La
24,759	74,572	3	8	Upper Kordjor

4.5.4 Investment and cost benefit analysis

Hypothetical costs and benefits, and the investment were analysed for the proposed system. The total initial investment would be ~ €12,236, including the greenhouse, hydroponic system components, water supply, energy supply, and personal protective equipment (Appendix H, Tab.05). Variable costs would be slightly higher at €12,892 annually. Variable costs would include direct inputs to lettuce production, cost for marketing, maintenance, and labour (Appendix H, Tab.06). For the revenue and net cash return calculation, the current open market price of €0.03 per head of lettuce was taken along with a self-marketing price of €0.29 per head that could be expected for the supermarkets (Appendix E and Tab.06)

4.5.4.1 Scenario I: Full investment financed with loan

Self-marketing conditions (i.e., price of €0.29 per head of lettuce) is required to achieve profitability with net cash revenue estimated at €6,996 per year (Appendix I, Tab.02). This estimate assumes that the loan of €12,241 is paid back over 10 years at 6% interest, resulting in an annual total payment of €1,663 (Appendix I, Tab.02). For this scenario, the theoretical payback period for the investment would be less than two years, the net present value being €37,029 and the internal rate of return 57% (Tab.15). Variable costs contribute 90% of total costs and the cost-benefit ratio would be 1.4 (Tab.16). Selling the lettuce at €0.29 per head would finally yield a monthly income of GHS4,001 or €583 (Tab.16). However, if hydroponically produced lettuce would be sold at the same price of €0.03 per head currently earned by the farmers in Accra, this will translate to a loss in net revenue of €13,634 per year (Appendix I, Tab.01). As a result, the credit taken up for the investment will not be paid back and farmers will lose money. To just cover costs, a break-even price of €0.2 per head is necessary (Appendix I, Tab.01).

Tab.15: Payback period (PP), net present value (NPV), internal rate of return (IRR), and monthly income hypothetically generated by the hydroponic system under scenario I.

PP	NPV	IRR
Years	€	%
1.7	37,029	57

Tab.16: Annual net revenue (NR), contribution of variable to total cost (CVT) and the benefit-cost ratio hypothetically generated by the hydroponic system under scenario I.

Monthly income		CVT	B/C
€	GHS	%	ratio
582	4,001	90	1.4

4.5.4.2 Scenario II: Half of investment provided

When half of the investment would be covered by subsidies or donations, selling the hydroponically produced lettuce at the current market price of €0.03 per head would still result in a negative cash flow of €12,802 per year (Appendix I, Tab.03). Here, the break-even price lies at €0.19 per head (Appendix I, Tab.03). However, selling lettuce for the self-marketing price of €0.29 per head would generate an annual net cash revenue of €7,827 (Appendix I, Tab.04). Assuming loan conditions of 10 years at 6% interest, the annual total payment would be €832. The theoretical payback period for half the investment would be 0.7 years, with net present value of the investment at €51,297, and an internal rate of return of 74% (Tab.17). With only half of the investment cost, the hydroponic system would generate a monthly income of GHS4,483 or €652. Variable costs would make up ~ 90% of total costs and the benefit-cost ratio would be 1.5 (Tab.18).

Tab.17: Payback period (PP), net present value (NPV), internal rate of return (IRR), and monthly income hypothetically generated for the proposed hydroponic system under scenario II.

PP	NPV	IRR
Years	€	%
0.7	51,297	74

Tab.18: Annual net revenue (NR), contribution of variable to total cost (CVT), and the benefit-cost ratio for the proposed hydroponic system under scenario II.

Monthly income		CVT	B/C
€	GHS	%	ratio
652	4,483	95	1.5

5. Discussion

This study investigated the potential of rolling out a hydroponic system relying on wastewater as a sustainable alternative to pathogen-transferring soil-based lettuce production in Accra, Ghana. A survey of irrigation water sources and irrigation methods currently used by urban farmers indicated a high risk of pathogen transfer of the current soil-based production system. Vegetable production in the city is also under pressure from reduced planting areas and soil degradation. Heavy use of pesticides poses an extra threat to human and environmental health. Average production sites were found profitable and created an income similar to the average paid employee in the country. Wastewater used for irrigation was measured to contain nutrient concentrations suitable for use as a nutrient solution for lettuce production for the proposed open hydroponic system. Typical constituents of wastewater such as heavy metals, solids or excessive salt concentrations were found to be lower than levels known to interfere with crop growth and development.

The proposed hydroponic system is expected to provide several environmental and economic benefits. Environmental benefits include the removal of macronutrients from the city's streams, potential reduction in soil salinity, and reduced use of insecticides. We can expect social acceptance to be high as most farmers, vendors, and consumers expressed interest in a wastewater-based hydroponic system. The proposed hydroponic system is expected to generate profit and compete economically with soil-based lettuce production if the lettuce is sold at prices similar to local supermarkets. This can cause farmer's incomes to triple. However, a higher selling price means that lettuce cannot be sold at the open vegetable markets where lower-income buyers get their vegetables.

5.1 Status of irrigated vegetable production in Accra

Irrigated urban vegetable production in Accra is a significant contributor to the city's open markets and creator of employment. The survey of the open vegetable markets in Accra showed that most of lettuce, herbs, cauliflower, and sweet pepper on offer were produced within the city (cf. Tab.05). Drechsel et al. (2007) found a similar contribution for Kumasi in the north of Ghana. The average benefit-cost ratio across the seven analysed crops was 2.9 (cf. Tab.03), suggesting that on average, farmers earned €/GHS2.9 for every Euro or cedi invested (Boardman et al. 2017). This compares well to the ratio of 2.8 found for irrigated vegetable production in Accra by Abban (2003). While a cost-benefit ratio ignores the actual height of involved cost and revenue, it is still a suitable and simple measure of profitability for comparing different crops (Boardman et al. 2017).

The accurate comparison of financial costs and benefits is necessary for understanding the current value of soil-based informal urban vegetation production. Labour costs in Accra average €37 per month, exceeding the 2018 minimum wage of ~ €1.41 per day (MELR 2019). Farmers achieved a monthly incomes of ~ €160 – 172, which is higher than previously reported incomes. For example, a monthly income of €34 – 48 was assumed for irrigated vegetable farmers in Accra (Drechsel et al. 2006; Obuobie et al. 2006; Veenhuizen and Danso 2007; Danso et al. 2014), but a recent study suggests €78 (Mumuni et al. 2017). Discrepancies may be attributed to inflation and overestimation bias because of the small area considered per crop (Flyvbjerg 2008; Bleaney et al. 2020).

However, some financial estimates from previous studies may be contested. Sources of the estimated income were missing for some studies (Obuobie et al. 2006; Danso et al. 2014). The figure of ~ US$40 – 57 was likely based on data from 2002 from the study of Danso and Drechsel (2003). However, income data for this figure was self-reported by farmers (Obuobie et al. 2006; Danso et al. 2014). It is therefore unclear what method was used and which cultivation areas or crop rotations were considered. In contrast, Mumuni et al.'s (2017) study has the advantage of using recent data obtained by interviewing 84 farmers in Accra. However, data on costs for water, labour, fertilizer, and other inputs were computed at a flat-rate for all vegetable patches. Thus, compared with previous studies, the detailed analysis of cost and revenues I used were consistent with the CBA-theory as benefits and costs were systematically catalogued (Boardman et al. 2017), and recorded incomes above US$200 per month have been reported elsewhere for wastewater irrigated vegetable farming in West Africa (Drechsel et al. 2006; Raschid-Sally 2013).

A growing challenge with soil-based urban vegetable production is loss of land to building infrastructure. From 2005 to 2010, the area under irrigated vegetable production in Accra shrunk by 19% (Danso et al. 2014). In support of this prevailing trend, my results show that the area under irrigated vegetable production further reduced by 59% from 2010 to 2018 (cp. Fig.12). However, the significant difference in the area under irrigated vegetable production in 2010 between this and the previous study is cause for concern. While Danso et al. (2014) reported 42 hectares under irrigated vegetable production in 2010, instead I found 702 hectares by comparing available satellite data and area measurements in QGIS. Differences in area estimates occurred because I included the Atomic Energy site and assumed that half of La and Dzorwulu North were irrigated. This was because the last two areas were near water sources and under irrigation in 2018. In contrast, Danso et al. (2014) designated them as "open space" production without reference to water supply, i.e., rain-fed or irrigation. However, discrepancies in the area estimates may also arise from the methods used. Danso et al.'s (2014) mapping was coarse as many reference features were misplaced and others missing.

This casts doubt on the reliability of their data. However, the trend of encroachment of agricultural areas by urban infrastructure was clear. For example, irrigated fields at the La were replaced by buildings between 2010 and 2018 while the Marine Drive site disappeared completely for unknown reasons (cp. Fig.11,13). Despite this, farmers compensated for losses by switching cultivation to other areas like Tema Highway and the Atomic Energy site (cf. Fig.12). This demonstrates the resilience of urban farming despite insecure tenure, i.e., none of the twenty interviewed farmers owned the land they farmed but continued cultivating land for up to twenty years (Danso et al. 2014).

Irrigated vegetable production in Accra continues to be a vector of wastewater pathogens and a source of chemical pollution from pesticide overuse. Most of the farmers on the ten major production sites in the city used water from streams and drains and applied it to the vegetables with sprinkler hoses, watering cans or hose pipes (cf. Appendix D, Tab.07). These irrigation methods help pathogen transfer because of plant exposure via foliar application and soil splash (Blumenthal and Peasey 2002; Amoah et al. 2011). Because of the prevalence of pests and disease, farmers applied three insecticides and one fungicide once per week (cf. Appendix D, Tab.05). Amoah et al. (2006) previously documented this high use of pesticides in Accra's urban vegetable production sites by linking it to excess insecticide residue on lettuce, cabbage, and spring onion that exceeded official residue limits by up to a factor of thirty. Besides accumulating on vegetables, frequent insecticide application has detrimental effects on biodiversity by harming non-target insects and causing chemical accumulation in waters (Sánchez-Bayo 2011; Beketov et al. 2013).

Increased soil salinity was found to be a potential side-effect when using wastewater for watering vegetables. Farmers interviewed in this study reported it as the major soil-related problem leading to production losses. Salinity is a common symptom of wastewater irrigated crop production due to high salt concentrations in wastewater (Pescod 1992). Fipps (1995) classed water with the measured EC, TDS and SAR of the irrigation water used by farmers in Accra as permissible for continuous irrigation only when leaching is practised. Therefore, it is plausible that long-term wastewater irrigation leads to saline conditions, decreasing yields because of enhanced energy expenses for water uptake or disturbances in plant nutrition (Rhoades et al. 1992; Läuchli and Grattan 2011).

5.2 Suitability of Accra's wastewater for lettuce production

Wastewater used for irrigation in the current soil-based vegetable production system has plant nutrients in concentrations suitable for use as a nutrient solution for lettuce production in the proposed open hydroponic system. However, low iron availability because of low concentrations in the wastewater and potential antagonistic effects of calcium, manganese and copper on iron uptake might be of concern.

Absolute nutrient concentrations in Accra's streams are suitable to grow lettuce hydroponically. While mean concentrations of essential macro- and micronutrients in the surface water were well below that of the two commercial solutions, except for chloride (cf. Tab.10), it is worth noting that commercial nutrient solutions are prepared following the principle of excess availability of all elements to prevent deficiencies (Maucieri et al. 2019). However, since lettuce can grow healthy at nitrogen concentrations as low as 6 mgl^{-1} and can deplete nitrogen concentration to below 0.3 mgl^{-1} (Swiader and Freiji 1996; Chen et al. 1997), it can be assumed that lettuce can grow and develop well at the average nitrogen concentration of 12.8 mg l^{-1} when water is exchanged at appropriate intervals (cf. Tab.14). Chloride toxicity is of chief concern only in woody perennials due to accumulation (Rhoades et al. 1992; Rhoades 2011). In annual crops, osmotic effects typically occur before specific ion effects of chloride (Maas and Grattan 1999). Therefore, the 238 mg l^{-1} of chloride is not expected to interfere with lettuce growth. Whether other plant nutrients are present in high enough concentrations needs to be discussed by analysing their concentrations relative to that of nitrogen, and potential synergistic and antagonistic effects.

Relative nutrient concentrations of wastewater suggest a risk of iron undersupply for lettuce. In relative terms, wastewater had high concentrations of calcium, magnesium, manganese, copper and boron while iron was in short supply (cf. Fig.17,18). However, these relatively high or low nutrient concentrations are not likely to cause toxicity or deficiency *per se*. Instead, relative concentrations indicate the potential of interactions, i.e., synergistic or antagonistic effects one nutrient has on the availability and uptake of another (Rietra et al. 2017). For example, the relatively high concentration of calcium may counteract relatively high concentrations of magnesium, manganese, copper and boron while worsening the relative shortage of iron because of antagonistic effects (Fig.22; Fageria 1983; Fageria and Baligar 1999; Kanwal et al. 2008). The antagonistic effect of calcium on magnesium for instance is attributed to magnesium being the weaker competitor for cation uptake (Jones 2012). However, high relative concentrations of magnesium have been found to decrease calcium uptake due to competition for metabolically produced binding compounds, and to have a synergistic effect on boron (Fig.22; Yamanouchi 1980; Fageria 1983; Maucieri et al. 2019).

The interaction and effects of calcium and magnesium alone demonstrate the complexity of nutrient interactions. The available literature on the subject rarely explore simultaneous interaction of more than two nutrients, does not allow for separation of effect at the crop species level, and seldom addresses more than one of the interaction sites (i.e., nutrient solution, root surface or in the plant) (Fageria 2001; Rietra et al. 2017; Maucieri et al. 2019; Sambo et al. 2019). Yet, when antagonistic and synergistic interactions are cancelling each other out (Fig.22, lower middle), every nutrient in relatively abundant supply in wastewater exerts an antagonistic effect on at least another nutrient in high supply. As it is difficult to quantify antagonistic interactions, it is reasonable to assume that the relatively high concentrations cancel each other out. However, iron which was found to be in low supply already, is at the receiving end of two antagonisms (Fig.22). Therefore, the low relative concentration of iron might negatively affect lettuce growth.

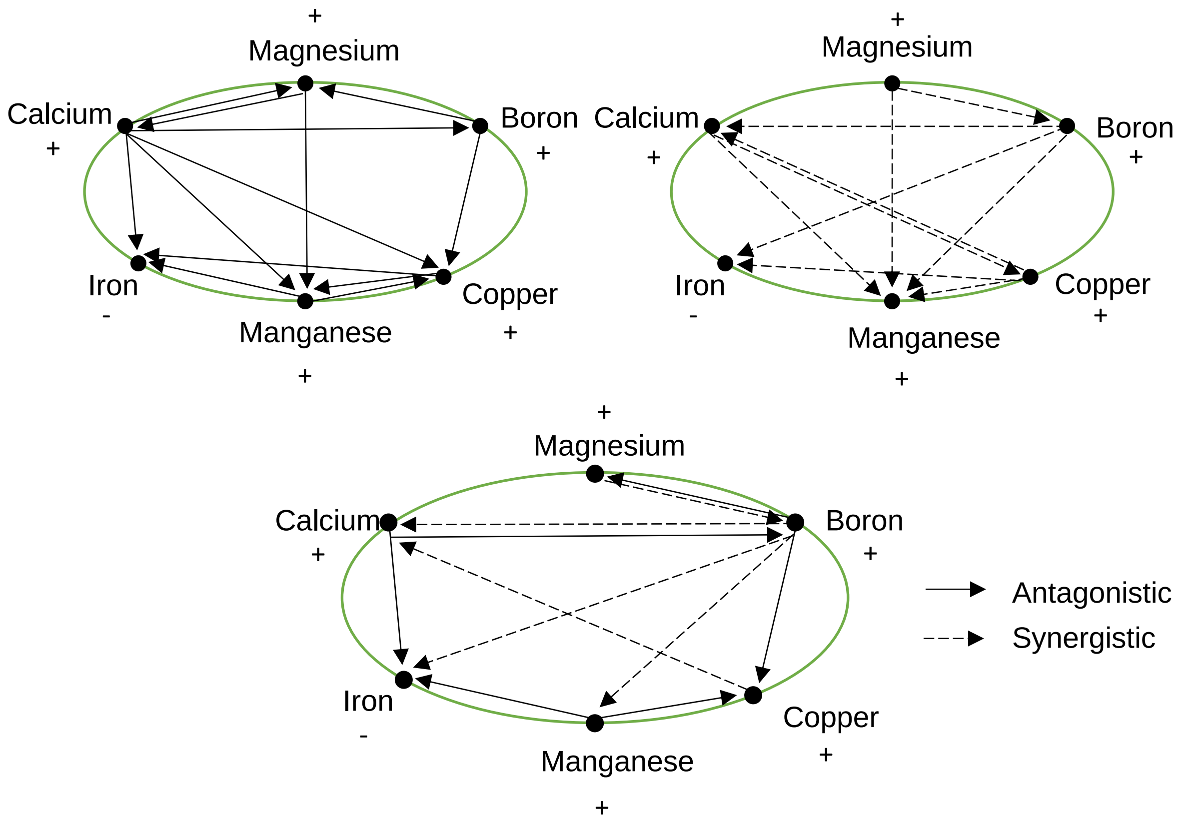

Fig.22: Antagonistic interactions (upper left), synergistic interactions (upper right) and combined interaction when antagonistic and synergistic are deleting each other (lower middle) between nutrients found in relative high or low concentration in the wastewater; plus (+) and minus (-) indicate measured relative over- or undersupply in the wastewater (Data sources: Leach and Taper 1954; Yamanouchi 1980; Fageria 1983; Läuchlie and Bieleski 1983; Sledlecka 1995; Fageria and Baligar 1999; López-Lefebre et al. 2002; Tariq and Mott 2007; Kanwal et al. 2008; Yruela 2009; Jones 2012; Maucieri et al. 2019).

Diurnal fluctuations in nutrient concentrations of wastewater need to be managed to avoid constraints on lettuce growth in the proposed hydroponic system. Results from a single day's study at the CSIR site showed fluctuations of nitrogen content and composition (cf. Fig.15).

Total nitrogen content fluctuated between 11 – 16% around the day's mean, amounting to absolute differences of up to 15 mgl^{-1} (cf. Fig.15). This concentration fluctuation can be taken care of by water storage, allowing for homogenization. The highest nitrogen concentration of the day coincided with higher ammonium concentrations compared with the rest of the day, which might be attributed to a peak in activity at nearby office complexes. Ammonium is the dominant form of nitrogen in human urine and in commercial cleaning agents (Kirchmann and Pettersson 1994; DeLeo et al. 2020). I observed a similar pattern of ammonium and nitrate concentrations at the Kordjor River (c.f. Fig.16). Ammonium was abundant in the Northern part of the river near buildings and nitrate close to the river mouth. However, these different forms of nitrogen, i.e., ammonium and nitrate, do not influence the water's suitability as a nutrient solution because higher plants can use both (Hawkesford et al. 2011). Yet, at higher pH and aerobic conditions, nitrate is the dominant form used by plants (Maathuis 2009). However, for a hydroponic solution receiving both nitrate and ammonia, Norström et al. (2003) found that plants act as a growth substrate for nitrifying bacteria.

Typical constituents of wastewater like heavy metals, solids or excessive salt concentrations are not expected to interfere with plant growth and development when using Accra's wastewater. pH and temperature also render the water suitable to be used as a nutrient solution.

Heavy metals and aluminium were either below detection or the recommended maximum concentrations for irrigation (cp. Tab.08) and also for use as a nutrient solution specifically, the measured values for Co, Cr, and Cu were far from toxic levels (Park et al. 2016; Sun et al. 2019; Samet 2020). The average measured total suspended solid concentration of 79 mg l^{-1} is expected to have a slight to moderate potential to clog sensitive equipment such as drip emitters (Ayers and Westcot 1985). Therefore, clogging of pipes in the hydroponic systems is rather unlikely. Vaillant et al. (2003) even showed that *Datura innoxa* (*Solanaceae)* used for treating domestic water removed ~ 98% of up to 400 mg l^{-1} suspended solids. These solids were trapped in the root systems and mineralized by bacteria. Measured indicators of salinity, i.e., EC and TDS of 1 dSm^{-1} and 666 mgl^{-1} are recommended for irrigation with leaching (Fipps 1995). Therefore, no negative effects are expected in an open hydroponic system where salts do not accumulate. However, it has been shown that some plants respond stronger to salinity when grown in nutrient solution compared to soil (Tavakkoli et al. 2010). For lettuce, Andriolo et al. (2005) found that shoot fresh mass increased from EC of 0.8 – 1.9 dSm^{-1} and dropped only above 2 dSm^{-1}.

The measured pH of 7 might affect the availability of nutrients such as iron and copper, which have a higher availability at slightly acidic pH (Bugbee 2004; Resh 2004). However, reduced availability does not necessarily lead to a deficiency and pH can become acidic with time as plants can influence the root surrounding for example with the release of exudates (Marschner et al. 1987; Bugbee 2004; Jones 2012). Yet, regular pH measurements might be advisable. The measured water temperate of 31 °C influences oxygen concentrations. Lower oxygen concentrations around 7.6 mgl^{-1} are expected compared to lower temperatures of around 20 °C where water has ~ 9.1 mgl^{-1} (Trejo-Téllez and Gómez-Merino 2012). For lettuce, however, Goto et al. (1996) identified the critical dissolved oxygen concentration for vigorous lettuce growth to be below 2.1 mgl^{-1}.

5.3 Socio-economic and environmental analysis for the proposed hydroponic system for lettuce production

The design and economic analysis of the proposed open hydroponic system showed that a hydroponic system using wastewater from Accra's streams to produce lettuce could be economically viable and socially acceptable. Cost-benefit analysis for the hypothetical system in a 200 m^2 greenhouse indicated that farmers could earn as much as €582 – 652 per month if the lettuce is sold at €0.29 per head (cp. Appendix I, Tab.02,04). This comes from an initial investment of €12,236 being paid back over 10 years at 6% interest rate. An investment analysis showed profitability for scenario I for paying back the full loan, and scenario II for paying back half of the loan (cp. Tab.15,17). An investment is understood to be profitable when the internal rate of return is greater than the discount rate, i.e., 6% in this case, and a positive net present value (Kay et al. 2016c). Between the two loan financing options, scenario II is preferable because of its higher net present value (74% versus 57%) and a higher internal rate of return (€51,297 versus €37,029). At the same time, the payback period for scenario II is 0.7 years compared to 2.7 years for scenario I (cp. Tab.16,18). It is worth noting here that payback periods do not measure profitability, but rather how quickly an investment contributes to the liquidity of an enterprise (Kay et al. 2016c). However, liquidity might be a critical factor to farmers who need to quickly settle their cash flow obligations. Still, a serious hurdle remains for the hydroponic system in that lettuce production under the current soil-based system has a much higher cost-benefit ratio (4.1 versus 1.5) (cp. Tab.03,16,18). However, hydroponic production would be economically preferable for farmers because it can generate more income.

A major impediment to investing in new technology is the willingness of current users to switch. In this study, there was considerable interest among farmers, vendors, and consumers in wastewater hydroponic farming when the design and function of the system was explained. However, the selling price of €0.29 per head of lettuce is several times the maximum of 50%

extra cost the consumers were willing to pay for a hygienic product. The price would also mean that the lettuce cannot be sold at the open vegetable markets where the buying prices average €0.03 per head (cf. Appendix E). In comparison, high-end markets like the Farmer's Market or supermarkets may be targeted instead (cf. Tab.06). Unfortunately, it is the majority of consumers who depend on the city's open markets for low prices and who are most exposed to pathogen contamination who will forego benefits. To guarantee that lower-income consumers also benefit from the new production system, a hydroponic system with prolonged storage may need to be set up to remove the pathogens from wastewater. The cleaned wastewater from the hydroponic system could then be used to irrigate adjacent fields to decrease pathogen contamination of the soil-based vegetable production (Mara et al. 2010).

The chief concerns of farmers over affordability and investment cost of a hydroponic system were taken into consideration in the design of the proposed system that uses simple equipment and requires limited technical expertise. Being an open solution culture system, i.e., water is not recycled and using no growth medium, the operation is simple, and costs are minimized because of less pumping requirement compared to closed systems (Paulitz 1997; Schröder and Lieth 2002). Also, the contribution of variable to total cost of the hydroponic system averaged 93% for the two investment financing scenarios, showing that running cost still dominate, with labour costs for one full time and two part-time workers being the largest contributor (c.f. Tab.16,18).

The proposed hydroponic system could help remove macronutrients from the city's streams, reduce high use of pesticides, and decrease risk of soil salinity. Assuming that the lettuce removes all measurable nitrogen and transpires 2 – 3% of the water (Barbosa et al. 2015; Sambo et al. 2019; Bliedung et al. 2020), 61 kg of nitrogen per year can be removed with one hydroponic system (cp. Tab.14). If phosphorus were taken up at the expected ratio to nitrogen (Hartz et al. 2007) an additional 7 kg of phosphorus, for example, could be removed from Accra's streams. This would considerably reduce the risk of eutrophication (e.g., Owusu Boadi and Kuitunen 2003; Monney et al. 2013). A simple hydroponic system such as the one designed could also be a solution to the additional challenges of the current production system that are decreased production area, soil salinity and high use of pesticides. Hydroponic lettuce production is independent of arable land and could reduce pesticide use due to the elimination of soil-borne disease and a protective greenhouse environment (e.g., Sardare and Admane 2013; Sharma et al. 2018; Maucieri et al. 2019). Irrigation of fields with hydroponic effluent of low salt concentrations could reduce soil salinity.

6. Conclusion

There was a keen interest in Accra's urban agriculture sector for hygienically grown vegetables, and consumers were willing to pay more. A survey of current vegetable production and marketing indicated a significant proportion of crops sold at the vegetable markets were from urban patches. However, a survey of urban vegetable production showed they relied on unsafe wastewater irrigation practices and used high amounts of pesticide. As an alternative, I have presented a simple hypothetical hydroponic system for growing lettuce (i.e., a crop with good financial returns) to address health and environmental shortcomings of soil-based irrigated farming. Water analysis showed that wastewater currently used for irrigation may be suitable as a hydroponic nutrient solution if we monitor concentrations of iron and pH. Although the proposed hydroponic system still has a steep initial investment, the economic analyses indicate that it can be profitable if lettuce is sold at a premium price. However, this means lettuce prices will be beyond the means of many consumers. Scaling-out of the proposed system might reduce costs by decreasing personnel for maintenance and security that accounts for most of variable costs. Alternatively, while recontamination from soil remains a risk, a solution is implementing a dual farming system with hydroponics providing safer irrigation water for the soil-based vegetable farming.

This study had limitations. The multi-disciplinary approach (i.e., economic, social and environmental) made it impossible to conduct a robust market assessment with more consumers. Because of resource constraints, biological indicators of wastewater confirming actual pathogen loads in wastewater were omitted. Also, water sampling in one season ignores seasonal variation of nutrient loads. Further studies can address these limitations by a) focusing on consumer preferences and willingness to pay with large samples; b) sampling physical, chemical and biological parameters of wastewater all year-round. This baseline study was however found beneficial. The findings are useful for setting up pilot systems for wastewater hydroponic crop production. Recommended pilot sites include CISR, La, and Upper Kordjor where key water parameters were collected. Such pilot studies can also reveal the actual transfer of wastewater pathogens onto lettuce, and confirm that sufficient water is available form streams throughout the year.

Wastewater irrigated vegetable production is widely practiced in cities of the Global South with poor wastewater collection and treatment systems (Raschid-Sally and Jayakody 2008). Low-cost hydroponic systems will not replace the need for efficient wastewater treatment systems nor will they solve farmer's issue with land tenure. However, wastewater hydroponics has immense potential for progressing urban agriculture to ensure that urbanization becomes a trend from which all urban dwellers are benefiting.

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