WORKING PAPER

THE POTENTIAL OF URBAN AGRICULTURE TO IMPROVE FOOD SECURITY: THE CASE OF RECIRCULATING HYDROPONIC SYSTEMS FOR VEGETABLE AND HERB PRODUCTION

Samkelisiwe Hlophe-Ginindza, Nadia Araya, Ian du Plooy, Silence Chiloane, Makgoka Moremi, Luxon Nhamo and Sylvester Mpandeli

Abstract

Urban agriculture has gained enormous popularity in recent years, mainly to produce vegetables and herbs for food and ornamentals for decoration. This paper focuses on the potential of recirculating hydroponic systems to improve food security in urban areas, through the production and supply of vegetables and herbs. Recirculating hydroponics is the growing of plants in a soil-less culture, using an active nutrient solution that is continuously recirculated through the system. There are several advantages associated with the implementation of these systems, including their ability to maximize crop productivity, making production systems economically feasible through the cultivation of high-value commercial crops such as lettuce, tomato, sweet basil and strawberry. These crops are commonly produced at high planting densities, even in less favourable production areas. In addition, since recirculating hydroponic systems operate under protected environments, a virtual indifference to ambient temperature and seasonality is possible; the systems make use of minimal land area and are suitable for mechanisation and disease control. We reviewed existing knowledge on recirculating hydroponics, including the various types that are mostly employed in urban areas, as well as potential yields of high-value commercial vegetable and herb crops that can be attained using these systems. The implementation of such systems can result in considerably higher land, water and nutrient use efficiencies as compared to conventional open-field soil cultivation, thus offering great potential to improve food security and farmers income generation in urban areas. However, a successful implementation of these systems requires knowledge and skills development, as well as high initial investment costs, understanding of the markets dynamics and, as a result, government support initiatives are needed to help farmers in this regard, such as provision of training, funding and incentives to emerging farmers.

1. Introduction and context

Urban agriculture, as reported by FAO (2007), involves the growing of crops and rearing of animals for food and other uses within and around cities and towns, and related activities such as the production and delivery of inputs, processing, and marketing of products. This results in increased availability, stability, and accessibility of food in the cities, which contributes to improved diet of urban consumers, income generation for urban households involved in production value chains, thus allowing them to meet their daily needs and contributing to household food security and nutrition (FAO, 2001). Urban agriculture also allows the selling of good quality fresh produce at relatively low prices, since most of the products can be sold immediately following the harvest, as the result of shorter distances between producers and consumers, as well as a more restricted number of intermediaries involved in the production value chain. There are many different approaches to large-scale commercial urban agriculture, including aquaculture, hydroponics, and a combination of the two systems, which results in aquaponics.

Urban agriculture has attracted global attention from urban planners and researchers because of its multi-functionality, which is expected to encourage rural development and generate employment (Marsden and Sonnino, 2008). Furthermore, it has been claimed that the social and environmental impacts of urban agriculture make a significant contribution to urban sustainability (Lovel, 2010; Surls et al., 2015). Social impacts include human health benefits (physical and mental), community development, and educational benefits. Urban agriculture is also credited with positive environmental impacts such as greening cities, boosting biodiversity, and improving natural resource efficiency.

The fast urbanisation of South Africa poses a challenge for cities where the employment hopes by the unemployed, particularly the youth, are scarce while agriculture, particularly its value chain offers opportunities for job creation in the Small and Medium enterprise space. Provided adequate support exists, urban agriculture may contribute to the growth of agriculture if supported to access markets. It is important to note that in South Africa, recently, there has been a rise of black farmers (Sihlobo, 2018), thus indicating that with the correct market access and other production and institutional support, the youth can enter this sector. The Gauteng Department of Agriculture and Rural Development (GDARD) has supported many farmers around the province with the provision of infrastructure (e.g. tunnels, irrigation systems, production inputs, etc.) in an effort to promote and encourage farmers to adopt and practice hydroponics as a method to address food security, as well as job creation and income generation. However, due to a lack of training, financial and technical support, several farmers ended up producing crops with low yields and of poor quality, with high input costs, which cannot be sustained. This resulted in the failure of most of their farming operations, whereby farmers ended up either abandoning hydroponic farming or opting for conventional soil cultivation practices. (Morifi et al., 2018). Therefore, this working paper explores the potential contribution of urban agriculture food security focusing on recirculating hydroponic systems for increased crop productivity, income generation, and welfare of farmers and consumers in urban areas.

2. Introduction to recirculating hydroponic systems

2.1 Concept of recirculating hydroponics

Due to a rapidly growing population, there is increased competition for industrial and residential land and a significant shortage in the amount and quality of irrigation water as well as arable land for agricultural purposes. The increasing pressure on land and natural resources emphasizes the need for innovative ways of increasing crop production with limited resources (Niederwieser and du Plooy, 2014). Agricultural scientists have developed techniques to address this need, and recirculating hydroponics is one of the methods which can be used in this regard, particularly in urban and peri-urban areas where the availability of land and water for crop production is very scarce. Recirculating hydroponics, simply referred to as a method of growing plants under soilless conditions or without soil, while using recirculating nutrient solutions to irrigate the plants (Niederwieser and du Plooy, 2014). These systems rely on pumps to actively move the nutrient solution to the planting bed, with the remaining nutrients, after root uptake, being recovered and reused into the system.

2.2 Advantages and disadvantages of recirculating hydroponic systems

With the implementation of recirculating hydroponic systems, it is possible to achieve maximum crop yields, making the systems economically feasible using high-value commercial crops, which are cultivated at high planting densities, even in less favorable production areas (Jones, 1997). In addition, since recirculating hydroponic systems operate under protected environments, a virtual indifference to ambient temperature and seasonality is possible; the systems make use of minimal land area and are suitable for mechanization and disease control. The main advantage of these systems as compared to planting in soil is the isolation of the crops from the underlying problems related to soil-borne diseases, soil salinity, and poor soil structure and drainage. The expensive and laborious tasks of soil sterilization are unnecessary in hydroponic systems in general, and a rapid turnaround in the production of crops is readily achieved. Recirculating hydroponics also can provide plants with all of the required nutrients in the correct ratios throughout the growing season, there is no need for weed control and the harvested produce is fresh and free of soil particles (Niederwieser and du Plooy, 2014). In addition, with recirculating hydroponics there is increased efficiency in the utilization of water, enabling the grower to manipulate some of the plant characteristics to meet consumer demands. Table 1 illustrates a comparative performance between soil and soilless production of lettuce and brassicas using vertical recirculating hydroponics. The assessment was conducted in terms of crop yield obtained, water, and energy requirements per kilogram of the harvestable produce.

Table 1: Comparative performance between soil and soilless hydroponic production of leafy vegetables, in terms of crop yield, energy, and water usage (van Ginkel et al. 2017).

Parameter	Soilless hydroponic production in shipping containers		Soil production	
	Lettuce	Brassicas	Lettuce	Brassicas
Plants per m^2	1305 - 1371	432	39	10
Crop yield ($kg\ m^{-2}\ yr^{-1}$)	193 - 202	64	7	3
Energy ($kWh\ yr^{-1}$)	115283	115257	2948	2757
Energy ($kWh\ kg^{-1}$)	19	61	0.20	0.45
Water ($L\ kg^{-1}$)	1.6	5.0	106	507

Results presented in Table 1 indicate that recirculating hydroponics production (particularly under vertical systems) has a considerably higher potential for increased crop productivity due to a higher number of plants cultivated per m^2 and substantially lower water usage (66 – 100 times lower) when compared to soil crop production (van Ginkel et al. 2017). Thus, as Sambo et al. (2019) reported, the water use efficiency (WUE) of crops grown in hydroponics varies from 7.3 – 630 kg m^3, which is substantially higher when compared to that under soil crop production (1.8 - 13.2 kg m^3).

Despite the numerous advantages described above, recirculating hydroponic systems have few drawbacks. The major disadvantages of these systems relative to conventional open-field agriculture include high investment costs, a high degree of knowledge and management skills required for successful operation and production, as well as high energy inputs. Energy consumption in hydroponics can be as high as 95 – 136 times more than with conventional soil cultivation, as illustrated in Table 1 (van Ginkel et al. 2017). This is particularly evident in fully environmentally controlled greenhouses and containers, where high energy usage is mainly attributed to artificial lighting, heating, and cooling requirements. Capital costs may be especially excessive if the structures are artificially heated and/or cooled. In addition, recirculating hydroponic systems use soluble fertilizers, which are more expensive than those commonly used for open field production, and lastly, there is a very limited variety of crops that can be grown profitably in a recirculating hydroponic system.

2.3 Commonly used recirculating hydroponic systems

2.3.1 Media-based grow bed (MGB) systems

These systems are simple to operate and the nutrients are stored below the tray used for plant growth or in a tank. A pump is submerged into the nutrient solution which, when switched on, pumps the nutrient solution up to the plant tray and floods the root system for nutrient and water uptake. After running the pump for about 20 or 30 minutes, the pump is switched off and the excess solution is allowed to drain slowly back into the reservoir for recovery (Figure 1). A typical example of these systems is the ebb-and-flow technique. This technique not only supplies the plant with all the nutrients that it needs, but it also pulls oxygen down to the roots when the nutrients are removed after flooding, further promoting proper plant growth (Nicola, 2007).

Figure 1: The ebb-and-flow technique used for the cultivation of cucumbers (picture taken by NA Araya on 20 March 2020, at Ichthys Aquaponics Farm).

The ebb-and-flow technique has been widely practiced for many years, although it is not commonly used commercially today, other than for hobby/home-type growing units. This system is also called the "flood-and-drain" technique. The growing system consists of the following components: (1) a watertight rooting bed containing an inert rooting medium, such as gravel, coarse sand, or volcanic rock; (2) a nutrient solution sump (equal in volume to the growing bed); (3) an electrical pump for transport of the nutrient solution from the tank to the growing bed, and (4) a piping system to cater for the delivery of the nutrient solution from the tank to the growing bed and its return to the tank (Nicola, 2007). In order to have the nutrient solution return through gravitational flow from the growing bed into the tank, the sump must be below the growing bed. Since this is a recirculating system, the nutrient solution is re-used until evident signs of salt buildup occur at the bottom of the reservoir, a time in which the old solution is replaced with a freshly made up nutrient solution. Prior to each use, the nutrient solution should be tested for pH and EC and then adjusted according to crop requirements (Niederwieser and du Plooy, 2014; Li et al., 2018). The nutrient solution may also need filtering after each circulation through the growing bed. The frequency of flooding of the growing bed is dependent on the atmospheric demand and growth stage of the crop, as well as the water retention ability of the substrate (Jones, 1997). Another type of MGB system used widely in South Africa is the gravel film technique (GFT) (Figure 2), where a thin layer of nutrient solution flows down the beds continuously by gravitation (Maboko and du Plooy, 2012).

Figure 2: Gravel film technique in which leafy lettuce is being grown (picture taken by TS Chiloane on 06 April 2015, at ARC-VOP).

In the GFT system, the nutrient solution is pumped to the top of the hydrolines and flows down by gravity in a thin layer (1-3mm), creating a good balance between the required oxygen and water (Maboko and du Plooy, 2013b). The nutrient solution is collected at the bottom and pumped to the top again using a pressure pump. The areas prepared for gravel systems should be completely leveled across the slope before the hydrolines are laid out. Folding a plastic sheet over a securely tightened steel wire should strengthen the sides of the gullies. The plastic sheeting used depends on the availability and the market price. Normally, a plastic sheet thickness of 50 microns will be sufficient, but it is not very durable. Using a plastic sheet thickness of 100 microns or even thicker will strengthen the hydrolines and will not be punctured very easily (Maboko and du Plooy, 2012). The hydrolines should be at least 6cm deep for optimal growth of crops with a shallow root system such as lettuce. For crops like tomatoes that have a large root volume, a deeper gully is recommended (Niederwieser and du Plooy, 2014). Sand and gravel are the most commonly used growing media in these systems.

2.3.2 Nutrient Film Technique (NFT) systems

The nutrient film technique (NFT) was developed to overcome the shortcomings of the ebb-and-flow system, such as the difficulty to practice this system on a large-scale and inefficient use of water and nutrients. In this system, the nutrient solution recirculates throughout the entire system by gravitation and enters the growth tray via a water pump without the control by a timer (Domingues et al., 2012; Maboko et al., 2011). The system is slightly sloped so that the nutrient solution is recovered, filtered, replenished, and re-circulated into the system. Plants are placed in a channel or a tube with their roots suspended in a thin layer of nutrient solution.

There are many advantages of the NFT system, which include the fact that many leafy greens can easily be grown, and commercially the system is widely used for lettuce production. A portion of the plant roots is left in the air, while another portion lies on a moist surface (capillary matting), which provides an adequate supply of water, oxygen, and nutrients to the rooting system. The system provides for the ease of plant establishment and the cost of the construction materials is relatively low (Heinen, et al., 1991; Ikeda et al., 1995).

The polyethylene channels may be either white or black but must be dark enough to keep light out. If light enters the trough, algae growth becomes a challenge. As the root mat increases in size, the nutrient solution flow rate down the hydroline or channel diminishes. Since part of the roots is constantly immersed in water or nutrient solution, the roots may become susceptible to fungal infections. As the nutrient solution flows down the channel, plants at the upper end of the trough reduce the oxygen levels and/or the nutrient concentration in the nutrient solution, a reduction that can be enough to significantly affect the growth and development of plants at the lower end. In addition, as the root mat thickens and becomes denser, the flowing nutrient solution begins to flow over the top and down the outer side of the root mat, decreasing its contact within the root mass (Lennard and Leonard, 2006). The flow interruption results in poor mixing of the current flowing nutrient solution with water and nutrients left behind in the root mat from previous nutrient solution applications. One of the means of minimizing these effects is to make the trough of no longer than 20-25 m in length (Niederwieser and du Plooy, 2014). Furthermore, the channel can also be made wider, which can accommodate root growth for longer-term crops. If the trough is formed from strips of polyethylene film, it can be discarded after each crop, thus not only increasing the costs but also necessitating sterilization of the permanent piping and nutrient solution storage tank. Most troughs used today are made from different plastic materials that are dark enough, structurally strong, and ultraviolet (UV) resistant. The design of the trough (width, height, and form) is normally influenced by the type of crop to be planted. Lack of structural strength can lead to unevenness in the trough bottom that allows the nutrient solution to settle in depressions that can lead to anaerobic conditions (Jones, 2005).

The NFT systems can be designed for either horizontal or vertical cultivation. Figure 3 illustrates some of the simplest set-ups of the NFT system, using PVC pipework. The systems can be operated either under shade nets or plastic tunnels, depending on crop requirements. The horizontal set-up is suitable for both leafy and vine crop systems, while the vertical one is often most appropriate for leafy crops grown on a commercial scale. The vertical set-up also allows for more efficient utilization of space within the hydroponic structure. In general, both system set-ups require continuous recirculation of the nutrient solution, resulting in highly efficient water and nutrients usage (van Ginkel et al. 2017). The production cycle is also very efficient in these systems since the growing channels are permanently installed in the hydroponic structures, which allows more rapid planting following the previous cropping season, soon after cleaning and sanitation of the growing channels. However, the initial investment cost is relatively high, but it is a long-lasting investment, especially if the system is properly managed and maintained.

Figure 3: Nutrient film technique with horizontal cultivation of vine tomatoes (left, https://purehydroponics.com/commercial-systems accessed on 17/10/2020) and vertical cultivation of leafy lettuce (right, https://www.edengreen.com accessed on 17/10/2020).

3. Potential yield of commonly grown high-value vegetable and herb crops in recirculating hydroponic systems

Recirculating hydroponic systems have been used to grow a variety of crops, including leafy, fruity, dual-purpose vegetables and herbs. Lettuce is the most commonly grown leafy vegetable on these systems, and it is mainly produced under the horizontal and vertical NFT pipe systems, as well as the GFT system (Chiloane, 2012; Goddek and Vermeulen, 2018; Touliatos et al., 2016). Other crops that have also received attention from researchers in active recovery systems are sweet basil, tomato, and strawberry. Sweet basil herb crop is mainly produced under the NFT pipe system (Maboko and du Plooy, 2013d; Walters and Currey, 2019). While tomato has been mostly cultivated under the GFT system (Field, 2002; Maboko et al., 2011; Maboko and du Plooy, 2013; Maboko et al., 2017b). Strawberry is commonly cultivated in vertical NFT pipe and vertical bucket column systems (Peralbo et al., 2005; Ramírez-Gómez et al., 2012; Ramírez-Arias et al., 2018). Table 2 illustrates the potential yield of these crops grown in various recirculating hydroponic systems. The yield is highly variable depending on the type of system used for production, as well as the system and crop management practices that are employed, such as planting densities/spacing and type of cultivar/variety.

Table 2: Potential yield of commonly grown high-value vegetable and herb crops in recirculating hydroponic systems

Crop type	Recirculating hydroponic system	Crop yield (g/plant)	Reference
Loose leaf lettuce	Gravel film technique	163.4 – 235.2	Chiloane (2012)
Butterhead lettuce	Horizontal nutrient film technique	239.1 – 334.6	Goddek and Vermeulen (2018)
Romaine lettuce	Vertical nutrient film technique	95.0	Touliatos et al. (2016)
Sweet basil	Gravel film technique	86.8 – 87.0	Maboko and du Plooy (2013d)
Sweet basil	Horizontal nutrient film technique	15.0 – 50.6	Walters and Currey (2019)
Fresh market – indeterminate growth tomato	Gravel film technique	5700 - 7608	Maboko et al. (2011)
Cherry – indeterminate growth tomato	Horizontal nutrient film technique	2104	Field (2002)
Fresh market – indeterminate growth tomato	Horizontal nutrient film technique	2962 - 4834	Field (2002)
Strawberry	Horizontal nutrient film technique	379 - 505	Peralbo et al. (2005)
Strawberry	Vertical bucket columns	231	Ramírez-Arias et al. (2018)
Strawberry	Three-layer vertical nutrient film technique	202	Ramírez-Arias et al. (2018)
Strawberry	Five-layer vertical nutrient film technique	207	Ramírez-Arias et al. (2018)

4. Conclusion

Urban agriculture is growing across urban cities and may have a role in improving food security in South Africa. However, succeeding as an agricultural entrepreneur in urban and peri-urban areas demands more than being technically competent in production skills and but a firm understanding of the markets and marketing strategies. There are several risks associated with succeeding including financial, land, technical, social, and psychological that emerging urban farmers face. Compounding these challenges, farmers must operate in a water scare and a difficult policy space that often impedes success for new entrants.

Furthermore, water quality is very important when it comes to fresh produce as it can directly impact market access opportunities, food safety, and quality. More studies are required to investigate unlocking alternative sources of water to support urban agriculture, particularly wastewater. Fresh produce has the potential to introduce foodborne diseases into processing plants and/or be detrimental to human health and so this highlights the importance of small-scale farmers making use of good hygiene practices during pre and post-harvest during the production of fresh produce. Limited access to resources and appropriate knowledge can impede small-scale farmers and pose barriers for them when trying to access markets to sell their produce. Understanding the small-scale farmer's socio-economics may provide some insight into how they can be assisted when it comes to capacity building and providing them with insight and essential knowledge so that they can become self-sufficient in the production of fresh produce and ultimately, they can gain market access.

References

1. Advanced Nutrients (2020). Identifying deficiencies in your hydroponic nutrients. https://www.advancednutrients.com/articles/identifying-deficiencies-in-your-hydroponic-nutrients/
2. Al-Tawaha, A.R., Al-Karaki, G., Al-Tawaha, A.R., Sirajuddin, S.N., Makhadmeh, I., Wahab, P.E.M., Youssef, R.A., Sultan, W.A.L. and Massadeh, A. (2018). Effect of water flow rate on quantity and quality of lettuce (*Lactuca sativa* L.) in nutrient film technique (NFT) under hydroponics conditions. *Bulgarian Journal of Agricultural Science*, **24**: 793-800.
3. Amsing, J.J. and Runia, W.T.H. (1995). Disinfestation of nematode-infested recirculation water by ultra-violet radiation. *Mededelingen Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen Universiteit Gent*, **60**: 1087-1092.
4. Bar-Yosef, B. (2008). Fertigation management and crops response to solution recycling in semi-closed greenhouses. In: Michael Raviv and J. Heinrich Lieth, editors, Soilless Culture: Theory and Practice. San Diego: Academic Press, 2008 341-424.
5. Bugbee, B. (2004). Nutrient management in recirculating hydroponic culture. In: Proceedings of the South Pacific Soilless Culture Conference. M. Nichols, (ed.). *Acta Horticulturae*, **648**: 99-112.
6. Cardoso, F.B., Martinez, H.E.P., Henriques, Da Silva D.J., Milagres, C.C. and Barbosa, J.G. (2018). Yield and quality of tomato grown in a hydroponic system with different planting densities and number of bunches per plant. *Pesquisa Agropecoaria Tropical*, **48**: 340–349.
7. Chidiac, J.R. (2017). Shallow aggregate ebb-and-flow system for greenhouse lettuce production. A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Horticulture. University of Arkansas. https://www.researchgate.net/publication/322292857_Shallow_Aggregate_Ebb-and-Flow_System_for_Greenhouse_Lettuce_Production
8. Cho, W.J., Kim, H.J., Jung, D.H., Kang, C.I., Choi, G.L. and Son, J.E. (2017). An embedded system for automated hydroponic nutrient solution management. *American Society of Agricultural and Biological Engineers*, **60**: 1083-1096.
9. Daryadar, M.K., Mairapetyan, S.K., Tovmasyan, A.H., Aleksanyan, J.S., Tadevosyan, A.H., Kalachyan, L.M., Stepanyan, B.T., Galstyan, H.M. and Asatryan, A.Z. (2019). Productivity of leafy green vegetable Kale in soilless cultivation condition. *Journal of Agricultural Science and Food Research*, **7**: 49–52.
10. De Kreij, C., Voogt, W. and Baas, R. (1999). Nutrient solutions and water quality for soilless cultures. PBG, Naaldwijk, Holland, brochure 196.
11. De Miranda, F.R., Da Silva, V.B., Dos Santos, R.F.S., Rossetti, A.G. and Da Silva, F.B. (2014). Production of strawberry cultivars in closed hydroponic systems and coconut fibre substrate. *Revista Ciência Agronômica*, **45**: 833–841.
12. Djidonou, D. and Leskovar, D.I. (2019). Seasonal changes in growth, nitrogen nutrition, and yield of hydroponic lettuce. *HorTscience*, **54**: 76–85.
13. Domingues, J.P.T., Sampaio, P. and Arezes, P.M. (2012). New organizational issues and macroergonomics: Integrating management systems. *International Journal of Human Factors and Ergonomics*, **1**: 351–375.
14. Dunn, B. (2013). Hydroponics. Technical Report. Oklahoma Cooperative Extension Service, HLA-6442. Oklahoma State University. http://doi:researchgate.net/publication/280235408_Hydroponics
15. FAO (2007) Profitability and sustainability of urban and peri-urban agriculture. Agricultural Management, Marketing and Finance Occasional Paper 19. FAO, Rome.

16. FAO (2001) Urban and peri-urban agriculture on the policy agenda, Final Report conference, by A.W. Drescher, R. Nugent, H. de Zeeuw.
17. Heinen, M., de Jager, A. and Niers, H. (1991). Uptake of nutrients by lettuce on NFT with controlled composition of the nutrient solution. *Netherlands Journal of Agricultural Science*, **39**: 197-212.
18. Field, S. (2002). Yield responses of tomato (*Lycopersicon esculentum* Mill.) to fruit thinning and plant spacing. Thesis presented in partial fufillment of the requirements for the degree of Master of Applied Science at Massey University, New Zealand.
19. Fraile-Robayo, R.D., Álvarez-Herrera, J.G., Reyes, A.J., Álvarez-Herrera, O.F. and Fraile-Robayo, A.L. (2017). Evaluation of the growth and quality of lettuce (Lactuca sativa L.) in a closed recirculating hydroponic system. *Agronomia Colombiana*, **35**: 216-222.
20. Furtado, D.F., Cavalcante, G., Chaves, A.R., Santos Junior, L.H.G. and Gheyi, H.R. (2017). Growth and production of hydroponic pepper under salt stress and plant density. *American Journal of Plant Science*, **8**: 2255–2267.
21. Ikeda, H., Wada, T., Mirin, T., Okabe, K., Tazuke, A. and Furukawa, H. (1995). Year-round production of spinach by NFT and DFT in the greenhouse. *Acta Horticulturae*, **396**: 257-264.
22. Jones, J.B. (1997). The essential elements. In: Hydroponics - A practical guide for the soilless grower. St. Lucie Press, Boca Raton, FL.
23. Jones, J.B. (2005). Hydroponics: a practical guide for the soilless grower. CRC Press. Boca Raton. Fla.
24. Kumar, P. and Simran, S. (2020). Nutrients for Hydroponic Systems. in: Akhtar SS, Maldonado AIL, Rodriguez-Fuentes H, Juan Antonio Vidales Contreras JAV and Reyes JMM (ed.) Urban horticulture necessity of the future. IntechOpen, Cambridge.
25. Lee, S., An, R., Grewal, P., Yu, Z., Borherova, Z. and Lee, J. (2016). High-performing window farm hydroponic system: transcriptomes of fresh produce and microbial communities in response to beneficial bacterial treatment. *Molecular Plant Microbe Interactions,* **29**: 969–976.
26. Lennard, W.A. and Leonard, B.V. (2006). A comparison of three hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an aquaponics test system. *Aquaculture International*, **14**: 539–550.
27. Lester, D. (2014). Using iron in soil, hydroponics & aquaponics. Grower Magazine 101. https://gpnmag.com/wp-content/uploads/08_Iron-Hydroponics_GPN0314%20FINAL.pdf
28. Li, Q., Li, X., Tang, B. and Gu, M. (2018). Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate Culture. *Horticulturae*, **35**: 1-9.
29. Maboko, M.M., du Plooy, C.P. and Chiloane, S. (2017). Yield of determinate tomato cultivars grown in a closed hydroponic system as affected by plant spacing. *Horticultura Brasileira*, **35**: 258–264.
30. Maboko, M.M. and du Plooy, C.P. (2008). Effect of pruning on yield and quality of hydroponically grown cherry tomato (*Lycopersicon esculentum*). *South African Journal of Plant and Soil*, **25**:178–181.
31. Maboko, M.M. and du Plooy, C.P. (2009). Effect of plant spacing on growth and yield of lettuce (*Lactuca sativa* L.) in a soilless production system. *South African Journal of Plant and Soil*, **26**: 195–198.
32. Maboko, M.M., du Plooy, C.P. and Bertling, I. (2011). Comparative performance of tomato cultivars cultivated in two hydroponic production systems. *South African Journal of Plant and Soil*, **28**: 97-102.
33. Maboko, M.M. and du Plooy, C.P. (2012). Effect of plant density and harvesting method on yield components of hydroponically grown amaranth. *Acta Horticulturae*, **947**: 415-421.
34. Maboko, M.M., du Plooy, C.P. and Chiloane, S. (2012). Effect of plant population, stem and flower pruning on hydroponically grown sweet pepper in a shadenet structure. *African Journal of Agricultural Research,* **7**: 1742-1748.
35. Maboko, M.M. and du Plooy, C.P. (2013a). High density planting of tomato cultivar's with early decapitation of growing point increased yield in a closed hydroponic system. *Acta Agriculturae Scandinavica,* **63**: 676-682.

36. Maboko, M.M. and du Plooy, C.P. (2013b). Effect of plant spacing and harvesting frequency on the yield of Swiss chard cultivars (*Beta vulgaris* L.) in a closed hydroponic system. *African Journal of Agricultural Research*, **8**: 936-942.
37. Maboko, M.M. and du Plooy, C.P. (2013c). Effect of plant spacing on growth and yield of lettuce (*Lactuca sativa* L.) in a soilless production system. *South African Journal of Plant and Soil*, **26**: 195-198.
38. Maboko, M.M. and du Plooy, C.P. (2013d). High-plant density planting of basil (*Ocimum basilium*) during summer/fall growth season improves yield in a closed hydroponic system. *Acta Agriculturae Scandinavica*, **63**: 748-752.
39. Maboko, M.M., Bertling, I. and du Plooy, C.P. (2013) Effect of Arbuscular Mycorrhiza and temperature control on plant growth, yield, and mineral content of tomato plants grown hydroponically. *HortScience*, **48**: 1470-1477.
40. Maboko, M.M., du Plooy, C.P. and Chiloane, S. (2017a). Yield and mineral content of hydroponically grown mini cucumber (*Cucumis sativus* L.) as affected by reduced nutrient concentration and foliar fertilizer application. *HortScienc*e, **52**: 1728–1733.
41. Maboko, M.M., du Plooy, C.P. and Chiloane, S. (2017). Yield of determinate tomato cultivars grown in a closed hydroponic system as affected by plant spacing. *Horticultura Brasileira*, **35**: 258-264.
42. Mampholo, B.M., Maboko, M.M., Soundy, P. and Sivakumar, D. (2018) Variety-specific responses of lettuce grown in a gravel-film technique closed hydroponic system to N supply on yield, morphology, phytochemicals, mineral content and safety. *Journal of Integrative Agriculture*, **17**: 2447–2457.
43. Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P. and Borin, M. (2018). Hydroponic systems and water management in aquaponics: a review. *Italian Journal of Agronomy*, **13**: 1-11.
44. Morifi, R., Maponya, P.I., van Niekerk, J.A. (2018). The sustainability in training hydroponic production to smallholder farmers in the Tshwane area, Gauteng Province, South Africa. *Journal of Agricultural Sciences*, **9**: 11-19.
45. Nicola, S. (2007). Ebb-and-flow and floating systems to grow leafy vegetables: a review for rocket, corn salad, garden cress and purslane. *Acta Horticulturae*, **747**: 585-593.
46. Niederwieser, J.G. and du Plooy, C.P. (2014) Guide to hydroponic vegetable production in South Africa. Agricultural Research Council, Roodeplaat, Vegetable and Ornamental Plant Institute, Pretoria, South Africa.
47. Nguyen, N.T., McInturf, S.A., Mendoza-Cózatl, D.G. (2016). Hydroponics: A versatile system to study nutrient allocation and plant responses to nutrient availability and exposure to toxic elements. *Journal of Visualized Experiments*, **113**: 54317.
48. Okemwa, E. (2015). Effectiveness of aquaponic and hydroponic gardening to traditional gardening. *International Journal of Scientific Research and Innovative Technology*, **2**: 2313 - 3759.
49. Pedrosa, A.W., Martinez, H.E.P., Matiello, E.M., Fontes, P.C.R. and Pereira, P.R.G. (2011). Influence of the N/K ratio on the production and quality of cucumber in hydroponic system. *Revista Ceres*, **58**: 619–624.
50. Peralbo, A., Flores, F. and López-Medina, J. (2005). recirculating nutrient solution in strawberry. *Acta Horticulturae*, **697**: 101-106.
51. Putra, P.A. and Yuliando, H. (2015). Soilless culture system to support water use efficiency and product quality: A Review. *Agriculture and Agricultural Science Procedia*, **3**: 283–288.
52. Ramírez-Gómez, H., Sandoval-Villa, M., Carrillo-Salazar, A. and Muratalla-Lúa, A. (2012). Somparison of hydroponic systems in the strawberry production. In: F.C. Gómez-Merino et al. (Eds.) Proc. II IS on Soilless Culture and Hydroponics. *Acta Horticulturae*, **947**.

53. Ramírez-arias, J.A., Hernández-Ibarra, U., Pineda-Pineda, J. and Fitz-Rodríguez, E. (2018). Horizontal and vertical hydroponic systems for strawberry production at high densities. *Acta Horticulturae,* **1227**: 331–338.
54. Rorabaugh, P.A., Jensen, M.H., Giacomelli, G. (2002). Introduction to controlled environment agriculture and hydroponics. Controlled Environment Agriculture Center Campus Agriculture Center, University of Arizona.
55. Saparamadu, J.S., Wijesekera, R.D., Gunawardhana, H.D. and Weerakkody, W.A. (2010). A low cost nutrient formulation with a buffer for simplified hydroponics systems. *Journal of Horticulture and Forestry*, **2**: 99–103.
56. Sambo P. , Nicoletto C. , Giro A. , Pii Y., Valentinuzzi F., Mimmo T., Lugli, P., Orzes G. , Mazzetto F., Astolfi, S., Terzano R. and Cesco S. , 2019. Hydroponic Solutions for Soilless Production Systems: Issues and Opportunities in a Smart Agriculture Perspective. *Frontiers in Plant Science*, **10**: 1-17.
57. Sharma N., Acharya S., Kumar K., Singh N. and Chaurasia O.P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. *Journal of Soil and Water Conservation*, **17**: 364-371.
58. Schwarz, D., Grosch, R. and Gross, W. (2004). Water quality for hydroponics: nutrients, bacteria and algae in rainwater ponds. *Acta Horticulturae*, **644**: 533-539.
59. Schnitzler, W.H. (2004). Pest and disease management of soilless culture. *Acta Horticulturae*, **648**: 1-15.
60. Schröder, F. and Lieth, J.H. (2002). Chapter 11: Irrigation control in hydroponics. http://141.56.36.15/fileadmin/user_upload/fis/CH-11-SCHROEDER-FINAL2.pdf
61. Van Ginkel, S.W., Igou, T. and Chen, Y. (2017). Energy, water and nutrient impacts of California-grown vegetables compared to controlled environmental agriculture systems in Atlanta, GA. *Resources, Conservation and Recycling*, **122**: 319–325.
62. Yang, T. and Hye-Ji, K. (2020). Characterizing nutrient composition and concentration in tomato-, basil-, and lettuce-based aquaponic and hydroponic systems. **Water**, **12**: 1259.
63. Walters, K.J. and Currey, C.J. (2019). Hydroponic greenhouse basil production: comparing systems and cultivars. *HortTechnology*, **25**: 645–65.