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The unique Namib desert-coastal region and its opportunities for climate smart agriculture: A review

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Abstract: Namibia is the driest country in sub-Saharan Africa, with surface water being only available for very limited periods during the year. This has seen the country importing up to 70% of its food requirements which exacerbates the food security challenge in the face of climate change. This review looks at the Namib Desert, and how its unique environment can be exploited for agricultural production. The cool but sunny desert makes it possible to produce crops under controlled environments with limited evapotranspiration. However, the high cost of inorganic hydroponic fertilizers makes adoption of hydroponics by smallholder subsistence farmers a great challenge thus the potential of hydroponics fertilized by organic nutrient sources like vermicomposts is discussed; highlighting research gaps. This review also highlights the potential of utilizing fog water for irrigation, a resource that is abundant in the Namib Desert, which can be crucial in desert greening. Though mushroom production is an established technology, the potential of using seaweeds from the highly productive Atlantic Ocean as mushroom substrate

Hupenyu Allan Mupambwa

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Hupenyu Allan Mupambwa works as a researcher at the Sam Nujoma Marine and Coastal Resources Research Centre of the University of Namibia. He is a research agronomist who holds a BSc and MSc in Agronomy and a Ph.D in Soil Science from the University of Fort Hare in South Africa. His areas of interest are in waste beneficiation, vermicomposting, bio-saline agriculture and organic soil fertility improvement. His Ph. D. research focused on optimizing the vermi-degradation of fly ash (a product of coal combustion) to allow for the generation of nutrient high organic soil fertility conditioners. To date, Hupenyu has authored or co-authored 15 peer reviewed manuscripts. He has also taught courses in Soil Science, supervised several undergraduate students and MSc students. Currently, he is involved in research on desert and coastal agriculture with emphasis on the unique Namib Desert.

PUBLIC INTEREST STATEMENT

The Unique Namib Desert-coastal Region and its Opportunities for Climate Smart Agriculture: A Review

Namibia is the most arid country in Southern Africa. Having limited water available for crop-based agriculture, the country imports a greater part of its food. However, the country has a unique coastal desert environment, with cool temperatures, bright sunshine and abundant fog, all of which can be used to drive climate smart agriculture in this Namib Desert. Much of the research done in this desert has focused on animal and plant ecology studies. However, our paper highlights the potential of technologies like hydroponics, fog water harvesting, mushroom production, composting using earthworms, use of renewable energy and use of sea-based resources in driving sustainable crop production in the Namib Desert. Though some of these technologies have been practised elsewhere, our paper highlights research gaps that can improve the adaptability of these technologies in the Namibian context. This paper will set the research agenda on desert agriculture for Namibia.

amendments and their potential in improving the nutrient value of mushrooms is also explored. This review highlights that agriculture is possible in this hyper-arid desert, with research being critical in driving its success.

Subjects: Agriculture & Environmental Sciences; Plant & Animal Ecology; Soil Sciences

Keywords: Namib Desert; organic hydroponics; aquaponics; fog harvesting; sea-water greenhouse

1. Introduction

Namibia is the driest country in sub-Saharan Africa, with surface water only available for very limited periods of the year (Wanke et al., 2014). In Namibia, rainfall is subject to wide within and between-year variations, with the highest coefficient of variation in Southern Africa (Eckardt et al., 2013). Apart from the wide variability in rainfall events across the country, rainfall events are also highly localized, with very low intensities (Aboutalebi, Jahromi, & Farahi, 2013). On average, Namibia receives 270 mm of rainfall annually, with the western coastal regions receiving around 20 mm of rainfall, whilst the eastern regions receive more than 700 mm, though only 5% of the country receives more than 500 mm per year (Sweet & Burke, 2006). Coupled to the aridity of the Namibian environment is the existence of two deserts, the Namib Desert and the Kalahari Desert, this review focuses on the Namib Desert. Though being hyper-arid, the Namib Desert, which is a coastal desert, has been the centre of research due to its unique flora, fauna and climate.

In Namibia, only 1% of the total land surface falls in the medium to high potential categories for rain-fed and irrigated crop production, which is dominant within the communal subsistence farmers (Sweet & Burke, 2006). Consequently, to feed its population, Namibia relies mainly on food imports from its neighbouring countries such as Zambia, South Africa and Angola. However, agriculture plays a critical role in the formal and informal economy of Namibia, supporting up to 70% of the population, with 90% of this being livestock-based (MAWF, 2015). This is in spite of the limited availability of arable land in Namibia. Crop production activities are very limited to rain-fed crops such as pearl millet (*Pennisetum glaucum*); sorghum (*Sorghum bicolor*) and maize (*Zea mays*). According to the Ministry of Agriculture, Water and Forestry of Namibia, the sole dependence on rain-fed agriculture significantly increases the vulnerability of farming systems especially rural households to food insecurity. Considering the current population growth within the country, Namibia needs to expand its agricultural productivity by about 4% a year to be able to meet the food requirements of this increasing population. This, therefore, highlights the need for extensive research into climate smart technologies that can allow the exploitation of Namibia's unique climatic environments and resources to enhance food production, in the arid country.

The Namib Desert is one of the unique environments in Southern Africa, where the desert runs along the Atlantic Ocean where the Benguela upwelling system sustains very high ocean primary production due to the upwelling of nutrient-rich waters forced by trade winds (Ohde & Dadou, 2018). This cold Benguela current which runs along the South West African coast is mainly responsible for the arid environment experienced in the Namib Desert as it suppresses rainfall over the desert (Norgaard & Dacke, 2010). To exploit this unique characteristic, the University of Namibia hosts the Sam Nujoma Marine and Coastal Resources Research Centre (SANUMARC), with part of its research focusing on exploring the Namib Desert and the Atlantic Ocean and become a centre of excellence in science and technology research in marine and coastal resources, thus contributing to national and global efforts to promote food security and poverty eradication (http://www.unam.edu.na/sanumarc). Apart from undertaking marine-focused research, SANUMARC is driving towards agricultural research that can identify and develop workable, climate smart technologies within the Namib Desert coastal region. This research seeks to take advantage of the unique climatic conditions, availability of seawater and the huge biomass generated from the primary producers within the Benguela powered the Atlantic Ocean. Though several researchers have focused on the Namib Desert, much of the work has been on desert geomorphology and ecology, with very limited research on the agricultural potential of this environment (Henschel & Lancaster, 2013). This review thus seeks to address the following questions concerning the Namib Desert coastal area:

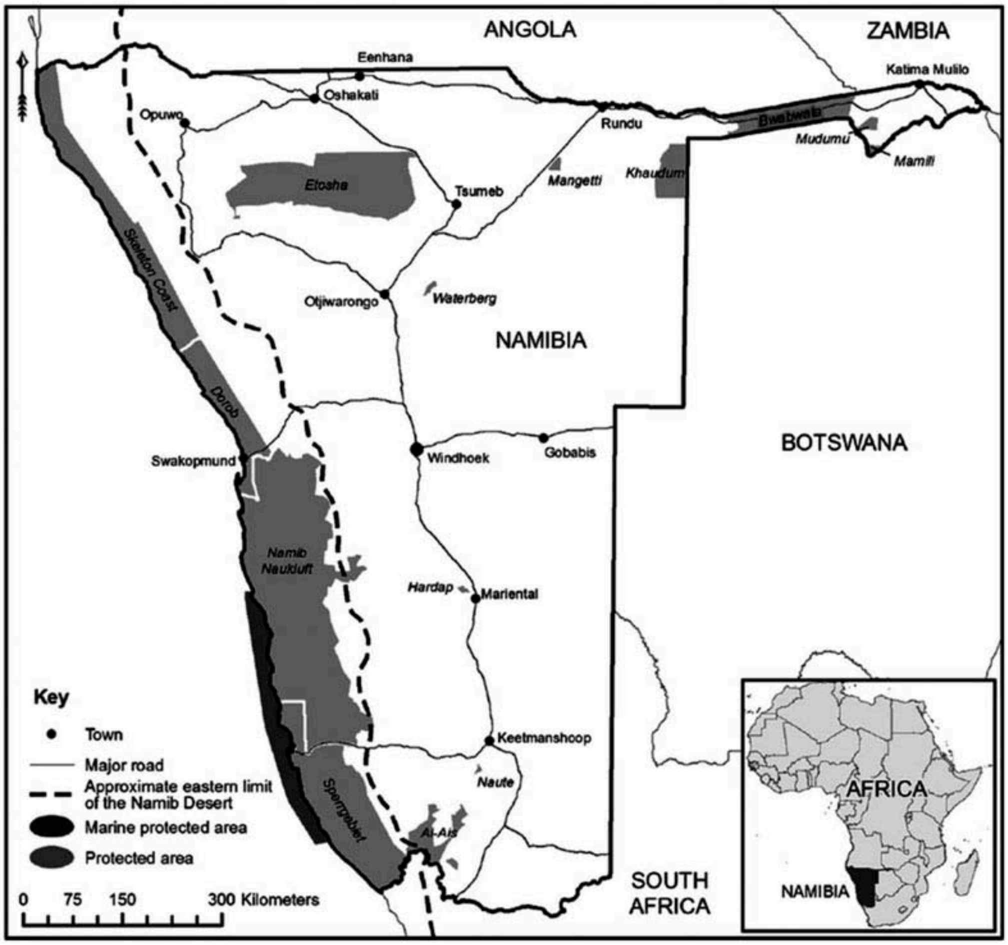
(1) What possibilities exist for climate smart agricultural technologies that can drive crop-based agriculture in this Namib-coastal desert area?

(2) What direction should future research on crop-based agriculture which can drive arid Namibia's food self-sufficiency in the Namib Desert take?

2. Climate and soil environments of the Namib Desert-coastal areas

The Namib Desert spans across three countries starting in South Africa, majoring in Namibia and ending in Angola, ranging from 50 to 150 km from the Atlantic coast inland, covering an approximate area of 130 000 km^2 as indicated in Figure 1 (Henschel & Lancaster, 2013). The hyper-arid to arid desert extends over 2000 km along with the west parts of Southern Africa between 14° S and 32° S, bounded inland by the Great Escarpment lying 120–200 km from the coast (Lancaster, 2002; Stone & Thomas, 2013). The Namib Desert is considered as one of the oldest deserts in the world, with current hyper-arid conditions estimated to date back 5 million years (5 Ma) ago with geological evidence suggesting that the onset of aridity may have occurred some 65 Ma ago (Geyh & Heine, 2014; Lancaster, 2002; Wassenaar et al., 2013). The aridity within the Namib Desert is understood to be caused by a combination of cool air masses under the influence of the cold Benguela Current together with high-pressure conditions in the subtropics (Geyh & Heine, 2014). In

Figure 1. Map of Namibia showing the vast Namib Desert and its approximate eastern border in dotted line, and some of the protected areas within the desert. Source; Wassenaar et al. (2013).



comparison with many other deserts in the world characterised by extremely high temperatures, moderately lower temperatures occur in this coastal desert mainly due to the influence of the cold Benguela Current, making the Namib Desert unique. This is in spite of a steep increase in temperature towards the Great Escarpment (Lancaster, 2002).

In the Namib Desert, annual rainfall ranges from approximately 15 mm on the coast to 80–100 mm near the great escarpment, where the desert ends and being the most arid part of Namibia, it is common to experience successive years of absolutely no rainfall. For instance, Swakopmund, a coastal town in the desert experienced a period of 10 years without any precipitation (Shanyengana, Henschel, Seely, & Sanderson, 2002). However, rainfall is not an important source of water in the Namib Desert; instead, advective fogs emanating from the cooling of moist oceanic air due to the Benguela Current are a critical feature of the Namib climate and ecology (Aboutalebi et al., 2013; Lancaster, 2002). It is interesting to note that this fog belt can extend over 100 km inland, with the annual fog occurrence being more predictable than rainfall, displaying a coefficient of variation of approximately 41% compared to 133% for rainfall (Lancaster, 2002; Shanyengana et al., 2002). The quantity of the fog precipitation increases from the coast where it averages 34 mm/year, reaching a maximum of 184 mm/year 35–60 km inland and then decreases sharply beyond 60–15 mm or less (Aboutalebi et al., 2013; Lancaster, 2002). Being an important source of water in the desert, fog occurrence has been widely researched in Namibia from mostly an ecological perspective (Ebner, Miranda, & Roth-Nebelsick, 2011; Henschel & Lancaster, 2013; Lancaster, 2002). However, apart from having several ecological implications, fog water can be an important source of water that can be used in crop production, an area that has been rarely researched in the Namib Desert environment. Though research has shown that the quality and quantity of fog within the coastal areas of Namibia is high enough to justify a fog collection project, there is no such large-scale project that has been implemented in Namibia (Klemm et al., 2012; Shanyengana et al., 2002). Future research needs to evaluate the potential of fog harvesting technologies under different water and soil management systems on crop, fruit and ornamental tree production, to evaluate the long-term sustainability of such technologies.

Apart from the potentially available water that can be harnessed from the coastal areas, the Namib also has temperatures which are atypical of desert environments. The mean annual daily maximum temperature is a cool 17°C along the coastal areas of the desert, whilst the minimum daily temperature averages between 13°C and 16°C (Lancaster, 2002). One of the major limitations to implementing agricultural activities in deserts is the high temperatures, which cause significantly high evaporative water losses, making crop water requirements very high. However, in the Namib Desert coastal areas, the lower temperatures significantly reduce the evapotranspiration losses of water an important characteristic of this area. Technologies that precisely apply water within the rooting zone, such as drip irrigation whilst minimizing evaporation through mulching, could be critical to research on, as these can be essential in managing harvested freshwater in dry coastal areas such as the Namib coastal areas.

Though various soilless technologies such as hydroponics and aquaponics are being widely promoted for crop production in desert environments as highlighted by Goddek et al. (2016) and Grewal et al. (2011); it is also important to understand the prevailing soil characteristics and how they influence agricultural activities. However, little information is known about the chemistry of the Namib soils despite its importance as a rich nutrient resource base (Abrams et al., 1997). Several researchers have instead looked at the Namib Desert soil characteristics and how they relate to ecological diversity (Johnson, Ramond, Gunnigle, Seely, & Cowan, 2017; Ronca, Ramond, Jones, Seely, & Cowan, 2015), and not in terms of their effect on agricultural potential. In these studies, soils of the Namib Desert have been observed to have very low organic carbon contents as well as low macronutrient concentrations, which are critical in crop production (Abrams et al., 1997; Johnson et al., 2017). The low organic carbon results in poorly structured soils, whilst the lack of water within the desert has resulted in soils with very low clay contents, which also contributes to the poor soil texture of most of the soils. Research on the possibility of using local coastal resources like seaweeds and seashells can be used as amendments for improving the overall soil quality of these coastal soils should, therefore, be prioritised (Ok, Lim, & Moon, 2011; Roberts, Paul, Dworjanyn, Bird, & de Nys, 2015).

3. Climate smart agriculture (CSA) in the desert

In order for Namibian agriculture to meet the food requirements of it increasing population, there is a need to adopt agricultural practices that increase the ability to withstand challenges posed by climate change and variability, thus ensuring food and livelihood security (Notenbaert, Pfeifer, Silvestri, & Herrero, 2017; MET-MAWF, 2015). Such adaptation options that can sustainably increase productivity, enhance resilience to climate change whilst reducing greenhouse gas emissions are known as climate smart agricultural technologies (CSA) (Khatri-Chhetri, Aggarwal, Joshi, & Vyas, 2017; Sain et al., 2017). Generally, CSA options integrate traditional and innovative practices, technology and services that are relevant to a particular location. This should be the guiding principle in undertaking research that addresses CSA in the Namib Desert context. Such technologies should be able to address the issue of the already scarce freshwater within this region, whilst taking advantage of the other resources available in this environment. In Namibia, the Ministry of Environment and Tourism through its Environment Investment Fund is promoting climate smart agriculture technologies with great potential in improving agricultural productivity in the country (UNICEF, 2018). Technologies such as hydroponics, aquaponics, improvement of crop production under saline conditions, introduction of alternate food crops like mushrooms, domestication of desert plant species and use of renewable energy in agriculture, which have been promoted as effective in desert agricultural systems are discussed in this review paper (Goddek et al. 2016; Mbaga, 2014). The review paper also identifies research gaps, which need to be addressed from a Namibian perspective, taking into consideration its hyper-arid environment and its proximity to the Benguela driven section of the Atlantic Ocean.

4. Soilless crop production under desert conditions (hydroponics and aquaponics)

As outlined in the previous section, the poor soil quality and water scarcity in the Namib makes it a difficult place to promote agricultural activities. Nevertheless, the very limited evaporative demands experienced in this coastal desert together with its proximity to the Atlantic Ocean generate interest in how these can be exploited for enhanced agricultural output. This interest is also driven by success stories recorded in other desert-like areas of the world such as Oman (Al-Ismaili & Jayasuriya, 2016); Israel (Appelbaum, 2011; Bruins, 2012); Egypt; China and USA (Crespi & Lovatelli, 2011). Technologies that can promote the minimal use of the scarce freshwater under desert conditions such as use of soilless cropping systems exploiting hydroponics have been critical among others like deficit irrigation, in driving agricultural productivity in such arid environments (Mbaga, 2014; Mohareb et al., 2017; Mowa, Akundabweni, Chimwamurombe, Oku, & Mupambwa, 2017). Another new technology that is receiving attention as a panacea to food insecurity is the combination of aquaculture and hydroponic systems called aquaponics. Aquaponics can be critical in enhancing both crop and fish productivity whilst reducing the overall water footprint of food production in arid environments existing in Namibia.

According to the Namibian Agronomic Board (http://www.nab.com.na) in 2015–16 financial year, Namibia consumed a total of 73 438 tons of horticultural products of which 67.9% of this were imports. What is worrisome is that this trend has actually been increasing from 2011 as shown in Figure 2, pointing to the need for a radical shift in policy, if Namibia is to be food self-sufficient in the face of a growing population and increased climate variability. If this situation does not change, the challenge of food insecurity and high food cost is likely to continue increasing mostly among subsistent farmers and rural communities of Namibia.

The University of Namibia has been driving research that can form a critical stepping stone towards enhancing food production and food self-sufficiency at household level through the use of hydroponics (Mowa, 2015; Mowa et al., 2017). Although hydroponics have been very successful at commercial level in developed countries such as The Netherlands; Belgium, USA, Latin America;

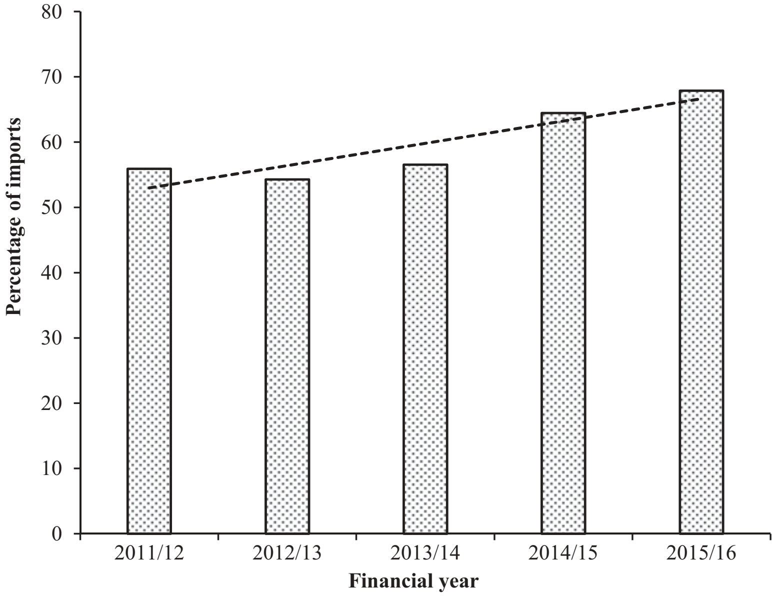


Figure 2. Changes in percentage of horticultural food imports showing a positive increasing trend within Namibia between 2011 and 2015. (Source, Namibian Agronomic Board; http://www.nab.com.na/controlled-crops/horticulture/market-statistics.php).

Germany, Italy, Russia; Australia; among others (Sardare & Admane, 2013; Orsini, Fecondini, Mezzetti, Michelon, & Gianquinto, 2010; Grewal et al., 2011); this has generally not been the case in developing arid countries like Namibia. In hydroponic systems, the source of nutrients is mainly chemical inorganic fertilizers, which are usually very expensive and beyond the reach of resource-poor farmers in developing countries (Aboutalebi et al., 2013; Mowa, 2015). Research focussing on generating optimized organic nutrient sources utilizing abundant animal (goat, cow and donkey) manures that can be effectively used in hydroponics can be crucial in enhancing adoption of hydroponics even amongst the resource-poor farmers in Namibia. Research on organic nutrient sources in hydroponics is currently very limited. Table 1 summarises some of the research that done so far.

As highlighted in Table 1, though several researchers have attempted to make use of different organic nutrient sources in hydroponics, there is still a paucity of information on the development of an optimized organic nutrient formula. Despite being a great challenge, a holistic approach that considers the following (i) the nutritional composition of the organic materials used, (ii) optimization and standardization of organic nutrient solution method of preparation (iii) development of effective models; can allow researchers to predict final nutrient composition of organic nutrient solutions, as proposed by Son and Okuya (1991). Research that optimizes organic hydroponic solution preparation and utilization is required to allow for the adoption of these cheaper nutrient solutions.

In generating organic nutrient sources, one technology that is gaining momentum due to its ability to enhance nutrient mineralization, creating a nutrient-rich final product is vermicomposting (Bhat, Singh, & Vig, 2017; Garcia-Sanchez, Tausnerova, Hanc, & Tlustos, 2017). During vermicomposting research, most researchers have focused on the nutrient composition of the solid vermicompost itself (Malinska et al., 2017; Mupambwa, Ravindran, & Mnkeni, 2016), with limited interest in the vermi-leachate. During vermicomposting, excess water which, is called vermi-leachate or vermi-wash can be collected. Unlike nutrient solutions produced directly from organic substances such as biogas digestates, vermi-leachates have great potential as effective nutrient sources in soilless crop production, due to their superior quality. These vermi-leachates are superior as they contain significant concentrations of macro and micronutrients, several enzymes, plant growth hormones and can also increase plant disease resistance (Quaik, Embrandiri, Rupani, & Ibrahim, 2012; Verma, Singh, Pradhan, Singh, & Singh, 2017). However, very limited studies have been carried out to evaluate the potential organic nutrient value of vermi-leachates particularly in

Table 1. Summary of research done evaluating the potential of organic nutrient sources in hydroponic vegetable production

Organic nutrient sources	Method of organic nutrient solution preparation	Nutrient content of solution	Observations and research gaps	Reference
Chicken manure, goat manure, cow manure, goat manure compost, and conventional hydroponic fertilizer	A 58.8 g of manure was immersed in 1 L of water whilst enclosed in a filter bag and left to brew for 7 days. The goat manure compost was prepared by thermophilic composting for 6 months, after which the compost was treated as in above.	Not determined.	The control with conventional hydroponic fertilizer yielded the highest results across all parameters measured. However, it was observed that composted goat manure yielded the highest among all other organic nutrient sources. This study points to the need for optimized mineralization of organic nutrient sources before they can be used in preparation of hydroponic nutrient solutions.	Mowa, 2015
Biogas digestate from a biogas digester treating food and vegetable waste; whilst a control of commercial hydroponic solution was also included.	Concentrated biogas digestate was diluted with de-ionized water to achieve a dilution factor of 5; 10; 15; 20; 30 and 50.	The diluted biogas digestate contained the following nutrient concentrations (mg/L): NH_4- 475; NO_3–68.2; Total P—28.1; Total K—558; Total Ca—171; Total Mg—256; Total Na—319.	The results clearly showed that growth of silverbeet was significantly higher in the control compared to all other treatments. Within the organic nutrient sources, the treatment with a dilution of 20 resulted in the highest growth and yield parameters, higher than even the 50% treatment. At 20% dilution, the nitrate and P levels were 87.8% and 92.7% lower than the control treatment, respectively. The fast depletion of nutrients within the organic nutrient sources points to a need to investigate influence of frequency of nutrient change on growth and yield.	Krishnasamy, Nair, & Bauml, 2012

(*Continued*)

Table 1. (*Continued*)

Organic nutrient sources	Method of organic nutrient solution preparation	Nutrient content of solution	Observations and research gaps	Reference
Fish waste, a by-product of the production of dried bonito fish flakes, with a conventional hydroponic fertilizer being a control treatment. Oyster shell lime was also used to supplement minor nutrients in all treatments.	The fish waste was added at a rate of 300g per 200L of water and inoculated with bark compost as a microbial inoculant for nutrient mineralization. The mixture was then aerated for 50 days before use.	The solution contained 123 mg/L of nitrates with no ammonium. The added oyster shells provided 11.9 mmol Mg, 9.67 mmol Fe, 2.17 mmol B; 1.53 mmol Mn; 0.077 mmol Zn; 0.0113 mmol Cu; 0.005 mmol Mo; and 62.7 mmol Ca.	The tomato fruit yield, Brix value and ascorbic acid content did not differ significantly between the organic and inorganic nutrient sources. Interestingly, for lettuce, the organic fertilizer gave a significantly higher yield and root weight compared to the conventional hydroponic fertilizer. This study shows that using a high N organic material like fish waste, can be critical in developing a workable organic hydroponic nutrient solution.	Shinohara et al. 2011
Biogas slurry from an unnamed organic source.	The biogas slurry was diluted with water 5.22 times with water, then supplemented with different P and Fe combinations to achieve 7 different treatments.	The biogas slurry contained the following nutrients: N- 0.73g/L; P—0.028g/L; K—0.74g/L; NH4–0.7g/L; NO3–8.62mg/L; Mg—227 mg/L.	The biogas slurry alone, showed a significantly lower lettuce shoot biomass compared to other treatments that had been supplemented with P and Fe. Unlike supplementing the nutrient solution with Fe or P singly, the combination of Fe and P supplementation significantly increased all parameters measured in this study. However, this study did not indicate why the slurry was diluted 5.22 times originally, which could have not been the optimum dilution level.	Liu et al. 2011

(*Continued*)

Table 1. (*Continued*)

Organic nutrient sources	Method of organic nutrient solution preparation	Nutrient content of solution	Observations and research gaps	Reference
Seaweed extracts that were prepared from two species (*Ulva rigida* and *Fucus spiralis*) collected in Morocco. A control of Hoagland's solution was also used.	Fresh seaweed was harvested, cleaned with tap water and shredded into smaller pieces. 1kg of each sea weed was then separately grounded then boiled with 1 liter of water for an hour, then filtered to remove solids. The filtrates were then diluted using water to make 25% extract of *Fucus spiralis* and 25% of *Ulva rigida*. These solutions were further mixed at different levels with or without Hoagland's solution to achieve the treatments in this study.	Extracts from *Ulva rigida* had the following elemental composition: Na (ppm)—42.4; Ca (ppm)—91.9; K (ppm)—55.8 and Total Nitrogen (%)—1.28. Extracts from *Fucus spiralis* had the following elemental composition: Na (ppm)—72.5; Ca (ppm)—51.2; K (ppm)—142.9 and Total Nitrogen (%)—0.56.	When beans was grown in a commercial hydroponic solution and foliar applied with the 2 seaweed extracts, the chlorophyll content was significantly higher than the unsprayed control. On leaf protein content, the control behaved similar to the 100 seaweed extracts when it was used a hydroponic solution. It was interesting to observe that the 2 seaweeds showed significantly different results on leaf protein content with 25% Hoagland's solution and 75% of *Fucus spiralis* being optimum, whilst 50% of Hoagland's solution and 50% *Ulva rigida* was optimum.	Latique et al. 2013

hydroponics (Quaik et al., 2012). Furthermore, the nutrient quality of vermi-leachates is highly dependent on factors such as chemical composition of original organic materials, vermicomposting process and moisture content of the vermicompost. Integrated research that involves optimization of the vermicomposting process, identifying optimum organic materials and vermicompost leaching frequency can allow for the development of commercially effective vermi-leachates as liquid fertilizers (Quaik & Ibrahim, 2013). Research in this direction will be crucial in driving the adoption of cheap nutrient sources for hydroponics among resource-poor in developing countries like Namibia. Another aspect with limited research is the possibility of using seaweed biochar to amend vermicomposts, which has the potential of improving or enhancing the nutrient value of vermicomposts and vermi-leachates. Most of the research on biochar has however focused on using terrestrial ligno-cellulosic materials which yield biochar with high C content but a low nutritive value (Roberts et al., 2015). It has been demonstrated recently that biochar derived from marine sources like seaweeds can yield material that has high essential nutrient value and low C content (Roberts et al., 2015), which is an important attribute in agriculture whose potential needs to be fully evaluated.

Most of the technologies discussed above have focused on generating cheap nutrient sources as a stepping stone in stimulating localised crop production at household level in Namibia and other developing countries. Another technology that is being promoted among commercial farmers in developed countries, with the potential to reduce freshwater footprint in food production is aquaponics. Aquaponics is an integration of aquaculture (fish production) with soilless crop production, which allows the nutrient-rich wastewater from fish production to be used as a hydroponic nutrient source, within a recirculating system (Buzby & Lin, 2014; Hu et al., 2015). Technologies like aquaponics that can make minimum use of the available arable space and the scarce water resources through the integration of fish production with soilless crop production are being promoted in hyper-arid environments as they result in higher food production with a limited water footprint (Goddek et al. 2016; Goddek & Keesman, 2017). In aquaculture systems, the highest cost emanates from the fish feed, with only 25% of the applied protein being converted to fish biomass leaving about 70% being excreted as nitrogenous compounds in the surrounding water (Endut, Ali, Wan Nik, & Hassan, 2009; Hu et al., 2015; Roosta, 2014a). Coupled to this, fish can retain between 15% and 40% of the available phosphorus in fish feed, whilst only approximately 2–20% of the carbon is also retained (Endut et al., 2009; Roosta, 2014a). The unutilized waste feed reduces water quality, making water quality monitoring in fish production very critical. Regulation of water quality is mainly done by constantly exchanging water at a recirculating rate of about 5–10% per day (Hu et al., 2015). Aquaponic systems allow for the bio-filtration of the wastewater allowing it to be reused in the aquaculture system within a recirculating aquaponic systems (RAS). Since Namibia is looking for opportunities to increase national food production under its harsh arid environments, this innovative technology can be fundamental in achieving this goal (Goddek & Keesman, 2017). However, the productivity of conventional aquaponic systems currently being applied in many countries is far from being optimum as it is necessary to make trade-offs within these systems in terms of pH, temperature and nutrients (Goddek et al., 2016; Goddek & Keesman, 2018; Thu & Andrew, 2017).

In two separate studies Endut et al. (2009); (2010)) evaluated the influence of hydraulic loading rate and plant ratios on the water quality parameters of spinach and catfish growth under greenhouse conditions. In these studies, they reported a hydraulic loading rate of 1.28 m/day with a flow rate of 1.6 L/min as optimum for fish and plant growth together with wastewater nutrient removal. Contrary to Endut, Jusoh, Ali, Wan Nik, and Hassan (2010), Zou et al. (2016); Roosta (2014b); Hu et al. (2014); Hu et al. (2015)) reported varying results on different aquaponic systems using different crops and different flow rates in RAS. It is important to note that, though several researchers have undertaken aquaponics research, most of them have tried to optimize only one component at a time such as crop density, fish density, flow rates, etc., within the whole system, resulting in inconsistent results. There is thus need for an integrated aquaponics research on effects of different fish species, planting densities, plant species, hydraulic loading rates and hydroponic systems on water quality and nutrient dynamics in RAS (Buzby & Lin, 2014; Effendi, Sri, & Yusli, 2016; Endut et al., 2010). Such information could be critical in modelling yield responses in aquaponics systems, thus helping as a decision tool in commercial aquaponic systems.

Though there is still room for optimization research on RAS, there is another school of thought, which of late has been promoting the idea of a decoupled aquaponic system (DAS) or multi-loop aquaponic system proposed by researchers at Wageningen University and Research (Goddek & Keesman, 2018; Goddek et al., 2016). Under a RAS, the crops and fish have different aquatic chemistry requirements, thus compromises need to be made on both the fish and crop requirements, with the drawback of reducing the efficiency of the aquaponics system (Goddek et al., 2015). Research on DAS, though still in its infant stage can also be crucial as it can allow for the use of pesticides for pest control, which are highly toxic to fish under RAS (Pilinszky et al. 2015). However, the DAS technology requires huge investments in capital intensive materials and the profitability of such systems will need to be determined, particularly in developing countries like Namibia, before being fully promoted as a best practice technology in aquaponics.

5. Bio-saline agriculture

As indicated earlier, scarcity of freshwater is a serious hindrance to Namibia's crop production, making the country highly susceptible to climate change and food insecurity. Globally, agriculture consumes more than 85% of all the freshwater from aquifers, streams and lakes, making it impossible to increase agricultural production without increasing scarce freshwater use (Atzori et al., 2016). However, in countries like Namibia, one of the major challenges, caused by aridity is salinity of soils. Salinity is a worldwide land degradation problem affecting about 800 million ha (Li et al., 2016). If agricultural production is to increase, there is a need to expand agriculture into degraded lands like saline soils whilst looking for alternatives to freshwater for irrigation. Technologies that can create alternatives to freshwater such as using saline water, brackish and treated wastewater, fog harvesting and seawater desalination, among others, have potential in driving crop production in most arid countries (Klemm et al., 2012; Liu et al., 2015; Wang, Huo, Zhang, Wang, & Zhao, 2016a).

Though direct seawater irrigation still remains impractical, in countries such as Israel, Iraq, Kuwait, China and the USA, saline water irrigation in other cases such as horticulture and small-scale agriculture seems potentially viable (Atzori et al., 2016; Wang et al., 2016a). When applied directly to soil, saline seawater contains large concentrations of Na^+ and Cl^-, which at high levels in soil are toxic to plants and can directly impact soil physical properties through clay dispersion particularly in already saline soils found in arid areas in countries like Namibia (Martinez-Alvarez, Martin-Gorriz, & Soto-Garcia, 2016). Notwithstanding these potential challenges, several researchers have looked at the potential of utilizing this highly abundant water resource for irrigation, and it is emerging as a feasible water source in agriculture when properly treated either through desalinisation or blending with freshwater.

In countries like China, with vast tracks of saline coastal areas, several researchers have looked at different methods of reclaiming these degraded soils and utilizing seawater for irrigation. In one experiment, Li, Kanga, Wana, Chena, and Xua (2015a) evaluated the potential of using seawater for irrigation of a glycophyte, Chinese rose (*Rosa chinensis*) by mixing it with freshwater to achieve salinity levels of 0.8; 3.1; 4.7; 6.3 and 7.8 dS/m, under a drip irrigation system. In this study, they reported that the highly saline soil was significantly salt leached by using the drip system with the salt-sensitive crop being able to grow at salinity levels of up to 7.8 dS/m. In another study, Li, Kang, Wan, Chen, and Chu (2015b) used soil matric potential (SMP) to schedule drip irrigation of a salt-sensitive crop using seawater/freshwater blends. It was observed in that study that a SMP of between −5 and −10 kPa and water salinity of up to 4.01 dS/m can be used for rose drip irrigation. In a similar study, Sun et al. (2012) also reported that drip irrigation in a saline soil that maintains the SMP at around −5 kPa can effectively reduce the salinity toxicity even in salt-tolerant crops. It, therefore, seems that with careful management, saline seawater can be an ideal alternative for freshwater particularly in coastal regions (Liu et al., 2015).

With the use of saline water for irrigation, it is important to note that maintaining the soil matric potential (SMP) in the root zone at a certain critical level is paramount in avoiding salt toxicity and osmotic stress (Liu et al., 2015; Sun et al., 2012). Drip irrigation is being widely considered as the most promising irrigation system that can be used for saline water irrigation as it can precisely apply water constantly and uniformly thus maintain high SMP in the root zone (CChu, Kang, & Wan, 2015). In addition to precise irrigation methods, directly amending alkaline soils with organic matter rich materials like cow dung has the potential of improving soil physical and chemical properties, making organic amendments a feasible strategy for saline soil reclamation (Liu et al., 2015; Ouni et al., 2013). However, in saline water irrigation studies, many of the studies have been done in non-saline soils or in hydroponics, with few focusing on both saline soils and saline water (Liu et al., 2015). It would be interesting to observe the influence of other practices such as addition of organic matter to saline degraded soils, which improves water-holding capacity and drip irrigation systems and how it can enhance the use of use of saline water. There is limited information on evaluating an integrated system involving saline water irrigation of a saline soil amended with organic matter, using efficient irrigation systems and its influence of on soil quality and productivity. Research on such systems can generate essential knowledge that can allow for a certain level of freshwater substitution with saline water in crop production in arid Namibia.

6. Fog harvesting

The coastal areas of the Namib Desert receive most of its water as advective fog rather than normal precipitation rainfall, a peculiar characteristic of this desert (Aboutalebi et al., 2013). Most of the animal and plant species that are found in this desert have thus adopted mechanisms of harvesting this fog for survival. Examples include the Namib dune bushman grass (*Stipagrostis sabulicola*) and the diverse darkling beetles (Coleoptera, Tenebrionidae) (Ebner et al., 2011; Henschel & Lancaster, 2013). This phenomenon has seen several researchers evaluating the potential of fog harvesting using different mechanisms as a supplementary water source in the Namib Desert (Shanyengana et al., 2002). The harvesting of fog water can be a simple and sustainable technology for obtaining freshwater, which has the potential of creating the much-needed irrigation water for vegetable crops in arid countries (Klemm et al., 2012). However, in Namibia, researchers who have looked at the potential of fog harvesting have focused more on fog water quality and fog net collecting efficiency rather than the quantity of fog, which is more critical if fog is to be used in crop production (Shanyengana et al., 2003; Wang, Kaseke, & Seely, 2016b).

Shanyengana et al. (2002), reported fog water quantities of 508–3308 ml/m^2 of netting/day on wet days and 104–1074 mL/m^2 of netting/day on dry days throughout the year at three sites in the Namib Desert. From such information, it is clear that with a large 8 m^2 fog collector, one can collect up to 26.4 L of water on a wet day and 8.6 L of water on a dry day, translating to more than 700 L per month with an 8 m^2 collector. Such amounts of water can be critical in growing different crops and other drought-tolerant tree species that can be used in desert re-greening, starting at the coast. However, long-term studies are needed to validate in space and time such findings before undertaking wide-scale projects. Eckardt and Schemenauer (1998), studied the quality of fog water in the Namib Desert and observed that it was extremely good and is unlikely to contribute to salt accumulation to the soil. Such clean fog water can also be mixed with saline seawater at an optimized level with the impact of possibly increasing the water available for crop production after fog harvesting. However, this fog harvesting research in Namibia was done about two decades ago, and there is a need to re-evaluate the potential of fog water collection in Namibia, under this climate change era. Actual field studies also need to be undertaken to evaluate the full-scale potential of fog water irrigation under different crops in Namibia. It is also important to note that despite the growing importance of fog water collection in arid areas, its potential has not been fully exploited mainly due to lack of national water policies and action plans that consider fog water collection as a means of addressing water shortages (Qadir, Jimenez, Farnum, Dodson 4, & Smakhtin, 2018).

7. Coastal resources in food production

The coast of the Namib Desert is very cool with the ocean being very productive. As a way of trying to exploit these conditions for food production, the University of Namibia initiated research on gourmet mushroom production focusing on oyster mushrooms (Kaaya et al., 2012; http://www.unam.edu.na/sanumarc). Edible mushrooms have been shown to be a valuable source of nutrients and bioactive compounds that are essential in the human diet (Guillamon et al., 2010). On a dry-weight basis, mushrooms are comparable and at times superior in nutrition to other traditional foods, which has seen them being used as alternative sources of supplements in natural foods as they are rich in minerals such as potassium, iodine; beta-glucans, phenolic compounds and antioxidant compounds amongst other nutritional properties (Nagy et al., 2017; Ogidi et al., 2017). Table 2 shows nutrient and mineral comparison of oyster mushrooms to traditional foods, indicating the nutritional superiority of mushrooms.

Table 2 clearly shows that mushrooms can have up to 31% more crude protein, 14% more fat, 24% more carbohydrates and 225% more calcium, compared to traditional grain crops like cowpeas. This superiority in nutrient content has driven researchers into looking at possibilities for enhancing mushroom nutrient and trace metal concentrations (Hausiku & Mupambwa, 2018; Assuncao et al., 2012; Da Silva et al., 2012),with mushrooms being saprophytic feeders that are able to grow on a wide range of ligno-cellulosic materials. However, the substrate composition has a direct influence on their final nutrient content (Pushpa & Purushothama, 2010; Singh, 2017). In a study in which two different kinds of saw-dusts (hardwood and softwood) were used to produce *P. ostreatus*, a 50.8% higher crude protein content was observed in the hardwood compared to the softwood, indicating the direct influence of substrate on mushroom quality (Ogundele, Salawu, Abdulraheem, & Bamidele, 2017). In Namibia, limited research has been undertaken to try and improve the health-related nutrients in oyster mushrooms by altering the substrate composition, with much of the research focussing on simply improving mushroom yield (Kaaya et al., 2012; Molloy et al., 2003). This limited research has been further compounded by the lack of ligno-cellulosic material due to the unproductive terrestrial environment in Namibia making mushroom cultivation a challenge. However, the high primary productivity of the marine environment results in the production of high quantities of unwanted beach cast seaweeds whose high nutrient value can be exploited in mushroom substrates (Hausiku & Mupambwa, 2019).

Kaaya et al. (2012) carried out a study where they substituted veld grass with varying levels of seaweed (0–20%) and grew mushrooms (*P. sajor caju*). Their findings revealed that mushrooms grown on the 10% seaweed-amended substrate had higher iodide content compared to the treatment with no seaweed. The potential economical and health benefits of these seaweeds remain untapped, particularly in Africa (Kaaya et al., 2012). In Asia, seaweeds are considered a rich source of nutrients and health-related bioactive compounds, which are included in the traditional diet as an important marine medicinal food (Besada et al., 2009; Rajapakse & Se Kim, 2011). Though seaweeds contain lipids in small amounts not exceeding 5% of their dry weight, the essential fatty acids from two biologically important groups, i.e., omega-3 and omega-6 polyunsaturated fatty acids (PUFAs) represent the significant part of seaweed lipids (Misurcova, Ambrozova, & Samek, 2011). Of late, these PUFAs have been identified to be functional food and nutraceuticals with several human health benefits (Rajapakse & Se Kim, 2011). Apart from these fatty acids, seaweeds also contain essential amino acids, functional polysaccharides; vitamins and minerals (Rajapakse & Se Kim, 2011). Due to these health related benefits of seaweeds, they have potential as amendments for the traditional ligno-cellulose based mushroom substrates, an area where research is still very limited. With mushrooms being saprophytic feeders, it is possible that by amending traditional substrates with nutrient and mineral-rich seaweeds, the health-related nutrients in mushrooms can be enhanced when grown on these substrates. This has been observed by Da Silva et al. (2012) and de Assuncao et al. (2012), who reported enhanced

Table 2. Comparison of proximate and mineral composition of two mushroom species relative to traditional legume grain crops and meat

Parameter		***Pleurotus* species**	***Agaricus* species**	**Jack bean (*Canavalia* species)**	**Cowpeas (*Vigna* species)**	**Beef**
	References	**Igbokwe, Nebo, Ezenwelu, Nwajiobi, & Odili, 2015; Sharif et al., 2016; Genccelep, Uzun, Tuncturk, & Demire, 2009**	**Genccelep et al., 2009**	**Olalekan & Bosede, 2010**	**Olalekan & Bosede, 2010**	**Williams, 2007**
Crude protein (%)		31.5	25.4	26.2	24.1	23.2
Fat (%)		5.0	1.6	1.95	4.4	2.8
Carbohydrates (%)		69.9	54.4	57.8	56.6	-
Crude fibre (%)		19. 0	12.3	1.07	1.0	-
Calcium (mg/g)		1.3	0.4	0.2	0.4	0.05
Potassium (mg/g)		21.9	18.1	2.2	1.0	3.6
Sodium (mg/g)		1.5	0.17	2.0	1.2	0.5
Magnesium (mg/g)		1.7	9.7	1.4	1.0	0.3
Iron (mg/g)		0.7	0.2	0.2	0.8	0.02
Zinc (mg/g)		0.1	0.1	1.6	1.6	0.05
Copper (mg/g)		0.05	0.04	0.3	0.6	0.001
Phosphorus (mg/g)		3.5	2.4	37.6	29.4	0.17

Selenium and Lithium concentrations in mushrooms grown on substrates amended with different materials. It is also critical to develop affordable substrate sterilization methods and post-harvest technologies that can be used by local Namibian farmers as a driver towards promoting household mushroom production.

8. Potentially useful desert plant species identification and domestication

In arid countries like Namibia, planning and managing sustainable agriculture presents both challenges and enormous opportunities (Shelef et al., 2016). Whereas the major challenge in arid environments is scarcity of water, it is interesting to observe that arid and semi-desert places are the origins of plant and animal domestication that happened some 10 000 years ago (Shelef et al., 2016). Moreover, many of the wild relatives of the domesticated species still exist in desert areas but these are gradually disappearing due to resource exploitation such as mining in countries like Namibia (Bidak, Kamala, Halmy, & Heneidya, 2015). From a sustainable agriculture perspective, more attention should be given to domestication of local desert species for commercial use rather than importing new alien species, which has potential consequences. Most deserts are rich in plants that have adapted to growing under extreme water supply (xerophytes) and high salinity (halophytes), which have potential to be used commercially for food and animal feed production; development of pharmaceuticals, salt phytoremediation and generation of biofuels. A comprehensive review by Shelef et al. (2016) regarding potential domestication of plants from the Negev Desert showed that several plant species have potential as pharmaceuticals, food crops, feed for livestock and robust rootstocks. Such studies are lacking in the Namib Desert, which is among the oldest deserts in the world. Moreover, seed bank studies can be a crucial starting point for such studies.

One plant which is endemic to the central Namib Desert that has the potential for domestication and commercialization is a melon known locally as nara, naras or !nara (as written in the Khoekhoegowab language and scientifically known as *Acanthosicyos horridus*) by the local Topnaar people (Eppley & Wenk, 2001). The nara melon has been observed to be highly nutritious with the seeds containing around 32% protein and 46% oil (Masaaki, 2005). This melon has been critical in sustaining wild animals such as oryx, springbok, mice, beetles, jackals as well as people in the Namib Desert (Masaaki, 2005). Though several researchers have looked into the ecology of this melon, which is believed to have been in existence since some 40 million years ago, there has been very little effort on domestication of this xerophyte (Masaaki, 2005). Research at the Sam Nujoma Campus of the University of Namibia has also initiated a desert soil seed bank characterization experiment, with the intention of not only quantifying soil seed banks, but identifying potentially beneficial desert species that can be used as food, feed for animals or in pharmaceuticals. Such studies can be critical in identifying species that can be possibly grown with harvested fog water mixed with seawater, due to their already existing genetic tolerance to arid environments.

9. Renewable energy and agriculture in the coast

Namibia produces only 36% of its required electricity thus most of the electricity used is imported from neighbouring countries (Dall & Hoffmann, 2017), making most agricultural activities powered by electricity uneconomic. Such activities include the generation of freshwater from seawater through desalination, which requires a lot of electricity for powering the reverse osmosis process, making the water generated very expensive (Pryor & Blanco, undated). Namibia has the largest electricity-powered desalination plant in Southern Africa, the Trekkoppje desalination plant by Areva Resources Namibia, which mainly supplies water to high-value mining activities within the Namib Desert (Dall & Hoffmann, 2017). However, though being a big desalination power plant, none of this water is used in agricultural activities in the Namibian coast. This is a dream shared by the current governor of the Erongo Region of Namibia who has stressed that the region needs to construct desalination plants, which can allow for the establishment of irrigation schemes right in the Namib Desert thus contributing to food security (www.namibtimes.net). Bearing in mind the cost of running reverse osmosis–based desalination power plants, there is a need for the development and adoption of innovative methods that can allow for the production of cheaper freshwater for crop production from seawater.

Technologies that make use of renewable energy such as the seawater greenhouse are already being promoted in other arid countries like Oman to generate freshwater from seawater for crop production cheaply and sustainably (Al-Ismaili & Jayasuriya, 2016). Though the Namibian coast experiences less sunlight thus is generally cold, parts of the desert within a few kilometres from the coast receive significant sunlight coupled with higher temperatures. These higher temperatures create an opportunity for thermal desalination of seawater using the recently proposed seawater greenhouse technology. The seawater greenhouse makes use of the hot temperatures generated by the greenhouse to evaporate seawater, whose humidity is then used to humidify and cool the greenhouse and also collected as freshwater for watering the crops (Al-Ismaili & Jayasuriya, 2016; Mbaga, 2014). Such technologies can be evaluated and optimized for the Namibian Desert environment, and such research can generate crops in Namibia under its arid conditions. In Australia, a technology that harvests the sun's energy by concentrating the suns energy into a central tower, which generates a lot of heat which can then be used to desalinate seawater through distillation (Kalogirou, 2005). If Namibia has to make use of the vast water supply from the Atlantic Ocean in driving desert agriculture, there is need to evaluate technologies employing renewable energy in generating freshwater.

10. Conclusions

Agriculture in desert environments has received very limited research attention throughout the world due to their high temperature and limited water availability. However, in Namibia, the coastal desert, the Namib Desert whose environmental conditions are regulated by the cold Atlantic Ocean, presents a cool desert with plenty of sunlight. These unique conditions in the Namib Desert can be exploited for crop production in this arid country. This review highlights that very limited research has been linked to crop production, with much of the work being on ecology. Research on optimized soilless crop production called hydroponics may be critical in driving crop production in the Namib Desert. Processes that can generate cheap organic nutrient sources such as vermicomposting are proposed as having potential in creating home-made organic nutrient sources, thus driving crop production at household level in Namibia. The review also proposes more research on optimized aquaponics in Namibia, which can allow the integration of aquaculture and crop production, with limited wastewater generation in this arid environment. The Namib Desert also receives substantial amounts of its water as fog, which has great potential to be harvested as a freshwater source for desert re-greening. However, very limited research has been done in this regard, with much of the fog research having been either ecologically based or only focusing on fog water quality. Finally, due to the availability of seawater in the coastal desert, research on evaluating the potential of using renewable energy to convert the saline water into freshwater for crop production is critical in developing sustainable crop production in this region. However, it is also imperative to mention that of the suggested technologies proposed in this review, there is a need for government buy-in to fund and evaluate the feasibility of these technologies.

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