TEMPERATURE DYNAMICS WITHIN A LOW-COST AQUAPONIC SYSTEM AND THE POSSIBLE EFFECTS OF CLIMATE CHANGE

by

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PREFACE

The candidate, while based in the Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa, completed the research contained in this dissertation. The research was financially supported by the Department of Economic Development, Tourism and Environmental Affairs.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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DECLARATION 1: PLAGIARISM

I, Minenhle God’slove Mkhize, declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) this thesis does not contain other persons’ data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this thesis does not contain other persons’ writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this thesis is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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ABSTRACT

The agricultural sector is facing impeding challenges due to climate change. There is enough evidence showing that climate change has a significant impact on agricultural production. Marginalized communities that lack financial resources and depend on agricultural crop production, are the most vulnerable to climate change effects, which further exacerbates their food insecurity. Existing literature hypothesizes that aquaponics, using Tilapia, has potential in addressing climate change effects in agriculture. However, the low average winter temperature hinders successful adoption of low-cost aquaponic systems using Tilapia fish. The implication of cool conditions (South African temperatures) are more extreme for a low-cost, poorly resourced aquaponic users because they lack temperature regulation systems to maintain optimal temperatures and are simply subject to the surrounding environmental conditions. Therefore, the purpose of this study was to understand the temperature dynamics of a low-cost aquaponic system and the possible effects of future climate change.

A study was conducted at KwaDeda, a poor rural community in the Ndwedwe area of KwaZulu-Natal. The two objectives were to (1) understand how the surrounding environmental air temperature affects the water temperature of a low-cost aquaponic system and, to (2) assess the implications of future climate change on a low-cost aquaponic system. Two weather stations (22 km apart) were installed, one to measure hourly environmental air temperature conditions and the other to measure the conditions within the plastic tunnel of a low cost aquaponic system (from June – November 2019).

The environmental air temperature had no immediate relationship with water temperature. However, there was an observed lag of 4 hours from the environmental air temperature peak to water temperature peak, which varied slightly with seasonality. The conditions within the tunnel were generally hotter than the outside environmental conditions during the day, however, at night, the tunnel air temperature dropped to be the same and sometimes even lower the outside environmental temperature. The air temperatures in winter and resulting water temperatures of the low-cost aquaponic system was well below the optimum range for *Tilapia* (22-32 °C). Low-cost systems provide limited means to control water temperature. Therefore, further investigation into low-cost methods to reduce the cooling of the tunnels at night, which later results in cooling of the water, is required.

The projected future climate was shown to be both advantageous and disadvantageous for the low-cost aquaponic system. The projected increase in average air temperature due to

climate change will be positive for South African conditions, which are generally quite cool for Tilapia. However, extreme weather conditions such as intense storms, high wind speed and hail, that are predicted with climate change, may be a threat to low-cost aquaponic infrastructure. Research into improving the design of low-cost tunnels that can withstand adverse weather conditions is recommended.

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Lastly, God in Heaven this is my love letter to you. Thank You!

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CHAPTER 1: INTRODUCTION

This chapter introduces the background of climate change and aquaponic system farming methods. The justification, aim and objectives focusing on understanding the temperature dynamics of a low-cost aquaponic system and the possible effects of climate change on agriculture are discussed. The thesis outline is also presented.

1.1 Rationale for the Research

Climate change is the average increase or decrease in mean annual air temperature over a long period of time, typically over at least 30 years or more (Rosegrant *et al.*,2008; Hussen, 2014). Climate change is characterized by the modification of weather conditions that may have negative or positive impacts in different areas (Society and Academy, 2014). For example, in colder regions that experience frost, increasing mean annual air temperature may be beneficial by increasing the length of the growing season. However, in warmer interior regions, increasing mean annual air temperature has negative consequences, because the temperature increases beyond the optimal temperature thresholds that crops and animals can survive – leading to severe agricultural production losses. Extreme weather conditions that have been linked to climate change are floods, drought, variable rainfall, cyclones and hail storms (Jury, 2013). As a result, this extreme weather has been associated with pest outbreaks, topsoil erosion, water scarcity and physical crop damage. Hence, in many parts of the world, agricultural food production has decreased, and this has affected food security both globally and locally.

Many South African population in rural regions depend on small-scale or subsistence food production for their survival and livelihood (FAO, IFAD, UNICEF, WFP, 2018). Resource poor are extremely vulnerable to climate risks (Davis *et al.* 2007). As a result, poverty, hunger, and famine are exacerbated due to increase in food insecurity in poor households (IPCC, 2014). Food security is a state that “exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (World Food Summit 1996, p. 28). There is therefore a need for innovative agricultural practise that will produce food sustainably and assist improve food accessibility in the face of climate change effects to poor communities.

Aquaponics is an emerging, innovative agricultural practise that is recognized worldwide (Love et al., 2015b). Aquaponics includes growing plants using fish effluent that is rich in nutrients required for plant growth in a circulating system i.e. fish and plants are grown symbiotically (Carlsson, 2013; Mchunu *et al*., 2018b; Rakocy, 2007; Sanchez, 2014). Mchunu, Lagerwall & Senzanje (2017a) conducted an aquaponics study in South Africa and stated that aquaponics has the potential in addressing climate change effects and food security. This is because aquaponics conserves scarce natural resources like water and soil i.e. water is recirculated from fish to plants and aquaponics is a soilless system. Furthermore, aquaponics produces both meat (fish) and vegetables, which are rich in protein source, omega 3 and various vitamins and minerals that benefit the human body (FAO, 2017.; FAO, 2014.). Aquaponics has the potential to address food insecurity and, conserve natural resources in the wake of changing climate (Mchunu *et al*., 2017a; Mchunu, *et al*., 2018b); however, there have been no studies conducted to confirm this hypothesis, in particular, the effects of temperature changes on productivity of aquaponics.

The adoption of aquaponics within the agricultural sector in South Africa has been challenged because of low average winter air temperatures – as low as 17 ℃ (Rakocy *et al*., 2006; Mchunu *et al*., 2018b). The ability of fish to produce enough nutrients for plants and food productivity in the system are as a result reduced (Tyson *et al*., 2011). Currently, aquaponics research is focused on understanding fish and plant biological symbiotic relationships and how to properly maintain the system rather than the temperatures (Lennard, 2012). However, studies have indicated that climate and water temperature are critical in an aquaponics system (Elia *et al*., 2015; Mullins *et al*., 2015; Sallenave, 2016; Sta, 2017; Kim, 2018). Mchunu *et al*., (2018b) stated that there is limited information on the environmental climatic variables to assist local aquaponic practitioners to maximize their production.

There is, therefore, a need for studies to show the relationship between environmental variables in particular air temperature and water temperature and how the future projected climate will affect a low-cost aquaponic system.

1.2 Problem Statement

Aquaponics is “the cultivation of fish and plants together in a constructed, recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrition. This is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers” (Thorarinsdottir, 2015 p. 29).

Aquaponics has the potential to address climate change effects in agriculture such as poor production due to unfavourable climate conditions, and water scarcity (FAO, 2014; Goddek *et al*., 2015; Mchunu *et al*., 2017a).

The significant challenge however, in adopting aquaponics using Tilapia in South Africa, is the low average environmental air temperature (<17 °C), particularly, during winter months. *Tilapia* species are known to be resilience to harsh conditions, can live in a wide range of water temperatures, and can be easily accessed. Despite these factors, *Tilapia* have not thrived in aquaponics systems in South Africa possibly, in part, due to low average temperatures. Sophisticated systems that have temperature regulators such as water heaters and coolers and air conditioners perform better, because climate conditions are regulated. However, a low-cost aquaponic systems adopted often by poor communities, who lack financial resources, do not have climate regulators. As a result, low-cost aquaponic systems are vulnerable to acute climate fluctuations due to prevailing environmental conditions to which they are exposed. The projected increase in climate vulnerability increases the risk and lowers the sustainability of the system.

One of the main drivers for success and failure of aquaponics is water temperature (FAO, 2014). Water temperatures that are variable, that is, too low or too high, are detrimental to fish and plants, resulting in high bacteria populations, which can lead to severe system imbalance and failure (Hatfield *et al*., 2015).

A successful assessment of environmental air temperature and water temperature will be beneficial to aquaponic practitioners in terms of understanding how the spatial and temporal climate affect the water temperature of the system. Moreover, the assessment of climate change projections and the potential impacts these will have on a low-cost aquaponic system will be beneficial to aquaponic practitioners and policy developers. The results will provide an indication of the potential vulnerable areas that need to be addressed to be prepared for future climate scenarios.

1.3 Aim

- To measure and assess the temperature dynamics of a low-cost aquaponic system during a winter season, and comprehend the possible effects of future climate change predictions on the sustainability of a low-cost aquaponic system.

1.4 Objectives

The objectives of this research were to:

- Assess the relationship between environmental air temperature and water temperature in a low-cost aquaponics system;
- Identify the expected climate change scenarios for KZN and assess the risks associated with climate change predictions on the low-cost aquaponic systems over the next 30 years.

1.5 Research Questions

The questions that this research aimed to answer are as follows:

- Is there a relationship between water temperature and environmental air temperature in a low-cost aquaponics system?
- What are the expected climate change scenarios for KZN in 2050?
- What is the impact of risks associated with climate change on a low-cost aquaponic system over the next 30 years in KZN?

1.6 Outline of the Dissertation

The dissertation is structured according to paper format, which is an acceptable format outlined by the University of KwaZulu-Natal under the Discipline of Agrometeorology. The main chapters (2 to 4) are intended for publication. The structure of these chapters includes the introduction with relevant literature, detailed method and materials, results and discussion and conclusion with recommendations.

Due to the format used there is duplication of information which overlaps between the chapters. For example, in methods and materials section, the Ndwedwe site was the study area for both experimental Chapter 3 and 4. As a result the description of the study area, the figures used, and equipment installed were defined in both chapters. However, each chapter addresses different objectives making them unique from each other. In addition, the duplication in references is due to the focus on climate change and the aquaponics theme which is common to all chapters. A brief description of each chapter follows.

Chapter 2: Literature Review: In this chapter, the background literature on climate change, aquaponics and environmental variables is reviewed.

Chapter 3: Relationship between water temperature and environmental variables in a low-cost aquaponic system: This chapter addressed the relationships between environmental air temperature outside the tunnel, the air inside the tunnel and the water and whether using solely a tunnel provides adequate climate control.

Chapter 4: Implications of climate change in a low-cost aquaponic system: This chapter will identified the risks associated with climate change predictions on a low-cost aquaponic system over the next 30 years in KZN.

Chapter 5: Synthesis and Conclusion: This chapter makes conclusions based on the result obtained, and gives recommendations for further study.

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CHAPTER 2: THE EFFECTS OF CLIMATE ON AGRICULTURAL FOOD PRODUCTION AND SECURITY; AQUAPONICS AS THE POTENTIAL SOLUTION

The following section reviews the current literature of climate change and aquaponic system. The conceptual framework of the literature is provided at the end of this section summarizing the themes and relationships observed from the literature.

2.1 Introduction

Climate change is a threat in global and local agricultural food production and food security (Kleinwechter *et al*., 2015). It has been documented that the future climate projection will exacerbate food loss due to climate change effects (IPCC, 2014). Marginalised communities, particularly those in Sub-Saharan Africa will bear the brunt of climate change effect because they lack financial resources to cope after extreme climate events like floods or drought (Altman *et.al*., 2009; Rogerson, 2010; FAO, 2014). This pushes marginalised communities toward critical food insecurity.

The aquaponic system has been documented to possess potential to address climate change insecurity in households (Goddek *et al*., 2015; Shafeenas, 2016; Mchunu *et al*., 2018b). Aquaponics is an emerging practice worldwide, including in South Africa. Aquaponics grows fish and plants in one circulating system and comprises three organisms, i.e. fish, plants and bacteria (Rakocy *et al*., 2007). Aquaponic scientists have documented that the *Tilapia* fish species are an aquaponics superlative species (Love et al., 2015b). This is because *Tilapia* can survive in a wide range of water temperatures and quality conditions (FAO, 2014). Furthermore, *Tilapia* are a good protein source, with omega 3 and various vitamins that benefit the human system (Rakocy *et al*., 2006; Love *et al*., 2015; Yildiz *et al*., 2017).

Tilapia are, however, a warm water species that require average temperatures of 22-32℃ throughout the year and their production is hindered in South African cool climate conditions with an average of 17 ℃ in winter (Tyson *et al*., 2011; Mchunu *et al*., 2018b). A sophisticated system that can control climate using expensive climate regulators is not impacted as much as a low-cost aquaponic system that depends on the surrounding environmental conditions. It is documented how the environmental variables affect water temperature (Rutherford *et al*., 2010; Daigle *et al*., 2014; Girjatowicz, 2019). However, there is insufficient information on how the environmental variables affect the water temperature of a low-cost aquaponic system and no study has assessed the impact of risks associated with climate change on low-cost aquaponic systems.

2.2 Global Warming and the Definition of Climate Change

Naturally, the climate and the weather of the Earth is driven by energy from the sun (Balasubramanian, 2017). The sun releases radiation heating the Earth's surface (IPCC, 2014). The Earth emits infrared radiation into the atmosphere as the surface of the earth cools. Greenhouse gases such as Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O) and Ozone (O_3) trap some of this infrared radiation and prevent it from escaping the atmosphere which causes warming (Ako & Baker, 2009; IPCC, 2007). This heating and cooling process of the Earth is natural, and it is crucial for the survival of all living organisms (Cicerone, 2014). However, increased concentrations of greenhouse gases through anthropogenic activities has accelerated the natural global warning to an extent that is hazardous for organisms living on Earth (IPCC, 2007).

Greenhouse gases absorb and emit infrared radiation, and therefore, if they occur in high concentrations, they disturb the energy balance of the Earth. The IPCC (2015) states that the activities that intensify the accumulation of greenhouse gases in the atmosphere are energy (forest fuel combustion, natural gas leakage, industrial activities and biomass burning), agriculture (paddy fields, animal husbandry (ruminants) and fertiliser usage) industries (metal smelting and processing, cement production, petrochemical production and miscellaneous), waste management (sanitary landfill incineration, biomass decay). These are daily human activities that are likely to change the future climate (Treut *et al*., 2007).

Climate change is the increase or decrease in the mean annual global temperature over a long period of time (Cicerone, 2014; IPCC, 2014; FAO, IFAD, UNICEF, WFP, 2018). A long period of time refers to the geological time-frame that is measured in a period of 30 or more years. Natural global warming results in a climate change over a long period of time. Scientists have shown evidence of climate change effects such as droughts, more severe tropical storms due to the warmer temperature of oceans, increased frequency of melting ice in the Arctic ocean, permafrost areas, glaciers and polar areas, and sea level rises due to melting glaciers and the thermal expansion of water (Cicerone, 2014). These events are caused by climate change due to greenhouse gas emissions; however, anti-climate change activists disagree that these events are caused by greenhouse gas emissions caused by human activities and it remains a contentious issue.

2.3 Climate Change Effects on Agriculture and Food Security

Climate change affects global average weather conditions so that pleasant or unpleasant conditions result, depending on the location of the area (Thomas & Twyman, 2007; Benhin, 2015). For instance, in cold South African regions like the Drakensberg, warmer conditions elongate the planting season, whereas in warm regions like Pietermaritzburg, floods and tornados become more frequent (Schulze, 2016). The changes in climate conditions interferes with crop production (Roux, 2018). This is because crops only thrive under certain optimal climatic conditions.

Crop optimal conditions are affected by climate change effects such as the increase in global average air temperature, droughts and floods (FAO, 2014). Cardinal temperatures are defined as four temperature thresholds that explain the living organism conditions: absolute minimum, absolute maximum, optimum minimum and optimum maximum (Hollinger *et al*., 2003). Optimum temperatures are conditions where living organisms can grow and produce well, absolute temperatures are conditions beyond or below the climate threshold where a living organism can survive and produce, and hence they are detrimental. Climate change in some instances pushes climate conditions into absolute conditions. Much crop productions that is exposed to the environment is severely affected, subsequently reducing food production and increasing food insecurity status (FAO, IFAD, UNICEF, WFP, 2018).

Food production is linked with absolute climate conditions and this can result resulting in the slate of food insecurity (Kleinwechter *et al*., 2015). The World Food Summit (1996), defines food security as the states that, "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". There is enough evidence showing that drought, floods and heat waves have affected food production over past years (Naab, Abubakari and Ahmed, 2019). Food price vitality and spikes have been linked to extreme weather phenomenon on a global scale and mostly at a local scale where marginalised communities reside, and therefore food security is undermined to a great extent by climate change effects (FAO, 2014).

Food security has four pillars: food availability, accessibility, utilisation and stability (DAFF, 2013). The following section describes how climate change affects food security:

Food availability – available food depends on the produced yield, distribution and exchange in the market (FAO, IFAD, UNICEF, WFP, 2018). Climate change affects food yield through flooding, water scarcity, seasonal changes, increasing temperature, and unreliable rainfall in most cases (Roux, 2018). As a result, to compensate food loss, imports become relevant which in turn affects the economy negatively. Furthermore, higher CO_2 content in the atmosphere increases plant growth rates, however it decreases the amount of nitrogen and protein content in some staple foods. This results in the exacerbation of insects in agricultural fields as they consume more leaves – so they can obtain enough nitrogen for their metabolism. All these factors affect food availability in markets and households. In addition, climate change affects global and local temperatures. As a result, a trend of decreased yields has been noted worldwide, affecting food availability (FAO, 2018).

Food accessibility – accessibility is when produced food available at the markets can be acquired through purchasing it or growing it (FAO, IFAD, UNICEF, WFP, 2018). Affordability of preferred food is an important factor in food accessibility. However, affordability is affected by food price vitality and spikes affecting mostly the marginalised communities (Zakari *et al*., 2014). Davis *et al*. (2007) states that poor and marginalized communities substitute food purchase with subsistence farming. However, in the face of climate change effects, these communities are severely affected because they lack resources. For example, increases in temperature would increase the cost of post-harvest produce due to increased refrigeration costs which would decrease availability and access.

Food utilization – refers to the ability to utilise nutrients during food consumption (FAO, IFAD, UNICEF, WFP, 2018). Burke *et al*. (2010) states that to meet food utilisation one should be able to answer these questions: Does the food consumed consist of all the adequate nutrition required to live healthily and to be productive? Is the food safe to consume, and does not cause any form of diseases? Can one use the nutrients contained by the food? Therefore, increased average air temperature affects food utilization by reducing nutrient content in plants. In addition, more food contamination and spoilage are experienced due to warmer conditions. Food preparation and storage is a significant factor for all households, because about 1 in 10 people worldwide die due to eating contaminated food (USDA, 2015).

Food stability – stability refers to the continued provision of food at all times whether through purchase or farming (FAO, IFAD, UNICEF, WFP, 2018). Availability, accessibility, and use should not be affected by economic, social, natural and political factors. Climate change puts food stability at very high risk, and adverse weather *inter alia* increases unemployment, decreases food production, threatens human health, and fluctuates food prices (DAFF, 2013). Marginalised communities are vulnerable, because they don't have financial support to sustain their farming practices.

Climate change is a serious threat to agriculture – both livestock and crop production (Rosegrant *et al*., 2008). Crop production is very sensitive to ambient environmental conditions. Due to climate change, the environmental conditions are changing at an unprecedented rate and in most cases they are bad for optimal crop growth (Hatfield & Prueger, 2015). Marginalised communities, where most unskilled farmers reside, are in the edge of poverty line. This is due to the lack of capacity to recover from extreme climate events (IPCC, 2014). Therefore, there is a need for more investigation into how to produce food sustainably in the face of adverse climate effects. This is crucial for a country like South Africa that is more vulnerable to climate change effects and lacks natural resources like water and arable soil (Mchunu *et al*., 2018b). Innovative solutions will help improve food production sustainably and improve the food security status of marginalised communities.

2.4 Aquaponics History, Definition, Advantages and Disadvantages

In 2000 years ago, there was a system of farming called chinampas initiated by poor people living in the valley of Mexico also known as "floating garden of Mexico". Chinampas were rectangle island layered with strips of mud and vegetation compost to make soil nutritious with canals in between that grew fish (Boatvelluc, 2007). Similarities between aquaponics and chinampas is that food is grown in a floating media and nutrients are directly supplied to plants from fish waste. Chinampas were able to provide food for more than 2 million people 2000 years back (Boatvelluc, 2007). The key success of chinampas were good water management, during floods the chinampas canals acted as a drainage and during droughts water from the canals absorbed and infiltrated in the porous chinampa soil. This allows sustainable food production in any climatic condition (Shafeena, 2016).

Aquaponic system era began at the times of 1970 by pioneer and scientist called Dr. Jim Rakocy at the University of Virgin Island (UVI) for more than thirty years back (Thorarinsdottir, 2015). In UVI the combination of aquaculture and aquaponics was developed. *Talapia* was the aquaponics species and floating raft beds growing lettuce were used in hydroponics. To date, many aquaponics have been developed from small-scale to commercial production (Harry *et al*., 2018). Aquaponics has been successfully adopted in many parts of the world including European countries (Denmark, Spain), United State, Australia, South Africa (Lennard, 2012).

Aquaponics is defined as "the cultivation of fish and plants together in a constructed, recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrition (Rackocy, 2006). This is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers" (Thorarinsdottir, 2015, p. 9) (Figure 2.1). Aquaponic systems combines two traditional production systems: hydroponics and recirculating aquacultural systems. Aquaponics is a closed loop system; water is recirculated from the fish tanks to plant tanks (Rakocy *et al*., 2006; Elia *et al*., 2015).

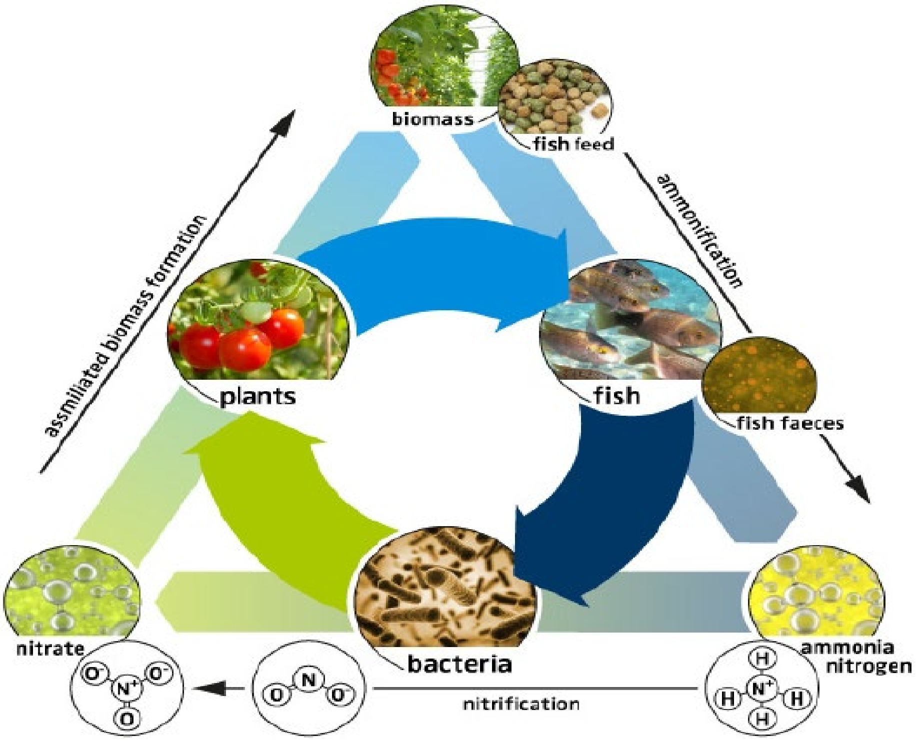


Figure 2.1 Schematic diagram showing the cycle of the aquaponic system (sourced from Goddek, S. *et al.* 2015)

FAO (2014) and Mchunu *et al*. (2018b) states that aquaponics has the potential to address climate change effects in agriculture and food insecurity in marginalised communities. This is because aquaponics recycles water which is a scarce natural resource and is in demand as the population is increasing. Aquaponics uses 90 % less water in comparison to traditional farming methods and can be 30 % more productive when using an intensive system (Tyson *et al*., 2011). For South Africa, aquaponics can be a possible solution as the water resource is declining due to climate change effects. For example, in Cape Town Province, it is estimated that 3 hectares of freshwater with approximately 3 million cubic meters of water has evaporated within the period of 2015–2017 (Wolski, 2018).

According to Altman *et al*., (2009) and FAO, IFAD, UNICEF, WFP (2018), South Africa is food secure at a national level, but food insecure at a household level. Aquaponics addresses food insecurity by providing nutritious fish meat and vegetables. Fish is low-fat meat with high protein levels and omega 3, which is very good for the heart. Leafy vegetables provide *inter alia* vitamin A, K, and C, fiber, mineral irons, and calcium, which are required for a healthy and active lifestyle (Rakocy *et al*., 2006). Furthermore, 25 years of research indicate that the fish effluent is compatible with plant nutrient demand and therefore can be used as a farming technique to produce food (Rakocy *et al*., 2006).

The literature clearly indicates that the initial installation costs of aquaponics is high (Sunny, 2019). Hobby scale (a fish stock of 10-20 kg/m^3 and 500-1000 litre fish tanks), subsistence scale (a fish stock of 20-40 kg/m^3 and 1 000-2000 litre fish tanks) and commercial scale (fish stock of 100-300 kg/m^3 and 4000-50 000 litre fish tanks) have price ranges between R5000 and R500 000. However, prices range significantly, and it depends on the type of materials used. For poor communities that live with less than USD1.25 per day to afford such a system could be problematic. Goddek *et al.*, (2015a) states that aquaponic systems are more expensive than the equivalent scale of recirculated aquaculture or hydroponics. This is disadvantageous for these communities, because they cannot access the benefits of aquaponics. This opens a niche area in the literature for research on a low-cost aquaponic system.

Aquaponics growth conditions for fish requires annual temperature range between 22 to 32 °C which is impossible for South African low climatic conditions (using *Tilapia* species). South African winter conditions can be reduced to as low as 10-16 °C. Therefore, there is a need to understand the South African climatic conditions as it is stated to affect the successful adoption of aquaponic system (Lapere, 2010).

2.5 South African Climatic Conditions

South Africa is located at the southern tip of Africa (Boko *et al*., 2007). The surrounding cold Benguela ocean current (West coast) bring cooler conditions to Western Cape and Western part of the Northern Cape (Zengeni *et al*., 2016). The warm Mozambican current brings humid air and warm water down along the East coast from the equatorial zone resulting in to tropical to subtropical conditions in the KwaZulu-Natal coastal areas (Benhin, 2015).

South Africa mean minimum and maximum air temperature ranges between 3-24 °C (Figure 2.2). The North Eastern provinces i.e. KwaZulu-Natal, Mpumalanga and Limpopo experience a hot climate in comparison to the rest of South Africa areas with a summer temperature reaching 45 °C (Boko *et al*., 2007). Lesotho experiences cooler conditions than the rest of the country with minimum and maximum average of 3-12 °C. The North Western part of South Africa i.e. Western Cape and Northern Cape are dominated by arid or desert regions with summer and winter temperatures between 22-40 °C and 2-20 °C, respectively. In KwaZulu-Natal the average temperatures range between 16-24 °C with diurnal summer and winter temperature ranging between 18.4-33 °C and 8-17 °C, respectively (Zengeni *et al*., 2016).

Van Der Waal (2000) states that in South Africa the climatic conditions are low (<17 °C) for many fish species to establish. Mchunu *et al*. (2018b) conducted an aquaponics survey in South Africa and found that farmers needed to adjust their water temperature so that *Tilapia* could be established. The FAO (2014) and South African aquacultural farmer (Cuthbert 2009, pers. comm., 22 September) further agrees that fish ponds in South Africa needs further water temperature adjustment for *Tilapia* to grow profitably.

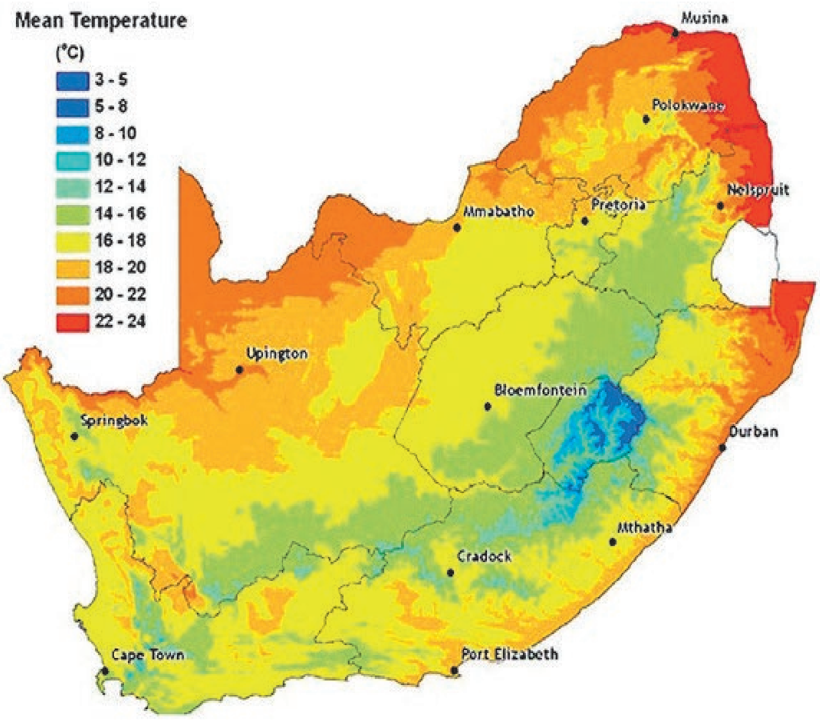


Figure 2.2 South African mean annual temperature (sourced from Mohapeloa, 2018)

2.6 Definition of a Low-Cost Aquaponic System

The low-cost aquaponic systems have been adopted from commercial systems by poor communities. According to this study, a low-cost aquaponic system is a low-tech system using low-cost, locally available material. It is a system that has a closed-loop with a maximum of 30 m^2 for the growing area. The production of fish and plants within a small area allows small-scale farmers to achieve the daily income target of USD1.25 and food and nutrition security set by the Sustainable Development Goals 2030 (FAO, 2014).

Low-cost aquaponic systems lack the accessibility to climatic regulators to maintain the system at optimal conditions. Example of climatic regulators include air and water temperature heaters and coolers. As a result, the system experiences the diurnal fluctuation as it is affected by the environmental conditions. Studies have hypothesized that aquaponic (low-cost and commercial) system have the potential to address climate change effects on agriculture by sustainably producing enough food while using resources efficiently (Lennard, 2012). However, there has been no study that tested this hypothesis.

2.7 Will the Low-Cost Aquaponics Survive on the Projected Climate Change Effects?

The Intergovernmental Panel for Climate Change (IPCC) is a worldwide body of intergovernmental scientists from the United Nations (UN) or World Meteorological Organization (WMO) that provides scientific reports and future projections of climate change through assessing thousands of climate change publications. The IPCC uses different models to project possible future climate and these models are continuously being upgraded and improved to increase accuracy (Meehl *et al*., 2007). To date, the results generated by IPCC have been trusted and used by many scientists and worldwide government policy-makers (Meehl *et al*., 2007).

IPCC (2014) latest report (Fifth Assessment Report) has projected the world climate for the next 30 years (2050), South African future projection will be extrapolated from this data. According to IPCC, South Africa is expected to experience an increase in annual average temperature of at most 2℃ (Figure 2.3). The projected increase in annual average temperature is expected to change the environment in the following way:

- The coastal areas and cities are expected to experience intense flooding due to an increased sea level of 0.58 m (RCP8.5) and/or 0.20 m (RCP4.5). This will result in damage of infrastructure and agricultural lands.
- The rainfall intensity is expected to increase (high uncertainty in the magnitude); however, longer dry periods are expected.
- Fish communities are expected to be harmed by warming of the ocean.
- The frequency and intensity of storm surges in the coastal areas are expected to increase.

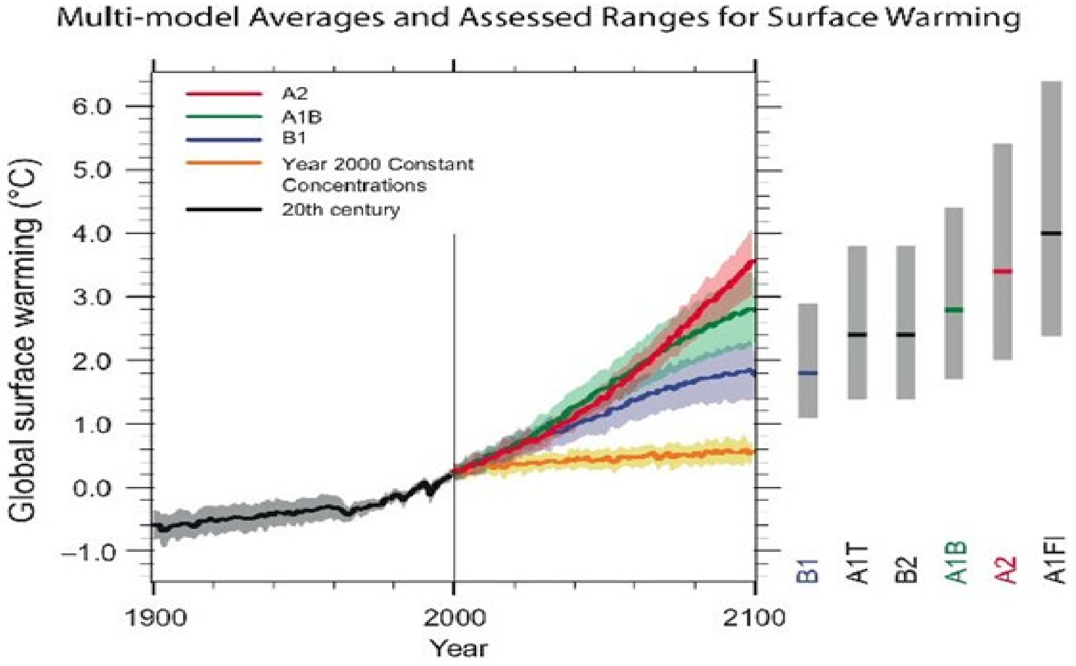


Figure 2.3 Multi-model averages and assessed ranges for surface warming (sourced from IPCC, 2014)

Future climate change effects include increasing mean annual air temperature by approximately 2 °C, increased dry spells and erratic rainfall. This poses questions like: Will aquaponics still use 90 % less water in comparison to traditional farming methods or will the evaporation interfere with water use in the aquaponic system? Will there be fish species suitable for the projected climate? Will the increased air temperature detrimentally affect plants and fish in aquaponic systems? Current documents have hypothesised that aquaponics has the potential to address climate change effects. However, there is an information gap showing how aquaponic systems will respond to the changing projected climate in both low-cost and sophisticated aquaponic systems. This is crucial information, because the aquaponic system is still an emerging practice, and therefore before practitioners and government invest in aquaponic systems, they should be aware of risks associated with climate change in aquaponics – as aquaponics is widely known to address climate change effects.

2.8 Factors Driving Success and Failure of Aquaponics Ecosystem

There are critical factors that need to be considered for the success of the system. This section lists and describes the four most crucial aquaponics water quality parameters. In addition, it is important to note the factors that will make the system vulnerable to failure (FAO, 2014; Sallenave, 2016; Yildiz *et al*., 2017).

2.8.1 Dissolved Oxygen (DO)

The DO refers to the amount of Oxygen dissolved in the water and it is measured in milligrams per litre (Hatfield & Prueger, 2015). The DO is the important water quality parameter in aquaponics because fish, bacteria and plants need oxygen for their survival (Bugbee, 2004). Naturally, oxygen from the atmosphere dissolves at the water surface. Additional DO is recommended for optimal conditions of plant roots, fish and bacteria (FAO, 2014). Air pumps are used to supplement oxygen in aquaponic systems, and the recommended DO in aquaponics is 5-8 mg/litre (FAO, 2014). Water temperature affects the amount of DO in water (D'Amato *et al*., 2007). When water temperature increases DO decreases and this is because cold water holds more oxygen than warm water (D'Amato *et al*., 2007). A rise of 10°C in water temperature can result in the doubling of fish respiration, and this decreases the amount of oxygen in the water (Sallenave, 2016). As a result, suffocation and solubility of toxic substances (ammonia) become very high – lessening water quality and thus killing fish (Hartleb, 2013).

2.8.2 pH

The pH refers to the number of H^+ ions available in the water. pH has a scale from 1-14 where neutral is 7 (Rakocy, 2006). From 0-7 the solution is acidic and from 7-14 the solution is alkaline (Rakocy, 2004). In simple terms, the more H^+ ions increase, the more the solution becomes acidic. The pH affects the aquaponic system because fish, plants and bacteria survive only within certain pH thresholds (Landis, 2010). For plants, if the pH is above or the below the optimal range, plants will not be able to access the nutrients from the solution even if the nutrients are available in water, and this phenomenon is called nutrient lock-out (FAO, 2014). The pH recommended for plants is 6.0 – 6.5, where all the nutrients are available for uptake. The optimal pH level is 6-7, which is good for all organisms (Rackocy, 2010). A low pH affects fish by burning their skin and reducing productivity when below a pH of 5.(Landis, 2010).

2.8.3 Total nitrogen: ammonia, nitrite, nitrate

Nitrobacter and *Nitrosomonas* are two groups that are responsible for nitrogen conversion so that it can be available for plant intake. *Nitrosomonas* converts ammonium to nitrites, and a nitrite is a form of nitrogen that can be absorbed by plants (Elia *et al.*, 2015). The optimal water temperature ranges for nitrifying bacteria is 25-30 °C; however, at 4 °C there will be no activity, at 18 °C growth rate will start to decrease by 50 % and by 75 % at 7-10 °C (FAO, 2014). the absolute temperature range of nitrifying bacteria is below 0°C and above 49 °C. During the cooler season, it is important to monitor nitrite, because *Nitrobacter* bacteria are more sensitive to lower temperatures than *Nitrosomonas* – in order to avoid toxic accumulations (Rakocy *et al.*, 2006). Aquaponics that is fully functioning should have nitrite and ammonia levels close to zero or between 0.25–1.0 mg/litre.

2.8.4 Water temperature

It is well documented that water temperature drives the success of aquaponic system because of the three organisms of an aquaponic system – i.e. fish, plants and bacteria – which depend on water temperature conditions for their survival (Rakocy *et al.*, 2006). The three organisms have their unique optimal water temperature threshold where they can live and reproduce (Table 2.1). However, as mentioned above, the aquaponic system is a closed loop and therefore water temperature is compromised (Table 2.2). The recommended temperature for the optimal growth of all three organisms is 18-30 °C (FAO, 2014). To minimise energy costs, it is recommended to use fish and plants that are suitable for the surrounding environmental climate (Love *et al.* 2015b).

Prior literature has documented that the most farmed fish species in the world, including South Africa, is *Tilapia* (Mchunu *et al.*, 2018b). Love *et al.* (2015b) conducted an international survey and discovered that the most farmed fish were *Tilapia* (69 %), ornamental fish (43 %), catfish (25 %), other aquatic animals (18 %), perch (16%), bluegill (15 %), trout (10 %), and bass (7 %). Mchunu *et al.* (2018b) conducted a South Africa survey and discovered that *Tilapia* are also the most farmed fish (82 %), followed by trout (30 %), and barbel/catfish (18 %). *Tilapia* are widely preferred because it is a eurytherm, and can survive or function in a wide range of different body temperatures (Yildiz *et al.*, 2017). *Tilapia* can survive in a temperature range of 9-42.5 °C; however, the optimal water temperature is 22-32 °C (FAO, 2014; D'Amato *et al.*, 2007).

Carlsson (2013) and Yildiz *et al.* (2017) states that in an aquaponic system, water temperature fluctuation should be limited. Water and climate regulators such as water and air heaters and coolers are used to keep the system at optimal temperatures. However, the disadvantage of these regulators is that they consume a lot of energy and they are expensive to maintain (Love *et al.* 2015b). They are, however, crucial for the success of an aquaponic system because they optimally regulate water temperature (FAO, 2014). An alternative to using water regulators, is to change the fish species that adapt to the environmental conditions. For example, during cooler months trout (<18 °C) are used because it prefers cooler temperatures and during the summer months *Tilapia* are used (22-32 °C) (D'Amato, 2007). However, in a country like South Africa, particularly in KZN, trout cannot be used because it is not permitted and therefore *Tilapia* are the recommended species (Mchunu *et al.*, 2018b).

Table 2.1 Optimal water quality tolerance for nitrifying bacteria, plants, and fish in both warm and cold water (FAO, 2014)

Organism type	Temp (°C)	Ph	Ammonia (mg/litre)	Nitrite (mg/litre)	Nitrate (mg/litre)	DO (mg/litre)
Warm water fish	22-32	6-8.5	< 3	< 1	< 400	4-6
Cold water fish	10-18	6-8.5	< 1	< 0.1	< 400	6-8
Plants	16-30	5.5-7.5	< 30	< 1	-	> 3
Bacteria	14-34	6-8.5	< 3	< 1	-	4-8

Table 2.2 Compromise of all three aquaponic (fish, bacteria, and plants) organism water quality optimal conditions (FAO, 2014)

	Temp (°C)	pH	Ammonia (mg/litre)	Nitrite (mg/litre)	Nitrate (mg/litre)	DO (mg/litre)
Aquaponics	18-30	6-7	< 1	< 1	5-150	> 5

It is important to note that water temperature is crucial for all water quality parameters. If water temperature is significantly fluctuating, it can affect the whole system (FAO, 2014). Therefore, water temperature should always be kept optimal. Water heaters and coolers are used to keep the water temperature at a threshold where fish, plants and bacteria can thrive (Love *et al*. 2014a). Ultimately, DO, pH, water and air temperature and nitrogen levels are frequently monitored using meters so that they are kept at the optimal threshold. Failure to control and monitor these parameters will lead to system failure.

The challenge with using climate and water regulators is that they are not financially feasible for poor communities and using low-cost aquaponic system for these communities is the alternative (Lennard, 2012; Lapere, 2010; Goddek *et al.*, 2015a) . However, a low-cost aquaponic system is more affected by the environmental climate variables – because there are no sophisticated climate regulators and temperature measurement devices.

2.9 Measurement of Air Temperature and Water Temperature

Measurement of temperature started around 1.5 AD by Galen when he noted the 'complexion' of a person based on four observable quantities (Ring, 2007). The oldest temperature measurement tool was a thermometer, which was an air-thermoscope explained in Natural Magic (1558, 1589). Glass thermometers such as those in use today evolved from this thermoscope. In the 20th century, the evolution of temperature measurement tools has been based on accurate measurements and scales. The International Temperature Scale of 1990 (ITS-90) is the document used today to define temperature measurements. To date, temperature can be measured within 0.001 °C over an extended range, however, it is still not a simple measurement (Ring, 2007).

The World Meteorological Organization (2008), states that temperature measurements are classified in to three groups namely, probes, thermometer and non-contacts. Thermometers are temperature measurements that are widely known and used worldwide (WMO, 2008). Thermometers can be used to measure the temperatures of liquids, solids and gases.

Examples of thermometers are Bi-metal Thermometers and Glass Tube Thermometers . Probes sensors are temperature measurements that work by monitoring change in the resistance of the given area or liquid, solid or gas (Somerville *et al*., 2014). Examples are resistance elements, thermopiles and semiconductor. Non-contact sensors are devices that measure temperature without being in contact with it. Non-contact sensors use infrared radiation to sense the temperature from the distance (Somerville *et al*., 2014). The examples of non-contact sensors are single reading devices and camera field devices.

These devices have been widely used to measure and store data of the air and water temperature by recording the data on a datalogger (WMO, 2008).

2.9.1 Previous measurements and results of water and air temperature

Water & Bureau (2011) conducted a study to find the relationship between air and water temperature of a field stream in New Mexico. They concluded that there was a relationship between water and air temperature. Heat flux of air temperature during the day becomes positive due to the influence of solar radiation and subsequently increases the water temperature (Nascimento *et al*., 2011). An air-water temperature relationship was supported by model documentation called SSTEMP water temperature (IPCC, 2015). It was concluded that air temperature was a powerful determinant of daily water temperature (IPCC, 2015).

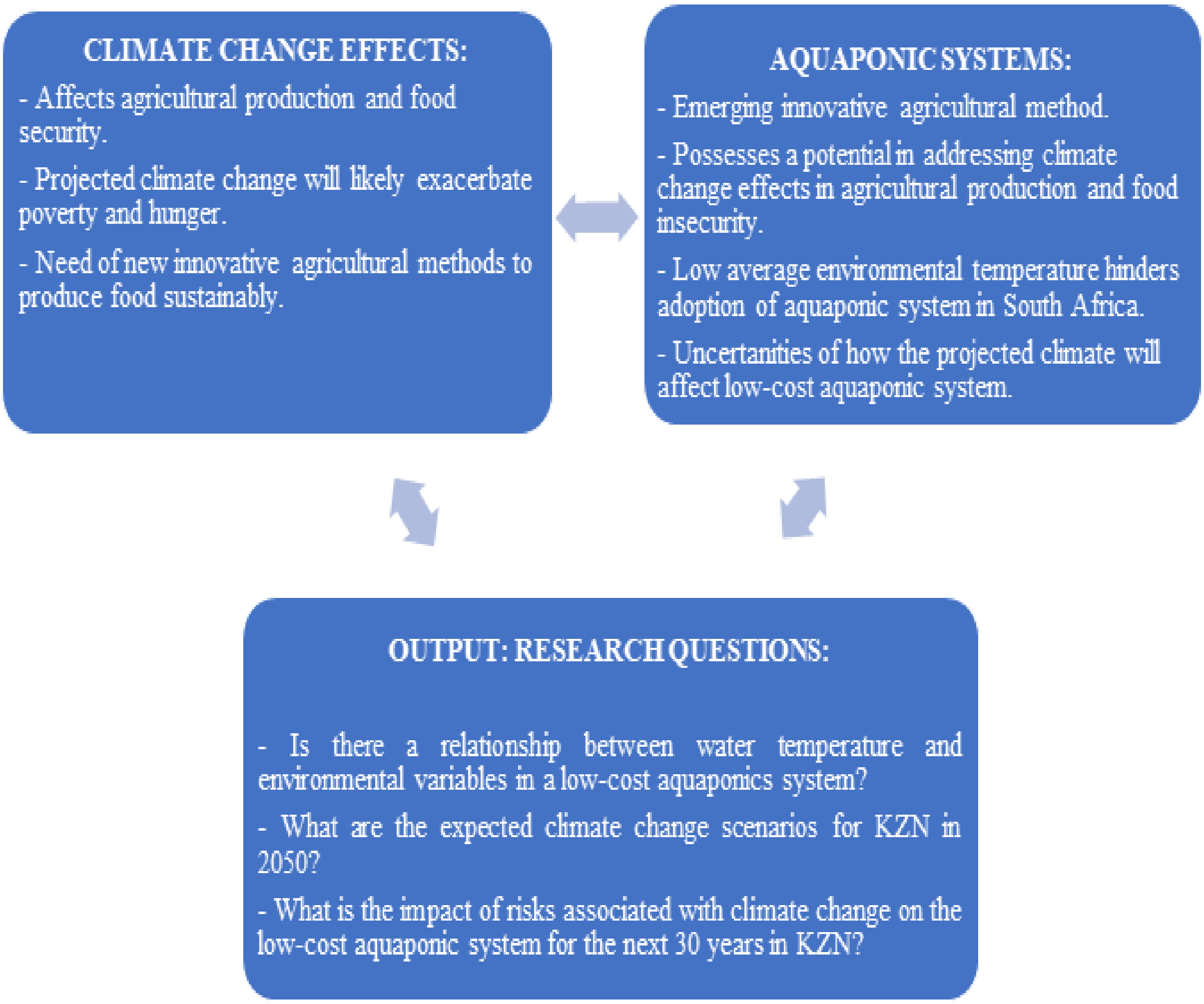
Love *et al*. (2015b) conducted a study about the energy and water use of an aquaponic system in the United States of America. The findings of this study also indicated a relationship between water and air temperature which agreed with Water & Bureau, (2011); however, this study was based inside a tunnel. Love *et al*. (2015b) states that during the summer season when the air temperature is mostly high, the water temperature was above 22 °C. Due to excess heat cooling was required to promote optimal conditions of fish, bacteria, and plants. However, during the winter season when the air temperature was low, the water temperature dropped. This indicated a strong correlation between air and water temperature even under a controlled environment. Additionally, readings obtained from a thermostat showed that at night when the solar/terrestrial heat had completely escaped, the water temperature dropped (Love *et al*., 2015b).

Bello *et al.*, (2017) conducted a study on the impact of climate change on water quality (water temperature and dissolved oxygen). The Hydrological Simulation Program FORTRAN (HSPF) and a regression model were used to find and analyse the impact of climate change on water quality on the river of Malaysia. The finding of this study indicated that under projected climate change scenarios of increasing mean annual air temperature and rainfall, the dissolved oxygen and water temperature would not be affected (Bello *et al.*, 2017). However, the effects of climate change on water temperature and oxygen was observed when mean annual air temperature increased with a decrease in rainfall (Bello *et al.*, 2017).

The relationship between solar radiation and air and water temperature is well documented by scientists and information is widely available (USDA, 2015). However, there is insufficient information published on this relationship within aa low-cost aquaponic system. The FAO (2011) states that the weakness of aquaponics is that uncontrolled water temperature, and thus water temperature fluctuation, results in a disastrous failure of the whole system (Somerville *et al*., 2014; Love *et al*., 2015b).

2.10 Conclusions

According to the literature there is a direct link between climate change and poor food production and food insecurity. Aquaponics is an emerging practice worldwide and is hypothesised to have potential in addressing climate change effects. However, aquaponics faces challenges that need to be addressed so that it can be adopted successfully. Therefore, the following chapters will aim to close the gaps relating to the relationship between environmental air temperature and water temperature in a low-cost aquaponics system and the risks associated with climate change predictions on the low-cost aquaponic systems observed in the literature. Chapter 3 considers how the environmental variable air temperature affects water temperature within the low-cost aquaponic system and Chapter 4 focuses on the impact of risks associated with climate change on a low-cost aquaponic system. Figure 2.4 is a summary of the themes and relationships observed from the literature.



CLIMATE CHANGE EFFECTS:

- Affects agricultural production and food security.
- Projected climate change will likely exacerbate poverty and hunger.
- Need of new innovative agricultural methods to produce food sustainably.

AQUAPONIC SYSTEMS:

- Emerging innovative agricultural method.
- Possesses a potential in addressing climate change effects in agricultural production and food insecurity.
- Low average environmental temperature hinders adoption of aquaponic system in South Africa.
- Uncertanities of how the projected climate will affect low-cost aquaponic system.

OUTPUT: RESEARCH QUESTIONS:

- Is there a relationship between water temperature and environmental variables in a low-cost aquaponics system?
- What are the expected climate change scenarios for KZN in 2050?
- What is the impact of risks associated with climate change on the low-cost aquaponic system for the next 30 years in KZN?

Figure 2.4 Conceptual framework of the literature review

2.11 Acknowledgments

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CHAPTER 3: THE MICROCLIMATIC CONDITIONS INSIDE A LOW-COST TUNNEL HOUSING AN AQUAPONIC SYSTEM

3.1 Abstract

Aquaponic farming offers the potential to address the climate change impacts in agricultural food production. However, according to the available literature, aquaponics in South Africa is hindered by low average temperatures. As a result, even *Tilapia* fish species that are known to be able survive in a wide range of water temperatures, cannot thrive in South Africa due to the water temperature being too cold. Therefore, the purpose of this chapter is to understand how the environmental conditions (mainly air temperature and relative humidity) affect the water temperature of a low-cost aquaponic system with only a tunnel to control temperature. Two measurement systems were used in this study which were located at Ndwedwe and Swayimane. The Swayimane station recorded environmental weather data (outside the tunnel) – located 22 km away from the aquaponic tunnel (data collection site). The Ndwedwe station recorded environmental variables and water temperature inside the tunnel over a period of four months.

The air temperature affects water temperature after a lag of 4 hours and this lag varies seasonally. The tunnel infrastructure (polyethylene plastic material) played a significant role in increasing air temperature during the day; however, at night and in the early morning the opposite was true. There was a relationship between tunnel and environmental air temperature; however, the improper infrastructure allowed an exchange of air temperature decreasing the quality of results.

The recorded daily aquaponic average water temperature was 18.6 °C, which is less than the recommended optimal water temperature for warm fish species (22-32 °C). The *Tilapia* were, however, able to survive the cold conditions but these were potentially not the optimal conditions. It was concluded that at Ndwedwe in KZN, South Africa, using a tunnel alone to improve water temperature is not enough to optimise conditions during the winter period. Additional heat is recommended to increase water temperature Low-cost aquaponics systems ideally require some form of temperature control or a warmer area than was found during the winter in Ndwedwe.

Keywords: *Air temperature; environmental variables; low-cost aquaponic system; water temperature*

3.2 Introduction

Agricultural crop production has been facing impending challenges of adverse weather conditions (Breman, 2014). There is evidence proving that some challenges are increasingly caused by climate change (Rosegrant *et al*., 2008). Climate change is characterised by unreliable rainfall, droughts, floods and pest infestation (Schulze, 2016). Farmers adaptation strategies for climate change and population growth have included a shift into intensified agriculture through mechanisation, fertiliser use, irrigation, fuel and the use of genetically modified seeds (Roux, 2018). The consequences have included water and environmental pollution, soil infertility, and ecosystem disturbance (Breman, 2014). To date, agricultural production is responsible for emitting significant amounts of methane (CH_4) and nitrous oxide (NO_3) into the atmosphere (Tadross & Johnston, 2012). Ultimately, there is a need for innovative crop production methods that will be sustainable and not exploit natural resources.

Mchunu, Lagerwall and Senzanje (2018b) conducted an aquaponic study in South Africa and concluded that aquaponics has the potential to address challenges faced by agricultural crop production. Aquaponics is "the cultivation of fish and plants together in a constructed, recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrition (Mchunu *et al*., 2018b). This is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers" (Thorarinsdottir, 2015, p. 29).

Aquaponics is a farming system in which plants and fish grow concurrently. Plants from hydroponic systems absorb nutrients from a combined aquacultural fish system – i.e. fish and plants are grown symbiotically (Carlsson, 2013; Lennard, 2012; Mchunu *et al*., 2018b; Rakocy, 2007; Sanchez, 2014). It is also defined as a system that serves a dual purpose simultaneously (Love *et al*., 2015). First, it recycles aquaculture effluent that is hazardous to the environment (FAO, 2014; Rakocy, 2007; Mchunu *et al*., 2018b). Second, it effectively uses the nutrients from the fish effluent (rich in nitrogen and phosphorus) to grow plants (Rakocy, 2007). Biological processes, water temperature, pH, oxygen, and dissolved solids are crucial for the success of this system.

The *Tilapia* fish species has been proven to be a superlative for aquaponics (Rakocy, Masser and Losordo, 2006; Love *et al*., 2015; Yildiz *et al*., 2017). This is due to its ability to survive in a wide range of water temperatures and water quality conditions. Moreover, *Tilapia* are a good source of protein, omega 3 and various vitamins that are beneficial for human health (FAO, 2014).

The challenge noted in adopting aquaponics in South Africa are the low temperature conditions and their effect on fish establishment (Mchunu *et al.*, 2017a; Mchunu *et al.*, 2018b). As a result, the ability to produce enough nutrients for plants and food productivity in the system is reduced (Rakocy *et al.*, 2006; Mchunu *et al.*, 2018b). In addition, sophisticated commercially available aquaponic systems are not financially feasible, making it difficult for marginalised communities to access the benefits of aquaponics. Low-cost aquaponic systems face the challenge of fluctuating water temperature. According to this study, a low-cost aquaponic system is a low-tech system using low-cost, locally available material. It is a system that has a closed-loop with a maximum of 30 m^2 for the growing area. The production of fish and plants within a small area allows small-scale farmers to achieve the daily income target of USD1.25 and food and nutrition security set by the Sustainable Development Goals 2030 (FAO, 2014; Mutisya *et al.*, 2015).

Low-cost systems do typically not have electronic temperature control and therefore, depend on the microclimatic factors surrounding the aquaponic system. There is currently insufficient information on how environmental variables affect water temperature in a low-cost aquaponic system. The environmental variables considered in this study were air temperature and relative humidity. The overall aim was to understand how microclimate affects the water temperature of aquaponics. This study aims to address if using solely a tunnel provides adequate climate control and how air temperature affects water temperature in a low-cost aquaponics system.

3.3 Methods and Materials

This section addresses the following objective of the study;

- Assess the relationship between environmental air temperature and water temperature in a low-cost aquaponics system;

3.3.1 Research area

The research was carried out within the province of KwaZulu-Natal in South Africa, in the rural area of KwaDeda, Ndwedwe (29.3245°S, 30.8901°E, alt. 962 m.a.s.l). Ndwedwe is a coastal area situated 20 km away from the KwaZulu-Natal coast. Large areas of Ndwedwe are characterised by dramatic steep topography (Municipality, 2018) (Figure 3.1). The

Mkhomazi river, near KwaDeda, is where most local people obtain their water for domestic use, which is difficult to access due to steep topography. Ndwedwe experiences a humid subtropical climate (Cfa) and has a mean annual precipitation of 1133 mm (Kumirai & Africa, 2017; Municipality, 2018). The warmest month is February with a minimum, maximum and average temperature of 23 °C, 28 °C and 26 °C, respectively. July is the coldest month with minimum, maximum and average temperature of 8.8 °C, 21.9 °C and 15.5 °C, respectively (Figure 3.2).

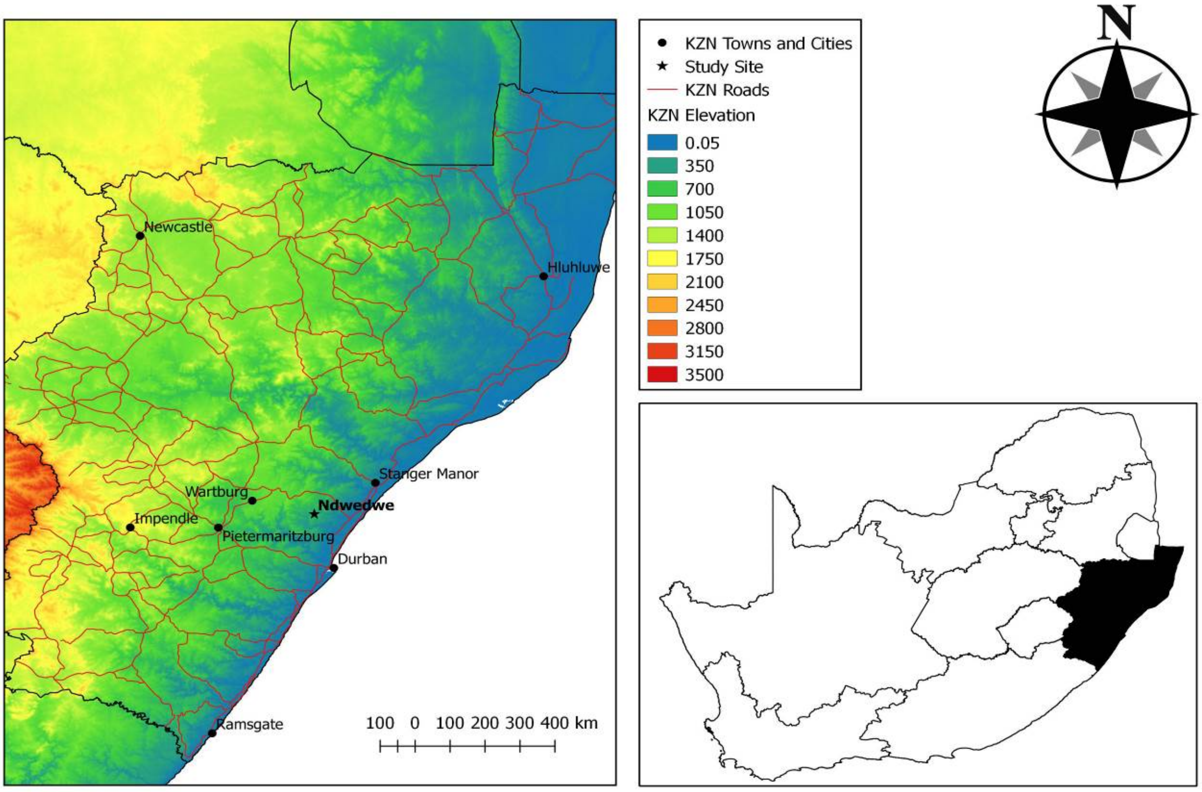


Figure 3.1 The location of the Ndwedwe study site in KwaZulu-Natal, South Africa. The site is in the KwaDeda township (29°30'0"S, 30°56'0"E)

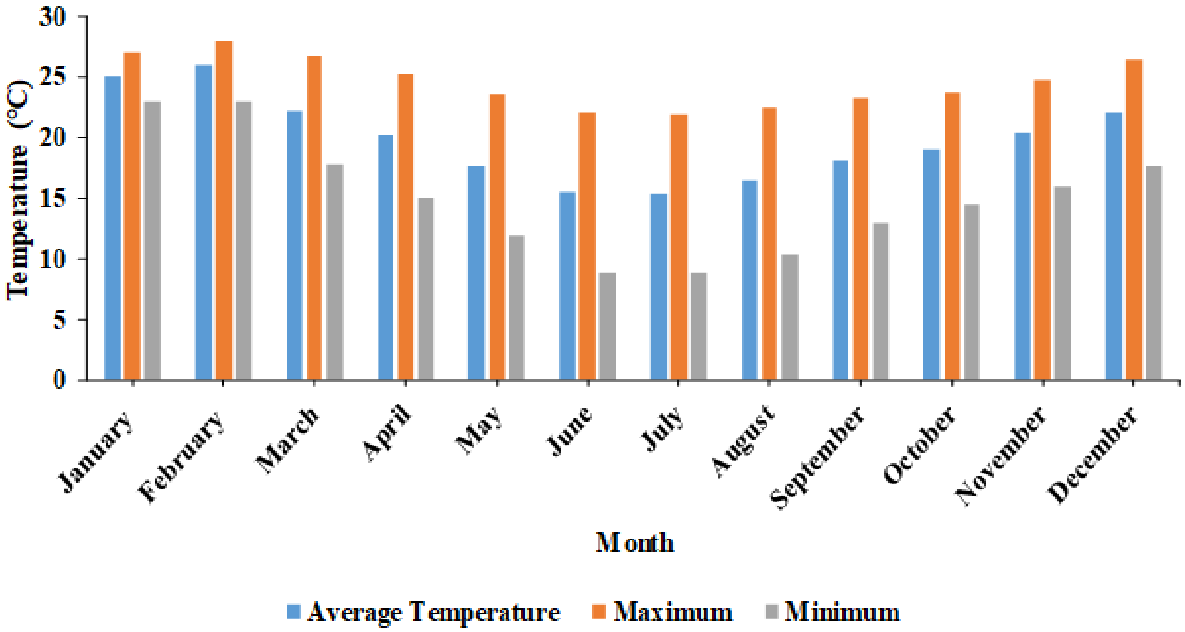


Figure 3.2 Minimum, maximum and average monthly temperatures at the Ndwedwe research site

3.3.2 Ndwedwe low-cost aquaponic system

In KZN there were a number of operational low-cost aquaponic systems – e.g. Northdene Aquaponic System, Ndwedwe Aquaponic system and Amandawe Youth Aquaponic System. The focus of this study was a low-cost aquaponic system. The threshold used to identify the low-cost aquaponic system was:

- A system using minimal technology and constructed out of low-cost, locally available material;
- Water used in a closed-loop system with a maximum of 30 m^2 for the growing area;
- Production of fish and plants allowing a small-scale farmer to achieve the daily income target of USD1.25 and food and nutrition security, which was set by the Sustainable Development Goals 2030 (FAO, 2014).

The Ndwedwe aquaponic system fulfilled all the requirements that were used to identify the low-cost aquaponic system. In the Ndwedwe aquaponic system, a gravel/vermiculite bed and floating raft bed were used to grow the plants in. A gravel/vermiculite bed was installed because of its ability to mineralise bacteria. Such material is commonly available and is used in building and construction. The floating raft bed was used by the farmer to see if there would be any growing difference between the gravel and floating beds. The planting area was 1 x 1.2 m with 300 l water capacity. The *Tilapia* fish were also grown in the same plastic tanks as those of the plants. Lettuce, pepper (green, red and yellow), beetroot, spinach, cabbage, jam tomatoes, beans, basil and parsley vegetables were grown – as they are commonly consumed by the local community (Figure 3.3).

There were six equal tanks for plants and three equal tanks for fish. Water from the system was moving from the fish tank to bio filter > filter > planting area (grow bed) > fish tank (Figure 3.4). The water system was a closed system requiring topping up every week with approximately 20 l. The water capacity of fish and vegetable tanks was 1000 l and 300 l, respectively and required a 230 VAC power source**.** The fish tank was submerged 40 cm underground to provide insulation by isolating the tank from the surrounding environmental conditions. In addition, sawdust was added to the soil around and in direct contact with the fish tanks to improve insulation**.**

The aquaponic system operated with a tunnel that was constructed in 2017. The tunnel is known as a hoophouse tunnel (Figure 3.5). The tunnel has a tube-shaped infrastructure usually made from white polyethylene plastic material. The purpose of the tunnel was to control environmental variables such as air temperature, wind speed, rainfall, solar heat, protect crops from harsh weather conditions and extend the planting season (Liu *et al.*, 2019). The Ndwedwe tunnel was constructed from white polyethylene plastic material, and light mesh was added on top of the plastic to form the roof. Tunnel aspect was east – west to maximise radiant solar heat gain. The tunnel was generally poorly constructed, and the lower edges allowed the exchange between environment and tunnel air. There were gaps around the door allowing air to get in and out.

The KwaDeda aquaponic system was installed at the homestead of Mr Philane Ngcobo, the operator. It was initially built by the Durban University of Technology and was funded by Enactus and Ford (2017).

Figure 3.3 Ndwedwe low-cost aquaponic system

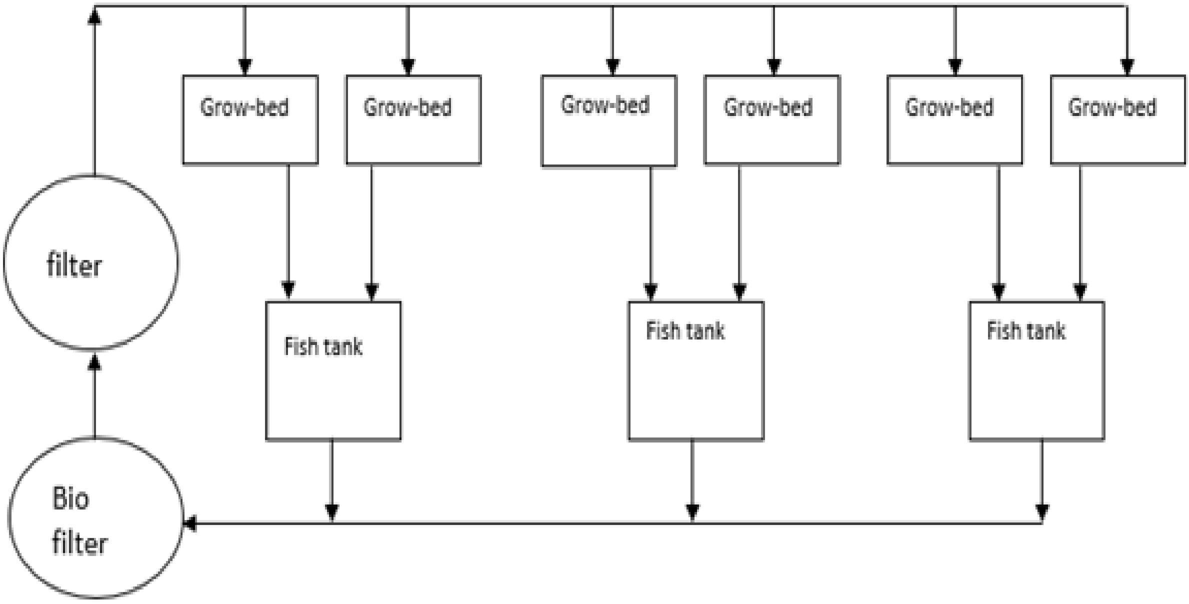


Figure 3.4 Schematic diagram of Ndwedwe aquaponic system (arrows indicating water flow)

Figure 3.5 Ndwedwe aquaponics tunnel infrastructure

3.3.3 Equipment and sensors used

An automatic weather station (Figure 3.6) at Swayimane High School (29.4878° S, 30.6603° E: 22 km from Ndwedwe) provided supporting meteorological information describing the outside environmental conditions. Air temperature and relative humidity (CS215, Campbell Scientific Inc., Logan, Utah, USA), were made every 10 s (Figure 3.7). Appropriate statistical outputs were stored on a datalogger (CR3000, Campbell Scientific Inc.) at hourly and daily intervals and downloaded automatically using a modem (http://143.128.64.9:5355/Sw_weather/index.html). The data was collected within the period of four months (end of June to mid - October). Equipment was installed according to recommendations of the World Meteorological Organisation (WMO, 2008) with a raingauge at 1.2 m above the ground and the remaining sensors at 2 m above the ground.

An online measurement system was also installed inside the tunnel (29.5325°S, 30.9360°E) of the aquaponics system (Figure 3.6) to measure air temperature and relative humidity (CS215, Campbell Scientific Inc.), photosynthetically active radiation (LI190R, LI-COR) and plant and a fish water temperature (107, Campbell Scientific Inc.). Measurements were recorded every 10 s and statistical outputs were stored hourly and daily on a datalogger (CR310, Campbell Scientific Inc.). Data were downloaded hourly and published on a website for both stations (http://143.128.64.9:5355/Aqua_KwaDeda/index.html) (Figure 3.8). The water temperature sensors were cable-tied in the water tanks and the remaining sensors were installed at a height of approximately 2 m above the ground. However, not all variables reported on this study will be used, but they provided supporting information for other research being conducted at the site. The environmental air temperature, tunnel air temperature and, tunnel water temperature was collected to address Objective 1.

Figure 3.6 Automatic Weather Stations of Swayimane (left) and Ndwedwe (right)

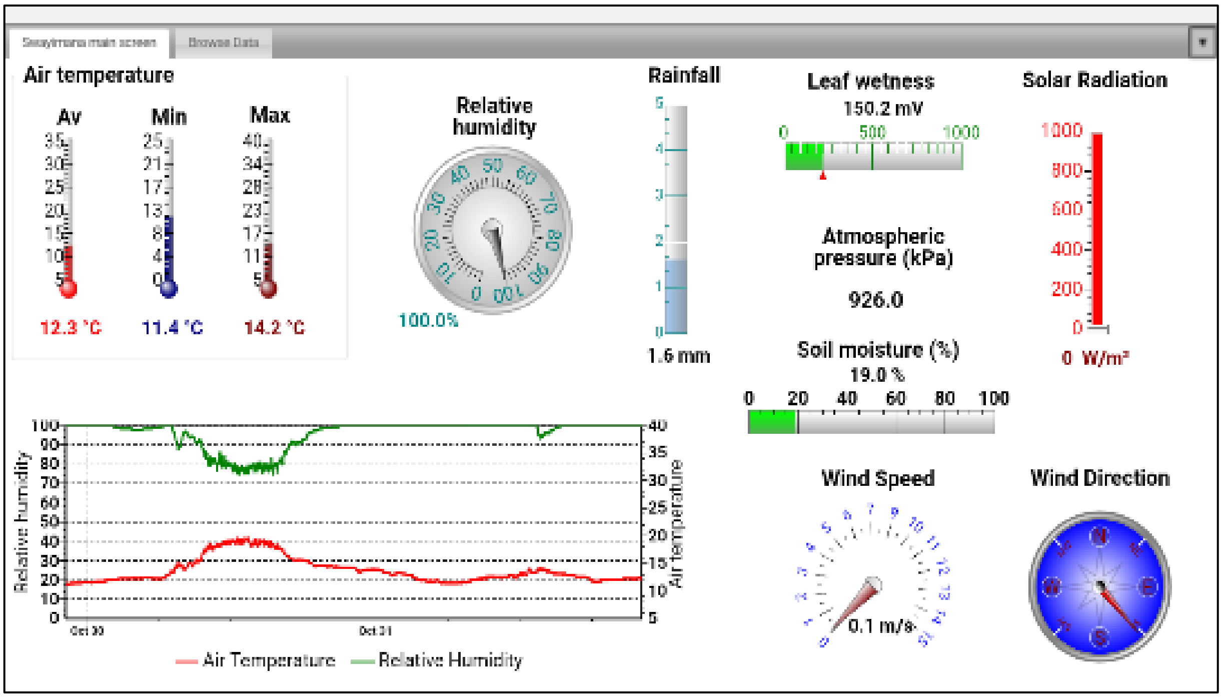
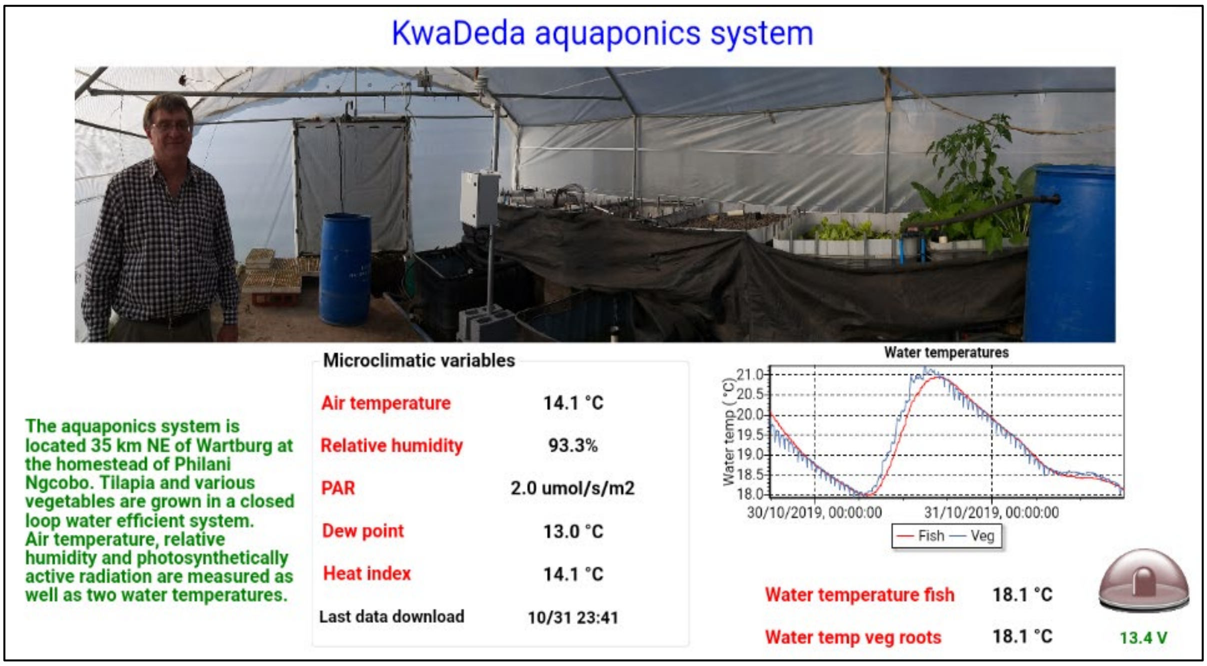


Figure 3.7 Website showing environmental near real-time conditions. Station located at Swayimane


KwaDeda aquaponics system

The aquaponics system is located 35 km NE of Wartburg at the homestead of Philani Ngcobo. Tilapia and various vegetables are grown in a closed loop water efficient system. Air temperature, relative humidity and photosynthetically active radiation are measured as well as two water temperatures.

Microclimatic variables

Air temperature	14.1 °C
Relative humidity	93.3%
PAR	2.0 umol/s/m2
Dew point	13.0 °C
Heat index	14.1 °C
Last data download	10/31 23:41

Water temperature fish	18.1 °C
Water temp veg roots	18.1 °C

Figure 3.8 Website showing inside the tunnel near real-time conditions at Ndwedwe aquaponic system.

3.4 Results and Discussion

This section will be addressing this following objective of the study:

- Assess the relationship between environmental air temperature and water temperature in a low-cost aquaponics system.

3.4.1 Air and water temperature within the tunnel

The minimum to maximum air temperature within the tunnel was 3.2-47.5 ℃, while the minimum to maximum water temperature was 13.4-25.9 ℃. The average of air and water temperature was 19.2 ℃ and 18.7 ℃, respectively (Figure 3.9). In general, there was a poor relationship between hourly water and air temperature and the coefficient of determination (R^2) was 0.08. Both temperature variables followed a diurnal trend (Figure 3.10).

The difference between water and air temperature can be explained by air and water properties, and the influence of the aquaponic infrastructure. Water (4.2 $\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$) has high specific heat capacity when compared to air (1.04.2 $\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$). Specific heat is the amount of heat energy needed to increase the temperature of a substance per unit of mass (Tadross & Johnston, 2012). Hence, water heats up and cools down more slowly than air, with the same addition or subtraction of energy. Consequently, more diurnal fluctuation was observed in air than with water temperature. As a result, water temperature had a similar fluctuation to air temperature; however, air temperature had a higher diurnal fluctuation than water temperature (Figure 3.10). In addition, in a few rare cases on cold days, the water temperature would be higher than air temperature during the day, because it absorbs and release heat more slowly than air.

Due to the specific heat properties of air and water, there was a constant lag of four hours observed between air temperature peak and water temperature peak. For instance, on 30 July (hottest day recorded by the station) the maximum air temperature was observed at 14h00 whereas water temperature increased until 18h00. Stefan (1992) obtained similar results using lag time of regression models between daily water and air temperatures. Moreover, due to deep water (water capacity 1000 l), less surface area exposed (fish tank area 1 x 1.2 m) and slow movement around the system, water was able to conserve the heat. The result concurs with the explanation of Illinois Environmental Protection Agency (2014), which stated that if water is deeper and has less surface area exposed, the heat will be conserved and the opposite is true.

The lag time of water and air temperature was approximately four hours during winter. Lag duration generally increased as environmental air temperature became warmer (Figure 3.11). The seasonal fluctuation observed showed more lag duration at the exit of winter season. The extended lag may be attributed to higher air temperatures and higher average fluctuation.

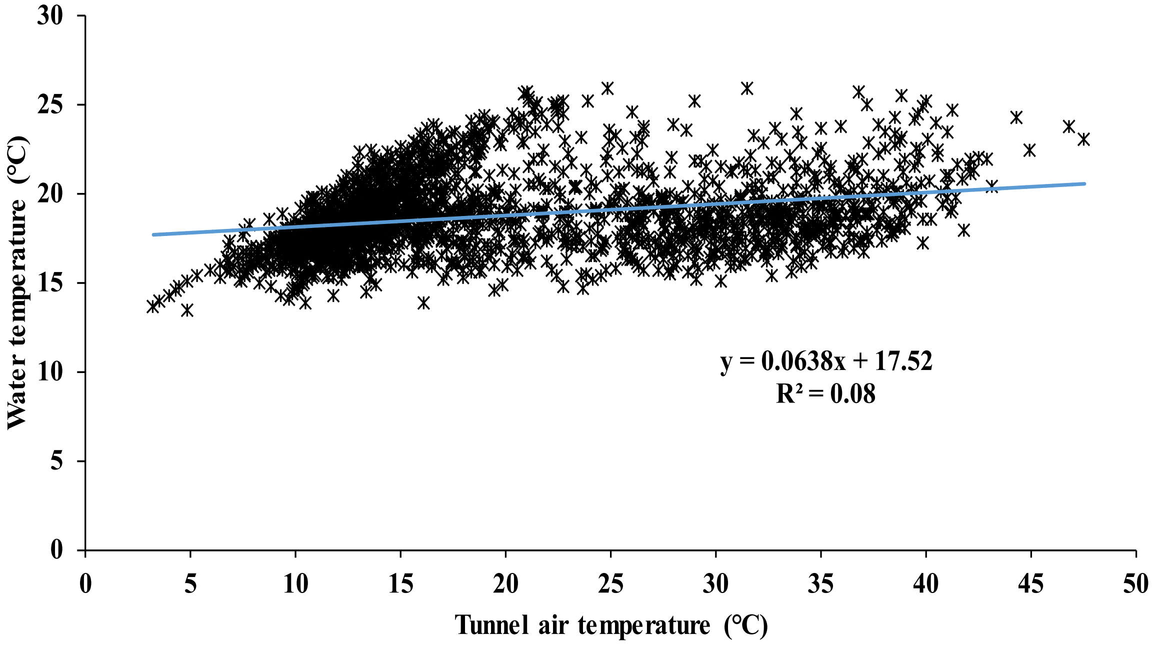


Figure 3.9 The hourly average relationship between air and water temperature in a tunnel environment from June to October 2019

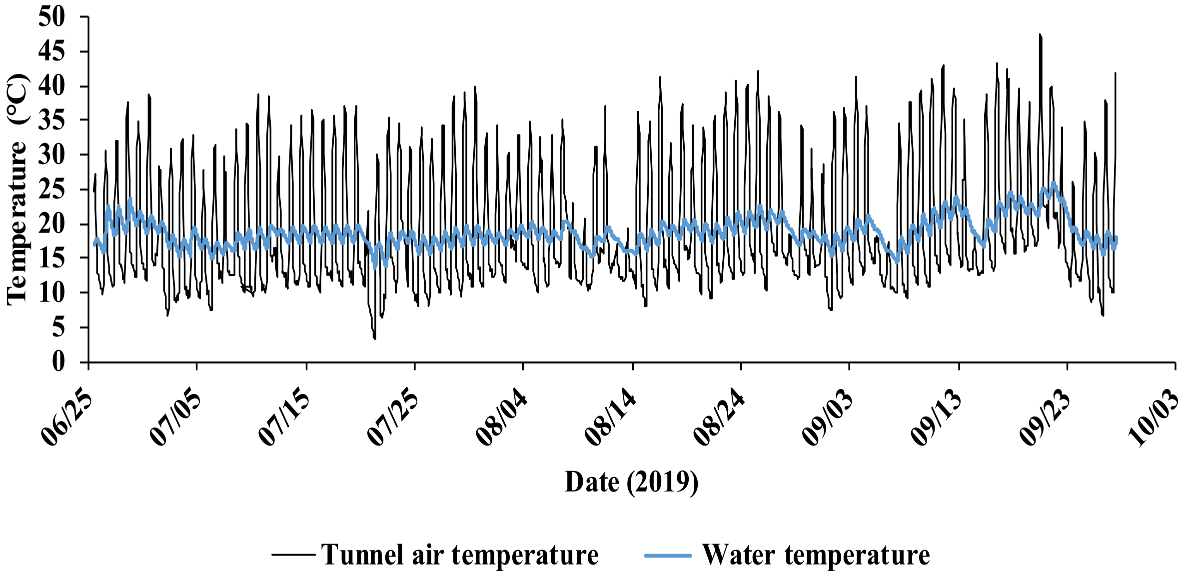


Figure 3.10 The hourly average air and water temperature calculation from June to September

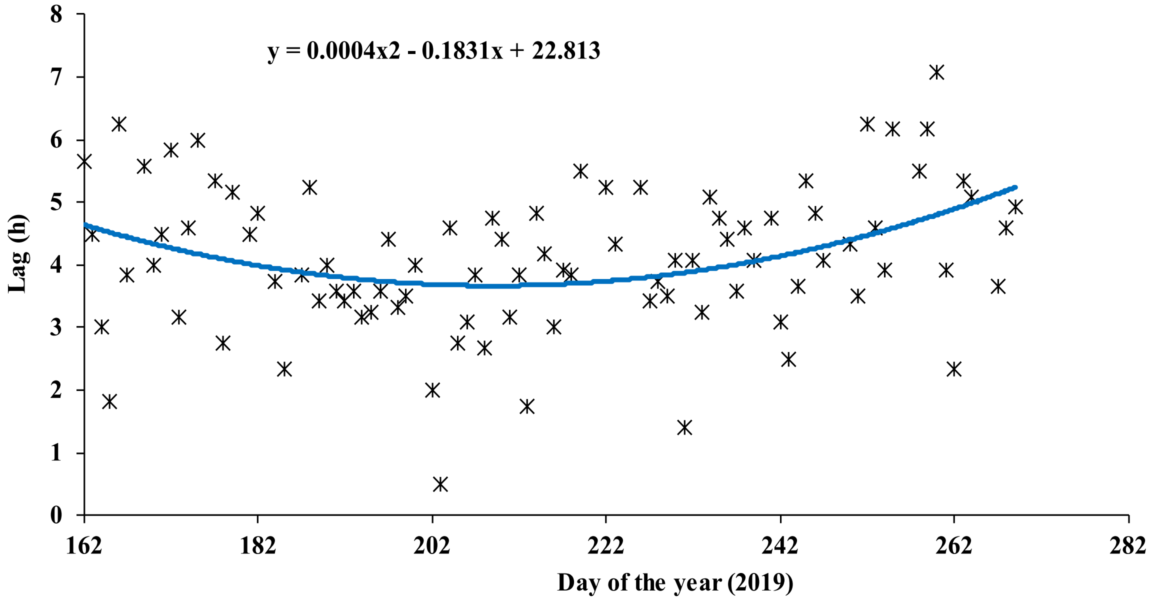


Figure 3.11 The hourly average lag graph from air temperature peak to water temperature peak from June to October 2019

3.4.2 Fish tank water temperature and plant tank water temperature

The minimum to maximum fish water temperature was 13.4-25.9 ℃. The minimum to maximum planting area water temperature was 13.2-26.1 ℃. The average water temperature of the fish and planting area was 18.7 ℃ and 18.7 ℃, respectively, with an average difference of 0.0054 °C, which is negligible. The coefficient of determination (R^2) was 0.98 and with a linear relationship between them (Figure 3.12).

The strong correlation between fish tank water temperature and plant tank water temperature could be a result of a closed system configuration. The water was circulated from the fish tank, through filters, then to the plant tank and finally returning to the fish tank (Figure 3.4). However, a five-minute data collection interval indicated that in most cases planting area water temperature was higher than fish tank water; however, the difference should not be considered significant. The slight increase in the planting area was a result of gravel used to support the plants' roots. Gravel has the properties of high albedo, meaning it absorbs more heat than it reradiates (Division, 2011).

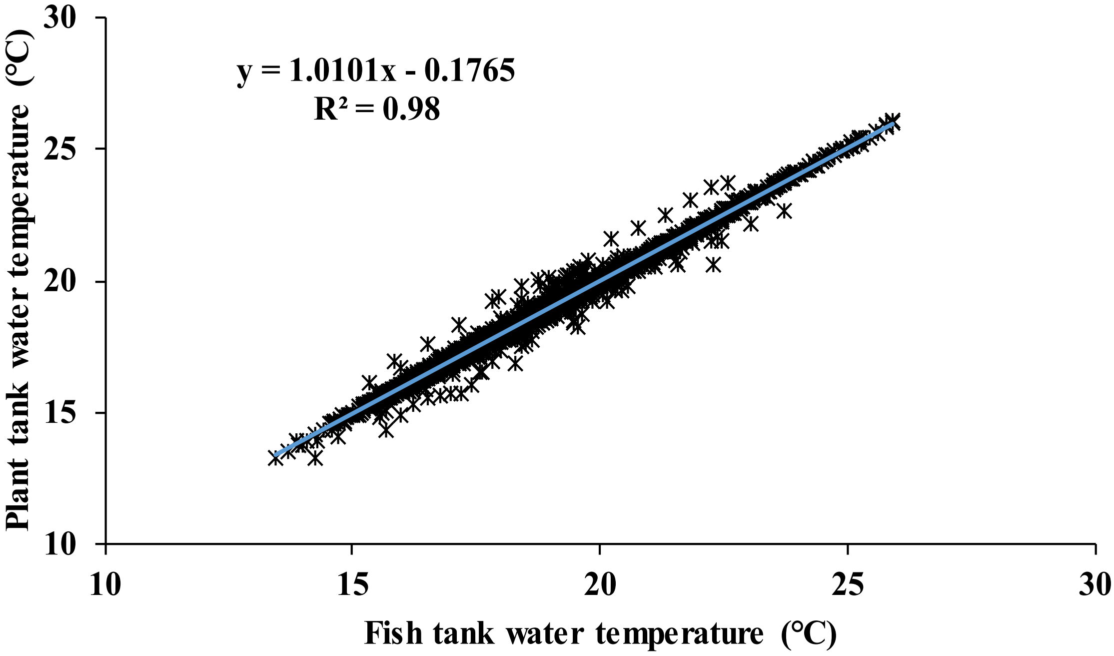


Figure 3.12 The hourly average relationship between fish tank water temperature and plant tank water temperature from June to October 2019

3.4.3 Environmental and tunnel air temperature

A diurnal fluctuation was observed in both temperature variables. Tunnel average air temperature (19.2 °C) was higher than environmental air temperature (15.9 °C). The minimum and maximum environmental air temperature was 3.9 and 35.3 °C, respectively. The minimum and maximum tunnel air temperature was 3.2 and 47.5 °C, respectively (Figure 3.13). The coefficient of determination (R^2) between the two hourly average temperatures was 0.68.

The tunnel experienced a significant increase in air temperature during the day. For example, on 21 July (coldest day recorded) the environmental air temperature had 11.8 °C readings at 12:00 pm whereas tunnel air temperature had a reading of 29.9 °C. Tunnel infrastructure increased air temperature by 18.1 °C; however, the difference varied depending on the time of the day (Figure 3.14). However, at night through to early mornings, tunnel air temperature was lower than environmental air temperature. According to the literature, many studies have related decreasing air temperatures at night to the fact that polystyrene and other plastic films allow the escape of solar heat (Jun *et al.*, 2018). The implication of the transparency of plastic film to visible light and long wavelengths is that solar heat escapes – i.e. heat energy or infra-red energy (Wien *et al.*, 2006; Thipe, 2014; Jun *et al.*, 2018). In addition, the Ndwedwe tunnel was unsealed, and the lower edges allowed exchange between environmental and tunnel air. As a result, the warmer air inside the tunnel continuously mixed with the cooler environmental air. The following section will expand on the difference between environmental and tunnel air temperature.

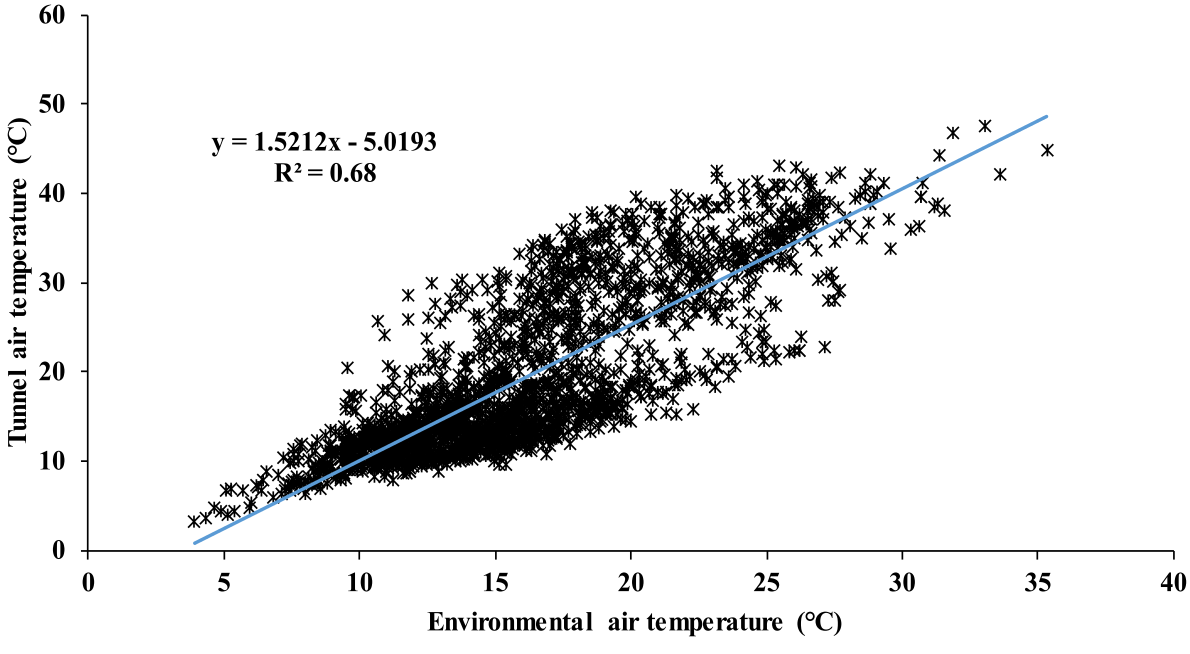


Figure 3.13 The hourly average relationship between environmental and tunnel air temperature from June to October

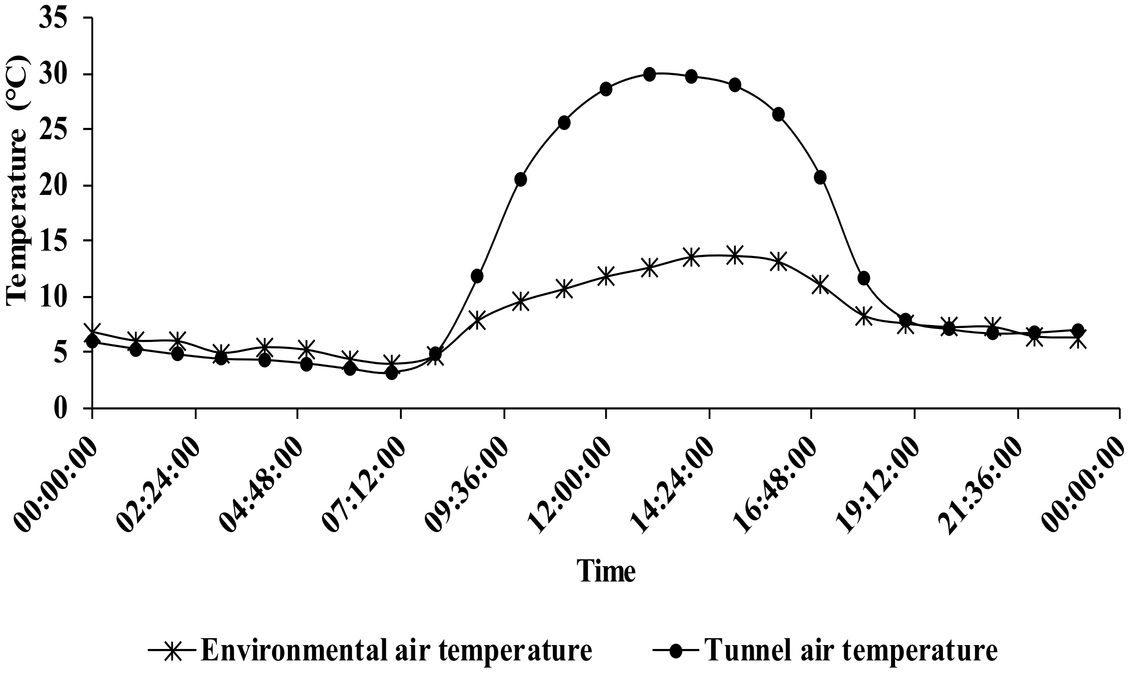


Figure 3.14 A typical example of tunnel infrastructure impact on air temperature during the day (21 July 2019)

3.4.3.1 Difference between environmental and tunnel air temperature

The tunnel increased air temperature by an average of 2.2 °C during the period of data collection (June to October 2019). During the day, the tunnel was observed to have a significant impact by increasing tunnel air temperature by 5.6 °C on average. The tunnel air temperature fluctuated seasonally, and the fluctuation increased from winter to summer as the environmental air temperature became warmer. However, at night and into the early mornings, the air temperature difference was negative, with an average of -2.1 °C, indicating that the tunnel was colder than the surrounding environment (Figure 3.15).

The average positive values lasted from 8:00 am to 18h00 pm, depending on how hot/cold the day was. During the day, the tunnel increased air temperature inside the tunnel. However, at night when solar radiation heat gain/terrestrial heat had escaped the tunnel, air temperature drops to ambient temperature or below. The environmental air temperature was observed to be warmer than tunnel air temperature around 19:00 to 7:30 on several days. On average, tunnel air temperature was lower than environmental air temperature by -2.05 °C. Love, *et al.*, (2015) obtained similar results, finding that at night tunnel air temperature drops to ambient temperature or below. As a result, between the night and into the early mornings the tunnel infrastructure had no benefit in terms of insulating air and water. However, the improper tunnel infrastructure and water inside the tunnel must be considered because they could be attributed to extra cooling of air temperature inside the tunnel (Water & Bureau, 2011).

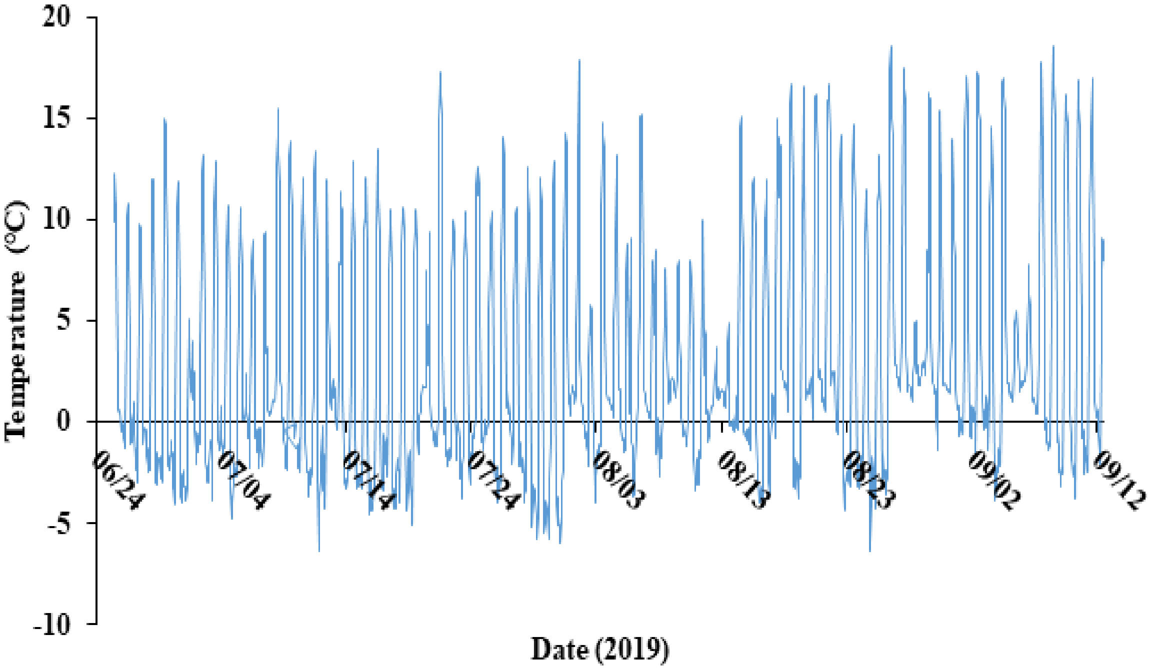


Figure 3.15 Difference between hourly average environmental and tunnel air temperature over a three-month period over the transition from winter to spring

3.4.4 Microclimatic parameters measured inside the tunnel

3.4.4.1 RH inside the tunnel environment

In this section, the purpose is to advise on the critical aquaponics climate parameters that involve plants, tunnel environment and labour working inside the tunnel. This section reports on the Relative Humidity (RH) and heat index under a tunnel environment.

A diurnal fluctuation was observed in both RH variables. Both tunnel environment and the surrounding environment RH readings had the correlative average of 66.6 % and 63.4 %, respectively. The minimum to maximum RH of tunnel environment was 10.9-100 %, respectively. The minimum and maximum RH of the surrounding environment was 8.9 and 100 %, respectively (Figure 3.16).

According to ASABE (2015), the optimal range of tunnel RH is around 50-70 %. During the day RH was generally about 30 % and at night RH increased to approximately 82 %. The increase in RH at night could be attributed to respiration from fish and plant water tanks and a decrease in air temperature. However, both high and low RH is detrimental for plant conditions (FAO, 2015; Shamshiri *et al.*, 2018; Biernbaum, 2013). High RH encourages bacterial and fungal diseases, affects germination stage, and favours foliar diseases in plants (ARC, 2013). Low RH drives water out of plants leaves through transpiration (FAO, 2015). Therefore, it is important to note that RH was generally within acceptable limits, although there were short periods with low RH (10 %) and high RH (100 %). The increase in RH could be attributed to transpiration from the plants and evaporation from open water.

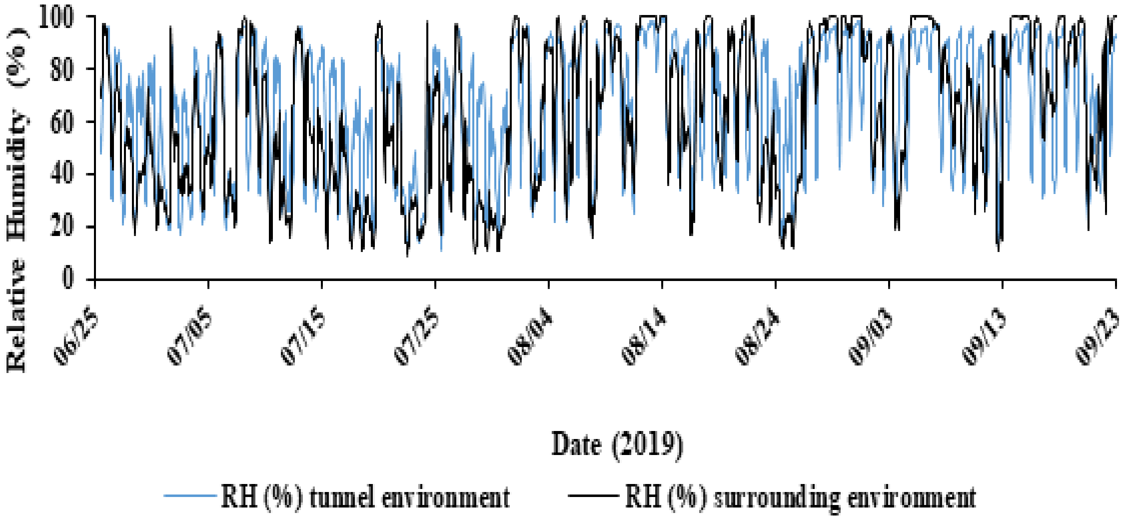


Figure 3.16 The hourly average RH readings between inside the tunnel and outside (the surrounding environment)

3.4.4.2 Heat index inside the tunnel environment

A diurnal fluctuation in heat index was observed with higher values experienced as the season changed from winter to summer. The minimum, maximum and average heat index was 3.2, 52.1 and 19 °C, respectively (Figure 3.17).

The heat index is the actual heat/temperature that is felt by the human body. According to the OSHA (2014) there are ranges of heat index where it's dangerous for a human to work under. The average heat index recorded inside the aquaponics tunnel was 19 °C, which is safe to work in. However, during the hot days the readings reach 52.1 °C – which is extremely dangerous and detrimental for human beings. The tunnel environment is unsafe to work in during hot days at high peak temperatures and the danger progresses as the season become hotter. The implication of working under the tunnel during a high heat index (33-45 °C) is fatigue, dehydration, nose bleed and collapse.

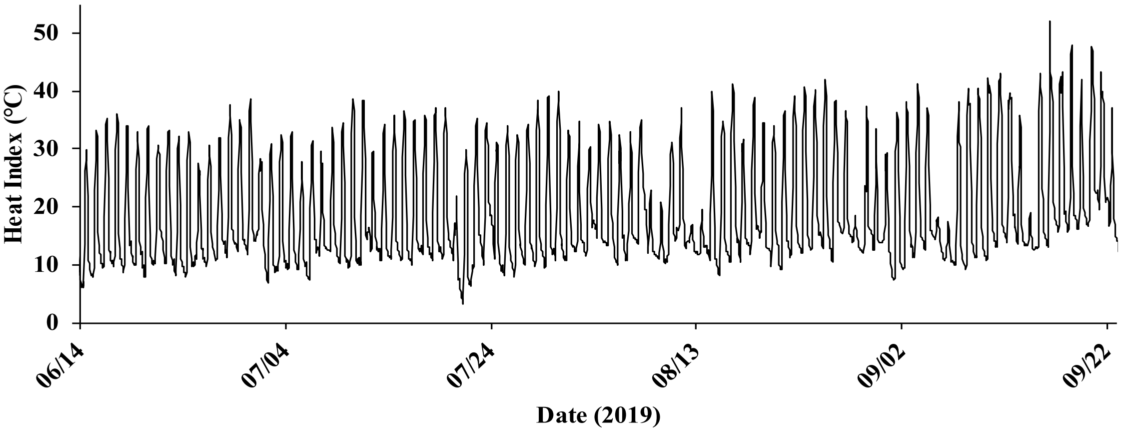


Figure 3.17 Heat index inside the tunnel environment over a three month period over the transition from winter to spring

3.5 Conclusion and Recommendations

Aquaponics is an emerging practice in South Africa and worldwide. This system of food production possesses great potential to address food insecurity in households. This is because it provides nutrition from fish and vegetables. Aquaponics is water efficient, environmentally friendly and potentially produces high vegetable yields from small plots of land. Aquaponics potentially addresses the overexploitation of natural resources such as arable land and water, as well as the unavailability of agricultural land. However, the disadvantages of aquaponics are that there is a high cost to establish a system and to maintain it, and there is a lack of information and expertise. Therefore, the expansion has been limited to commercial systems that can employ specialists. However, for the low-income group there is a need for simplified methods to help guide the practitioners on how to start, operate and sustain low-cost systems.

The objective of this study was to understand the relationship between environmental variables and water temperature of a low-cost aquaponic system. The result indicated that the tunnel infrastructure increased average air temperature by 2 °C. However, during

the day the tunnel increased air temperature by 5 °C and at night after the solar heat had escaped the air temperature dropped to ambient or below. Therefore, an additional layer or thicker plastic film is recommended to reduce the escape of terrestrial radiation at night, although the impact on day-time solar irradiance should be investigated.

There was a lag in temperature between water and air temperature inside the tunnel. The lag was found to be 4 hours from air temperature peak to water temperature peak. Generally, however, air temperature is not a good indicator of water temperature. The average water temperature was 18 °C, which was low in comparison to that recommended for aquaponics using *Tilapia* (22-32 °C). However, the *Tilapia* fish species survived low water temperature conditions, proving that it is a resilient species.

The average water temperature was observed to increase from 18 to 20 °C as the season shifted from winter to spring. This indicated that extended warm periods increase water temperature. The heat index towards the end of spring frequently exceeded the extremely dangerous levels and heat index levels should be noted before working in the tunnel during summer, in order to avoid dangerous working conditions

It was further observed that the low-cost aquaponic system was operational despite non-ideal conditions in terms of water temperature. With additional low-cost heating using locally available resources or indigenous knowledge systems, raising the water temperature to optimal thresholds would be beneficial particularly during winter season, and this requires further research.

3.6 Acknowledgments

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My supervisors: Dr Alistair Clulow, Dr Simon Taylor, Mr Ntobeko Mchunu and Dr Gareth Lagerwall – I thank you for your support.

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CHAPTER 4: IMPLICATION OF CLIMATE CHANGE IN A LOW-COST AQUAPONIC SYSTEM

4.1 Abstract

Climate change will have an unequivocal impact on agricultural crop production. Poor communities that depend on subsistence or small-scale farming are the most vulnerable, because they don't have resources to adjust their practices and survive poor seasons. Low-cost aquaponics farming methods have the potential to address the effects of climate change and food insecurity in poor communities. The purpose of this chapter was to identify the risks associated with climate change predictions on low-cost aquaponic systems.

The risks associated with climate change predictions on low-cost aquaponic systems were identified by assessing the current microclimatic conditions in the face of the future predicted climate. Chapter three results of how the environmental variables affect low-cost water temperature were used, and, the Intergovernmental Panel for Climate Change (IPCC) Fifth Assessment Report was used to identify the air temperature, rainfall and extreme events projected for KwaZulu-Natal, South Africa (2050).

The increase in mean annual air temperature is likely to increase the water temperatures, favouring conditions for *Tilapia* (22-32 °C). The frosts during winter will likely decrease because of warmer winter seasons. However, it was found that evaporation is a threat in a low-cost system because climate coolers like fans, wet walls and blowers are not available to minimise water loss. Ultimately, plastic tunnel infrastructure can be threatened by projected extreme weather like heavy rainfall and hail.

The conclusion of this study unpacked the threats and benefits of the projected climate change scenarios on the low-cost aquaponic system operated at Ndwedwe. It is recommended that the low-cost aquaponic system should be properly constructed by experts to minimise damage from the projected strong hail and heavy rainfall. Further studies are recommended for improved estimations of water temperature in the low-cost-aquaponic system. More information regarding future water temperatures will help practitioners to prepare for future water temperature fluctuations and evaluate the type of fish species that will possibly adapt best to that environment.

Keywords: *Climate change models; Climate change projections; Intergovernmental Panel on Climate Change; KwaZulu-Natal region; Low-cost aquaponic system;*

4.2 Introduction

Climate change is the average increase or decrease in mean annual temperature over a long period of time, which in this context refers to 30 years and above (Falco *et al*., 2019). There is evidence showing that climate change is caused by greenhouse gases (methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O)) that are naturally and anthropogenically emitted into the atmosphere and that causes positive radiative forcing (Fairbrother, Johansson Sevä and Kulin, 2019). The result of an increased concentration of greenhouse gases in the atmosphere has been observed to cause global warming and change weather patterns and affect ecosystems (Jury, 2017).

Climate change models are sophisticated mathematical representations that use quantitative methods to simulate climate important drivers such as land surface, atmosphere, ice and oceans to project future climate (Kattsov *et al*., 2013; Treut *et al*., 2007). According to climate change models, KZN has been predicted to have an average of 1.2-2°C increase in mean annual air temperature and an increase in extreme rainfall with prolonged dry days and drought (IPCC, 2014). To date, agricultural productivity has been affected by climate change through increasing temperatures, unreliable rainfall and extreme events such as heavy rainfall and high winds (Naab *et al*., 2019). As a result, crop production, e.g. maize and wheat, has significantly decreased over the past 20 years in South Africa (Nikolov & Petrov, 2016). There is therefore a need for innovative agricultural methods that will produce food sustainably.

Mchunu *et al.* (2018a) conducted an aquaponic study in South Africa and concluded that aquaponics may contribute positively to the challenges that are faced by agricultural crop production. Aquaponics is "the cultivation of fish and plants together in a constructed, recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrition. This is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers" (Thorarinsdottir, 2015 p. 26).

In aquaponic systems, plants and fish grow concurrently. Plants from hydroponic systems absorb nutrients from a combined aquacultural fish system – i.e. fish and plants are grown symbiotically (Carlsson, 2013; Lennard, 2009; Mchunu *et al*., 2018a; Rakocy, 2007). It has also been defined as a master system that serves a dual purpose simultaneously. Firstly, it recycles aquaculture effluent that is hazardous to the environment (FAO, 2014; Rakocy, 2007; Mchunu *et al*., 2018a). Secondly, it effectively uses the nutrients from the fish effluent (rich in nitrogen and phosphorus) to grow plants (Rakocy, 2007). Biological processes, water temperature, pH, oxygen, and dissolved solids are crucial for the success of this system (Sallenave, 2016).

The *Tilapia* fish species has been proven to be a superlative species in aquaponics (Rakocy, Masser, & Losordo, 2006; Love *et al*., 2015; Yildiz *et al*., 2017). This is due to its ability to survive in a wide range of water temperatures and water quality conditions. Moreover, *Tilapia* fish are a good protein source, and have omega 3 and various vitamins that benefit the human body.

It is well recognised that climate change will significantly influence agriculture into the future (Gomiero, 2016; Kleinwechter *et al*., 2015). It is therefore critical to assess the vulnerability of a low-cost aquaponic system under climate change predictions to determine whether it possesses potential to address food security within the context of climate change. Climate change projections, such as a 1.2-2 °C increase in mean annual temperature, extreme rainfall with prolonged dry days and drought may threaten low-cost aquaponic systems. Therefore, the study aims to identify the impact and risks associated with climate change on low-cost aquaponic systems during the near future (30 years) in KZN. With aquaponics promoted as a possible solution to food insecurity in many developing countries, it is important to assess its sustainability under projected climates.

4.3 Methods and Materials

4.3.1 Ndwedwe geographical location

The research was carried out within the province of KwaZulu-Natal in South Africa, in the rural area of KwaDeda, Ndwedwe (29.3245°S, 30.8901°E, alt. 962 m.a.s.l). Ndwedwe is a coastal area situated 20 km from the coastline. Large areas of Ndwedwe are characterised by dramatic steep topography (Municipality, 2018) (Figure 4.1). Ndwedwe experiences a humid subtropical climate (Cfa) and has a mean annual rainfall of 1133 mm (Kumirai & Africa, 2017; Municipality, 2018). The warmest month is February with minimum, maximum and average temperature of 23 °C, 28 °C and 26 °C, respectively. July is the coldest month with minimum, maximum and average temperature of 8.8 °C, 21.9 °C and 15.5 °C, respectively (Figure 4.2). Historically, Ndwedwe experiences most of its rainfall during the summer months (October to March) – with the most rain in February. The mean annual precipitation results in heavy flooding and intense summer storms. Recently, the Ndwedwe area has experienced low rainfall in comparison to historical rainfall (Municipality, 2018) and water availability is currently one of the major issues in this area. The Mkhomazi River, near the KwaDeda area is where most local people obtain their water for domestic use; however, due to steep topography, water is difficult to access.

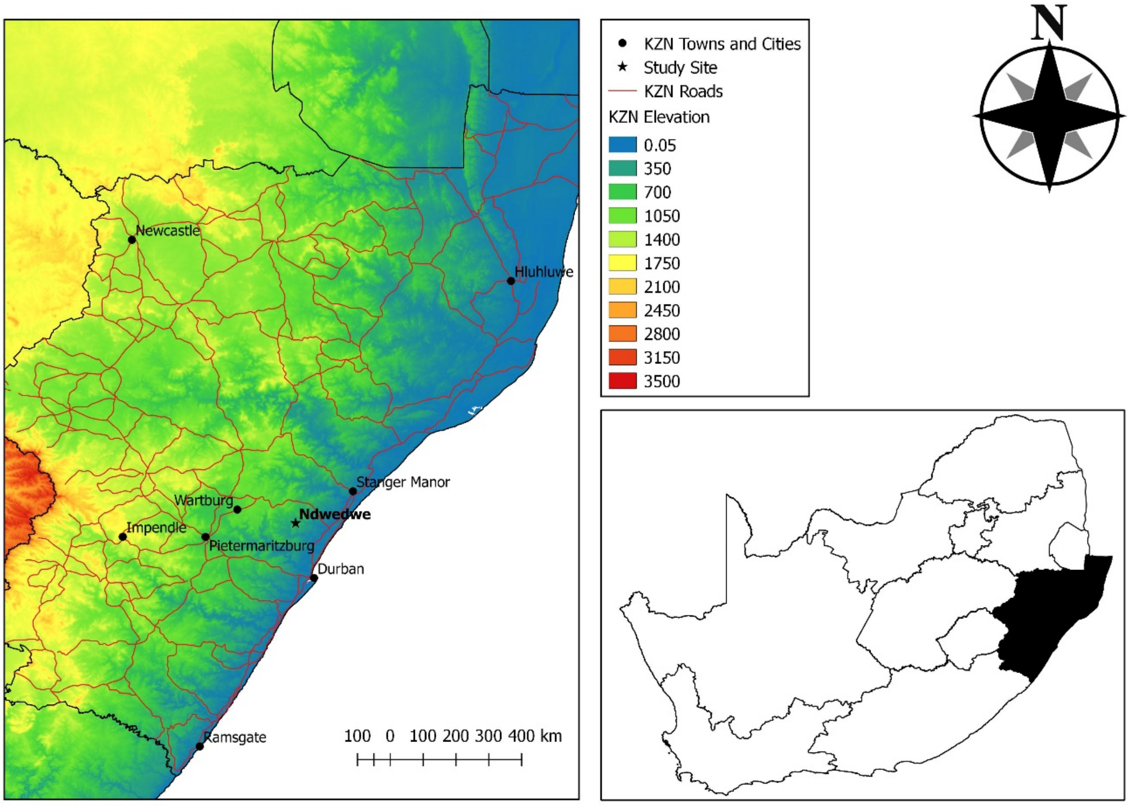

Figure 4.1 The location of the Ndwedwe study site (29°30'0"S, 30°56'0"E) in the KwaDeda township of the KwaZulu-Natal province, South Africa

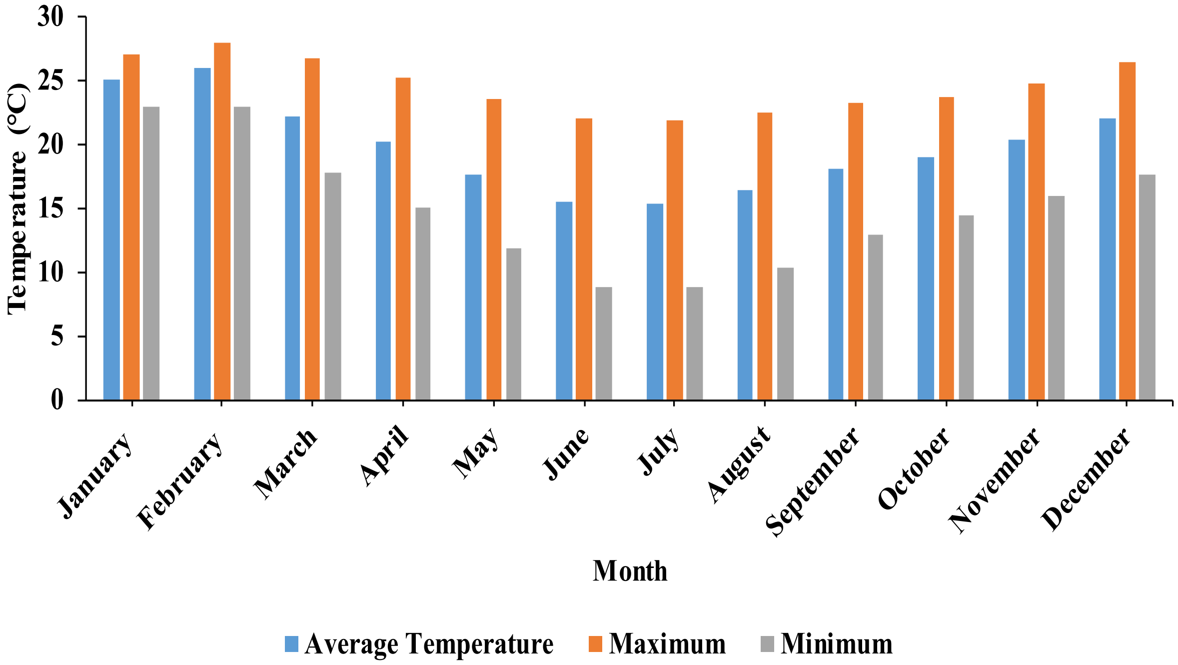

Figure 4.2 Minimum, maximum and average monthly temperatures at the Ndwedwe research site

4.3.2 Ndwedwe low-cost aquaponic system

The low-cost aquaponics system operated within an impoverished community called KwaDeda. According to this study, a low-cost aquaponic system is a low-tech system using low-cost, locally available material. It is a system that has a closed-loop with a maximum of 30 m^2 for the growing area. The production of fish and plants within a small area allows a small-scale farmer to achieve the daily income target of USD1.25 and food and nutrition security set by the Sustainable Development Goals 2030 (FAO, 2014).

The aquaponic system was operating under a high tunnel that was constructed in 2017 (Figure 4.3). The high tunnel is known as a hoophouse construction in some countries. The tunnel is a tube-shaped infrastructure usually made from white polyethylene plastic material. The purpose of the tunnel is to control environmental variables such as air temperature, wind speed, rainfall, solar heat, to protect crops from harsh weather conditions and to elongate the planting season (Shamshiri *et al*., 2018). Ndwedwe's tunnel infrastructure was constructed from white polyethylene plastic material, and light mesh was added on top of the plastic roof. Tunnel aspect was east – west to maximize radiant solar heat gain. However, the tunnel at Ndwedwe was poorly constructed in places, and the lower edges allowed exchange between environmental and tunnel air.

The Ndwedwe system had no water or air temperature regulators such as blowers, fans and water heaters, because they were stated to be expensive for the farmer. During hot days the tunnel was opened and closed as it became cooler – to regulate the inside air temperature. The farmer used Indigenous Knowledge Systems (IKS) to regulate air and water temperature of the fish and plants. The IKS included the use of sawdust left over from poultry farming to insulate the tanks. A black plastic sheet covered fish tanks to attract solar radiation and to supplement insulation. Furthermore, the fish tanks were submerged 40 cm into the ground to protect them from cold air at night as well at rapid fluctuations in air temperature. During the winter a geyser blanket was used to cover the fish tanks for better insulation of water temperature. However, according to the farmer, and water temperature probe data, the geyser blanket did not have a significant impact water temperature. An electric (230 VAC) pump was used to circulate the water and cost approximately R200 per month to run.

Figure 4.3 Ndwedwe aquaponics tunnel infrastructure

4.3.3 Theoretical framework

A theoretical framework was designed to understand the idea of the chapter – so that the aim and the research question can be answered (Bokhari & Masood, 2018) (Figure 4.4). In this chapter the focus will be on the current recorded microclimatic conditions in the Ndwedwe area, KZN, and the projected air temperature, rainfall and extreme events. The focus will be on air temperature, rainfall and extreme events, because it is hypothesized that they will potentially affect the low-cost aquaponic system and thus its success as a farming method in the future. The aim of this chapter was to understand the implication of climate change for the low-cost aquaponic system using future (2050) projected climatic data.

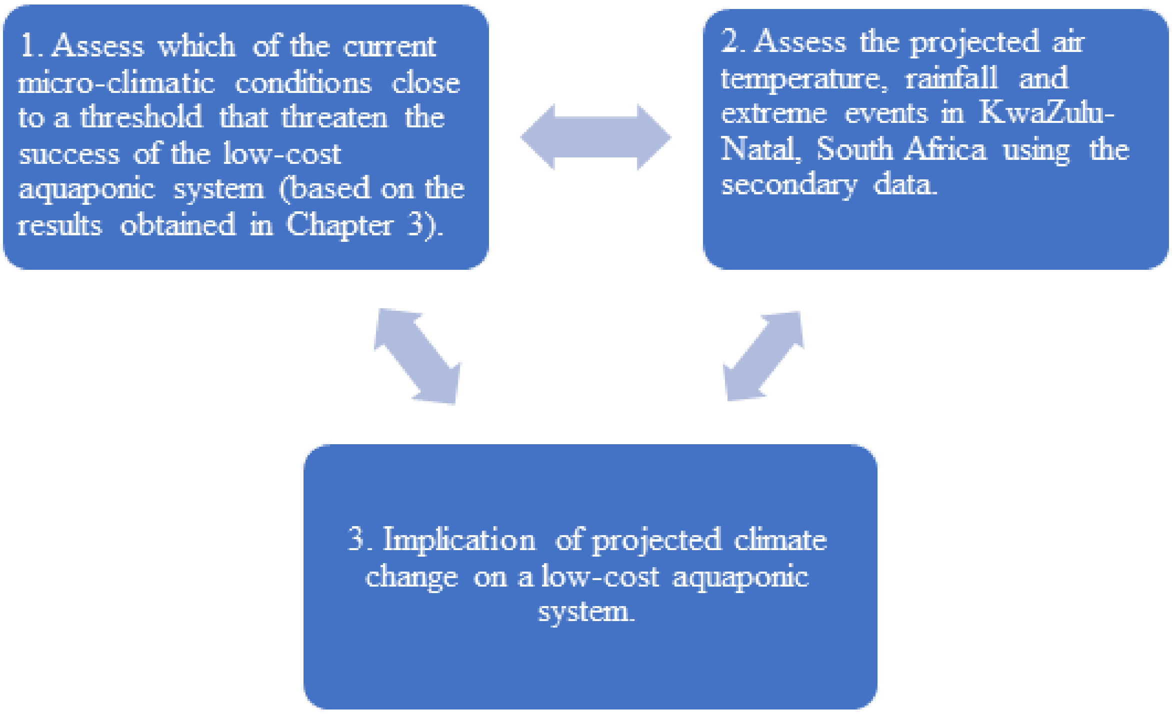

Figure 4.4 Theoretical framework

4.3.4 Methods used to determine the threshold that threatens the success of the aquaponics system

The results presented in Chapter 3 were used to determine the current low-cost aquaponic climatic conditions. The data were collected using an automatic weather station (Figure 4.5) at Swayimane High School (29.4878°S, 30.6603°E: 22 km from Ndwedwe), which provided supporting meteorological information describing the outside environmental conditions: rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA), air temperature and relative humidity (CS215, Campbell Scientific Inc., Logan, Utah, USA), and solar irradiance (LI-200X, LI-COR, Lincoln, Nebraska, USA) were recorded every 10 s. Appropriate statistical outputs were stored on a datalogger (CR3000, Campbell Scientific Inc.) at hourly and daily intervals and downloaded automatically using a modem. Equipment was installed according to recommendations of the World Meteorological Organisation (WMO, 2008), with the rain gauge at 1.2 m above the ground and the remaining sensors at 2 m above the ground.

An online measurement system was also installed inside the tunnel (29.5325°S, 30.9360°E) of the aquaponics system (Figure 4.5) to measure air temperature and relative humidity (CS215, Campbell Scientific Inc.), and plant and a fish water temperature (107, Campbell Scientific Inc.). Measurements were recorded every 10 s and statistical outputs were stored hourly and daily on a datalogger (CR310, Campbell Scientific Inc.). Data were downloaded hourly and published on a website for both stations. The water temperature sensors were cable-tied in the water tanks and the remaining sensors were installed at a height of approximately 2 m above the ground.

The relationship between the environmental variables air temperature and water temperature of a low cost aquaponic system were investigated using regression methodology and coefficient of determination (R^2) from Microsoft Excel 2016 (refer to Chapter 3), and correlation analysis from IBM Statistical Package Social Science (SPSS). Low-cost aquaponic threats were determined by assessing the climatic conditions that are close to the thresholds that could threaten the system.

With only temperature predictions, associated with climate change over the next 30 years, for air temperature, it was necessary to determine whether relationships exist between environmental air temperature and the tunnel air and water temperature. If relationships exist, then from air temperature predictions, it will be possible to infer likely trends in tunnel air temperature and tunnel water temperature (Objective 2).

Figure 4.5 Automatic Weather Stations of Swayimane (left) and Ndwedwe (right)

4.3.5 Methods used by the IPCC to project climate data

The data were collected from existing projections of climate change over the next 30 years. Existing projections refer to internationally recognised literature (McCray, & Chen, 2012). Well-known climate change publishers are the Intergovernmental Panel on Climate Change (IPCC). The IPCC is a worldwide body of intergovernmental scientists from the United Nations (UN) or World Meteorological Organization (WMO) that is devoted to providing scientific reports and future projections of climate change through assessing thousands of climate change publications. The projected climate thresholds of South Africa, KZN, were extracted from these reports to analyse how the global climate change affects the temperature of the local Ndwedwe area.

The IPCC use global climate models to understand possible future climate trends. The climate models are sophisticated mathematical representations that use quantitative methods to simulate important climatic drivers such as the land surface, atmosphere, ice and oceans. Model accuracies and reliability are tested using the Hindcasting processes. The Hindcasting process tests a model by making predictions of the present using historic data – i.e. predicting known data. If the model accurately predicted the past, it is assumed that it can predict the future. However, uncertainty of models exists, which is caused by fluctuations of air temperature, ocean currents, and wind patterns – amongst other things. The IPCC models are continuously being upgraded and improved to increase accuracy. In addition, there has been research focussing on downscaling to increase the spatial resolution of climate predictions (USDA, 2012; Schulze, 2016). To date, the results generated by IPCC have been trusted and used by many scientists and worldwide government policy-makers.

4.4 Results and Discussion

This section will be addressing this following objective of the study:

- Identify the expected climate change scenarios for KZN and assess the risks associated with climate change predictions on the low-cost aquaponic systems over the next 30 years.

4.4.1 Assessment of the current microclimatic conditions which are close to a threshold that threatens the aquaponic system

The microclimatic conditions of the aquaponic system located at Ndwedwe were collected in the period of winter to spring (June-October) 2019. The minimum to maximum environmental air temperature was 3.9-35.3 °C. The minimum to maximum tunnel air temperature was 3.2-47.5 °C (Figure 4.6). The minimum to maximum water temperature was 13.4-25.9 °C (Figure 4.7). The average of environmental air temperature, tunnel air temperature and water temperature were 15.9 °C, 19.2 °C and 18.7 °C, respectively.

All three temperature variables had a diurnal trend, but tunnel air temperature had a more extreme maximum and minimum temperature than environmental and water temperature. There was a trend of increasing average temperature in all three temperature variables from winter to the spring season. Due to the low-tech design of the system, water and air temperature were not altered to meet the optimal conditions for both fish and plants. Therefore, water temperature of the system was recorded to have an average of 18.7 °C, whereas the optimal condition for *Tilapia* ranges between 22 °C and 32°C. The water temperature never entered the optimal range for *Tilapia*.

The *Tilapia* fish survived the sub-optimal temperatures, due to their ability to survive in a wide range of temperature conditions. However, they had slow growth. FAO (2014) states that if the optimal condition of *Tilapia* are met, they can grow to a size of 60-100 g within a month, whereas at the Ndwedwe aquaponic system *Tilapia* weight was 35-40 g for two months. In addition, Love *et al.*, (2015) agreed with FAO (2014) and stated that during the winter season large expenditure went toward heating the water so that the fish can grow optimally and reach market size. Therefore, there was a threat in the low-cost aquaponic system located in a cooler region during most times of the winter season. This is due to temperatures below *Tilapia*'s optimal conditions, as there was no water heating and the *Tilapia* did not grow optimally.

The tunnel air temperature was significantly higher than the environmental air temperature with the difference averaging 5.6 °C during the day. The vegetables (summer and winter vegetables) that were grown in aquaponics were tomatoes, cabbage, beetroot, basil, pepper, parsley, onions and spinach. The recommended air temperature for summer and winter vegetable plants are 15-29 °C and 12-18 °C, respectively. The recommended root temperature for both winter and summer vegetable plants is 10-21 °C and 16-24 °C (ARC, 2010). Crops that were planted grew well despite the extreme air temperature during the day. However, germination and flowering stages were affected by hot temperatures, for example, some of the pepper and tomato flowers were slightly burned. However, there was no significant plant damage such as wilt and fruit bolts as a result of high temperatures. This could be attributed to water availability in plant roots – indicating that plant root temperature is more important than air temperature (Castle & Bevington, 2008). Water availability to the roots played a significant role in protecting plants from heat damage.

Tunnel air temperature was lower than ambient temperature by -2.1 °C, on average, during the night into early mornings. Love *et al*., (2015) obtained similar results, stating that at night, tunnel air temperature dropped to ambient temperature and below. According to Jun, Hwang and Yune (2018), Jun *et al*. (2018), Thipe (2014) and Wien *et al*. (2006), the drop of air temperature at night could be attributed to the polyethylene films that allow the escape of terrestrial radiation at night. There were cool conditions close to frosting observed during the winter season, as the temperature at night was around 3 °C on some occasions.

During the winter months 100-150 l of water was added every week into the system, with a total water capacity of 6 300 l. During the late winter to spring months, 200 l of water was added to the system every week. This is likely as a result of increased evaporation as a result of the increased air and water temperatures, with the progression from winter to summer. The local farmer running the aquaponic system observed that the aquaponics system used significantly less water than field farming, which used approximately 2000 l every week. However, KwaDeda is prone to dry spells and the observed threat is that the aquaponic systems require water throughout the year, whereas field agriculture is generally seasonal.

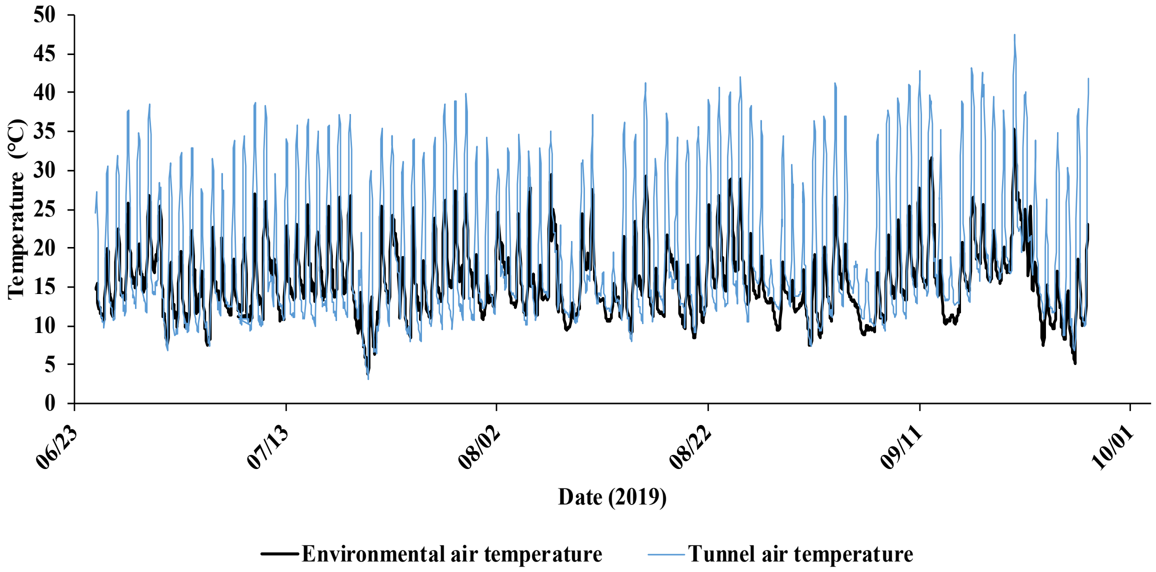

Figure 4.6 The hourly average of environmental and tunnel air temperature from June to October

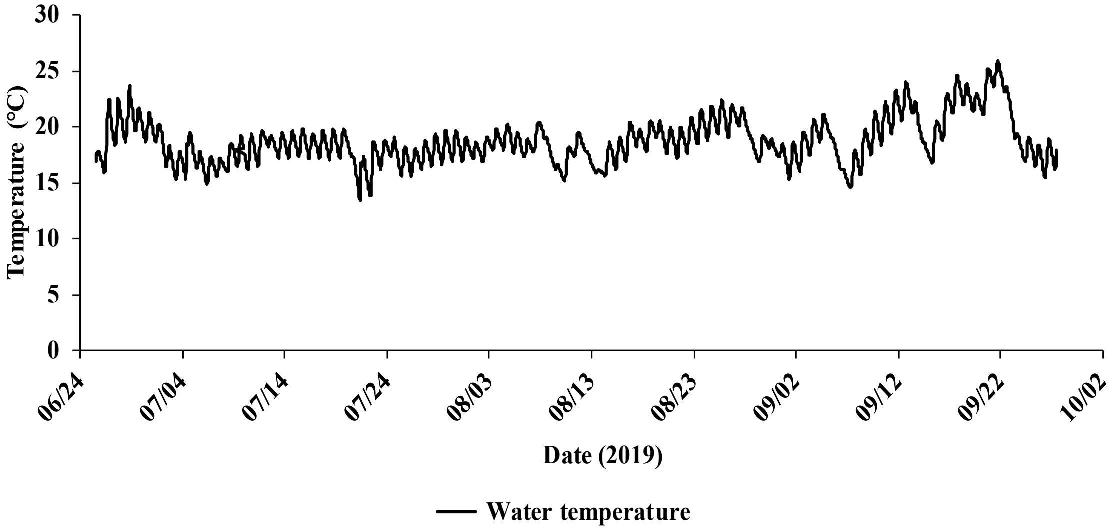

Figure 4.7 The hourly average water temperature from June to October

4.4.2 Assessing air temperature, rainfall and extreme event projections for KwaZulu Natal, South Africa, by the IPCC (Fifth Assessment Report, 2014)

South Africa is located at the southern tip of Africa. It is surrounded by the cold Benguela ocean current (West part) and warm Mozambican ocean current (East part). The ocean currents play a significant role in modifying South Africa's climate. The warm Mozambican current brings humid air and warm water down along the east coast from the equatorial zone, whereas the cold Benguela current brings a cooler and drier climate to the west coast from the Atlantic Ocean (Azzarri & Signorelli, 2019). The KZN region is located in eastern South Africa, where KwaDeda area is situated. This region is in a subtropical coastal climate zone with seasonal rainfall falling predominantly in summer. However, for the past 50 years the rainfall frequency has decreased in all South African hydrological zones (Schulze, 2016). The extreme climate events that have been observed in this region include droughts and storms with intense rainfall causing flooding resulting in much damage to infrastructure and the loss of human life.

According to the IPCC (2014), projections for the year 2050 for the KZN region forecast a mean annual temperature increase of 1.5 to 2 °C with high confidence (under the scenario of B1 and A2, respectively). However, the coastal regions are projected to experience less warming with a mean annual temperature increase of 1.0 to 1.5 ℃ in comparison to the interior regions (due to the ocean that regulates air temperature). Increases in mean annual temperature accelerate the melting of ice at the poles causing the sea level to rise by 0.58 m (RCP8.5) and/or 0.20 m (RCP4.5) (IPCC WG1AR5, Chapter 13). As a result, more flooding is expected in coastal areas. Fish communities are projected to be significantly impacted by temperature, the rise of sea level and ocean acidification. Increased ocean temperature decreases its ability to be a carbon sink. Furthermore, it results in decreases in the amount of dissolved oxygen in the oceans – adding to the significant fish extinction.

The rainfall is predicted to shift, with a delay in the onset of summer rains. In addition, changes in frequency and intensity are expected. As a result, extreme events of rainfall with high intensity and longer dry periods are expected. However, there is less confidence in rainfall prediction versus temperature due to model uncertainties. The annual surface evaporation is predicted to increase as a result of increased global surface heat over the land

and ocean and increased dry periods. The GCM, CMIP3 and AR4 project that all regions of South Africa will experience intense drought and dry conditions during the summer months; however, drought conditions will be more intense in the western provinces (Eastern Cape, Western Cape, North West) – progressing upwards Botswana and the Namibian desert. There are predictions that winds and tropical cyclones will increase in intensity and frequency in KZN (Figure 4.8).

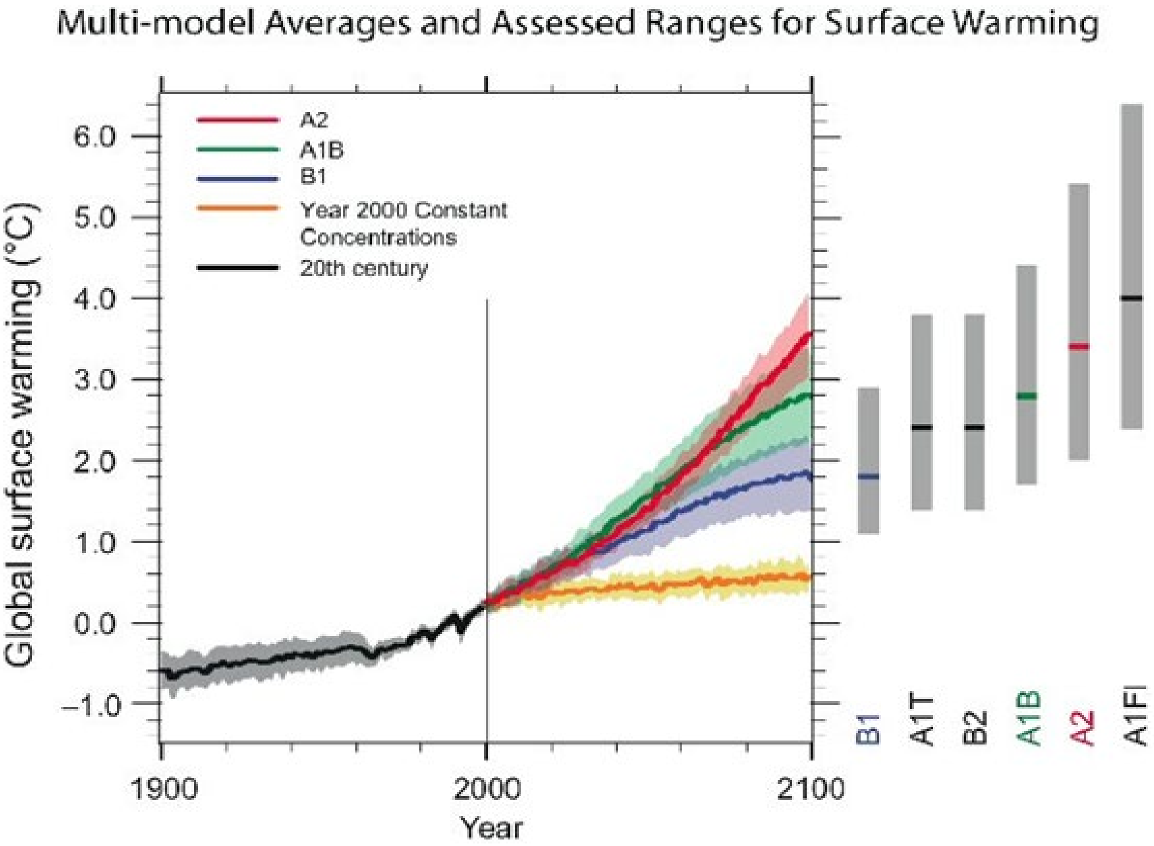

Figure 4.8 Multi-model averages and assessed ranges for surface warming (IPCC, 2014)

From the IPCC AR5 (2014) there are predictions according to location within South Africa. The arrow in the eastern part of South Africa in Figure 4.9 indicates the location of Ndwedwe where the annual average temperature is projected to increase by 1.2-2 °C by 2050. The projected scenarios and extreme events provided by the IPCC are described as:

- The coastal areas and cities are expected to experience intense flooding due to an increased sea level of 0.58 m (RCP8.5) and/or 0.20 m (RCP4.5). This will result in damage to infrastructure and agricultural lands.

- The rainfall intensity is expected to increase (high uncertainty in the magnitude), however, longer dry periods are expected.
- Fish communities are expected to be harmed by warming of the ocean.
- The frequency and intensity of storm surges in the coastal areas are expected to increase.

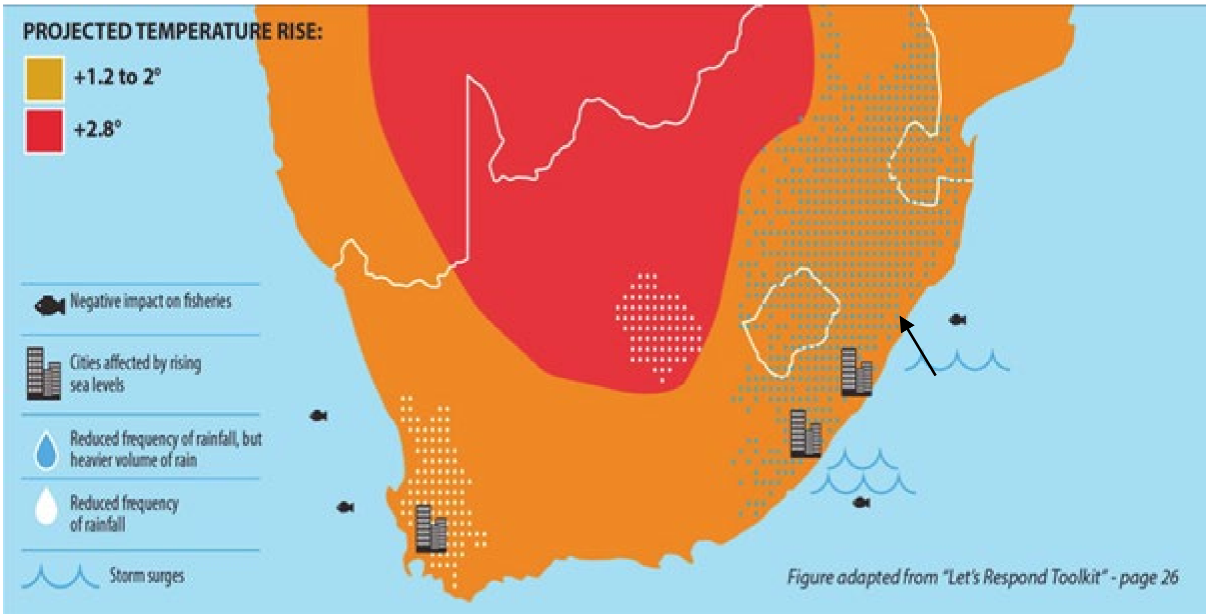

Figure adapted from "Let's Respond Toolkit" - page 26

Figure 4.9 Summary of climatic extreme events projected in South Africa (Rosegrant *et al.*, 2008)

4.4.3 Correlation of environmental air temperature, tunnel air temperature and water temperature of the low-cost aquaponic system: Results from IBM Statistical Package Social Science (SPSS)

There was a strong, positive correlation between the two variables (r =0.82, n = 2260, p < .001) indicating that the projected increase in mean annual air temperature is likely to result in an increase in tunnel air temperature (Table 4.1).

There was a medium, positive correlation between tunnel air temperature and tunnel water temperature, (r = 0.09, n = 1620, p > .001). The correlation coefficient indicates a poor relationship. This might be attributed to the differences in specific heat capacity of air and water temperature.

There was a strong, positive correlation between environmental air temperature and water temperature (r =0.07, n = 2260, p < .001). The correlation coefficient indicates a poor relationship. This might be attributed to the tunnel infrastructure and the differences in specific heat capacity of air and water.

Table 4.1 The correlation of environmental air temperature, tunnel air temperature and water temperature of the low-cost aquaponic system generated from the SPSS.

Correlations

Spearman's rho		Tunnel air temperature	Environmental air temperature	Fish water temperature
Tunnel air temperature	Correlation Coefficient	1.000	.818**	.092
	Sig. (2-tailed)		0.000	0.000
	N	2260	2260	1620
Environmental air temperature	Correlation Coefficient	.818**	1.000	.075
	Sig. (2-tailed)	0.000		0.002
	N	2260	2260	1620
Fish water temperature	Correlation Coefficient	.092	.075	1.000
	Sig. (2-tailed)	0.000	0.002	
	N	1620	1620	1620

**. Correlation is significant at the 0.01 level (2-tailed).

4.4.4 Implication of projected climate change on a low-cost aquaponic system: Results from Microsoft Excel 2016 Scatterplot regression

4.4.4.1 Air temperature

The coefficient of determination ($R^2 = 0.68$) indicated a good relationship between the environmental and tunnel air temperatures. Therefore, if the environmental air temperature increases by 2 °C there is likely to be an increase in tunnel air temperature. However, the increase in tunnel air temperature is not directly proportional to the increase in environmental air temperature, with the increase in tunnel temperature being 1.5 times that of air temperature (Figure 4.10). During the winter season, the threat of frost observed in plants inside the tunnel is likely to decrease in the future – as the temperature is expected to be warmer. For example, frost days in winter are reduced due to warmer temperatures in the Western Cape Province of South Africa (Plessis, 2016).

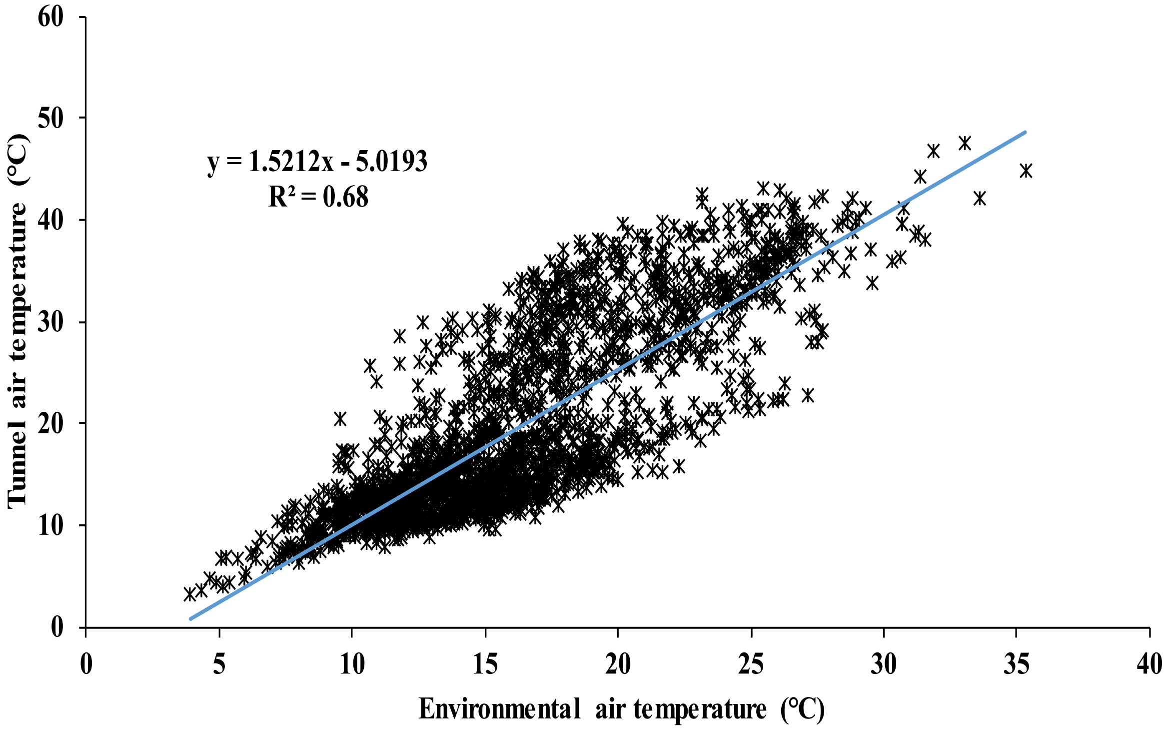

Figure 4.10 Average hourly relationship between environmental and tunnel air temperature measured at Ndwedwe (tunnel air temperature) and Swayimane (environmental air temperature) from June to October

4.4.4.2 Water temperature

The coefficient of determination indicated a poor relationship between hourly average environmental air temperature and water temperature (R^2 = 0.08). However, at a daily average interval, the relationship of environmental air temperature and water temperature was improved (R^2 = 0.68).

The improved relationship between water and tunnel air temperature using daily data could possibly be due to the high specific heat capacity of water compared to air (air 1.04.2 $kJ\cdot kg^{-1}\cdot K^{-1}$ and water 4.2 $kJ\cdot kg^{-1}\cdot K^{-1}$) and the lags shown in water temperature changes (see Chapter 3). Hence, water heats up and cools down more slowly than air, with the same addition or subtraction of energy.

However, the coefficient of determination of 0.76 was found when the average daily water temperature was lagged by one day, again likely the result of the higher specific heat capacity of water versus air (Figure 4.11). The threat of low water temperatures stunting fish growth observed inside the tunnel is likely to only decrease in the future as the tunnel air temperature is expected to be warmer. This is a positive indication for warm water species used in aquaponics like *Tilapia*. However, an increase in water temperature decreases the amount of dissolved oxygen in water which will also affect fish, bacteria and plant life. It should be noted that warming of water is not directly proportional to air temperature, and an increase in water temperature is approximately half (0.52) the increase in air temperature.

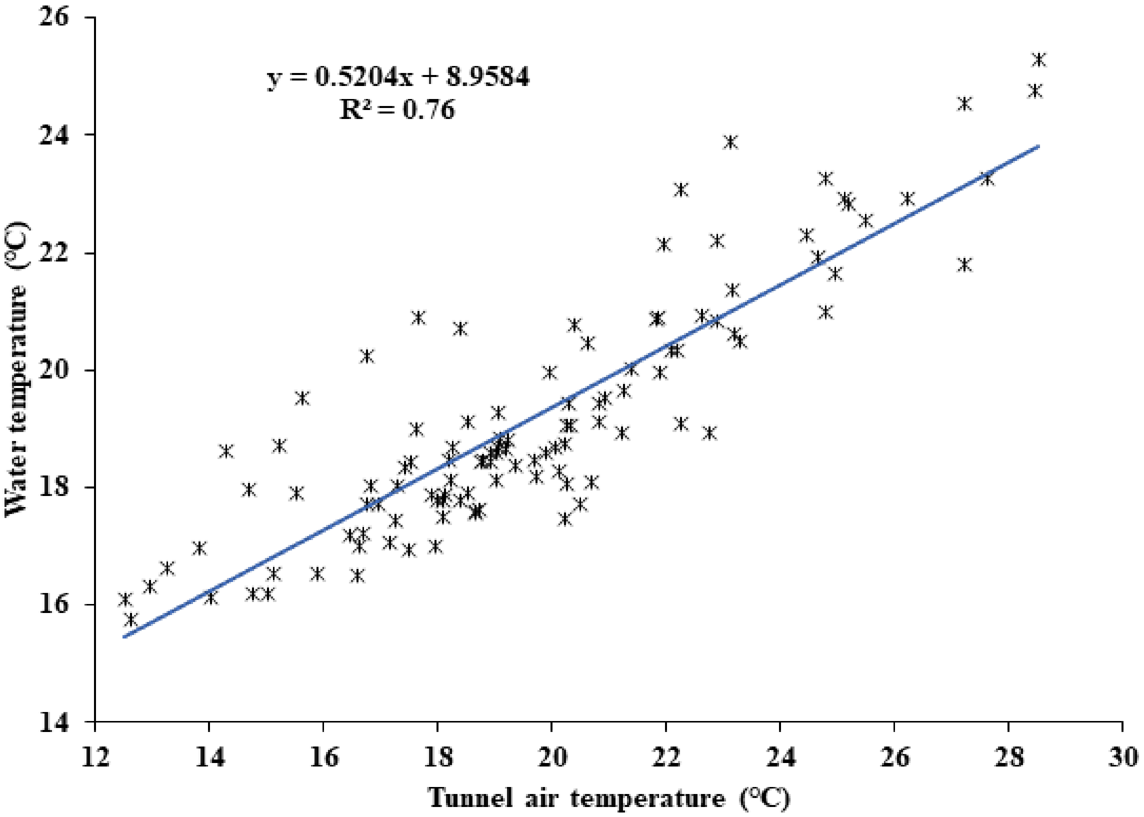

Figure 4.11 The relationship between daily average tunnel air temperature and water temperature

4.4.4.3 Water requirement

Currently, the Ndwedwe aquaponics operator reported (Ngcobo, September 2019) that in winter months approximately 100-150 l of water was added every week to the system (full water capacity 6 300 l). In spring and the summer months, approximately 200 l of water was added to the system every week. This increase is likely due to increased evaporation in summer when temperatures and radiation are higher and they drive evaporation higher. The IPCC projected that the annual surface evaporation is expected to increase as a result of an increase in the mean annual air temperature. Furthermore, studies indicate a good relationship between environmental variables (air temperature, solar radiation, wind and RH) and evaporation (Shamshiri *et al*., 2018). Therefore, if the tunnel air temperature is expected to increase, it is likely that evaporation will increase. However, if the RH is high, less evaporation will be expected. The observed microclimate data inside the aquaponic tunnel showed that the average daily RH was 38 % and 78 % during the day and night, respectively. As a result, during the day when the air is dry – more evaporation is expected.

It should be noted that the need to top-up the system water is not only caused by total evaporation (water evaporation and plant transpiration). Leaks and operational loss (cleaning tanks) also resulting in the need for adding water to the system. During the data collection period, system leaks were checked for regularly and were repaired.

Climate change projection poses two threats for the water requirement in this low-cost aquaponics system situated in a dry area. First, evaporation is likely to increase outside (rivers and lakes) and inside the tunnel. Second, extended dry periods are expected in the future. In rural areas such as Ndwedwe, where water is obtained from rainwater harvesting and rivers, water to add to the system may not be available when it is required.

4.4.4.4 Tunnel cover

A commonly used plastic material to cover tunnels is polyethylene, because it is strong and relatively cheap. Historically, KwaZulu-Natal has experienced extreme climate events such as hail storms and heavy rainfall that damaged and/or destroyed tunnel plastic covering (Schulze, 2016). For example, hydroponic farmers experienced devastating losses due to plastic tunnel infrastructure that was wrecked by heavy storms in southern KwaZulu-Natal, in 2015 (Labuschagne & Zulch, 2016). Therefore, with a projected increase in extreme events due to climate change, it is likely that there will be an increase in damage to such covers. Table 4.2 summarises the possible impact of the projected climate change in a low-cost aquaponic system.

Table 4.2 The implication of climate change projections of the low-cost aquaponic system: Results from microclimate data of a low-cost aquaponic system at Ndwedwe and IPCC climate projection at KZN, South Africa

Areas of vulnerability of the low-cost aquaponic system	Projected change in climate for KwaZulu-Natal, South Africa	Possible impact on aquaponics
Low average water temperature that threatens fish growth (18.7 °C).	Increase in mean annual air temperature by 1.2-2 °C.	Increase in water temperature in the long-term.
Low average air temperature in winter threatening plants with frosts (3 °C).	Increase in mean annual air temperature by 1.2-2 °C.	Increase in average air temperature in winter.
Water requirement.	Increase in mean annual air temperature by 1.2-2 °C. Extended dry periods.	Increase in water requirement through increased evaporative losses. Reduction in available water.
Plastic covering material of tunnel.	Increase in destructive extreme events (hail, extreme rainfall).	The plastic covering material (polyethylene) is susceptible to breakage/damage.

4.5 Conclusions and Recommendations

The climate change projection models have proven that the additional GHGs in the atmosphere are a result of human activities such as burning fossil fuels and agricultural practices. As a result, GHGs are accumulating in the atmosphere and trap terrestrial heat, resulting in anthropogenic climate change and global warming. Subsequently, floods, droughts, unreliable rainfall and heat waves become frequent. Resource-poor rural communities are the most vulnerable to climate change because they are isolated and don't have financial resources to recover after devastating agricultural losses. Most of these communities rely on subsistence or small-scale agriculture for their survival. A shift in climate is likely to have significant implications for their food security.

Some researchers state that aquaponic systems have the potential to address the effects of climate change and threats to food security. Aquaponics combines hydroponics and aquaculture into one system, where fish and plants grow together. This system conserves scarce natural resources like water through reuse. Aquaponics is a soil-less system that is advantageous for South Africa where additional arable land is lacking. Aquaponics therefore has the potential to address food security challenges because it produces both meat (fish) and vegetables. Fish are a good protein source, and of omega 3, and vegetables have various vitamins that benefit the human body. However, aquaponic systems have a high initial installation cost and poor communities cannot participate due to a lack of financial support.

However, low-cost aquaponic systems have been adopted from commercial systems by poor communities. Though there are no microclimate regulators such as air and water heaters and coolers, the system survives. *Tilapia* fish species were used at Ndwedwe because *Tilapia* can survive high fluctuations in water temperature and poor water quality. However, there were threats and opportunities observed in the low-cost aquaponic system including fish growth, high water temperature, increased evaporation during hot days, and the plastic material of the tunnel being susceptible to physical damage.

The study findings indicated that the increase in mean annual air temperature will not be a threat to the low-cost aquaponic system. It is possible that an increase in environmental air temperature will result in an increase in water temperature, favouring optimal conditions for *Tilapia* that require warmer water than is currently available at Ndwedwe. However, an increase in water temperature decreases dissolved oxygen in water, which will require more power to pump oxygen. Decrease in dissolved oxygen is also projected to affect the fish community in the sea, and hence aquaponic systems that can be adjusted to meet the optimal conditions of fish will be in great demand. The high air temperatures in the tunnel can be dangerous for humans, but the plants did not show significant symptoms of heat damage during hot days – because of water availability to the roots that acts as a cooling mechanism for plants.

Frost during winter is likely to decrease because of warm winter seasons due to expected increases in mean annual air temperature. However, evaporation is a threat to the low-cost systems and increased temperatures are likely to result in increased evaporation – as were observed in the changes in evaporation from winter to spring. The extended dry periods that are projected under climate change are a potential threat to aquaponics if located in an area where water is difficult to access, such as in Ndwedwe. Covering fish tanks may be useful for minimising water loss though evaporation. The threat of damage to the plastic tunnel infrastructure through extreme weather events including high winds, intense rainfall and hail, should however be considered when building aquaponic systems. There is a need for a design of a low-cost tunnel that is strong so that it is not vulnerable to extreme weather conditions.

Low-cost aquaponic systems have the potential to produce food sustainably in future, with the projected climate conditions up to 2050, and offer potential to meet the challenges of food security and climate change in poor communities. However, further studies are recommended for improved estimations of water temperature in the low-cost-aquaponic system. More information regarding future water temperatures will help practitioners to prepare for future water temperature fluctuations and evaluate the type of fish species that will possibly adapt best to that environment.

4.6 Acknowledgments

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My supervisors: Dr Alistair Clulow, Dr Simon Taylor, Mr Ntobeko Mchunu and Dr Gareth Lagerwall – thank you for your support.

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CHAPTER 5: SYNTHESIS AND CONCLUSION

5.1 Overview of the Study

Aquaponics is gaining attention worldwide and available information focuses on the operational information to assist practitioners to kickstart their systems. There is enough information showing that aquaponics has the potential to combat food insecurity worldwide. The available information is however more focused on the expensive commercial scale operation, putting a barrier on poor communities who wish to adopt an aquaponic system. There is a lack of information on low-cost, small-scale aquaponic operation, particularly, in relation to how the environmental variables affect the water temperature of a low-cost system. This information is significant because the literature reveals that environmental conditions affect water temperature – which can in turn lead to system failure. In a low-cost aquaponic system there are no microclimate regulators such as air and water heaters and coolers. As a result, a study was conducted to understand the relationship between the environmental variables (air temperature and relative humidity) and water temperature of a low-cost aquaponic system (Chapter 3). The findings were:

- The average water temperature was 18 °C, which was low in comparison to recommendations for *Tilapia* (22-32 °C). *Tilapia* fish can survive in a temperature that is below their optimal requirements. However, it was recognised that low average water temperature stunted *Tilapia* growth.
- The tunnel infrastructure increased the average air temperature inside the tunnel by an average of 2 °C. During the day, the tunnel increased air temperature by an average of 5 °C and at night the air temperature dropped to ambient or below by an average of -2.1 °C.
- There was no relationship between water and air temperature inside the tunnel; however, there was a lag observed. The lag was discovered to be 4 hours from tunnel air temperature peak to water temperature peak. Therefore, air temperature inside the tunnel is not a good indicator of water temperature inside the tunnel.
- Environmental variables such as air temperature have a significant impact on the climate dynamics inside the tunnel despite not being able to identify a fixed relationship between them (air temperature and water temperature).
- An additional study (Chapter 4) was conducted to understand the implication of climate change on a low-cost aquaponic system. Some researchers state that aquaponic systems can address climate change effects because these systems conserve scarce

natural resource like water, through reuse. However, there was no study in the literature to address or prove this statement. Furthermore, aquaponics is a soil-less system which is advantageous for South Africa that lacks additional arable land. The climate models have confidently projected the mean annual air temperature to increase by 2 °C by the year of 2050 in the South Africa, KZN region, and this will have the following implications for the environment:

- The coastal areas and cities are expected to experience intense flooding due to an increased sea level of 0.58 m (RCP8.5) and/or 0.20 m (RCP4.5). This will result in damage to infrastructure and agricultural lands.
- The rainfall intensity is expected to increase (high uncertainty in the magnitude; however, longer dry periods are expected.
- Fish communities are expected to be harmed by warming of the ocean.
- The frequency and intensity of storm surges in the coastal areas are expected to increase.

These projections were assessed to identify the implication of the climate change projections on the low-cost aquaponic system. The findings of this study concluded that:

- The increase in mean annual air temperature will not threaten the low-cost aquaponic system. There is a possibility that the increase in environmental air temperature, will result in an increase in water temperature, favouring the optimal conditions for *Tilapia*, which require warmer water than is currently experienced at Ndwedwe. However, this benefit comes with the threat of a decrease in dissolved oxygen, requiring more power usage for an oxygen pump.
- Plants did not show significant symptoms of heat damage during hot days, because of water availability to the roots systems, which acts as a cooling mechanism for the plants, by moderating their temperature. Furthermore, the chance of frost occurring during winter is likely to decrease because of expected increases in mean annual air temperature.
- Increased evaporation is a threat to low-cost systems because there are no air or water coolers and gaps in the plastic allow the exchange of air and water vapour resulting in water loss from the system. Together with extended dry periods that are projected under climate change, the systems will need to be near an available

water resource. In Ndwedwe this would be problematic, as the community rely on river flows.

- The threat of damage to the plastic tunnel infrastructure through extreme weather events including high winds, intense rainfall and hail should be considered when building aquaponic systems in the future.

5.2 Restatement of the Aims and Objectives

Aim:

To measure and assess the temperature dynamics of a low-cost aquaponic system during a winter season and to synthesise the possible effects of future climate change predictions on the sustainability of the low-cost aquaponics system.

The first part of the aim – to measure and assess the temperature dynamics of a low-cost aquaponic system during a winter season – was successfully addressed in Chapter 3. The second part of the aim was to synthesise the possible effects of future climate change predictions on the sustainability of the low-cost aquaponics system, and this was successfully addressed in Chapter 4.

Objectives:

- Identify a suitable low-cost aquaponics system installed in a rural community of KwaZulu-Natal (KZN) that is productive;
- Set up monitoring equipment within a lost-cost aquaponics system
- Identify nearby weather stations to provide environmental weather data;
- Assess the relationship between environmental variables and water temperature in a low-cost aquaponics system; identify the expected climate change scenarios for KZN;
- Identify the risks associated with climate change predictions on the low-cost aquaponic systems over the next 30 years in KZN.

Both aims and objectives of this study were successfully addressed in their respective chapters. However, there were limitations and challenges that were encountered during the course of the research, and they are discussed in the following section.

5.3 Research Limitations and Challenges Encountered

A challenge encountered while conducting this study was to find a suitable low-cost aquaponic system and an owner willing to allow research to be conducted. The financial threshold for identifying the low-cost aquaponic system was: an operating system using a low-tech system and of low-cost and manufactured from locally available material. In addition, it needed to be a closed-loop system to save water and have a maximum of 30 m^2 for the growing area; the production of fish and plants within a small area allowing small-scale farmers to achieve the daily income target of USD1.25 and food and nutrition security, which was set by the Sustainable Development Goals 2030 (FAO, 2014). A number of aquaponic systems that were available, were either above the threshold of the required low-cost aquaponic system or were experiencing complex political and relational difficulties preventing access and research. However, the Ndwedwe aquaponic system was aligned with the selection threshold of the low-cost aquaponic system, and the farmer was enthusiastic to support the research.

Modelling future water temperature conditions from the expected increase in average air temperature for the area was a challenge, however, Microsoft Excel 2016 was used to understand the possible future water temperature conditions using the current relationship between air and water. There are no studies modelling future water temperatures inside an aquaponic tunnel.

5.4 Recommendations for Future Research

- Continued measurement into summer to develop a model describing the relationship between air temperatures outside and water temperatures inside. This may require multiple regression to include solar irradiance, relative humidity and wind speed.
- More detailed projections of how air temperature is likely to change, rather than just an increase in the average, would allow for improved estimations of water temperature in the aquaponic system. More information regarding future water temperatures will help practitioners to prepare for future water temperature fluctuations and evaluate the type of fish species that will possibly adapt best to that environment.
- Extrapolate the water temperature model to other areas, to provide a map showing suitable areas where aquaponics with different fish species have a potential to thrive.
- Investigate low-cost methods to reduce the cooling of the tunnels at night, which results in cooling of the water.
- Investigate low-cost methods of heating water during the day.
- Investigate low-cost methods of minimising evaporation and water loss.
- Design a low-cost tunnel that is strong enough not to be vulnerable to extreme weather conditions.

- Investigate the possible impacts of climate change on water quality issues within the aquaponic system.

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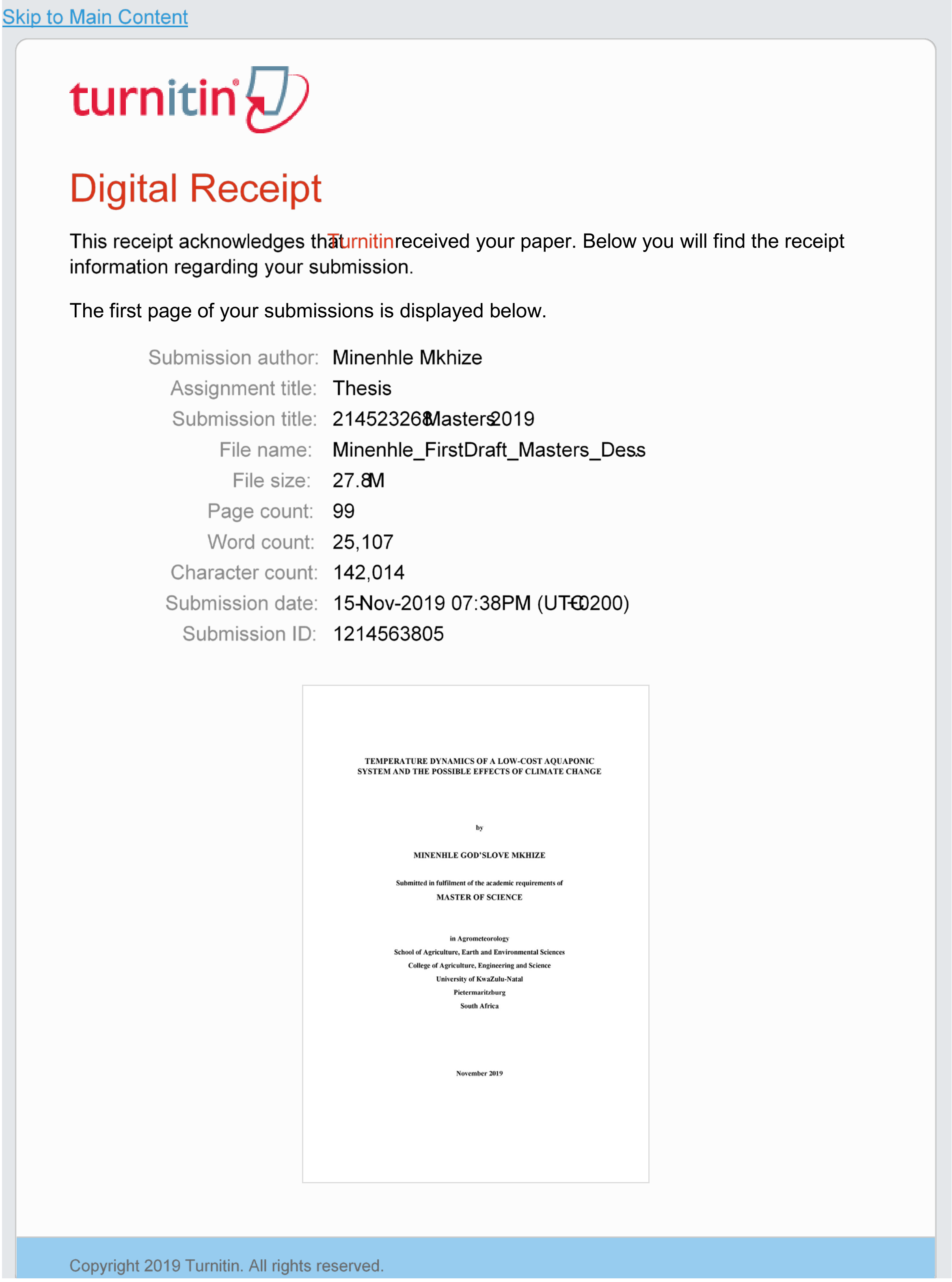

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TEMPERATURE DYNAMICS OF A LOW-COST AQUAPONIC SYSTEM AND THE POSSIBLE EFFECTS OF CLIMATE CHANGE

by

MINENHLE GOD'SLOVE MKHIZE

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in Agrometeorology
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College of Agriculture, Engineering and Science
University of KwaZulu-Natal
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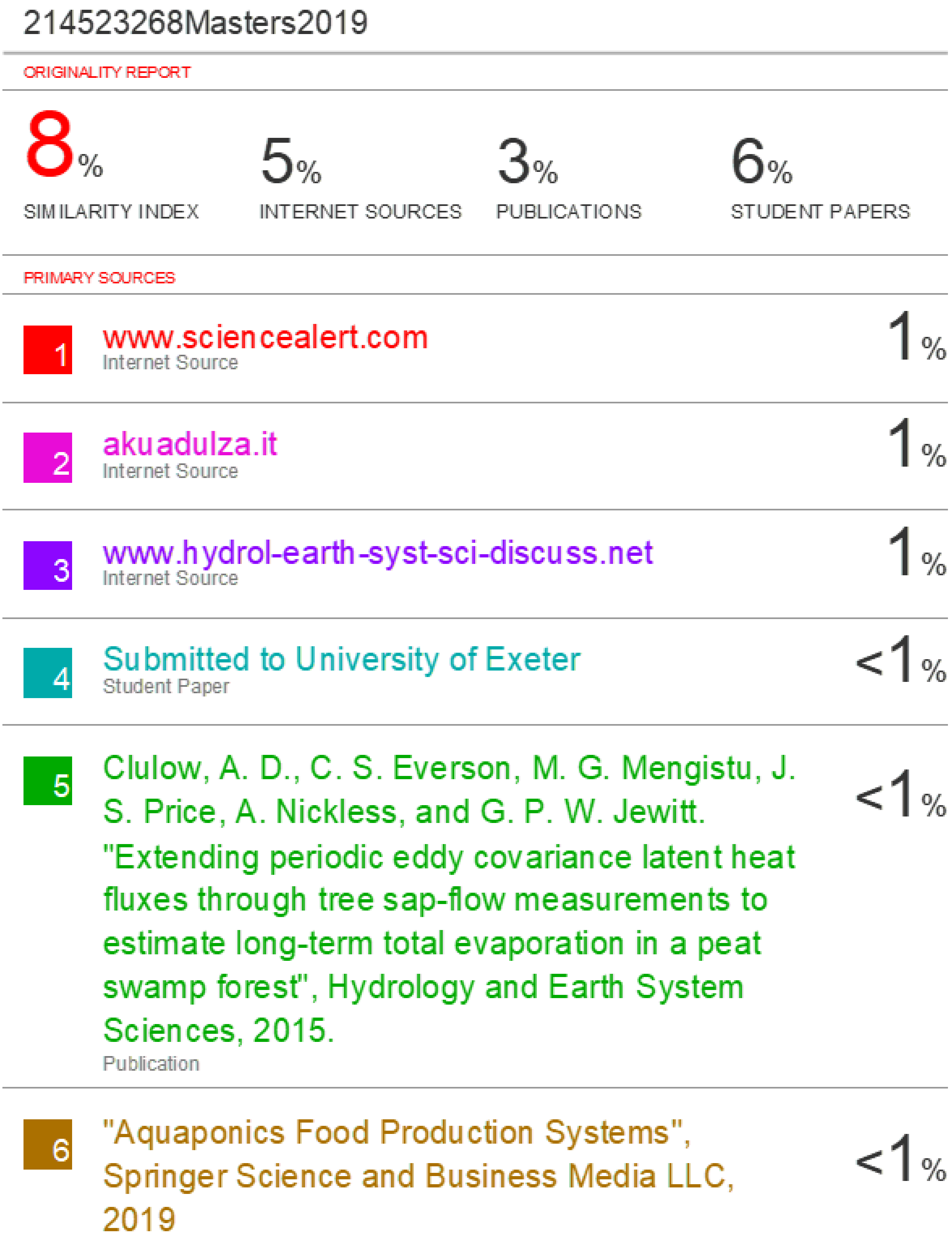

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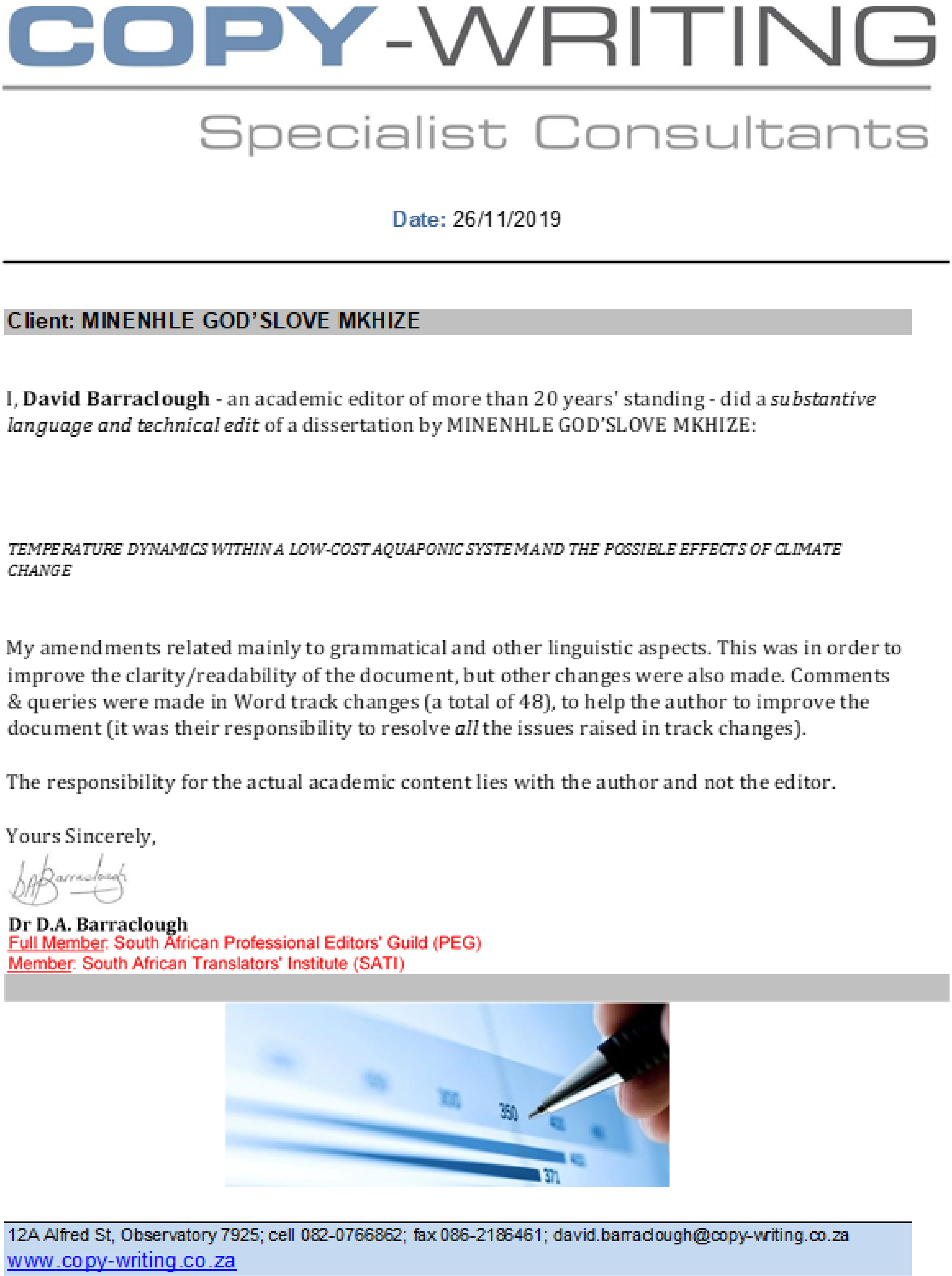

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TEMPERATURE DYNAMICS WITHIN A LOW-COST AQUAPONIC SYSTEM AND THE POSSIBLE EFFECTS OF CLIMATE CHANGE

My amendments related mainly to grammatical and other linguistic aspects. This was in order to improve the clarity/readability of the document, but other changes were also made. Comments & queries were made in Word track changes (a total of 48), to help the author to improve the document (it was their responsibility to resolve *all* the issues raised in track changes).

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