Investigating supplementary semi saline irrigation of taro and yam in Tonga

by

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Candidate's Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

Lily McDonald Date:25/08/2025

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Abstract

Water security is an issue which plagues Pacific Island Nations and Territories (PICTs) despite being surrounded by water. Due to the genesis of coral atoll islands, such as Tonga ‘tapu, Kingdom of Tonga (Tonga) groundwater storage is minimal, and infrastructure is insufficient to capture enough rainfall for fresh water to support the island for more than 30 days. When it does not rain, crops growing under rainfed systems suffer from reduced inputs, increasing the negative effect of a drought, where fresh water must be flown in through foreign aid. Breakthroughs in thermodiffusive desalination technology presenting cheaper, more efficient and lower maintenance options for irrigation may provide relief from the consequential impacts of these droughts. Whilst the technology is vastly improved from preceding options, the product is brackish water which is mildly saline — unsuitable for human consumption. It is little understood how the environment and common crops grown in Tonga will react to supplementary saline irrigation.

To evaluate the potential of this technology, the study conducted two field trials to assess the salinity tolerance of taro and yam to semi saline irrigation. Four treatments for taro, including pumped groundwater, rainfall only, 30mmol/L NaCl and 60mmol/L NaCl were applied at select rates based on actual rainfall. For yam, pumped groundwater and 60mmol/L NaCl was applied periodically to yams which were planted under rainout shelters to prevent rainfall interference. Plant growth parameters and physiological measurements were observed and analysed using statistical packages available in RStudio.

The study found that under the treatments, taro exhibited no effects up to 30mmol/L NaCl and minor decrease in corm yield at 60mmol/L NaCl. For yam, no yield effect was identified up to 60mmol/L NaCl treatment. The soil analysis indicated that due to the management of saline application, soil salinity was temporarily raised and would likely return to baseline salinity levels if given appropriate periods of rest.

Further study is required to assess the long-term impacts and best practice for supplementary saline irrigation. However, these results indicate that supplementary saline irrigation at rates up to 60mmol/L NaCl may provide a sustainable solution to supporting Tonga’s water security issues, however further studies will need to be conducted to assess the impact of semi saline solution to Tongan soils over time and multiple cropping cycles. Furthermore, the taro trial would benefit from being repeated in low rain conditions.

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List of acronyms and abbreviations

ENSO	El Niño – Southern oscillation
EC	Electrical conductivity
MAFF	Tonga Ministry of Agriculture, Food and Forest
PICTs	Pacific Islands Countries and Territories
SPAD	soil plant analysis development
SPCZ	South Pacific Convergence Zone
Tonga	Kingdom of Tonga
Tonga Land Act	the Land Act

Chapter 1: Introduction

Climate change is predicted to result in increasing periods of drought for many Pacific Island Nations and Territories (PICTs), including Tonga. An impact of drought is reduced yield for crops grown on these islands, either for market or subsistence. Newly available desalination technology has made it possible to efficiently and effectively reduce the salinity of seawater, a readily available resource (Xu *et al.*, 2024). It may be possible to use desalination technology to partially irrigate crops during drought, with minimal impacts on yield and environmental health (Myrans *et al.*, 2024).

Water insecurity is an issue of increasing importance in Tonga (Ministry of Agriculture and Food Forests and Fisheries, 2016). Droughts as short as two weeks can cause negative impacts to crops grown under rainfed systems (Iese *et al.*, 2021), leading to negative impacts on both food security and economies. Although climate modelling has been unable to provide a clear direction on whether periods of drought in Tonga will increase or decrease, severe weather events and tectonic movements causing tsunamis also cause water insecurity and food insecurity. Tropical cyclones, occurring on average 2.6 times a year in Tonga (Tu'uholoaki *et al.*, 2022) bring damaging winds which damage water supply infrastructure. Tsunamis can also cause influx of highly saline sea water, severely damaging soils (Antille *et al.*, 2022), and as a result, crop productivity. To add to these water insecurities faced in Tonga, the groundwater supply is under increasing strain. Saltwater intrusion and overconsumption place increasing pressure on the shallow aquifers (White and Fatai, 2009), making them a vulnerable resource that is not suitable for irrigation.

Desalination is a potential option for irrigation during periods of drought, to prevent crop damage and hence minimise economic impacts during periods of high water insecurity. Large desalination plants are expensive, require complex maintenance, and large amounts of energy (Xu *et al.*, 2024; Curto *et al.*, 2021). Discovery of successful methods for thermodiffusive desalination which are more feasible to implement in remote areas provides an avenue worth exploring. Whilst this new technology is yet to produce water with low enough salt levels for human consumption, it may be suitable for supplementary saline irrigation under appropriate management (Lloyd *et al.*, 2021; Myrans *et al.*, 2024; Minhas, 1996; Oster, 1994; Shahrokhnia and Wu, 2021). Whilst studies across the world have largely focused on tolerating salinity because of naturally saline conditions present in arid areas, it is relatively unexplored whether managed irrigation in locations with well draining soil, such as the island of Tonga ’tapu, Kingdom of Tonga (Tonga) can improve crop yield without unacceptable impacts on soil or crop quality.

To evaluate the potential of irrigation with saline water, crops of significance to Tonga were selected for field trials. Both *Colocasia esculenta* (taro) and *Dioscorea* spp (yams), are culturally and economically significant in Tonga. Both species are highly plastic, and considered ‘orphan’ crops, meaning they are unstudied compared to other crops of equal significance. Furthermore,

there are few known studies on their salinity tolerance, amongst other traits (Matthews and Ghanem, 2021; Obidiegwu *et al.*, 2020). For taro, the chosen cultivar is ‘huli mao’, and for yam, two cultivars were available; ‘kaho kaho and ‘lose’.

Whilst there are many variables to consider in this experiment, the research objective was narrowed primarily to the exploration of the potential to implement supplementary semi saline irrigation in Tonga. Hence, the research questions to evaluate in this study were as follows

Research Questions

1. How does salinity impact yam growth parameters?
2. How does salinity impact taro growth parameters?
3. What is the impact of supplementary semi saline irrigation on Tongan soils?

To evaluate the research questions, a traditional literature review was conducted to assess the contemporary and available information on relevant identified topics, including feasibility assessment of supplementary semi saline irrigation, Tongan soils, taro, yam and evaluation of salinity impact on plants. This guided the methodology of the field trials, which were assessed statistically to identify significant impacts from the treatments and evaluate the research questions above.

Chapter 2: Literature Review

This literature review has focused on identifying current information to the research and identification of relevant gaps in the existing literature. As the research project is on evaluation of the potential for successful supplementary saline irrigation for agriculture in Tonga, focus was given to assessing the justification for implementation of the desalination technology. Hence, this section explores various interdisciplinary topics to form an understanding on not only the gaps in existing research, but the potential for emerging technologies to expand research horizons.

2.1 Water supply in Tonga

Tonga is a country made up of 170 islands in the southwest of the Pacific Ocean, all have a similar climate, exempt rainfall patterns between the north and south islands. The climate in Tonga is tropical, with average temperatures ranging between a minimum of 18℃ and maximum of 32℃ (Tonga Meteorological Service, 2024). Annual rainfall in Tonga sits at about 2500mm and 1800mm annually for the northern and southern islands respectively. These differences in rainfall are attributed to the South Pacific Convergence Zone (SPCZ), which is a distinct geographical band of intense rainfall and high cyclone activity (Brown *et al.*, 2020), resulting in higher rainfall for the northern islands. Despite the differences in annual rainfall, both the northern and southern islands in Tonga have a wet season which occurs between November and April, followed by a dry season between May and October, with 60-70% of rainfall occurring in the wet season (Tonga Meteorological Service, 2024). Despite being surrounded by water, freshwater suitable for anthropological use in Tonga is extremely limited. This is due to impacts from climate variations, environmental events such as eruptions, and limited groundwater capacity.

Weather events such as an El Niño can jeopardise water supply, resulting in periods of up to 20 days without rainfall, and in extreme cases, 30 days (Myrans *et al.*, 2024). El Niño is the result of above average sea surface temperatures and is a part of the El Niño-Southern oscillation (ENSO) phenomenon, which also includes La Niña and neutral states. In Tonga, an El Niño event is coupled with decreased rainfall, whilst La Niña is accompanied by increased rainfall. Long periods of drought caused during an El Niño can impact agricultural crops severely, and has become of increasing concern (Ministry of Agriculture and Food Forests and Fisheries, 2016). More significantly, during periods of drought, it is common for emergency freshwater supplies to be flown in (ESCAP, 2015). Some climate studies predict that El Niño events are set to become more extreme, with either less rainfall or more variability in the distribution of rainfall (Shin *et al.*, 2022; Geng *et al.*, 2022). Despite a lack of consensus on the future intensities of El Niño, there is consensus across climate models that ENSO will continue to dominate interannual climate variability (Lee, 2023), signifying that drought will remain a continued threat to Tonga's water supply.

Another climate threat to freshwater supply is cyclones, which occur on average 2.6 times annually, with no statistically significant variation between ENSO states (Tu'uholoaki *et al.*, 2022). Cyclones impact freshwater supply through several avenues, including damage to infrastructure and groundwater contamination (Falkland and White, 2020). Other than groundwater supply, collection of rainfall for freshwater is common in Tonga, using roofs and gutters to capture and direct the water into storage. When the infrastructure is damaged from extreme weather events such as a cyclone, supplies can rapidly dwindle. Further, cyclones create storm surges, causing sea water to over-wash the island and infiltrate the fresh groundwater supply (Falkland and White, 2010).

While Tonga may receive an abundance of water from rainfall, due to limited storage capacity and unpredictable climate conditions, water security is yet to be achieved. This showcases the need to explore potential alternative water sources, which may alleviate the social and economic consequences of serious droughts and cyclones, and their negative impacts on water security.

2.2 Can saline water provide supplementary irrigation in drought?

Desalination has become more affordable and increasingly efficient and there are various technologies which produce different water quality (Elsaid *et al.*, 2020). Desalination is often used to achieve freshwater security, with the most popular technologies including: reverse osmosis (RO), Multi-Stages Flash desalination (MSF) and Multi-Effect distillation (MED) (Curto *et al.*, 2021). These methods are often unsuitable for use in remote areas, as a phase change is required to complete the process. This phase change causes salt accumulation within the device, reducing efficiency and resulting in shorter lifespans of the device (Zhang *et al.*, 2022). Further issues that limit the ability to successfully adapt desalination technologies for use in the pacific context includes high cost and heavy reliance on imported diesel for energy (Burn *et al.*, 2015). A potential solution to this issue is to turn to newly emerging technologies, that may be more efficient on both a technical and cost basis. A recent advance resolved standing issues with the previously inefficient method of thermo-diffusive desalination (Xu *et al.*, 2024). The thermo-diffusive desalination prototypes allow for high sodium concentrated solutions to be turned into water that has low contents of sodium, moving from roughly 30 000ppm down to 500ppm (Xu *et al.*, 2024).

While heavy and ongoing application of saline solution may negatively impact the soil and environment over time (Wang *et al.*, 2016), several studies have concluded that with appropriate management, the impacts are considered acceptable and tolerable (Oster, 1994; Yang *et al.*, 2018; Cucci *et al.*, 2019; Mohanavelu *et al.*, 2021; Minhas, 1996). These studies are mostly conducted in arid climate zones, with annual rainfall between 25mm up to 500mm, whereas in Tonga, annual rainfall is up to 2500mm. Furthermore, these studies provided ongoing saline irrigation across the

entire growing period. From these outcomes, it is likely that supplementary saline irrigation for short periods of time, in Tonga where rainfall is relatively high, will have minimal impacts on soil quality if managed properly.

Appropriate management to prevent the application of saline water from increasing the salinity of the soil profile typically includes a leaching period to flush the profile (Oster, 1994; Shahrokhnia and Wu, 2021). Determination of how much leaching is required to maintain soil quality and prevent groundwater infiltration requires analysis of the soil matrix, irrigation systems, water quality and crop types. Several open access modelling programs exist for determining appropriate application rates, such as “SALEACH”, “Rhoades” and “WATSUIT”, all with similar inputs and assumptions (Rhoades, 1974; Wu *et al.*, 2012; Shahrokhnia and Wu, 2021). In India, where most annual rainfall occurs within 2-3 months, (Minhas, 1996) identified that application of a saline solution had the highest benefits when applied in minimal amounts, infrequently. This aligns with the intended uses in Tonga. It is recommended that if saline solution is to be applied, a well-drained soil is ideal (Mohanavelu *et al.*, 2021). Furthermore, it was also found that soils which have a higher water holding capacity are easier to manage with repeated saline applications.

Whilst there are yet to be studies conducted on supplementary saline irrigation in the field for pacific islands, globally, there is increasing focus on the topic. In many areas, PICTs included, various pressures threaten to force agricultural systems into adapting to the use of saline water (Morales-Garcia *et al.*, 2011). These reasons include but may not be limited to drought, rising sea levels, mismanagement and overpopulation (Morales-Garcia *et al.*, 2011; Lloyd *et al.*, 2021; Myrans *et al.*, 2024). These studies highlight the important of understanding crop responses to salinity, so that where management is an option, it is conducted in the most sustainable manner possible. To conclude, with appropriate management, supplementary irrigation with a semi saline solution is a potential solution for improving food security in areas such as Tonga, and a topic with increasing traction globally, as water security continues to decrease across most climate and environmental types.

2.3 Soils in Tonga

Understanding the soil type and formation is critical to designing a suitable management system for supplementary saline irrigation. Existing research has successfully characterised soils in Tonga, but lack historical data input to understand current and future trends in key soil characteristics (Stockmann *et al.*, 2024b). Thus, this section focuses on the latest available information for soil types across Tonga, particularly those found at the field trial location.

The main island, Tonga tapu, is a raised atoll, which is formed by coral growth on top of rising volcanic islands (Montaggioni *et al.*, 2023). The first soil horizon is comprised of medium to heavy clay, overlaying coral limestone (Antille *et al.*, 2022).

Tongan soils are predominantly well drained, allophanic soils, that have clayey textures (Stockmann *et al.*, 2024a). Allophanic soils are soils that are derived from volcanic product, such as ash, and are rich in allophane, an aluminium rich aluminosilicate (Hewitt *et al.*, 2021). A key characteristic resulting from this genesis is that Tongan soils are typically "well drained" (Stockmann *et al.*, 2024a), which supports effective management for practices such as saline irrigation. In (Antille *et al.*, 2022), it is suggested that due to the soil types in Tonga, while tsunamis pose a risk to increasing soil salinity, many soils would support sufficient leaching to recover and continue to support crops.

Studies have found that the nitrogen, phosphorus and potassium are sufficient across Tonga tapu soils to support plant growth, however soil organic carbon may be declining (Stockmann *et al.*, 2024b), and so will soil nutrients if not replenished (Antille *et al.*, 2022).

2.4 Agriculture in Tonga

Analysing the agricultural system in Tonga is important for understanding which crops are important in Tonga requires inquiry into elements of cultural, economic and social significance. Agriculture accounts for approximately 16% of gross domestic product in Tonga (Pacific Agriculture Policy Project, 2025). The primary form of sale for crops grown in Tonga is through municipal markets and roadside vendors (Underhill *et al.*, 2020). Tonga tapu, the main island, is considered as the agricultural hub of Tonga, accounting for majority of land used for farming and sales (Underhill *et al.*, 2020; Stockmann *et al.*, 2024b). It is estimated that 80% of people living in Pacific Island Countries and Territories are engaged in growing majority of their food either themselves or through family, for both subsistence and livelihood (Thomas *et al.*, 2025), indicating agriculture is a significant part of day-to-day life for majority of locals in Tonga.

Root crops are the most predominantly cultivated crop in Tonga, followed by an assortment of perennial crops, including kava, mulberry and vanilla (Tonga Statistics Department, 2015). The top five main crops (cassava, yam, yautia, sweet potato and swamp taro) are all annual root crops, representing approximately 47% of total cultivated land area in 2015 (Tonga Statistics Department, 2015). Other predominant crops identified in more recent publications include coconut, pumpkins and bananas (Myrans *et al.*, 2024).

Of these crops, (Myrans *et al.*, 2024) selected six focus crops (pumpkin, cassava, sweet potato, yam, taro and banana) to evaluate existing studies understanding their salinity tolerance. Of these, it was found that while all the studied root crops lacked research, both taro and yam stood out as particularly neglected (Myrans *et al.*, 2024). Despite the lack of scientific understanding on these crops' physiological response to salinity, they still are economically and culturally significant, as described in sections 2.5-2.6 of the literature review. This makes taro and yam ideal choices for this research, in characterising their responses to supplementary saline irrigation.

2.5 Taro Overview

Colocasia esculenta (taro) is considered to be the ninth largest crop as a source of calories in the world (Rashmi *et al.*, 2018). The domesticated cultivars of the crop are predominant in Africa, Asia, Caribbean Islands and Pacific Islands, and grows wildly in even more locations. Within Tonga, there are at least 44 identified cultivars, many expressing distinct phenotypical characteristics across size, shape and colour (Ramanatha *et al.*, 2010). Taro is often described as an "orphan crop" by researchers (Matthews and Ghanem, 2021), due to the lack of study on the plant when compared to other major crops, despite its global significance. This has been hypothesised to be the result of "perception gaps", caused by various reasons including limited international exchange, amplifying a negative feedback loop to limit the visibility of taro to research funding (Matthews and Ghanem, 2021).

Despite the lack of visibility in funded research, existing studies on taro show that it is a highly valuable and nutritional food source. The main food source produced by the plant is the corm, which is tuberous and contains typically 69% moisture, 25% starch, 1.5% dietary fibre, 1.1% protein and 1% sugar for its fresh weight (Ramanatha *et al.*, 2010). The blades and petioles (plate x) are also a food source and often consumed. The blades have the highest protein content of the three, at approximately 11% protein (dry weight) (Temesgen and Retta, 2015; Ramanatha *et al.*, 2010). When compared to other crops, taro contains twice the carbohydrate content of potatoes and more protein in the corm than yam, cassava or sweet potato (Temesgen and Retta, 2015). The corm, which is a swollen subterranean plant stem used for nutrient storage (Sheikh *et al.*, 2022) contains an array of nutrients including minerals, vitamin C, thiamine, riboflavin and niacin (Matthews, 2010). Finally, taro is a hypoallergenic food source, an ideal carbohydrate source for young children, due to containing uniquely tiny starch granules when compared to other starch sources (Saqib *et al.*, 2025).

2.5.1 Salinity tolerance taro

The salinity tolerance of taro has been studied in several cases but is still considered unresearched when compared to other crops (Lloyd *et al.*, 2021). In existing studies, taro has been found to show promise as a salt tolerant crop, for levels of salinity below 50mmol/L NaCl (Vaurasi and Kant, 2016; Lasso-Rivas *et al.*). Taro is considered a non-halophyte, which is a plant which does not naturally grow in saline conditions, such as seawater or a salt marsh (Flowers *et al.*, 1986). When compared to other non-halophyte species, taro was found to be relatively salt tolerant up to levels of 200mmol/L NaCl, where it was still able to produce corms, albeit up to 43% smaller than those in the control treatment (Lloyd *et al.*, 2021).

These previous studies have all been in-vitro or glasshouse studies, with saline treatments used at high rates, rather than for supplementary irrigation. It is currently unknown if a short term application of a salinity treatment will impact the plants the same way. Furthermore, (Vaurasi and

Kant, 2016)tested four different varieties, finding that number of roots and plant height differed across cultivars and treatments. This is expected in taro, as the species is highly plastic, cultivated globally and genetically diverse (Miyasaka *et al.*, 2019; Devi, 2012). This indicates further studies should be conducted to evaluate the salinity tolerance of taro to supplementary saline irrigation, in Tonga, to evaluate whether new desalination technology can support Tonga during drought periods.

2.6 Yam overview

There are over 600 species of yam identified globally (Obidiegwu *et al.*, 2020; Afoha *et al.*, 2019; Demuyakor *et al.*, 2013). For this research, two popular cultivars grown in Tonga have been chosen: 'kaho kaho' and 'lose'. These cultivars come from the species *Dioscorea alata* and *Dioscorea rotundata* (*D. alata* and *D. rotundata*) and have been chosen due to their availability and predominance in Tonga. Both species are grown across the yam growing regions of the world including South East Asia, the Pacific and West Africa (Sugihara *et al.*, 2020). Yam, similar to taro, is often considered as an "orphan" crop (Obidiegwu *et al.*, 2020), with little scientific research completed presently, particularly on their salinity and drought tolerance. Despite this, they remain an economically and culturally significant root crop for many countries, including Tonga, where they are also central to the calendar, with festivals and events often involving yams (Bennardo, 2017; Wumbei *et al.*, 2022).

Further to their cultural significance, recent studies on yams have highlighted their potential as a nutritional food source containing medicinal/therapeutic properties (Obidiegwu *et al.*, 2020; Padhan and Panda, 2020; Lebot *et al.*, 2023). They contain fibre, starch, sugar, proteins, minerals and vitamins including, ascorbic acid, thiamine, niacin, and riboflavin (Adebowale *et al.*, 2018). Yam's high potassium content, coupled with the presence of other micro and macro minerals required by the human body make it stand out as a nutritional carbohydrate source (Baah *et al.*, 2009). The medicinal qualities of yam require further exploration, but compounds such as diosgenin, dioscin and dioscorin are found to be anti-inflammatory or antioxidative, with potential to reduce risk of cardiovascular disease (Kaur *et al.*, 2021). Overall, yams provide many people globally with a healthy carbohydrate source, that supports intake of other essential food types including fibre, minerals and vitamins. It is important to note that these studies are conducted across the many different species of yam, and while most show promise, there is variability across the *Dioscorea* spp. which studies should continue to account for, when researching (Adebowale *et al.*, 2018; Obidiegwu *et al.*, 2020).

2.6.1 Yam subspecies

Yams belong to the genus *Dioscorea* and family Dioscoreaceae. Two prominent economical subspecies include *D. alata* and *D. rotundata*. As two different species in a highly diverse genus, there are differing physiological and morphological characteristics, which may impact their

tolerance to drought and salinity conditions. Both are grown across the Pacific and in Tonga, primarily for their tubers. *D. rotundata* is noted as having white flesh, and was introduced into the pacific from French territories such as New Caledonia (Wilson and Hamilton, 1988). *Dioscorea alata*, or water yam, is another common species, known for occasionally producing aerial tubers in some cultivars (Wilson and Hamilton, 1988). While phenotypical differences such as spines and leaf shape for *D. rotundata*, it is not clear how the produce between the two species differs. Rather, it is cultivars within these species where clear differences may arise, as shown in (Soibam *et al.*, 2017; Demuyakor *et al.*, 2013; Cornet *et al.*, 2014). Furthermore, while studies on pacific yam varieties are few (Wilson and Hamilton, 1988) , no literature was identified in this review providing further context on physiological and morphological traits of yams available in Tonga, showcasing a gap in research.

2.6.2 Salinity tolerance yam

There are only two published studies which evaluate the salinity tolerance of yams. None of these studies have been conducted on yams sourced from PICTs. In (Ndouma Mbondjo *et al.*, 2020), salinity tolerance of a *D. rotundata* cultivar from Ghana was evaluated over 6 weeks from planting, at salinities of 50, 100 and 200mmol/L NaCl. They were not grown in field, but in sand bags. It was found that at 100mmol/L, deleterious effects on plant biomass occurred. The second study was conducted in-vitro over a period of 6 weeks on subcultured *D.alata* plantlets. Here, it was found that plantlets were unable to root at 200mmol/L NaCl treatment, and that growth was seriously inhibited at 100mmol/L NaCL treatment (Wheatley *et al.*, 2003).

Both studies did not grow yams to full term, however they showcase that there is potential for yams, a non-halophyte to grow in saline conditions up to 100mmol/L NaCl. It is unknown still the salinity range yams can grow in, whilst being able to also provide quality produce. Each of these studies were conducted with the saline treatment applied throughout the duration of growth. This differs from supplementary irrigation, where saline application would only occur during a drought. As the total amount of saline would be less if similar solution strengths are applied during supplementary irrigation, it is highly likely that the yams will be able to grow, given their ability to adapt in levels up to 100mmol/L NaCl.

2.7 Evaluation of salinity impact on plants

It is important to explore previous studies measuring the impact of salinity on plants, to gain an understanding of the key dependent variables. This ensures the design of the trial works to produce quantifiable outcomes that are relevant to the research area.

As identified in previous sections of this review, few studies evaluating the impact of salinity on taro and yam in field trials have been conducted. However, many salinity trial studies on more popular crops have been conducted. This section is split into two parts: growth parameters and physiological responses.

Growth parameters in this review refer to the physical growth aspects of the plant, which can be measured in terms or size, mass or volume. In most trials, yield, which is mass, is the primary measure of a plant's success (Gomathi and Thandapani, 2014; Singla and Garg, 2005). This is because the yield is a direct measure of the saleable and edible portion of the crop. To determine the quality of the crop yield, several factors including nutritional quality, taste and water content should be considered (Ghoname *et al.*, 2019) . Additionally, yield and crop quality in some cases can increase at low levels of salinity (Rouphael *et al.*, 2018; Ghoname *et al.*, 2019), whilst non valuable plant parts such a leaves, stems and roots of the crop decrease in biomass (Munns and Tester, 2008; Singla and Garg, 2005). However, in root crops, such as potatoes, cassava and ginger, it was found that salinity stress at 50mmol/L NaCl resulted in significant reductions of yield (Chourasia *et al.*, 2022). At levels of salinity above 100mmol/L NaCl, we can expect non-halophytes to begin to show significant decline across various growth parameters (Safdar *et al.*, 2019), however below these levels varied responses are likely to occur. This highlights the value of contextualising taro and yam salinity tolerance, as there is little basis for predicting how growth parameters will respond to saline treatments.

Physiological response in this review, refers to measures of biochemical processes within the plant, which impact plant growth and development. This includes chlorophyll content, stomatal conductance and protein content. Chlorophyll content measured across several growth points can act as an indicator of the plant's photosynthetic capacity and response to stressors (Shah *et al.*, 2017). Stomatal conductance, a measure of plant gas exchange, can also indicate a plant's response to stress. Under stressors such as salinity stomata may close, leading to other negative effects in biomass due to reduced ability to photosynthesise efficiently (Rahnama *et al.*, 2010; Brugnoli and Lauteri, 1991). Stomatal conductance has therefore been shown to be effective for screening for salinity tolerant cultivars (Rahnama *et al.*, 2010) and understanding plant responses to stress (Lloyd *et al.*, 2021).

Finally, while most studies focus on plant constituents such as vitamins, minerals and organic compounds (Lloyd *et al.*, 2021), it is not always economically feasible or accessible to do so. An alternative is to explore plant protein content, which is noted to be profoundly impacted by salinity (Kosová *et al.*, 2013). Several studies have found that increases in salinity are associated with a decrease in soluble protein (Ashraf, 1997; Lloyd *et al.*, 2021; Akula and Ravishankar, 2011), indicating that protein is a potential marker for understanding the impacts of salinity.

2.8 Summary

This literature review has explored a wide range of literature to cultivate an understanding of not only the feasibility and relevance of the study, but the practicalities of conducting a salinity field trial. It has been identified that the potential benefits of supplementary irrigation in areas with well-draining soil is valuable, if managed properly. Furthermore, relevant crops must be

screened prior to further implementation. Relevant crops should be chosen not only on their significance to a geographical location, such as Tonga, but also for their salinity tolerance. In cases where salinity tolerance and response is unknown, such as in taro and yam, further study is necessary.

Chapter 3: Methods

3.1 Overview

The previous chapter was put together to discern and understand the risks and potential outcomes of incorporating supplementary saline irrigation into Tonga's agricultural system. Based on positive preliminary findings from other studies, it was found that a trial studying the effects of salinity, excluding drought would be a suitable first step toward identifying the true potential of supplementary saline irrigation.

Due to the project being run internationally in a remote location, it was important that the experimental design would be easy to implement and maintain, in case of the event where labour became unavailable in the short term, or intense weather events occurred. Despite keeping the experimental design relatively simple, there are still certain interfering variables which could not be controlled. These have been noted where identified.

The statistical analysis looks to draw relevant relationships within and between the two different species, analysing primarily the impact of the saline treatment from control on different measured parameters. Because of the differences in the way the trials were run (primarily the use of rainout shelter in yam, but not taro), the data sets were analysed separately. Rstudio and packages were chosen for statistical analysis. Methods used in statistical analysis were informed by previous similar studies (Lloyd *et al.*, 2021). It is important to note that the focus of this research is to evaluate whether there is a significant difference between treatments, not confirm that the treatments yield identical results.

Two field trials were conducted during their normal growing periods. Both trials used a random block design and applied treatments varying from 0mmol/L NaCl to 60mmol/L NaCl. Treatments were chosen within the viable ranges provided in (Xu *et al.*, 2024). Plants were watered weekly with there relevant treatments after establishment at 4 weeks, for the duration of their growth to harvest. At harvest, plants were immediately tested for a range of growth parameters, to identify if the application of the saline treatment had a significant impact on plant growth. Soil was also tested to evaluate the immediate impact of the treatments and identify if the management approach was successful in avoiding deleterious impacts to soil quality.

3.2 Experimental Design

The taro trial began prior to the yam trial, and minor adjustments were made based on improving the level of control in the experiment. The experiment was based at Vaini Experimental Farm in Tonga tapu, Tonga (Plate 1.). MAFFs provided the project with staff who supported planting, management and harvest for both trials. Throughout the trial, we corresponded via teleconference to discuss issues and methods. The harvest was a collaborative effort, and I was present to support the harvest analysis.

Plate 1. Coordinates of trial location: Vaini experimental farm, Tonga tapu (Google Earth Pro, 2025)

3.2.1 Taro trial

The taro was planted on the 5th of June 2024, and harvest took place on the 30th of April 2025. Setts with a diameter larger than five centimetres from the base of the petiole were planted (Plate 2.). Above the threshold, the size of the sett typically does not impact final yield (Jill Wilson, 1987).

The setts were planted in rows that were 1.5 metres apart, and columns 1 metre apart. A randomised complete block design was used. This was chosen over an alpha lattice design. This choice was made to ensure that the likelihood of incorrect treatment application was minimised during the trial.

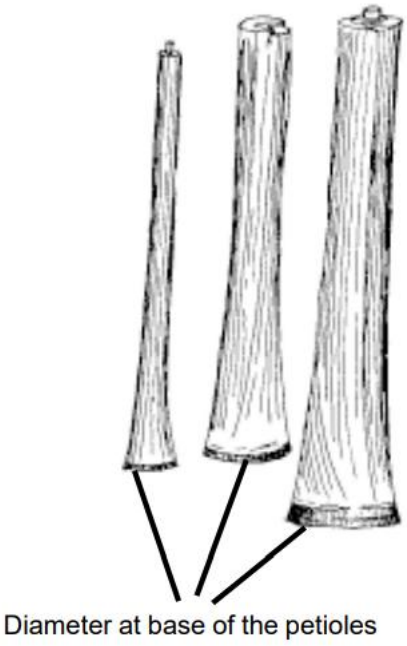


Plate 2. Point where the diameter for taro setts was measured for planting (Jill Wilson, 1987)

Four treatments were applied. The first, was rainfall, where no irrigation occurred. additionally, groundwater pumped into a water storage contained was applied at the same rate as a 30mmol/L NaCL treatment and 60mmol/l NaCL treatment.

For this trial, irrigation was administered at a rate of 1 litre per plant for any week where the rainfall was less than 30mm, exempt the rainfall treatment which received no irrigation. This rate was chosen to simulate demand irrigation and to not provide water in excess. For dryland cultivation of taro, it is estimated that a total of 1500mm of rain is required to be distributed

uniformly across a growing period of twelve months for ideal growth results (Wang and Higa, 1983). Taro is able to be grown between six and twelve months, depending on the cultivation style and length of the wet season. In Tonga, taro is commonly grown for 9 months, during the wet season (Onwueme, 1999). A preventative pesticide treatment was applied in July.

3.2.1.1 Rainfall

Rainfall data was collected by the Tongan Meteorological Service from the closest available station, Fua'amotu. This was used to decide when to water the taro, as aforementioned in the previous section.

3.2.2 Yam trial

The yams were planted on the 24th September 2024 and harvest took place on the 1st May 2025. Yams were planted from equally sized mini setts. Rainout shelters were constructed (Plate 3), so that plants did not receive any rainfall water. Yams were planted using a spacing of 1.5mx1.5m, to allow for sufficient drainage and plant growth between plants. A random block design was also used, as explained in the taro trial section above.

Plate 3. Image of rainout shelters constructed over yam plants in the trial. Date taken: 25th September 2025.

In (Wumbei *et al.*, 2022) and (Ikpe *et al.*, 2023), a range of 1000mm rainfall to 2000mm provided continuously is stated as ideal for yam growth, highlighting that short periods of drought are not favourable for yield. Yams are grown typically between a period of 5-10 months (Wumbei *et al.*, 2022), however in Tonga, MAFFs advised yams are typically grown for ten months, so a period of 10 months was chosen for the trial.

In this trial, all plants were administered with one litre of no salt water twice a week for the first 6 weeks of growth. After three weeks, plants assigned to salinity treatment were given one litre of 60mmol/L NaCl treatment and plants assigned to groundwater treatment were given 1 litre of ground water, twice per week (total 2 litres of assigned treatment per week, per plant), for the remainder of the growth period. The ground water was pumped from the ground into water storage containers for this trial. In November, soil plant analysis development (SPAD) and stomatal conductance was collected, using a SPAD meter to measure units of chlorophyll and a dynamic porometer respectively.

3.2.3 Treatment summary

The yam and taro underwent different treatments sets, sample size and treatments for each species is detailed below (Table 1.). Additionally, two different cultivars were able to be secured for the Yam trial.

Table 1. Summary of salinity treatments for taro and yam trial and total number of plants per treatment

		Yam		Taro
Treatment	mmol/L NaCl	kaho kaho	lose	huli mama'o
Groundwater	0	16	16	45
Rainfall	0	-	-	45
Low salt	30	-	-	45
High salt (salt)	60	16	16	45

3.2.4 Soil

Soil data was collected prior to the trial. The trial site for both the taro and the yam are adjacent to each other, in a field with unchanging slope. Due to time restrictions, soil composition was taken only at the beginning of the taro field trial, which was measured through fractionation.

Soil electrical conductivity (EC) was measured for both the taro and yam. For the taro, once at planting and once at harvest. For yams, only at harvest. Soil EC was measured using a 1:5 dilution method at a room temperature of

The location of the research study contains a dark reddish brown clay which is friable towards the surface with lapilli present (volcanic rock deposit). At depths below 32cm, the clay is firmer, and there is weathered lapilli present. Beyond a depth of 1m, pieces of coral limestone are dispersed. It is noted that this soil is well draining (Landcare Research, 2025). While unusual for a soil described as a clay, this is likely due to the fragmented friable composition at the top, allowing water to easily infiltrate. Towards lower depths, the weathered lapilli are porous and so is the coral limestone, allowing water to continue to infiltrate and drain rapidly through the profile.

3.2.5 Harvest

At harvest for the both the taro and yam similar measurements were taken. The yield, fresh weight above ground, leaf water content, tuber/corm water content was taken. To ascertain water content, samples were weighed, then dried overnight in a drying oven, before weighing again.

For taro, as seen in (Lloyd *et al.*, 2021), leaf observations were taken for the total number of green and dead leaves, as well as leaf width and length for largest unfurled leaf on the plant.

3.3 Bradford protein assay

The Bradford protein assay was used to identify relative differences in protein content of the taro corm and leaf samples. Methods provided in (Kielkopf *et al.*, 2020) were followed, with the exception of reducing the amount of NaOH to extract plant proteins when analysing taro corms. For taro corms, 0.2mL of NaOH was used for protein extraction, rather than the standard 1mL. This was due to the low protein concentration falling outside the generated standard curve.

3.4 Analysis

To answer the research questions, the data was explored visually and statistically. Scatterplots and boxplots were used to compare variables of interest. Analysis of Variance (ANOVA) and t-tests were primarily used to identify if any significant differences were caused by the treatments. All data was checked to meet the assumptions of ANOVA using Levene's and Shapiro-Wilks tests. Correlation matrixes were used to scope and identify significant relationships as discussed in (Meier, 2022) and (Faraway, 2016). For all tests where the assumptions of ANOVA were not satisfied, non-parametric testing was used.

A p-value of 0.05 was found to be conventionally consistent with evaluation of salinity trials in the lit review (Lloyd *et al.*, 2021; Ndouma Mbondjo *et al.*, 2020), and thus was used for this research. Consideration was given to alternative p-values (Kennedy-Shaffer, 2019), but decided against to maintain consistency.

Chapter 4: Results

4.1 Taro

A total of 179 plants of 180 propagated grew successfully for observations throughout the trial.

4.1.1 Soil

Soil data collected for the taro trial found that at a depth of 0-15 cm, it is likely that the application of both groundwater treatment and high salt treatment increased the soil salinity. Due to limited observations, no statistical analysis was conducted. Figure 1. below visualises the impact of the treatment on soil salinity.

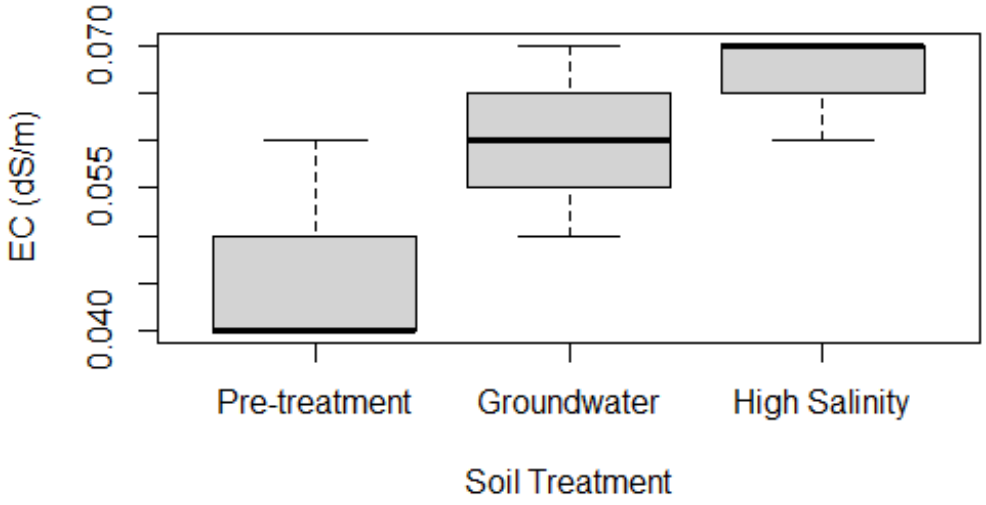


Figure 1. Boxplot of electrical conductivity for pre and post treatment at the taro trial site. The median soil EC (dS/m) for pre-treatment = 0.04, Groundwater = 0.06, high salt = 0.07.

4.1.2 Rainfall

From 1st June 2024 to 30th April 2025, a total of 2074.6mm (see Figure 2. Below) of rainfall was recorded in Fua'amotu, the closest weather station to the trial. During the trial, the watering threshold conditions were met for 22 of the 47 weeks.

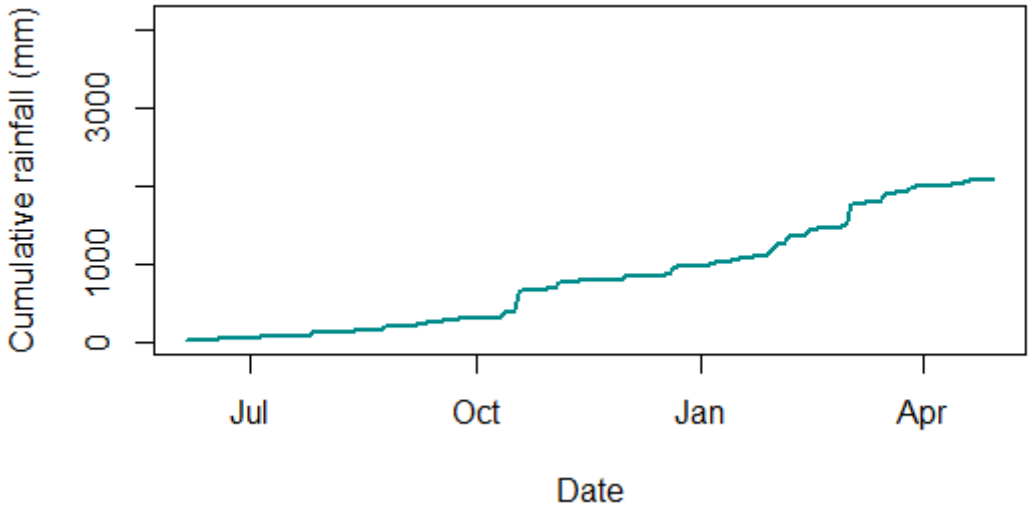


Figure 2. Cumulative rainfall (mm) during the taro trial growth period.

4.1.3 Taro observations

4.1.3.1 Taro corm fresh weight

The fresh weight of the taro corms was found to differ significantly between treatments (ANOVA: $F(3, 173) = 2.779$, $p = 0.0427$). Tukey's HSD post hoc comparison revealed that only the high salt treatment was found to have significantly lower fresh corm weight than the groundwater treatment ($p = 0.047$). No other pairwise comparisons yielded significant results ($p > 0.05$). The mean difference between high salt and groundwater treatments was approximately 199 grams (C.I. = 95% , 396g – 1.78g). The rainfall and low salt treatment were not found to be significantly different compared to the groundwater treatment. The boxplot below (Figure 3.) shows the distribution of corm fresh weights for taro by treatment, highlighting the increased variability in groundwater and rainfall treatments.

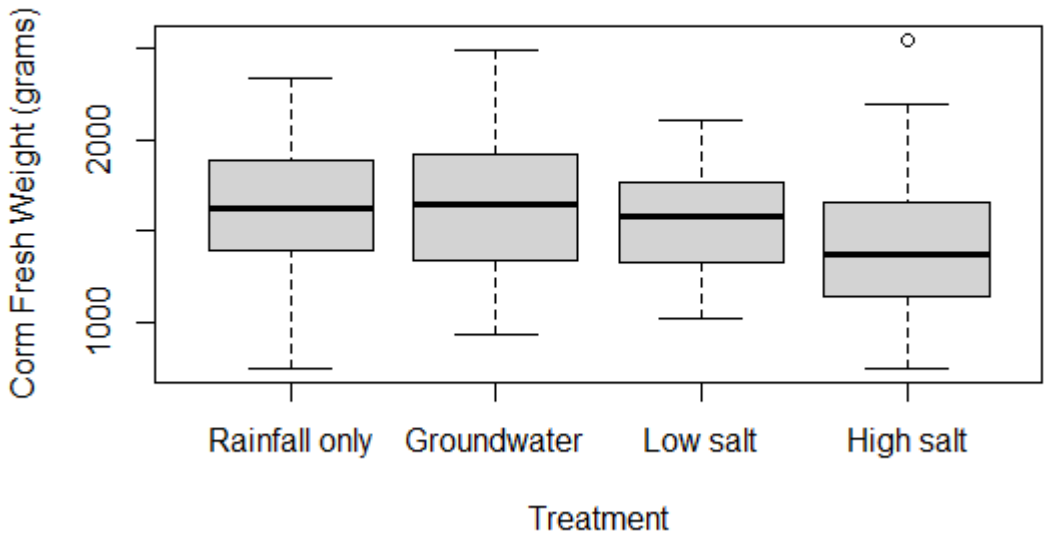


Figure 3. Boxplot of taro corm fresh weight by treatment. The median corm fresh weight (kg) for treatments left to right is: 1621.6 , 1648.7, 1464.2, 1373.6.

4.1.3.2 Taro above ground fresh weights and observations

4.1.3.2.1 Stump

A Kruskal-Wallis test was performed to compare the effect of treatment on stump fresh weights, as the data violated the assumption of normality. The test found that there was near statistically significant difference between the treatments ($\chi^2(3) = 7.29$, $p = 0.063$).

4.1.3.2.2 Petioles and leaves

A Kruskal-Wallis test was performed to compare the effect of treatment on combined petiole and leaf fresh weight. The test found that there was a statistically significant difference ($\chi^2 = 11.02$, $df = 3$, $p = 0.012$). Further evaluation using Dunns multiple comparison test with Bonferroni adjusted p-values revealed a near significant difference between the groundwater and high salt groups (adjusted $p = 0.6$). No other significant pairwise comparisons were identified.

4.1.3.2.3 Leaf observations

Leaf traits assessed on the day of harvest prior to plant destruction included the count of green leaves and dead leaves, leaf length and width. A Kruskal-Wallis test was conducted on the subset of data collected, comparing the effect of treatment on each trait. No significant differences were found as shown in table 2. Below.

Table 2. Results of Kruskal-Wallis test for effect of treatment and leaf observations

Observation	X^2	P value
Number of green leaves	0.99	0.80
Number of dead leaves	0.82	0.84
Leaf length	1.61	0.66
Leaf width	0.59	0.90

4.1.3.3 Taro dry matter percentage of corms and leaves

Kruskal-Wallis test revealed that treatment also had a significant effect on dry matter content of corms ($\chi^2 = 19.29$, df = 3, $p < 0.001$) and leaves ($\chi^2 = 10.77$, df = 3, $p = 0.013$). Dunns test using Bonferroni adjustment revealed that in corms, dry matter content was significantly higher than in the high salt treatment (adjusted $p < 0.001$). For leaves, dry matter content of groundwater treatment was significantly higher than rainfall only treatment (adjusted $p = 0.015$).

4.1.3.4 SPAD and Stomatal conductance

Stomatal conductance and SPAD (chlorophyll) were measured at 16 and 27 weeks. It was found that there was no statistically significant difference between treatment and change in stomatal conductance or SPAD between 16 and 27 weeks, although the low salt treatment exhibited a near significant increase (see table 3 below). In general, stomatal conductance increased and chlorophyll content decreased during this period.

Table 3. Analyses of treatment effect on SPAD and stomatal conductance at 16 and 27 weeks

Trait	Treatment	Change between week 16 and 27	Wilcoxon V	P value
Stomatal Conductance	Rainfall only	increase	1	0.125
	Groundwater	increase	2	0.188
	Low salt	increase	0	0.063
	High Salt	increase	3	0.313
Chlorophyll	All treatment	decrease	120	>0.001

4.1.3.5 Protein contenn

ANOVA was used to assess the effect of treatment of relative protein content and leaves. Figure 4 below indicates that high variance and small sample size reduce the likelihood of detecting a treatment effect for corm protein content, even though the assumptions of ANOVA were met. The results indicated that the treatment had no significant effect on the relative protein content for both corm and leaf protein. For corm, ($F(3, 16) = 1.30$, $p = 0.310$) and for leaves, (F(3,

16) = 0.80, p = 0.511).

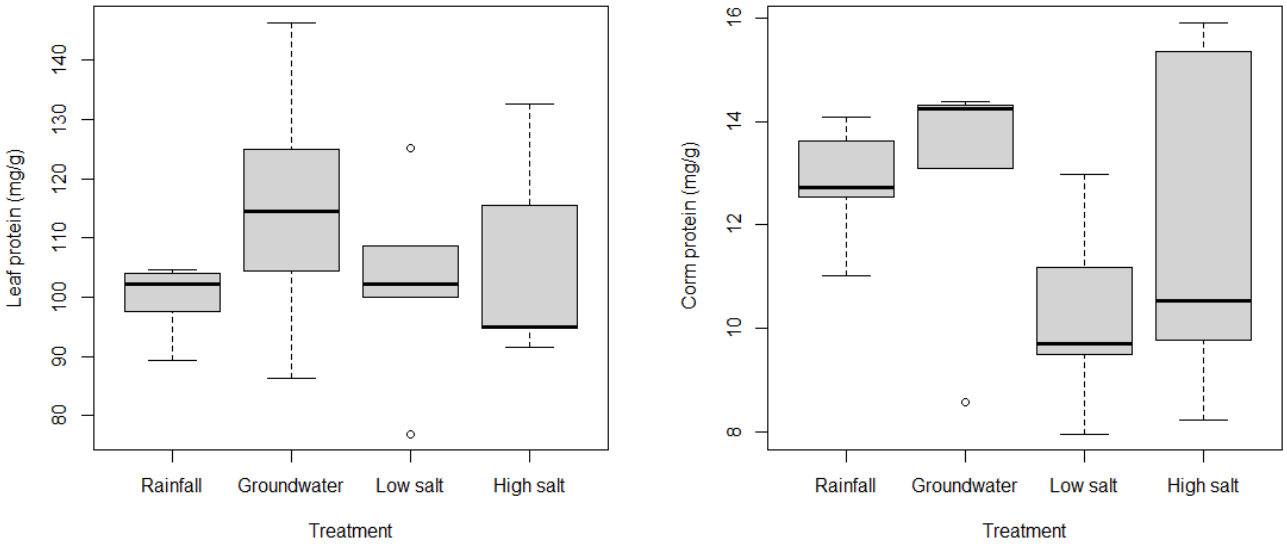


Figure 4. Boxplots of protein content for taro leaf and corm (left to right) by treatment.

4.2 Yam

A total of 32 of 32 propagated plants were observed throughout the duration of the trial.

4.2.1 Soil

Soil data collected for the yam trial found that at a depth of 0-15 cm, application of the salt treatment significantly increased soil salinity when compared to the groundwater treatment (figure 5). ANOVA looking at the interaction between treatment, soil electrical conductivity and cultivar confirmed that soil electrical conductivity was significantly different between treatment ($F(1, 8) = 9.88$, $p = 0.014$), and with no effect of cultivar ($F(1, 8) = 0.044$, $p = 0.839$). The interaction between treatment and cultivar was also not significant, indicating treatment effects on soil salinity were not influenced by cultivar ($F(1, 8) = 0.044$, $p = 0.839$). The mean soil EC (dS/m) for groundwater treatment is 0.05 ± 0.007 and for salt treatment is 0.13 ± 0.04.

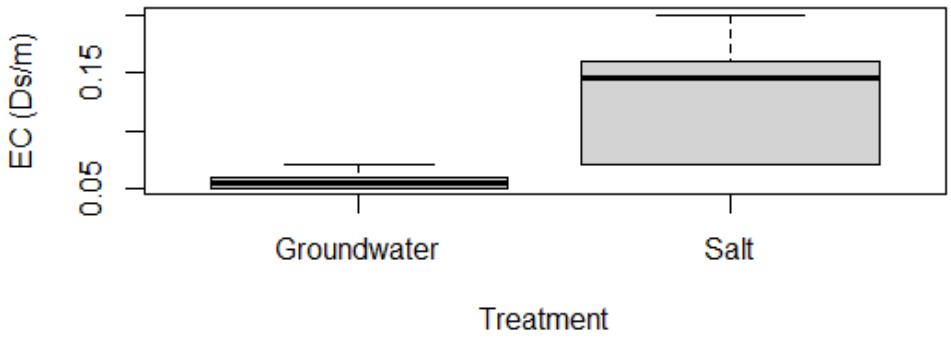
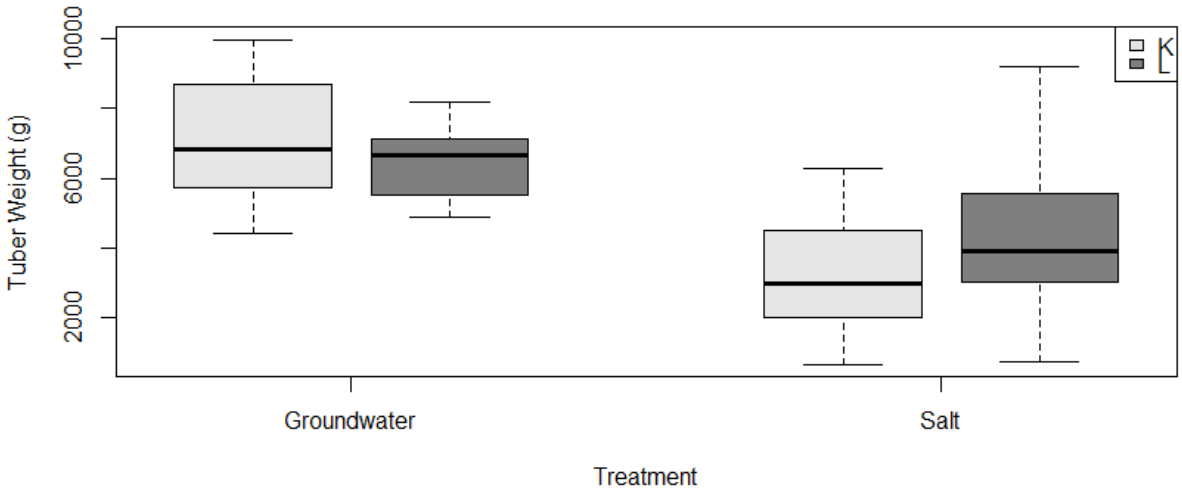


Figure 5. Boxplot of soil EC post harvest. Median EC for groundwater and salt was 0.055 Ds/m and 0.145 Ds/m respectively.

4.2.2 Yam tuber fresh weight

Welch two sample t-test found that there was no significant difference in tuber fresh weight between the two treatment groups (t(28.65) = -0.27, p = 0.79). The mean tuber weight for the between the two treatments across combined cultivars was 5.18kg and 5.41kg, for groundwater and salt respectively.

Further analysis was conducted using a two-way ANOVA for the effect of treatment and cultivar on tuber weigh. It was further confirmed that there was no significant difference between the groundwater and salt treatment (F(1, 28) = 0.12, p = 0.74), however cultivar had a highly significant effect (see figure xx below), where the cultivar Kaho kaho is significantly higher in weight on average compared to Lose (F(1, 28) = 18.67, p < 0.001). There was no significant interaction between treatment and cultivar (F(1, 28) = 1.67, p = 0.21).



4.2.3 Plant above-ground fresh weight

Above-ground fresh weight (all biomass above ground) was analysed using a Welch two-sample t-test, revealing that there was no significant treatment effect (t = 0.45, df = 28.63, p = 0.66). The mean fresh weight was 1.96kg for the fresh treatment and 1.76kg for the salt treatment. Further analysis, using two-way ANOVA on the effect of treatment and cultivar on plant fresh weight, found that there was a significant effect for cultivar type (F(1, 27) = 41.61, p < 0.001), and no significant effects from treatment or interaction.

4.2.3.1 Tuber and leaf water percentage

Two way ANOVA for variation in water percentage in leaf and tuber found that for leaf water content, there no significant effects from treatment (*F(1, 27) = 0.24, p = 0.63*), cultivar (*F(1, 27) = 0.24, p = 0.63*) or interaction (*F(1, 27) = 0.24, p = 0.63*). The mean water content in

the leaves was similar, with Kaho kaho at 78.8% ± 0.54 and Lose at 79.3% ± 0.58 (see figure XX below).

However, in tuber water percentage, analysis found that cultivar had a highly significant effect on the tuber water content ($F(1, 28) = 55.75, p < 0.001$). There was no significant differences identified for effect of treatment ($F(1, 28) = 0.22, p = 0.65$) or interaction between treatment and cultivar on tuber water percentage ($F(1, 28) = 2.36, p = 0.14$). The mean water percentage in Kaho kaho was 75.7% ± 0.27 and in Lose 70.5% ± 0.64.

Chapter 5: Discussion

The primary goal of this thesis is to ascertain whether saline solution can be used for supplementary irrigation of taro and yam crops in Tonga, during periods of water insecurity. This chapter discusses the findings of the previous chapter (Results) in relationship to the primary research questions, as well the limitations and opportunities arising.

5.1 Can saline solution be used for supplementary irrigation of taro and yam in Tonga?

5.1.1.1 Taro salinity tolerance

The results of the Taro trial indicate that the cultivar Huli mao shows an acceptable tolerance to supplementary saline irrigation up to a salinity application rate of 1 litre 60mmol/L NaCL (high salt treatment) per plant with watering occurring every other week. While there were significant differences in corm sizes, with the high salt treatment significantly lower, the difference is small when compared to the alternative of no crops grown in a true drought year. Furthermore, the low salt treatment, of 30mmol/L NaCL, which is achievable through the desalination technology showed no significant yield effects.

Fresh weight, stumps and leaf quality (number of green leaves, dead leaves and size) were not significantly impacted by the two salt treatments, except for above-ground fresh weight between groundwater and high salt treatment. Similarly to the corm weights, the actual difference between the groundwater and high salt treatment above ground fresh weight average is negligible. As taro leaves are commonly used in cooking in Tonga, it is promising to see that the quantity of leaves is not impacted by the saline irrigation.

When assessing the nutritional value of the corms and leaves, the two most consumed taro parts, the results indicate that none of the treatments had significant impact on the relative protein content of the plants. It should be noted, that the method used for calculating the relative protein has limitations for its application to taro. The limitations include an inability to measure the total protein, as only soluble protein is measured in the Bradford protein assay. Due to there being no previous studies on the types of protein in taro, it is unknown what quantity of insoluble proteins exist the plant. However, the measurements still provide a relative indication, showcasing that under current growing systems, use of supplementary saline irrigation at similar rates would not significantly impact protein content of either the tuber or leaves.

Future studies into the impact of saline irrigation on other nutritional constituents of taro, including minerals, ascorbic acid, thiamine, riboflavin and niacin (Matthews, 2010), as well as the palatability would help provide further information on whether the supplementary saline irrigation is a sustainable option for food production in Tonga. Additionally, long term epigenetic impacts of the treatment could also be considered, accounting for differences across various cultivars and identifying successful plant modifications to combat saline conditions (Banerjee and

Roychoudhury, 2017; Rashid *et al.*, 2022). Further studies to understand the limitations and potential of supplementary saline irrigation in taro are required, however this initial trial indicates significant promise for taro to be considered an ideal crop for semi saline irrigation, despite being a non-halophyte.

5.1.1.2 Yam salinity tolerance

The yam trial was able to explore the impact of a 60mmol/L NaCl solution applied at a rate of 2 litres per week per plant across its growth period, compared to the application of pumped groundwater at the same irrigation rate. Rainout shelters were utilised, to prevent leaching of the treatment. Additionally, two cultivars were used in the trial, kaho kaho and lose, both described by local MAFFs staff as popular varieties with clear morphological differences.

Overall, the treatment had no significant impact on any of the measured parameters in the trial. Yam tuber fresh weight, the primary edible part of the plant was found to remain the same across treatments. Aboveground fresh weight also yielded no significant differences, indicating yam, another non-halophyte is a suitable candidate for supplementary irrigation. Interestingly, the tubers (total tuber weight across all tubers produced by one plant) from the salt treatment had a mean weight of 5.41kg, higher than the average of 5.18kg for the groundwater treatment. While this difference was not significant in this trial, a trial with greater replication would be required to determine if there are in fact small but consistent effects.

In Tonga, yam size is considered as a measure of success. Annually, at the festival of Inasi (first fruits festival), yams are presented to the royal family. This culturally significant event sets the tone for community for the rest of the harvest season, as a sign of good fortune. The larger the yam, the better (Bennardo, 2017). This study indicates that further exploration and incorporation of supplementary saline irrigation, is not likely to hinder the existing cultural practices, nor the economic value they provide.

However, it should be noted that this study has not evaluated the impact of the treatment on yam nutritional constituents or the palatability. Both should be considered if further studies are pursued, in order the confirm that the solution is viable in a practical application. Palatability should be further considered. It was noted during discussions with MAFFS staff that at harvest, yam varieties are typically chosen based on taste, strongly influencing market price. Should the saline treatment negatively impact price significantly, it would deter growers from utilising the technology, hence warranting further exploration.

5.1.1.3 Soil

Tonga presents a unique opportunity, not available in many locations globally. In general, the addition of salt into any landscape will have a strong negative impact on sustainability (Wang *et al.*, 2016). However, the coral atoll of Tonga tapu and presence of permeable lapilli allows water to rapidly drain, taking additional salt with it. This process of salt draining from the surface

is called leaching (Oster, 1994; Shahrokhnia and Wu, 2021). Soil analysis for both the taro and yam trial found that application of saline solutions across a period of 10-12 months had a negative impact on soil electrical conductivity, however these results require further exploration.

For the taro, the initial soil electrical conductivity prior to treatment was 0.046 ± 0.009 dS/m. After treatment, samples for groundwater and high salt treatment were also taken, finding that soil salinity under those treatments had increased to 0.060 ± 0.008 dS/m for groundwater and 0.067 ± 0.005 dS/m for high salt treatment. While an increase was observed, the sample size for each treatment was small (n = 3), creating a limitation in ability to draw significant conclusions. Nonetheless, a mean of 0.067 ± 0.005 shows promise, that the application of saline irrigation at a rate of 1 litre over 22 weeks across 47 weeks did not cause the soil to become overly contaminated. In (Rayment and Lyons, 2011), the soil ECs measured fall well within acceptable and low salinity levels. It would be valuable to understand how long it would take for soils to return to normal post treatment.

For the yam trial, data was only able to be taken at the end of the trial. For this, comparison is made between the two treatments, groundwater and salt. 6 observations were taken for each treatment, and it was found that there was a statistically significant difference between the two. An increase from 0.05 ± 0.007 dS/m to 0.13 ± 0.04 dS/m (groundwater and salt treatment respectively) is seen. Whilst 0.13 dS/m is the highest soil electrical conductivity result returned across the trials, it is still not considered a to be a high salt content (Rayment and Lyons, 2011).

The difference in means between the two trials is visibly larger than for Taro, this is likely due to the use of rainout shelters and weekly watering in the yam trial. Because of the higher watering frequency (weekly, rather than every other week) and zero rainfall reaching the soil for the duration of the trial, no leaching has been able to occur. Implying that, during the taro trial, rain events allowed the soil leaching process to begin as described in (Oster, 1994; Shahrokhnia and Wu, 2021).

Further investigation to understand the longer-term impact of the two trials is required, particularly to understand the amount of rainfall required to return to base salinity levels. Further investigation into the soil mineral composition and other characteristics could also allow for further understanding of the availability of nutrients and how they are impacted by the addition of NaCl.

Overall, the differences in outcomes between the two trials, provide promising results for the use of saline irrigation in locations with well drained soils. Furthermore, because of the islands coral limestone foundations, the groundwater aquifers are likely to remain unimpacted from this treatment, especially when compared to impacts of cyclones and tsunamis, which inundate the supply with sea water (Falkland and White, 2010; Falkland and White, 2020), which is up to 60 times more salty the range of treatments available from the desalination technology (Xu *et al.*, 2024).

There are many other inhabited coral atolls, globally, across the Pacific and Caribbean (Nunn *et al.*, 2016; Dickinson, 2009). Many of these nations also face water security challenges (Iese *et al.*, 2024; Cashman, 2014). If they have similar conditions to Tonga, further exploration of supplementary saline irrigation could be conducted in these areas, where the impact on soil environment is likely to be minimal, and sustainable to manage into the future, whilst support food and water security goals.

5.2 Limitations

Whilst the results of this study are promising, there are several limitations which warrant discussion. These arise from the uncertainties of conducting novel research, working in the field as opposed to in-vitro, and the remote nature of the study location.

As identified in the literature review, both taro and yam are both considered orphan crops (Matthews and Ghanem, 2021; Obidiegwu *et al.*, 2020). All previous studies on the salinity tolerance of both plants are limited to in-vitro study where plants were only grown for a portion of their typical growth time. Both field trials are novel in the respect that they evaluate the salinity tolerance in the field, in the Pacific – vastly different from the existing 5 studies in this area of research. Furthermore, studies on saline irrigation of plants are also limited. While some research has begun (Wang *et al.*, 2016; Oster, 1994; Mohanavelu *et al.*, 2021; Minhas, 1996), only one has begun to explore the potential of this in the context of supplementary irrigation (Myrans *et al.*, 2024). Finally, while the negative impacts of salinity is understood, research is still being undertaken to understand the thresholds and environmental responses to saline application under managed conditions. Because of the novel nature of this research, many of these findings will require further study to confirm their potential application in the future. Completion of further field trials to understand the long term impact of semi saline irrigation would support further quantification of its potential.

Furthermore, the open nature of being conducted in the field opened the two trials to several uncontrollable variables. In the case of the taro trial, rainfall was a major factor, given no rainout shelters could be constructed. To account for this factor, prevent overwatering and mimic expected usage of the technology (supplementary saline irrigation) the treatment was only applied when rainfall was less than 30mm per week. However, rainfall in this year was relatively high when compared to previous years (Tonga Meteorological Service, 2024). This may have reduced any existing differences to being insignificant, however in a year where a true drought occurs, the regime may have even more negative impacts on taro corm and leaf yield and quality. Furthermore, despite rainout shelters being constructed for the yam trial, severe winds from cyclones and heavy rain downpours may have damaged the shelters, or cause leaching through exceeding water holding capacity of the soil. When damage occurred, rainout shelters were re-constructed with the same materials within short periods of time, but it is unknown the severity

these impacts may have had on outcomes of the trial. When compared to previous studies, there are many uncontrolled variables which may have influenced the results, indicating that further studies would be valuable to confirm the positive findings. One such study could include the yam trial without rainout shelters, or trials in different locations geographically, particularly those with differing rainfall patterns.

Finally, the remote nature of the study being based in Tonga resulted in issues with oversight of the trial. Due to labour limitations, on some occasions watering times may have changed or being missed altogether. Furthermore, collection of growth indicators such as SPAD and stomatal conductance were hindered, due to limited opportunity to travel for suitable durations, as well as cancelled travel itineraries. Whilst these were overcome and the trial was still successfully run, these findings can only show preliminary indication, which require further evaluation prior to expansion to a commercial scale, to not only ensure taro and yam yield remains at a high quality, but also ensure the environmental impacts of supplementary saline irrigation are properly evaluated for suitable sustainable approaches.

5.3 Opportunities

Despite the previously highlighted limitation of this trial, it should not detract significantly from the potential of these preliminary findings. Furthermore, international development studies such as this one, provide opportunity for collaboration and cross-cultural exchange. From this study, the cultivars Huli mao, Kaho kaho and Lose have now being scoped as highly likely to be successful as crops for supplementary saline irrigation during periods of water insecurity in Tonga.

Furthermore, both trials would be easily replicated for further study in either Tonga, or other inhabited coral atolls. The investigation of supplementary saline irrigation to bridge water security gaps could be integrated into sustainable food policies, providing people with another option to achieve food security.

The strong potential of both taro and yam, despite being non-halophytes to successfully yield viable produce under saline conditions, may open them up to future studies globally. Whilst considered orphan crops scientific research, both taro and yam are still economically and culturally significant, feeding billions people annually across several continents. There is significant potential in pursuing research of orphan crops, which often have vast genetic pools to be uncovered, often revealing great opportunities to improve food security.

Finally, by supporting the continued production of taro and yam, two healthy carbohydrate sources, there is opportunity to improve the health of Tongan and other PICT nation communities. In Tonga, obesity is an increasingly major issue, alongside food, water and land insecurities. These locations due to climate change and their remote nature, can strongly benefit from cheap and effective technologies, which offer improved access to healthy foods without negatively impacting the agricultural potential of the land, or water security in the long term.

Whilst taro and yam are significant crops, other major crops in Tonga which remain unexplored regarding their potential for supplementary saline irrigation include melon, pumpkin and cassava (Myrans *et al.*, 2024).

5.4 Conclusion

The primary objective of this study was to evaluate the potential of supplementary saline irrigation in Tonga for taro and yam crops. This study has successfully identified that supplementary and complete (taro and yam respectively) saline irrigation at 60mmol/L NaCl, does not significantly impact yield of taro or yam crops. It was also found that while saline irrigation increased soil electrical conductivity, it was to within acceptable levels that are not expected to negatively impact plant growth. Furthermore, the unique well-draining qualities of the Vaini soils which cover a vast amount of agricultural purpose land in Tonga, indicate from the taro trial, that with sufficient rainfall, supplementary irrigation used appropriately is likely to be a sustainable solution for improving water security in Tonga, without negatively impacting agricultural land – a limited resource.

Furthermore, the cultivars huli mao (taro), kaho kaho and lose (yam) have now been studied for their salinity tolerance, as well as yield expectations. Further studies into their nutrient constituents as well as palatability will be of great value in the future, a well as further characterisation of other species and their cultivars for their salinity tolerance.

To conclude, this study represents the strong potential of supplementary saline irrigation, for non-halophyte crops in well draining soil. It has found that the impacts of 60mmol/L NaCl saline solution on plant yield and physiology is minimal if significant at all, opening the door for many future studies to investigate the potentials of supplementary irrigation using poor water quality sources, so that food can continue to be sustainably produced into the future, with the addition of relatively affordable resources, such as thermodiffusive desalination units.

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