# SUSTAINABLE APPLICATION OF WATER FOOTPRINT IN BLACK TEA AND BOTANICAL EXTRACT PRODUCTION SYSTEM

Report to the
**WATER RESEARCH COMMISSION**

by

**AE NESAMVUNI**
*KHANIMAMBO INNOVATIVE SOLUTIONS*

**WRC Report No 3128/1/24**
**ISBN 978-0-6392-0604-2**

**April 2024**

**Obtainable from**
Water Research Commission
Bloukrans Building, Lynnwood Bridge Office Park
4 Daventry Street
Lynnwood Manor
PRETORIA

orders@wrc.org.za or download from www.wrc.org.za

This is the final report for WRC project no. C2021/2023-00402.

# EXECUTIVE SUMMARY

A study was carried out with an aim to contribute to the sustainable tea production system through an application of water footprint in black tea and botanical extracts. The objectives were to: (a) evaluate the green, blue, and greywater footprint of tea industrial crop and its botanical extracts, (b) assess the level of vulnerability in the tea production system (black, green, and its botanical extracts) to climate extremes and variability, (c) determine the sustainable trade-offs in the use of linked natural resources water-and environment for the competitiveness of tea, (d) assess the water footprint of the tea crop in the context of future climate change scenarios in Limpopo and (e) identify and prioritize strategic intervention points in the tea production value chain for future sustainability.

Based on the said five main specific objectives, the following chapters written in paper form were developed: (1) Water footprint of tea and its botanical extract; (2) The vulnerability of the tea production system to climate change/extremes; (3) The water footprint of tea crops in the context of future climate change scenarios; (4) Economic trade-offs on water-energy-tea-environment nexus; (5) Assessment of long-term relationship between remotely sensed-derived indices and the standardised precipitation index (SPI) in the tea plantation: A case study of Mukumbani Tea Estate, Limpopo Province; and (6) Potential prospects of product development based on tea leaf analysis.

The Tshivhase-Mukumbani Tea Estate is in the Thulamela Municipality of Vhembe District within the Limpopo Province of South Africa. The tea estate comprises the Tshivhase Farm, located at 30.314: 30.367 E and -22.968: -22.994 S, and the Mukumbani Farm, located at 30.386: 30.437 E and -22.904: -22.940 S. The annual rainfall at Tshivhase-Mukumbani Tea Estate was estimated to be 1 758.0 mm, well above the minimum requirement for tea production. The ideal temperature for tea production is 18-25°C with a minimum recommended temperature of 13°C (average for the coldest month) and a maximum of 30°C (average for the warmest month). Temperatures at Tshivhase-Mukumbani Tea Estate are lower in winter, and this results in tea plants becoming dormant. Excessively high summer temperatures may result in wilting of tea leaves, especially at the Tshivhase Farm without irrigation. Not much can be done to change the temperatures for tea production at the estate.

Data was obtained from records kept on the estate, which included rainfall, green leaf (GL) yield, quantity, and quality of made tea (MT). Rainfall data will be for the period 1975 to 2012, while yield data will be for the years 2007 to 2019, following the revitalisation of the estate in 2006. Analysis of the influence of rainfall on tea production was based on averages for the variables for 12 months of the year. Information was also obtained through a review of literature that focused mainly on scientific journals and books. Records kept on the Tshivhase Estate provided mainly quantitative data, while the literature reviewed provided both quantitative and qualitative data. Quantitative data was captured and analysed through an Excel spreadsheet. The data was used to generate summary tables and graphs of pertinent statistical analyses.

Secondary data was collected by the factory over 17 years (2007-2023) to assess the Water-Energy-Food (WEF) nexus. Data was used to assess the interrelationships to address the question of how the business's sustainability or security is affected when various natural and social hazards disrupt the linkages between the three to four systems (water-energy-food-environment). Energy plays an important role in understanding business security within these connections. However, this study focused more particular attention on the relationship between water and food (tea), because water is a scarce natural resource in the surrounding communities to the tea estate.

Key integrated papers developed showed the following synopsis of the results:

### (a) Water footprint of tea and its botanical extract

The focus of this section was to justify and account for the freshwater use in the total lifecycle of green and black tea production, together with its botanical extracts, starting from the production stage and continuing to tea processing. Desktop data was used in this phase of the study based on the pilot plant data collected. Based on desktop studies, it was expected that the total green water content in black tea was 12 784.55 $m^3$/ton. The blue water footprint of black tea production will be expected to be around 65.79 $m^3$/ton. The annual greywater footprint of tea cultivation is expected to be 73 $m^3$/ton for tea cultivation. It means 73 $m^3$ volume of water is required to dilute the pollution load generated during the tea cultivation.

The virtual water content of black tea produced will be expected to be around 12 923.34 m$^3$ /ton/year. The botanical extract will be mainly the total polyphenols, which was 21.3 percent on average, with a minimum of 19.4 percent and a maximum of 25.8 percent for green tea. There is a potential to reduce water usage from the production of leafy green tea through processing and packaging. The seedling variety and some clones are tolerant to drought and do not need irrigation. The use of technology can also reduce the factory water usage during processing. The blue water footprint of black tea depends on the method of tea processing, e.g. use of boilers in tea drying will result in a higher blue water footprint in tea processing.

### (b) The vulnerability of the tea production system to climate change/extremes

The section investigated the influence of rainfall on tea production at Tshivhase Estate in Limpopo Province of South Africa. Rainfall and production data comprised green leaf yield, quantity, and quality of made tea obtained from records kept by the tea estate. Mean annual rainfall was 1 726 mm, declined with time, and currently exceeded the minimum 1 200 mm required for tea production. Monthly rainfall strongly influenced green leaf (GL) yield and quantity of made tea (MT). For tea harvested on the month of rainfall occurrence (0-month lag), coefficients of correlation (r) were 0.8634 (GL) and 0.8571 (MT), indicating strong positive linear relationships between rainfall and the production parameters. The relationships were modelled by regression lines: $Y = 1235x + 2864.5$ (GL) and $Y = 247.9x + 1712.3$ (MT). Accordingly, the coefficients of determination (r) were 0.7455 (GL) and 0.7346 (MT), indicating that 74.55% and 73.46% of the variations in GL and MT respectively, may be accounted for by variation in rainfall. With a 1-month lag from rainfall to harvesting, R-values increased to 1 (GL) and 0.9600 (MT), suggesting even stronger correlations, modelled by: $Y = 1365x – 16230$ (GL) and $Y = 277.69x – 2651.3$ (MT). Accordingly, the R-values were 0.9112 (GL) and 0.9217 (MT). Although the R-values for the 2-month lag remained statistically significant, they were less than those for 1-month and 0-month lags, suggesting a relatively weaker rainfall influence. The study showed a basis for supplementary irrigation decision-making for the months of the year when rainfall declines.

Though rainfall influenced the amount of green leaf production and manufactured made tea, there was no significant correlation between rainfall and tea quality.

### (c) The water footprint of tea crops in the context of future climate change scenarios

The context of this section was to focus on the water footprint of tea in the context of future climate change scenarios. The cultivation of tea requires specific climatic conditions that are suitable for the growth and development of tea plants. The optimal temperature range for the crop is between 15 and 25°C. The optimal temperature for tea growth is around 20-22°C, with rainfall of approximately 2 000-3 000 mm per year, and humidity of around 70-80%. The ideal sunlight required is 4-5 hours per day, with well-drained, fertile soil with a pH range of 5.5 to 6.5. The projection map suggests that the mean annual temperatures in the country would have increased from the initial observation data to the projected date (from 28°C to 31°C). Currently, the country is already experiencing an average temperature increase of 0.2°C per decade. This implies that over the course of the decade, 140 mmpa of rainfall would be shed by the end of the century. The results have serious implications in terms of tea production practice at Tshivhase-Mukumbani. Drought experiences of the Eastern African countries can also repeat themselves in South Africa leading to low productivity and reduced supply to the market.

### (d) Economic trade-offs on the water-energy-tea-environment nexus

This section encapsulates the literature reviewed and the results on the water-energy and food (WEF) nexus. The literature review covered two main areas (a) livelihood security and (b) the WEF nexus approaches and framework. The review was about the context of the WEF nexus and how it can be integrated into the livelihood methodology in addressing the benefits that the Tea Project can offer to the surrounding community. The key focus of the review has been an attempt that needs to be fully developed in the study to integrate sustainable livelihood methods and approaches with the WEF nexus. The report shows the seasonal trends in the growth of tea from September to May. Total green leaf-made tea and moisture loss followed the same trend with the highest values in December, January, and February. Trends over the 17 years were also developed in all tea attributes.

These indicated an increase from 2007 to the peak level in 2011 and a sudden decrease in 2012. This was mainly due to the labor strike that took four months to resolve during the tea growing season. This was followed by another sharp increase in 2014, and then a decrease over the years to 2023, due to reduced financial support from the Limpopo Economic Development Agency (LEDA). The reduced financial support meant reduced staff, benefits, and support in maintenance, and wear and tear of equipment. The results also indicated a strong relationship between water, energy, food, and the environment.

### (e) Assessment of the long-term relationship between remotely sensed-derived indices and the standardized precipitation index (SPI) in the tea plantation: A case study of Mukumbani Tea Estate, Limpopo Province

This section assessed the long-term relationship between the SPI and the remotely sensed data, by considering the seasonal variability of these variables in the Mukumbani Tea Estate, South Africa. The Landsat data was processed to derive the normalised difference vegetation index (NDVI), the normalised difference water index (NDWI), and the surface temperature for each season covering the years 1987-2022. The NDWI varied significantly between the autumn and winter seasons ($p$ = 0.0084 and $p$ = 0.0476 respectively). The autumn correlation analysis revealed that the SPI and NDWI are strongly and positively correlated in the period between 1987 and 2022 ($r$ = 0.91). The 2007 SPI seasonal anomalies suggested that the tea estate also suffered the effects of climate change which resulted in drought hazards. The model constructed for the autumn SPI was the only significant one ($p$ = 0.032). The predicted maps show that the SPI varies greatly across different parts of the tea plantation and this variation is also noticeable seasonally. The results from this study could be valuable for tea plantation management and decision-makers regarding intervention strategies aimed at minimising the effects of climate change on tea plant species.

### (g) Potential Value Added Products and Polyphenols Content of Green Tea

This report also delves into the dynamic landscape of the global tea industry, with a special focus on South Africa, examining market conditions, trends, risks, and most importantly, opportunities for growth and development.

The report underscores the strategic imperatives for seizing opportunities. It starts with a thorough market analysis, identifying target segments, trends, and competitive dynamics, paving the way for informed decision-making. Collaborating with industry experts, we advocate for innovative product development, leveraging tea and moringa's versatility to create tailored solutions that resonate with consumer preferences.  Ensuring a robust supply chain, coupled with stringent quality control measures, is paramount to maintaining product integrity and safety. In conclusion, this report serves as a strategic roadmap for industry stakeholders, government officials, and researchers alike, providing actionable insights to navigate the intricate landscape of the South African tea and moringa industries.

# ACKNOWLEDGEMENTS

The authors would like to thank the following persons and institutions:

- Water Research Commission (WRC) for funding and managing the project
- University of the Free State (UFS) for the Post-Doctoral Students Association over a period of the last two years (Ndwambi Khuthadzo, Mavhungu Tsumbedzo Jutas, Bernadette Webb, Mahopo Tjale Clopus)
- Dr S Hlophe-Ginindza (WRC) as Project Manager, chairing meetings and coordination of the project
- Prof. NS Mpandeli and Dr L Nhamo (WRC) for project support, advice, and facilitation
- The HOD – Ms. RJ Maisela – Limpopo Department of Agriculture and Rural Development for the permission granted to conduct the collaborative research project and facilitation to engage with officials and smallholder farmers
- The Limpopo Economic Development Agency, specifically Mr. Nyiko Mhinga for the permission to conduct the research and the use of secondary data at the VENTECO-Mukumbani Tea Estate. The Agency also appointed the Project Leader to chair the Task Team to develop the Turnaround Strategy for the Tea Estate
- Dr Johan Van Niekerk, Centre for Sustainable Agriculture, Faculty of Natural & Agricultural Sciences, University of the Free State for a platform and facilities for Post-Graduate Research Supervision at Doctoral Level.

The following members of the reference group are also thanked for their valuable contributions:

| | |
|---|---|
| Dr S Hlophe-Ginindza | Water Research Commission (WRC) (Chairman) |
| Prof. NS Mpandeli | Water Research Commission (WRC) |
| Dr L Nhamo | Water Research Commission (WRC) |
| Prof. JN Zvimba | Water Research Commission (WRC) |
| Dr KA Tshikolomo | Limpopo Department of Agriculture and Rural Development |
| Ms. P Mjadu | Department of Agriculture, Land Reform, and Rural Development |

| | |
|---|---|
| Dr S Mokgehle | University of Mpumalanga |
| Prof.  F Mudau | University of KwaZulu-Natal |

**Committee Secretary**

| | |
|---|---|
| Ms. S Fritz | Water Research Commission (WRC Administrator) |

The following persons contributed to the writing of this report:

Prof. AE Nesamvuni (Khanimambo Innovative Solution)
Dr K Ndwambi (Khanimambo Innovative Solutions)
Dr B Webb (Bio Solutiones Technicas)
Mr A Webb (Bio Solutiones Technicas)
Mr P de Bruyn (Bio Solutiones Technicas)
Mrs A Terblanche (Bio Solutiones Technicas)

## TABLE OF CONTENTS

## LIST OF FIGURES

# LIST OF TABLES

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **ARC** | Agricultural Research Council |
| **ARDC** | Agricultural & Rural Development Cooperation |
| **CMIP** | Coupled Model Intercomparison Project 5 |
| **DAFF** | Department of Agriculture, Forestry and Fisheries |
| **DEA** | Department of Environmental Affairs |
| **DLUSM** | Land Use and Soil Management |
| **FAO** | Food and Agricultural Organization of the United Nations |
| **Freq.** | Frequency |
| **GIS** | Geographic Information System |
| **ILO** | International Labour Organisation |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISMEA** | Institute of Mathematics & Economic Sciences Applied |
| **Kg** | Kilogram |
| **Km** | Kilometre |
| **KTDA** | Kenya Tea Development Agency |
| **LEDA** | Limpopo Economic Development Agency |
| **LGP** | Length of growing period |
| **LADC** | Limpopo Agricultural Development Cooperation |
| **LDARD** | Limpopo Department of Agriculture and Rural Development |
| **LIMDEV** | Limpopo Development Agency |
| **MAT** | Mean Annual Temperature |
| **Mm** | Millimetre |
| **Mmpa** | Millimetre per annum |
| **NDVI** | Normalised Difference Vegetation Index |
| **NDWI** | Normalised Difference Water Index |
| **NGO** | Non-governmental Organization |
| **PDA** | Provincial Departments of Agriculture |
| **PTO** | Permission to Occupy |
| **RCP** | Representative Concentration Pathway |
| **SAARC** | South Asian Association for Regional Cooperation |

| | |
|---|---|
| **SAFTA** | South Asian Free Trade Agreement |
| **SAPTA** | South Asian Preferred Trading Agreement |
| **SAWS** | South African Weather Service |
| **SDG** | Sustainable Development Goals |
| **SLA** | Sustainable Livelihood Approach |
| **SPI** | Surface Precipitation Index |
| **StatsSA** | Statistics South Africa |
| **Tmax** | Maximum Temperature |
| **TIL** | Trade Investment Limpopo |
| **TTC** | Tshivhase Tribal Council |
| **WRC** | Water Research Commission |

# Chapter 1 INTRODUCTION

## 1.1 Historical perspectives on tea production

Tea is the dried leaf of the tea plant. The two main varieties of the tea plant are Camellia Sinensis and Camellia assamica. Indigenous to both China and India, the plant is now grown in many countries, including South Africa. Tea was first consumed as a beverage in China sometime between 2 700 BC and 220 AD (L'Amyx, 2003). The now traditional styles of green, black and oolong teas first made an appearance in the Ming Dynasty in China (1368-1644 AD). Tea began to travel as a trade item as early as the fifth century, with some sources indicating Turkish traders bartering for tea on the Mongolian and Tibetan borders. Tea made its way to Japan late in the sixth century, along with another famous Chinese export product – Buddhism. By the end of the seventh century, Buddhist monks were planting tea in Japan. Tea first arrived in the West via overland trade in Russia. Certainly, Arab traders had dealt in tea before this time, but no Europeans had a hand in tea as a trade item until the Dutch began an active and lucrative trade early in the seventeenth century. Dutch and Portuguese traders were the first to introduce Chinese tea to Europe. The Portuguese shipped it from the Chinese coastal port of Macao; the Dutch brought it to Europe via Indonesia (Twinings, 2003a, b, c). From Holland, tea spread relatively quickly throughout Europe (L'Amyx, 2003).

## 1.2 Tea and human nutrition

Tea is one of the most popular and low-cost beverages in the world and has become the second-most consumed liquid after water (Hong & Yabe, 2015; Marx et al., 2017). The consumption of tea is probably influenced by its nutritional value. According to Ruan et al. (2003), tea plants can accumulate large amounts of fluoride in mature leaves from soils of normal F availabilities without showing symptoms of toxicity. The F contained in tea is readily released during infusion and thus is one of the important dietary F sources. Ruan et al. (2003) estimated the content of F in tea to be 100-300 mg/kg while Cao et al. (2006) estimated a wider range (100-430 mg/kg) of the content of this element in younger leaves, usually made into green and black tea. The F could contribute to human health by protecting teeth from caries. According to Gesimba et al. (2005), tea extracts have been shown to prevent cancer.

## 1.3 Tea and the impact of climate

According to Marx et al. (2017), climate is one of the controlling factors in agriculture since most crops are responsive to their surrounding climatic conditions. Tea depends greatly on climate for optimal growth; hence, changes in climatic conditions affect tea production (Wijeratne, 1996; Gesimba et al., 2005; Schepp, 2009; Kumar & Shruthi, 2014; Dutta, 2014; and Gunathilaka et al., 2017). As revealed by Kumar and Shruthi (2014), the effective production of tea requires a high annual rainfall of around 1 500-2 000 mm. The significance of rainfall for optimal production of tea was affirmed by Ochieng et al. (2016) who emphasized the importance of the adequacy and consistency of the rainfall.

Other than yield, rainfall was revealed to have some influence on the quality of tea produced (Gulati et al., 1996; Kottur et al., 2010). Tea quality is largely determined by concentrations of methylxanthine caffeine and polyphenolic catechin compounds responsible for tea stimulant, antioxidant, anti-inflammatory, and cardioprotective properties (Lin et al., 2003). The concentrations of methylxanthine and polyphenolic catechin compounds in tea plants vary with such factors as geographic location, season, and water availability (Ahmed et al., 2012; Ahmed et al., 2013) associated with rainfall variation.

## 1.4 Highlights of the tea industry in South Africa

The study conducted in 2015 – The South African Tea Industry: Challenges and Business Strategies – indicated that the South African tea-producing industry has been declining since 2000; this is due to a host of factors such as increased/high production costs occasioned by the regulated labour market, labour productivity levels, unfavourable international tea prices, removal of tariffs, exchange rates fluctuations, as well as increased competition from African tea-producing countries. These issues culminated in the closure of almost all tea estate projects in South Africa. Currently, there are 12 tea estates in South Africa.

**Table 1.1: The name of the tea estates, the provinces in which they are located and their operational status**

| No. | Name | Province | Status |
|---|---|---|---|
| 1 | Tshivhase | Limpopo | Operating at a loss |
| 2 | Mukumbani | Limpopo | Operating at a loss |
| 3 | Middelkop | Limpopo | Not operating |
| 4 | Grenshoek | Limpopo | Not operating |
| 5 | Ngoma | KwaZulu-Natal | Not operating |
| 6 | Richmond | KwaZulu-Natal | Not operating |
| 7 | Ntingwe | KwaZulu-Natal | Not operating for the past five years |
| 8 | Magwa | Eastern Cape | Operating at a loss |
| 9 | Majola | Eastern Cape | Operating at a loss |
| 10 | Paddock | Eastern Cape | Not operating |
| 11 | Senteeko | Mpumalanga | Not operating |
| 12 | Gradely | Mpumalanga | Not operating |

To date, out of the 12 tea estates in the country, only four are still operating, albeit at a huge loss. Ntingwe Tea Estate in KwaZulu-Natal has not been in operation for the past five years. However, the operation started again in the financial year (2022/2023). The Tea Estate is now placed under the Agribusiness Development Agency (ADA), which is the development agency under the Department of Agriculture and Rural Development (DARD) in the province of KwaZulu-Natal.

## 1.5 Background to the Tshivhase-Mukumbani Estate

Tshivhase and Mukumbani Tea Estates are projects solely owned by the Limpopo Economic Development Agency (LEDA) with 577 ha and 500 ha respectively. Tshivhase and Mukumbani were established by Sapekoe (Pty) Ltd in 1973 and 1983 respectively.

In 1998, the tea estates were taken over by Lipton Park (Pty) Ltd and the Industrial Development Corporation (IDC). The then Agricultural and Rural Development Corporation (ARDC) was also a minority shareholder.

During the 2006/7 financial year, the then Limpopo Department of Agriculture (LDA) bought out both Linton Park and IDC, resulting in the LDA being the 100% shareholder of both Tshivhase and Mukumbani Tea Estates through its agency, the ARDC. Since the year 2006, an attempt has been made to revitalize the Tshivhase-Mukumbani tea estates to create job opportunities through the effective and efficient development of tea value chains for differentiated markets. The capacity presently exists in varying degrees of operation to produce green and black tea in the tea companies in the country. New technologies to develop new products also exist to produce botanical extracts (LDARD, 2010). The opposite happens if these assets are not utilized; the tea bushes lose value and become an environmental risk to neighbouring farms with increased opportunity costs.

Though the tea estates are situated on the Tshivhase Territorial Council land, there has never been a formal working relationship arrangement with the Tshivhase Traditional Council (TTC) in terms of the Permit to Occupy (PTO) for the use of land. The ARDC was subsequently phased out and it was replaced by a new entity called the Limpopo Agribusiness Development Corporation (LADC) as a successor in title. The shareholder for LADC was the Limpopo Department of Agriculture. All these years both tea estates have been subsidized by grants from the LDA through the LADC. In 2012, four Limpopo provincial entities namely, LIMDEV, TIL, LIBSA and THE LADC were amalgamated into a single agency, known as the Limpopo Economic Development Agency (LEDA) as per the provincial EXCO Resolution. As a result, LEDA became the 100% owner of VENTECO Tea Estate (Pty) Ltd. Due to the poor performance of the tea estate, VENTECO Tea Estate (Pty) Ltd was then deregistered, and as a result, became an LEDA project under the Agribusiness Division.

The production of black and green tea is still at the centre of the business model at Mukumbani Tea Estate. This is inclusive of the botanical extracts pilot plant that may need a commercial model. At the time of writing this report, the proposed model was submitted to the Member of the Executive Committee in charge of Economic Development, Environment and Tourism.

## 1.6 Financial implications

VENTECO Tea Estate has been making a huge loss since amalgamation in 2012. This is precisely because the Limpopo Government Department of Agriculture had no longer allocated grants to the Tea Estate.

It was now transferred to the amalgamated LEDA. However, it is worthwhile to mention that, even when the estate was allocated grants, it continued making losses – even though not of this magnitude. It was this lack of dedicated government support and change in management structures that, among other things, stalled the growth of the project.

**Table 1.2: The losses incurred for the past four financial years (2019-2022)**

| Financial year | Total labour cost | Other costs | Loss incurred | % Labor cost |
|---|---|---|---|---|
| 2019 | R18 811 277 | R44 380 141 | R63 191 418 | 30% |
| 2020 | R24 650 116 | R48 631 839 | R73 281 955 | 33% |
| 2021 | R17 903 263 | R28 313 500 | R46 216 763 | 39% |
| 2022 | R20 391 213 | R20 759 462 | R41 150 675 | 50% |
| **TOTAL LOSS** | **81 755 869** | **R142 084 942** | **R223 840 811** | |

VENTECO Tea Estate has made an **accumulative loss** for the past four financial years amounting to **R223 840 811**. The reasons why it made such losses are clearly stated in the study conducted in 2015 known as “**The South African Tea Industry:**

**Challenges and Business Strategies"** which indicated that the South African tea-producing industry has been declining since 2000 due to a host of factors such as:

a) High labour costs
b) High production costs relative to other tea-producing countries
c) Lack of government support
d) Removal of trade barriers
e) Low worker productivity
f) Failure to innovate product development
g) Low-quality tea imports competing with quality locally produced tea
h) Weak industry association or lack of it
i) Disinvestment of big tea players.

## 1.7 Problem statement

The challenge with the tea industry started with the de-investments in South Africa when black tea became unprofitable due to some or all of the following points identified by Sapekoe (Pty) Ltd in 2005, namely: (a) high worker minimum wage rates, (b) no protection against tea imports from SADC, (c) high production cost structure, (*due to labour wages, electricity and inputs costs*), (d) the strong rand against the US Dollar, (e) land claims on tea estates, and lastly, it emerged that (f) The United Kingdom directors were not happy with RSA tea estates' bottom-line (Maloa, 2008).

At a global level, the tea industry continues to find it increasingly difficult to make ends meet, caught between rising costs on the one hand and stagnant or declining prices on the other. International and intra-regional efforts aimed at improving the tea market have met with little success, and a more practical option available to the industry is in the realm of cost reduction. There is no doubt that the two crucial cost elements – labour wages and estate supplies – are bound to rise, per se, but the thrust of this study is that these increases could, within limits, be neutralized in terms of unit costs of production, through enhanced competitiveness and efficient use of both water and energy resources.

The focus here is not just on labour competitiveness, but also on the other production factors that are involved in the growing, manufacturing and marketing of tea. Central to the said production factors are the water and energy nexus.

The understanding is that production practices that do not take into account the well-being of the environment, coupled with the expectation of higher profits, can lead to the deterioration of natural resources. This includes the trade-offs in the use of linked natural resources-water and environment, for the competitiveness of tea.

## 1.8 Aim of the study

The project aims to contribute to the sustainable tea production system through an application of water footprint in black tea and botanical extracts.

## 1.9 Objectives

1.9.1. To evaluate the green, blue and greywater footprint of tea industrial crop and its botanical extracts
1.9.2. To assess the level of vulnerability in the tea production system (black, green and its botanical extracts) to climate extremes and variability
1.9.3. To determine the sustainable trade-offs in the use of linked natural resources-water and environment for the competitiveness of tea
1.9.4. To assess the water footprint of the tea crop in the context of future climate change scenarios in Limpopo
1.9.5. To identify and prioritize key strategic intervention points in the tea production value chain for future sustainability.

## 1.10 Outline of the report

The report is organized in chapters such that Chapter 1 (this chapter) presents the Introduction and Chapter 2 presents Porter's Model of Competitiveness in the Context of Tea Industry. Chapter 3 Water Footprint of Tea and its Botanical Extract, Chapter 4 deals with the The Vulnerability of the Tea Production System to Climate Change/Extremes, Chapter 5 articulates the challenge for the Water Footprint of Tea Crops in the Context of Future Climate Change Scenarios, Chapter 6 presents Economic Trade-Offs on Water-Energy-Tea-Environment Nexus, Chapter 7 addresses Assessment of Long-Term Relationship Between Remotely Sensed-Derived Indices and the Standardized Precipitation Index (SPI) in the Tea Plantation: A Case Study of Mukumbani Tea Estate, Limpopo Province, Chapter 8 deals with Potential Value Added Products and Chapter 9 gives the Conclusions and

Recommendations. The limitations of the study were that the factory closed in July 2023 in preparation of the hand over to the Tshivhase Tribal Council. Factory floor based data on water footprint and energy could not be collected as planned. Instead, secondary data-records from the factory and pilot plant were used. This data was used in parts of chapters 3, 5 and 6.

The Publications and Capacity Building Report is presented in Annexure 1. The report is structured in such a way that each chapter is a standalone, assumes the form of a publishable manuscript, and is accordingly made up of items such as an abstract, introduction, research methodology, results, their discussion, and conclusions. As a result of this structuring of the report, an amount of information was repeated across some of the chapters, and this was necessary to ensure coherence and good flow of the presentation.

# Chapter 2 PORTER'S MODEL OF COMPETITIVENESS IN THE CONTEXT OF TEA INDUSTRY

## 2.1 Introduction

This section presents a review of relevant literature focusing on the concept of competitiveness, in the context of the tea industry, inclusive of factors that affect its competitiveness.

## 2.2 Concept of competitiveness

For the purpose of this section, it would be relevant to start off by engaging in the definition of competitiveness as the volume of literature on this subject has been growing in economics and business studies. The challenge is that there is no agreement as to what competitive means. Over the years there has been no shortage of definitions for competitiveness and why some nations, industries and sectors are competitive, and others are not. However, there has been a frustration on the lack of agreement on what needs to be measured.

This lack of coherence regarding the definition and measurement of competitiveness makes it difficult to compare research results as they accumulate around the world.

The Oxford English Dictionary (Oxford, 2002) defines competitiveness as derivatives of "competitive" which means the following: (a) having to do with competition, (b) strongly wanting to be more successful than others, (c) as good as or better than others of a similar nature. However, competition is defined as: (a) the activity of competing against others, (b) the occasion in which individuals compete, (c) the person or people with whom one is competing. Compete, competes, competing, competed mean to try to achieve something by overcoming others. The origin for compete is from the Latin word *competere*, which means, "to strive together". On the other hand, a competitor is: (a) a person who takes part in a sporting contest, and (b) an organization competing with others in business.

The word competitiveness also has some misunderstanding at international level relating to dividing the term into price competitiveness and non-price competitiveness. According to (Cho, 1994; Cho and Moon, 2005), price competitiveness includes insignificant remunerations, exchange rates and labour efficiency, whereas non-price competitiveness encompasses issues such as quality, marketing, service and market differentiation. Cho (1994) further expands by saying that the measure of export price, production cost, and wholesale price indices are used.

Increasing values are understood as weakening a country's global competitiveness. However, there are circumstances where countries do have global competitiveness with the concurrent increase in the value of their goods.

Esterhuizen (2006) showed that the evaluation tools for non-price competitiveness are quality status, durability, designs and consumer satisfaction. The challenge with non-price competitiveness measures is that there are no lessons learned to corroborate their impact.  Esterhuizen (2006) further indicated that price and non-price aspects are not supposed to be understood as the causes, but as the consequence of a country's global competitiveness. Freebairn (1986) and Delgado, Ketels, Porter and Stern (2012) defined competitiveness as "The ability to supply goods and services in the location and form and the time they are sought by buyers, at prices that are as good as or better than those of potential suppliers, while earning at least the opportunity cost of returns on resources employed". The definition was validated by the Institute of Mathematical and Economical Sciences Applied (ISMEA) in analysing the challenges of global competition on the European agro-food system (ISMEA, 1999). The definition by Freebairn (1986) includes (a) the competition at local and worldwide merchandise markets and thus the capacity to increase and sustain market segments, and (b) the competition in factor markets, that are income earners in the industry.

Sharples (1990) explains the difference between comparative and competitive advantage. He expands by indicating that comparative advantage is theoretical, which helps in explaining trade and optimal welfare in an undistorted world (Sharples, 1990). Firms and industries can only be said to be competitive, if they can sell at the going price. If they are competent to persist and grow their market share, they are said to be competitive.

The Agri-food Policy Directorate of Agriculture Canada (1993: v-vi) uses two approaches to define competitiveness: (a) one that looks at the results, the capacity to cost-effectively gain and sustain market share, and (b) the other that explains its attributes, that is, ability to profitably provide buyers with a product-price combination that is at least as attractive as that offered by other suppliers. Petit and Gnaegy (1994) stated that competitiveness is the capacity to develop and deliver goods and services to worldwide markets while guaranteeing increasing levels of real income as well as investment.

## 2.3 Competitiveness in the context of the South African economy

In the context of the South African economy, competitiveness should be about the specific industry or firm that should be competitive; the government can only create the enabling environment. Each sector of the economy should be able to sustain economic performance in local and international markets. Central to the discussion at hand is the difference indicated by Worley (1996) between comparative and competitive advantage. Worley (1996) shows that comparative advantage talks about how trade could benefit a country through more efficient use of resources such as land, labour and capital input in a trade-free environment. Worley further states that "competitive advantage on the other hand explains existing trading patterns as they occur in the real world, including all distortions and barriers to free trade, i.e. policy effects, price effects, product quality differences and industry marketing skills which are ignored by comparative advantage". By competitive advantage, we refer to tangible business opportunities within existing policy and price alterations.

Expanding on the concept of the (Cho, 1994; Cho and Moon, 2005) model of competitiveness at an international level, Esterhuizen (2006) indicated that the competitiveness of an enterprise is defined by the industry having a bigger marketplace through increased earnings and persistent growth when equated to competitors. For a country, it cannot be said it is internationally competitive purely because it has one or two prosperous businesses. A country needs to have multiple businesses with resilient competitiveness.

A country needs a source of competitiveness which can then be useful to several businesses. Countries, therefore, are globally competitive when they have numerous businesses with competitive benefit, based on shared foundations of competitiveness (Cho, 1994; Cho and Moon, 2005).

## 2.4 Porter's competitive advantage of industry

Competitive advantage analysis, as developed by Porter (2011), consisted of reviewing case studies of successful industries to identify the reason they are countries or localities. The idea was to generate a new viewpoint and tools, leading to a method of competitiveness that develops directly out of an evaluation of successful businesses. Simply stated, the approach was initiated to know in a simple, uncomplicated manner what works and why. In studying a hundred companies in ten industrialised states, (Porter, 2011) wanted to study if a country's prominence in an economic sector can be explained more sufficiently by variables other than the factors of production on which the theories of comparative advantage were based.

According to Porter (1990, 1998, 2011), a country's competitiveness depends upon the capability of its industry to invent and upgrade its product. He added that the national property is created and does not develop from a nation's natural abundance, such as its labour pool and its currency value. A company gains advantage against the world's best competitors from having strong local rivals, forceful home-based suppliers and demanding local customers. Porter (2011) stated that "In a world of increasing global competition, nations have become more, not less, important. As the basis of competition has shifted more and more to the creation and assimilation of knowledge, the role of the nation has grown. Competitive advantage is created and sustained through a highly localised process. Differences in national values, culture, economic structure, institutions and histories all contribute to competitive success. There are striking differences in the patterns of competitiveness in every or even most industries. Ultimately, nations succeed in particular industries because their home environment is the most forward-looking, dynamic, and challenging".

Innovative activities are a platform on which the industry achieves competitive advantage. Competitive companies look at innovation in the broad sense, inclusive of new technologies. They convert old ways of doing things into new ones to be competitive. Porter (2011) indicated that innovation can be exhibited in a new merchandise design, new production process, new promotion approach, appropriate leadership styles or a new way of conducting training. The cause why certain industries located in specific countries (a) have the capability of continued innovation, (b) robust pursue enhancements, (c) pursue refined source of competitive advantage and (d) are capable to overcome barriers to change, depend on four broad attributes of nations. According to Porter (2011), these attributes independently and as a system constitute the diamond of national advantage, the playing field that each nation establishes and operates for its industries. These attributes are (see Figure 2.1):

**Factor conditions.** The nation's position in factors of production, such as skilled labour or infrastructure, necessary to compete in a given industry (Porter, 2011).

**Demand conditions.** The nature of home-market demand for the industry's products or service (Porter, 2011).

**Relating and supporting industries.** The presence or absence in the nation of supplier industries and other related industries that are internationally competitive (Porter, 2011).

**Firm strategy, structure, and rivalry.** The conditions in the nation governing how companies are created, organised, and managed, as well as the nature of domestic rivalry (Porter, 2011).

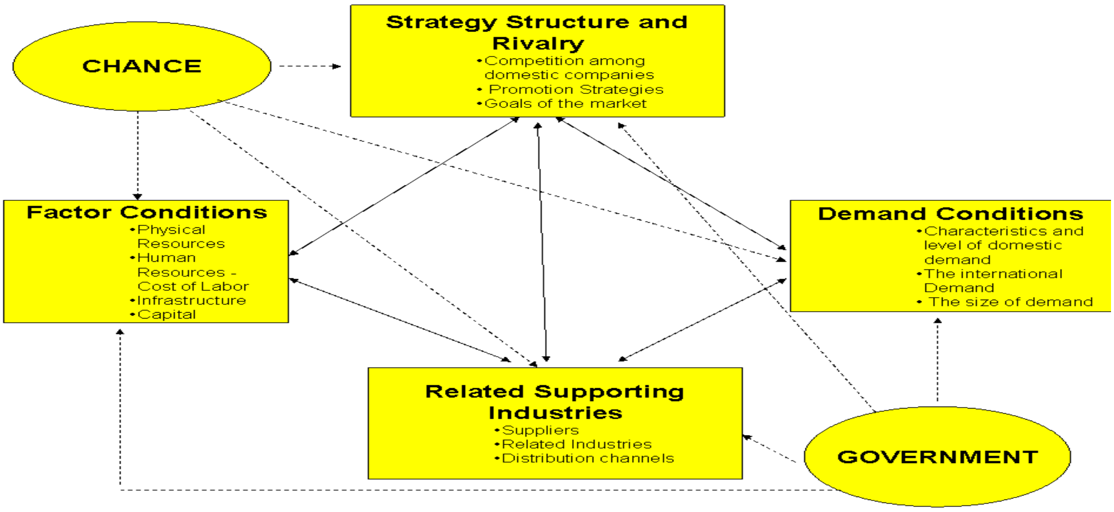


**Figure 2.1: Porter's diamond**
**Source: (Porter, 2011)**

The domestic situation in which businesses are developed and mature to compete is centred on these determinants (Porter, 2011). Esterhuizen (2006) explains the model by saying "each point on the diamond – and the diamond as system – affects essential ingredients for achieving international competitive success. The availability of resources and skills are necessary for competitive advantage in an industry; the information that forms the opportunities that companies perceive and the directions in which they position their resources and skills, the goals of the owners, managers, and individuals in companies, and most important, the pressure on companies to invest and innovate".

Added to the diamond model were two outside variables, namely, the role of chance and that of government. Chance events are occurrences that have little to do with circumstances in a nation and are often outside the power of an industry (or government) to influence. According to Porter (2011), this will include new inventions, major new technologies such as biotechnology and discontinuities in input costs such as the energy crisis, financial market shifts, foreign government decisions and wars. Such occasions can reverse sources of competitive advantage and create new ones.

The ability of an industry to respond will depend upon the status of the other parts of the competitive diamond. The latter also affects the environment for invention and entrepreneurship; hence, where they will occur.

The role of the government is best viewed in terms of its impact on the four determinants of competitiveness rather than a separate determinant. The model does not encourage government's role to be that of intervening in trade. Such interventions promote markets for inefficient industries to thrive. Porter (2011) further argued that government-appropriate responsibility is to be an enabler, to boost business to increase their targets and improve competitive performance, in the context of challenging circumstances. The inherent measure of being competitive belongs to entrepreneurs; government only provides the environment in which business can thrive. The environment in which companies could do business favourably should be provided by government, in line with conditions outlined in the diamond model. Successful government policies are those that create an environment where government play an indirect role, rather than direct.

## 2.5 Extension to the Porter diamond model

An extension to the Porter diamond model was made to accommodate international competitiveness in terms of sustenance, profitability, and growth. Such a model was called the double diamond framework. Further extensions were done to include the aspect of value addition to companies – which was referred to as the generalized double diamond model.

### 2.5.1 Double diamond framework and generalized double diamond model.

Several studies (Esterhuizen, 2006; Moon, Rugman and Verbeke, 1995; Rugman & D' cruz, 1993) concluded that successful managers shape their businesses upon both local and external diamonds to become internationally competitive in terms of sustenance, profitability, and growth. The double diamond framework was later adapted for application in large and all small economies. Companies based in small countries such as South Korea and Singapore target markets at international level, based on their capability to act in the international domain. The authors further defined the generalized double diamond model national competitiveness "as the capability of firms engaged in value-added activities in a specific industry in a particular country to sustain this value-added over long periods of time in spite of international competition".

### 2.5.2 The nine-factor model

Esterhuizen (2006), using the extended model of (Porter, 2011), explained the Cho (1994; Cho and Moon, 2005) arguments in terms of the limitations of Porter's original model to developing countries such as Korea. Cho (1990) modified Porter's diamond model to take into cognizance the Korean economic circumstance. Cho (1990) separated sources of global competitiveness into two broad groups: "physical" and "human" factors. By physical factors, Cho (1994; Cho and Moon, 2005) referred to capable incomes; related and associated businesses and local demand which, when combined, define the level of global competitiveness of a given country at a time scale. Cho (1994) defined human factors to "include workers, politicians and bureaucrats, entrepreneurs and professional managers and engineers". An external factor of pure chance is added to these eight internal factors to make a new paradigm nine-factor model.

Esterhuizen (2006) further explained the nine-factor model by showing the comparative significance of each of the eight physical and human factors variation as the country's economy increases from a less developed to a developed, semi-developed and finally to a fully developed stage. Esterhuizen (2006) emphasized the findings by Cho (1994; Cho and Moon, 2005) that the variation between the nine-factor model and the Porter diamond model are in the separation of factors and in the addition of new factors (see Figure 2.2). The diamond model comprises both natural and human labour endowment. The workers or labour mobilize the physical factors with the aim of gaining global competitiveness.

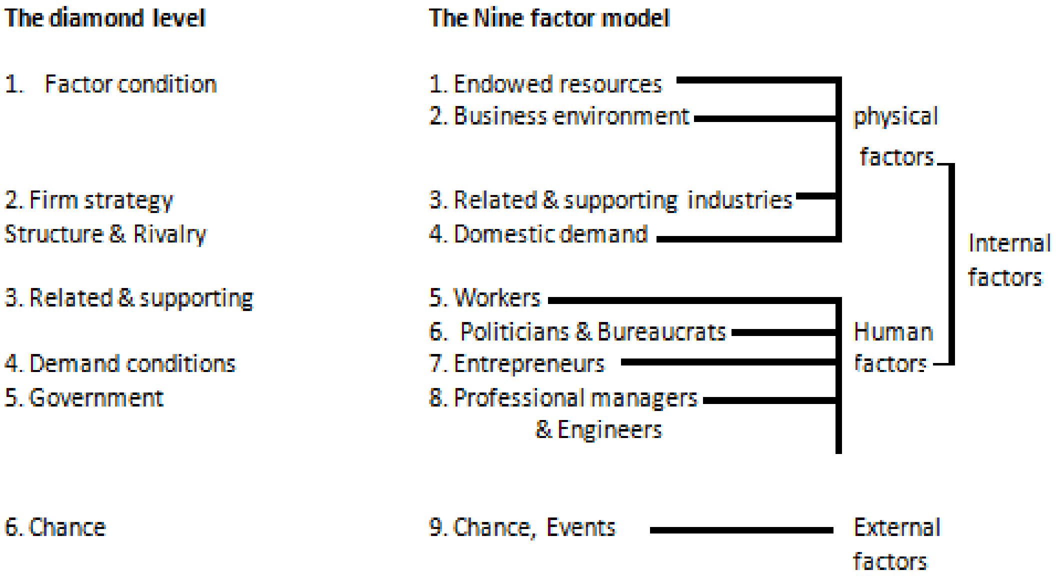


**Figure 2.2: Comparison of the diamond and the nine factor models**
**Source:(Cho & Moon, 2002)**

## 2.6 The Tea industry in context

Globally, tea trading has not been profitable due to the increase in inputs across its value chain and the low prices the product has been fetching in the market. Under the circumstance, there was no strategy left to intervene in the industry, other than to introduce cost-cutting measures by improving the efficiency of labour and inputs (Sivaram, 1994).

The emphasis in improving competitiveness should not be on only labour and production factors, but on other aspects of the production segments such as growth, industrialisation and promotion of tea. Increased competitiveness in the context of tea production should be to strive for more made tea produced with conservative production input. Global tea production is in the hands of the private sector which is profit motivated. The said motivation for improved earnings bodes well for improved competitiveness.

The strategy that is gaining momentum in the tea industry is one of ensuring that made tea is value-added, and also to put mechanisms in place to reduce cost by maximizing on the unit of each cost concerned, mainly labour and production inputs. Of concern for tea production expansion is that land is no longer available, and the cost associated with it has now become exorbitant to the government and private sector. (Melican, 2004).

### 2.6.1 Factors affecting competitiveness at enterprise level.

The factors affecting the competitiveness of the tea plantations have been studied and researched. Data that exists has been in the domain of the ILO (International Labour Organisation) from a labour perspective. The said data was on developing novel ways to improve competitiveness without jeopardizing the level and quality of jobs in the tea industry (Sivaram, 1994; Baffes, 2003; Melican, 2004). Critical matters identified have been the personal, socio-economic and health factors that can influence the wellbeing of employees. The biggest challenge has been the lack of measuring tools to quantify progress made or lack thereof in the tea industry (Sivaram, 1992). According to the ILO, the factors influencing competitiveness in the tea industry are: (a) *uncontrollable*, such as weather, temperature, altitude, tea variety, type of planting and age of bush, (b) *controllable*, meaning management practice, and (c) *related to worker competitiveness*, inclusive of wages and incentives, motivation, individual talent, experience, training, age, living environment and family earnings (Sivaram, 1994; Baffes, 2003; Melican, 2004) .

#### *2.6.1.1 Labor requirements*

Labor requirements as categorized by the ILO (Sivaram, 1994; Baffes, 2003; Melican, 2004), constitute plucking – which is the activity of harvesting that takes about 70% of the workdays and 40% of the production cost. The other activities such as fertilizing, weeding, pruning and factory processing take about 30% of the workdays and 60% of the production cost. It is estimated that CTC (cut, tear, and curl) methods of processing demands half of the labour as compared to the orthodox processing methods. Little has been done to invest in the replanting as this yield’s low returns to the estates. Instead, more work has been done on developing novel methods of dealing with labour recruitment and demobilization throughout the growing season (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.1.2 Production efficiency*

Sivaram (1994) indicated a variety of scales and tools to measure production efficiency. In his paper, the focus was on reducing costs through the efficiency of plucking, by increasing the amount of quality green leaf harvested per workday.

He further explained the other efficiency measures within the segment of processing, inputs, and the total management of the estate as being critical. There seems to be a consensus that the workday requirements and the labour per unit of area are the central measures on which to improve competitiveness. It should be noted that these measures of efficiency will vary from one nation to the other, region and continent. Technologies being introduced to the industry also create a variation worth registering through the introduction of computer programming (Sivaram, 1994; Baffes, 2003; Melican, 2004).

Though harvesting has been the focus of competitive linked strategies, the geo-physical approaches have also received some attention to improve productivity and efficiency. Such strategies include soil improvement programs, adaptations to the micro-climate, adaptive planting material, maximizing plucking quality shoots, novel strategies on pruning, and alignment of labour demands to tea bush growth. The biggest challenge to this effect has been the lack of cooperation from the workers' side who inherently will demand a worker labour-friendly approach (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.1.3 Novel labor schemes for competitiveness*

Due to shortages of labour, there has been an attempt to introduce mechanical harvesters, especially in periods with high leaf volumes. The biggest disadvantage has been its effect on the leaf quality, which will yield extremely poor made tea despite its effect on the savings on labour (Sivaram, 1994; Baffes, 2003; Melican, 2004). With its interest in labour, the ILO then studied a series of incentive schemes implemented to improve competitiveness.

One concept was that the pluckers (the labour force that is responsible for picking tea leaves) would be paid an incentive for a certain percentage of the leaf that was above the standard. The success of the scheme was to be extended to the total chain of production, such as fertilizing and leaf loading – to all activities of processing. The ILO also studied the linkages between health, motivation, welfare returns and the benefits to management to control common illnesses and competitiveness. The results showed that age and experience had a direct influence on competitiveness in women harvesters. An experience of 20 years as the threshold was found to have an impact on competitiveness.

As a requirement for new entrance pluckers, additional training is to be provided to help improve their effectiveness within this competitive trade (Sivaram, 1992; Sivaram, 1994; Baffes, 2003; Melican, 2004). The other central criterion of the case study was that women who had children below six years had poor productivity indexes, due to demand to take care of them. Their productivity increased when the children grew to school-going age.

The findings deal directly with the welfare of women working in tea estates for strategies and policies to provide for crèche and estate-based schools. For health-related occupational standards, the work of harvesting strains women in the neck and cervical spine due to the carrying of tea baskets, and scratches on their hands and toes. It should be obvious that protective clothing should be provided suitable for all weather (Sivaram, 1994).

#### *2.6.1.4 Size of the estate and competitiveness*

Within the industry domain, there has been a school of thought to the effect that competitiveness is higher in estates compared to smallholdings. The second school of thought is to the contrary, advocating for small farms on the basis that there tends to be a higher output per workday and higher land competitiveness per unit of area.

The challenge with small farms is that they do not have the advantage of the processing profits of made tea that accrue to big estates, as small farm activities end in the harvesting of green leaves. For tea to be profitable, efforts should be to ensure a model that leads to processing and/or any value, especially where smallholder farmers are involved.

The model should be coupled with a strong and efficient advisory system with appropriate factory infrastructure for processing of the green leaves (Chatterjee, 1982; Sivaram, 1994; Baffes, 2003; Melican, 2004).

### *2.6.1.5 Price of tea and competitiveness*

The global tea industry has been experiencing the same problem of an increase in production costs and prices declining in the world market. An intervention through the FAO (Food and Agricultural Organisation) to maintain prices could be sustained. From the government of Sri Lanka, an approach was to establish the Tea Producers Forum, which also took time to make an impact on the world tea market. The main trade negotiating platform has been the South Asian Association for Regional Cooperation (SAARC) negotiating a South Asian Preferential Trading Agreement (SAPTA) as well as a South Asian Free Trade Agreement (SAFTA). The trend in tea prices has shown a gradual fall in prices to about 7.7% in 1993.

There was a similar decline in North India of 12.9% (Sivaram, 1994; Baffes, 2003; Melican, 2004). Other recorded decreases in price were 8.5% in Colombo, Sri Lanka and 15.8% in Chittagong, Bangladesh (Government of Sri Lanka, 1980). According to Sivaram (1994) on his paper for the ILO, the processing input prices also followed a negative trend. Many countries experienced the highest cost of tea production valued at R16.17 per kg in Sri Lanka, R13.08 in India and R12.65 in Bangladesh for the year 1994. However, the cost recorded for the same year for Kenya was R10.56, which was much lower than the Asian countries. Caught within the paradigm of increasing costs and declining prices, the better evil for the industry, which is controllable, will be to deal with minimizing the costs of production inputs through enhanced competitiveness (Sivaram, 1994; ILO, 1994).

### *2.6.1.6 Value addition and competitiveness*

In the tea industry, value addition is no longer a matter of choice. The activities of value addition could take the form of well-priced teas, ensuring that blending and packaging happen in the source of production, ensuring processing of tea bags, differentiating into flavoured teas and green teas. The advantage of value addition is with the prices of the new value-added products; there is an added efficiency responsibility, mainly in the energy-saving domain of processing (Chatterjee, 1982; Sivaram, 1994; Baffes, 2003; Melican, 2004).

### 2.6.2 Labor absorptive capacity of tea enterprise

Several authors (Sivaram, 1994; Wesumperuma et al., 1985) showed that tea production is a land and labour-intensive business. What compounds the challenge in tea production is that both land and labour are no longer freely available and cheap. Added to the problem has been the need to maintain soil fertility and the scarcity of labour, due to migratory patterns from remote rural areas to the cities (Wesumperuma et al., 1985). Tea making, therefore, is inherently labour-absorbing – like most agricultural activities and programs. It is estimated by (Wesumperuma et al., 1985; de Silva, 1994) that 60% of the earnings of tea is agricultural in nature with about 40% being processing. The total value chain of tea production then absorbs a significant portion of labour in the various segments. These segments were researched and documented by Sivaram (1994) within the International Labor Organization document that explained each segment (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.2.1 Harvesting*

Harvesting is highly labour-intensive and will continue to be such due to the failure of mechanical harvesters. It is estimated that harvesting explains about 70% of the workdays and about 40% of the total cost of production. The main factors that impact harvesting are:

#### *2.6.2.2 Tea yield, plant density and leaf variety*

An increase in *yield* is achieved by embracing superior agricultural and management practices; *plant density* – estates with less tea bushes (8 500 per hectare/seedling) have lower green leaf production potential than those with more plants (about 12,500 per hectare in vegetative propagated tea); *leaf variety* – the small-leaved *China* variety yields less than the large-leaved "Assam" variety or the hybrid medium-leaved plants (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.2.3 Climate and topography*

Plucking output and competitiveness becomes lower in drought-stricken areas with higher elevation and steep areas. Due to the climatic demands, some estates irrigate the tea bushes to mitigate prolonged drought spells (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.2.4 Age of plant and leaf standard*

The yield of older tea bushes is much lower than that of replanted fields; – *leaf standard* – there has been a traditional "two leaves and a bud", which ensures quality, but does not generate the desired quantity compared to harvesting the third leaf (Sivaram, 1994).

#### *2.6.2.5 Plucking frequency and wage rates and incentives*

According to Sivaram (1994), a study comparing a seven-day interval (52 rounds) to a five-day interval (73 rounds) showed a different level of yield and profitability; *wage rates* – a proposed model should have an incentive that encourages workers to leave less leaf on the tea bushes, at the same time incentivising workers through extra earnings, acquired through better quality of the leaf for improved quality of made tea. (Sivaram, 1994; Baffes, 2003; Melican, 2004)

#### *2.6.2.6 Fertilizing*

Global tea production occurs in high rainfall areas which may lead to leaching of soil minerals. In such conditions, there is a direct association between the amount of fertilizer applied and the response in growth of the tea bushes. It has been estimated that about 1 kg of nitrogen is needed for every 10 kg of made tea based on precision fertilizer cost, subsidies, and the prices of tea. The implication for fertilizer applications relates to workdays for labour which is like other field activities. The only extra demand comes when fields must be fertilized in two or three rounds (Sivaram, 1994).

#### *2.6.2.7 Weeding*

Because tea estates are mostly based in rural areas, the activity of weeding adds to the cost of tea production. To reduce this cost, estates are now turning to chemical weeding. Management of estates also brings into the picture the whole question of soil conservation, wherein weeding is meant to minimize the negative effect, but not be totally removed to create ground cover for moisture (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.2.8 Pruning*

According to the ILO (Sivaram, 1994) data on tea bush management, a seedling tea bush can be pruned for over 50 years whereas a hybrid only 40 years. The activity of pruning is meant to give the bushes shape, form, and the appropriate height for pruning and plucking. Pruning is carried out when the amount of green leaf starts to decline. There are a variety of techniques to prune, which include (a) rejuvenation pruning, (b) clean pruning, (c) lung pruning, and (d) the cut-across at an optimum height. Pruning becomes even more important in estates where certain portions of the farm do not pluck and the buds grow beyond the standards of two leaves and bud (Topham, 2012, personal communication).

#### *2.6.2.9 Manufacturing*

The standards set by the tea industry are that the factory requires at least 4.5 kg of green leaf to process 1 kg of tea. The challenge in many parts of the world is the land available for the amount of made tea that can be produced. The processing methods also create a variation in the amount of made tea from green leaves. (Sivaram, 1994; Baffes, 2003; Melican, 2004). A comparison between the CTC (cut, tear and curl) and the orthodox methods shows that the CTC gives more cups of tea and quicker brewing than the orthodox method. This has led to the shift in processing methods to CTC at the ratio of 85:15 in India, 10: 90 in Sri Lanka, and 100 percent in Bangladesh. The competitive advantage of a shift into CTC is that labour requirement is half that of the orthodox method across all types of tea estates (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.2.10 Overheads*

A study done to determine the impact of welfare and worker productivity (Sivaram, 1992) indicated that big estates tend to have higher overhead costs compared to smallholder farms. This is mainly because big estates must provide housing, medical care, education, sanitation, and other provisions for the good of the workers.

It was estimated that five percent of the workdays are devoted to providing welfare-oriented services in the big estates. In terms of geographic regions, most countries in South Asia (e.g. Bangladesh, India) are large estates, except Sri Lanka which has experienced a growth in smallholder farms to 45 percent of the land area.

#### *2.6.2.11 Other field operations*

Labor required for other field operations demands male workers and constitutes about 15 percent of the workdays in an estate. The activities include mainly soil conservation, pest control and disease management.

### 2.6.3 Competitiveness indices in the tea industry

There are a variety of scales in the tea industry to measure production efficiency and its influence on reducing costs. The most important of these are discussed in 2.6.3.1 to 2.6.3.4 (Wesumperuma, Gooneratne, Fernando, 1985; Sivaram, 1992; de Silva, 1994).

#### *2.6.3.1 Plucking competitiveness*

Plucking competitiveness can be defined as the "amount of green leaf harvested per workday, the purpose being to increase it without loss of quality". The average field output for the South Asian countries is reported in Table 2.1. This includes the variation that is influenced by the type of plucking within an estate, elevation and region, elevation and regional differences. The said variations explain the differences in Table 2.1. (Sivaram, 1994). The average green leaf produced per day per worker was found to be about 24 in India and private estates in Sri Lanka. The values were far less when compared to between 40 to 50 kg per day per worker recorded in Kenya. Higher values were recorded in Zimbabwe – as high as 68 kg per day per worker. (Tea Board of Bangladesh, India and Sri Lanka, undated).

**Table 2.1: Average field output in South Asian countries (kg of green leaf per day per worker)**

| Country | Green leaf (kg)/day/worker |
|---|---|
| Bangladesh | 20 |
| **India** | |
| North | 24 |
| South | 25 |
| **Sri Lanka** | |
| State sector | 15 |
| Private estates/smallholdings | 24 |

**Sources: Sivaram, 1994**

### *2.6.3.2 Processing competitiveness*

The processing competitiveness can be defined in two ways (a) "the ratio of green leaf to made tea, and (b) the worker output at the factory". In this context the conversion of green leaf into made tea depends on the quality of leaf plucked, cautious handling and transport, and timely processing. The target is to get about 4.5 kg of green leaf converted into 1 kg of made tea. An improvement in the processing technique yielded a ratio of 4 kg green leaf to 1 kg made tea in Zimbabwe. Table 2.2 shows the data on worker outputs in the South Asian countries (Tea Board of Bangladesh, India and Sri Lanka, undated).

**Table 2.2: Average factory output in South Asian countries (kg of made tea per day per worker)**

| Country | Made tea (kg)/day/worker |
|---|---|
| Bangladesh | 18 |
| **India** | |
| North | 40 |
| South | 80 |
| **Sri Lanka** | |
| Up-country (Orthodox) | 45 |
| South Country (Orthodox) | 35 |
| CTC (cut, tear and curl) | 80 |

**Source: CIRCA 1993**

India South and Sri Lanka CTC tea yield the highest kg made tea (80 kg) per day per worker. The Kenyan method of CTC also has been recorded as yielding an output of about 110 kg of made tea per day per worker (Tea Board of Bangladesh, India & Sri Lanka, undated; Wesumperuma et al., 1985).

#### *2.6.3.3 Input competitiveness.*

The objective with inputs competitiveness should be to minimize the application of inorganic fertilizers in tea estates. Good practice in Kenya dictates that 20 kg of made tea be equated to 1 kg of nitrogen applied in the fields. An ILO report indicates that South Asian Estates have achieved half of the stated targets in Kenya (Sivaram, 1994; Baffes, 2003; Melican, 2004).

#### *2.6.3.4 Land-labor ratio.*

Sivaram (1994) indicated that “the main parameters determining the competitiveness of a tea estate, particularly in respect of its day-to-day operations, are the levels of labour utilization and the labour per unit area appropriate to the different levels of yield”. These requirements are indicated in Table 2.3 (Sivaram, 1994; Baffes, 2003; Melican, 2004).

**Table 2.3: Workdays and labour per hectare: requirements for different levels of yield**

| **Activity** | **Yield (kg per hectare)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 000 | 1 250 | 1 500 | 1 750 | 2 000 | 2 250 | 2 500 | 2 750 | 3 000 |
| Plucking | | | | | | | | | |
| Workdays | 362 | 418 | 466 | 507 | 512 | 515 | 518 | 520 | 522 |
| Labor per hectare | 1.51 | 1.74 | 1.94 | 2.11 | 2.13 | 2.14 | 2.15 | 2.17 | 2.18 |
| Other field | | | | | | | | | |
| Workdays | 125 | 120 | 115 | 115 | 110 | 110 | 105 | 105 | 100 |
| Labor per hectare | 0.52 | 0.50 | 0.48 | 0.48 | 0.46 | 0.46 | 0.44 | 0.44 | 0.42 |
| Manufacture | | | | | | | | | |
| Workdays | 26 | 31 | 36 | 41 | 47 | 52 | 58 | 63 | 69 |
| Labor per hectare | 0.11 | 0.13 | 0.15 | 0.17 | 0.20 | 0.22 | 0.24 | 0.25 | 0.28 |
| Overheads | | | | | | | | | |
| Workdays | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Labor per hectare | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| Total | | | | | | | | | |
| Workdays | 553 | 609 | 657 | 703 | 709 | 717 | 721 | 728 | 731 |
| Labor per hectare | 2.30 | 2.54 | 2.74 | 2.93 | 2.95 | 2.99 | 3.00 | 3.03 | 3.04 |

**[1](Sivaram, 1994)**

Table 2.3 indicates that the workdays required for an estate with production of 1 500 kg per hectare is 657, with an average of 2.74 workers per hectare. There will be a variation from state to state and from region to region within the same country. The other source of variation remains the type of plantation, be it smallholder or large estate. In comparison, the average number of workers for India was recorded as 2.5 and 2 for Bangladesh.

In Sri Lanka, there was a noticeable difference between estates which registered 3 to 3.5 workers per hectare and smallholdings which registered 1.5 per hectare. In East African countries the average recorded is about 2 per hectare through the influence of family workers (Tea Board of Bangladesh, India & Sri Lanka, undated; Wesumperuma et al., 1985).

## 2.7 Strategies to be considered for implementation by the tea industry.

Some of the strategies identified in the study by Khumalo et al. (2015) include the following:

- Dedicated differentiation strategy which will give focus to tea production of specialty quality
- Expansion of own tea brands emphasizing originality and distinctive attributes such as chemical-free tea, single estate low caffeine and catechin-rich tea
- Promotion of the demand for green tea extract, powdered tea and tailor-made products for the growing demand for specialty products
- Establishment of partnerships with proven tea-producing companies such as Rooibos Limited which produces green tea extract for the food industry
- Promotion of the tea estates as organic production and advocate organic certification
- Recapitalization of the tea estates to improve production efficiencies and investment in modern technology with the possibility of developing a small-scale sector of outgrowers

Efficiency of resource utilization could also mean the adoption of new business models by diversification into growing other agricultural products.

## 2.8 Conclusion

This section presented the review of relevant literature. The prospects of tea production in South Africa, specifically in Limpopo Province, will in the long run depend on her international competitiveness. At present, the cost of producing tea in South Africa is very high compared to the major tea producing countries such as Kenya, Malawi, Tanzania, Sri Lanka and India.

The increase in the cost of production of tea in South Africa has made the tea industry unviable with slight fluctuations in the international price of tea. Studying the total chain of production and alternative products from tea can assist to make tea economically and socially sustainable. Some of the strategies for consideration have been suggested.

# Chapter 3 THE WATER FOOTPRINT FOR TEA AND ITS BOTANICAL EXTRACT

## 3.1. Introduction

The global consciousness on matters that affect the environment has been enhanced due to the recognition of the adverse effects related to the production of agricultural commodities. Production practices that do not consider the well-being of the environment, coupled with the expectation of higher profits, can lead to the deterioration of natural resources. Water shortage and contamination with toxic waste are anticipated to be critical issues in most countries, due to increased water demand and poor management. Water scarcity will also be exacerbated by the effects of climate change and global warming. The concept of the “Water Footprint (WF)” was introduced by Hoekstra and Hung (2002) – and subsequently elaborated by Chapagain and Hoekstra (2004) – for efficient, equitable, and sustainable water use and its management. The concept has been developed into a tool to calculate the amount of water that is consumed and polluted in all processing stages of a production system. Therefore, WF is an indicator of direct and indirect gross water consumption and pollution due to the production of commodities. In the case of our study, this will be green and black tea, together with its associated botanical extracts. Three types of water are considered, namely, green water (GWF), blue water (BWF), and greywater (GRWF) in water footprint calculations (Jayasundara et al., 2016).

The green water footprint refers to the volume of rainwater evaporation from lands and crops or trees plus rainwater incorporated into the harvested product. The blue water footprint refers to the volume of surface and groundwater that evaporates or is incorporated into the product. Finally, the greywater footprint of a product refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. A summation of the water footprint for the tea crop and the water footprint to produce green and black tea together with its extracts is the total water footprint for the said products.

The intention is to articulate and account for the freshwater consumption in the total life cycle of green and black tea production together with its botanical extracts, starting from the production stage and continuing to tea processing.

## 3.2. Water footprint for black tea production

The water footprint of a product is defined as the total volume of fresh water that is used directly or indirectly to produce the product. Virtual water content in black tea is the water footprint for black tea production and tea crops. Theoretically, the water consumption in each processing step is expected to be measured using separate water meters during the research period (Jayasundara et al., 2016).

WF blue= Q / Y black tea…………………………………………………… (1)

Where:

Q = Quantity of spring water consumed ($m^3$)

$Y_{blacktea}$ = Quantity of black tea produced (ton)

Unfortunately, the Mukumbani Factory will not be running again this year until the finalization of the strategic investor. The green water content in the processed tea has to be calculated by incorporating the product fraction values. After each processing step, the weight of the remaining product is smaller than the original weight. Product Fraction (PF) in a certain processing step is the ratio of the weight of the resulting product to the weight of the original product. The green water content of the resulting product (expressed in $m^3$/ton) is larger than the green water content of the original product. It can be found by dividing the virtual water content of the original product by the PF (Chapagain and Hoekstra, 2007).

## 3.3. The green water evapotranspiration for the tea crop

Table 3.1. shows different variables required for the CROPWAT 8.0 model to produce a value of green water evapotranspiration (ETgreen) for the tea crop (Jayasundara et al., 2016). The study by (Jayasundara et al., 2016) revealed that ETgreen was 996.7 mm/year for tea crops. This means each year needs a water layer of 996.7 mm over the whole area on which the crop is grown. The average land productivity of tea estates is 1.9 tons per hectare. The tea cultivation in the study by Jayasundara et al., 2016 only depended on rainwater and not irrigation; water footprint of the tea crop solely depends on the green water footprint. Blue water footprint or the amount of water utilized for tea cultivation by means of irrigation – either surface water or groundwater – was not relevant, and it remains zero for upcountry tea cultivation.

This assumption also holds true for the Tshivhase-Mukumbani Estate. It was revealed that the amount of rainfall received was adequate to fulfil the water demand of the tea crop in the study. Further findings from the study indicated that crops with high land productivity have a smaller WF than crops with low land productivity. The average yield per hectare in the studied tea estates (Jayasundara et al., 2016) was lower than the average land productivity of tea estates in Sri Lanka, which Chapagain and Hoekstra reported in the year 2007. Therefore, it was recommended to adopt suitable crop and land management practices in the tea estates to improve land productivity.

**Table 3.1: Different variables were used to produce ETgreen by using CROPWAT 8.0 models (Jayasundra et al., 2016)**

| Variable | Sub variable | Value |
|---|---|---|
| Climate data | Minimum temperature (℃) | 14.10 |
| | Maximum temperature (℃) | 24.90 |
| | Humidity (%) | 81.00 |
| | Wind speed (km/day) | 89.00 |
| | Sunshine hours | 5.40 |
| | ETO(mm/day) | 3.24 |
| | Rainfall mm) | 2137.60 |
| | Effective rainfall (mm) | 1368.60 |
| Crop data | Crop coefficient | 1.15 |
| | Growth stage (days) | 364 |
| | Rooting depth( m) | 1.20 |
| | Critical depletion fraction | 0.45 |
| | Crop height (m) | 2.00 |

| Variable | Sub variable | Value |
|---|---|---|
|  | Total available soil moisture (mm/m) | 83.00 |
| Soil data-clay loam | Maximum rain infiltration rate(mm/day) | 37.00 |
|  | Initial soil moisture depletion (%) | 45.00 |
|  | Initial available soil moisture (mm/m) | 45.60 |

### The Calculation of the green water footprint ($m^3$/ton) for green and black tea production

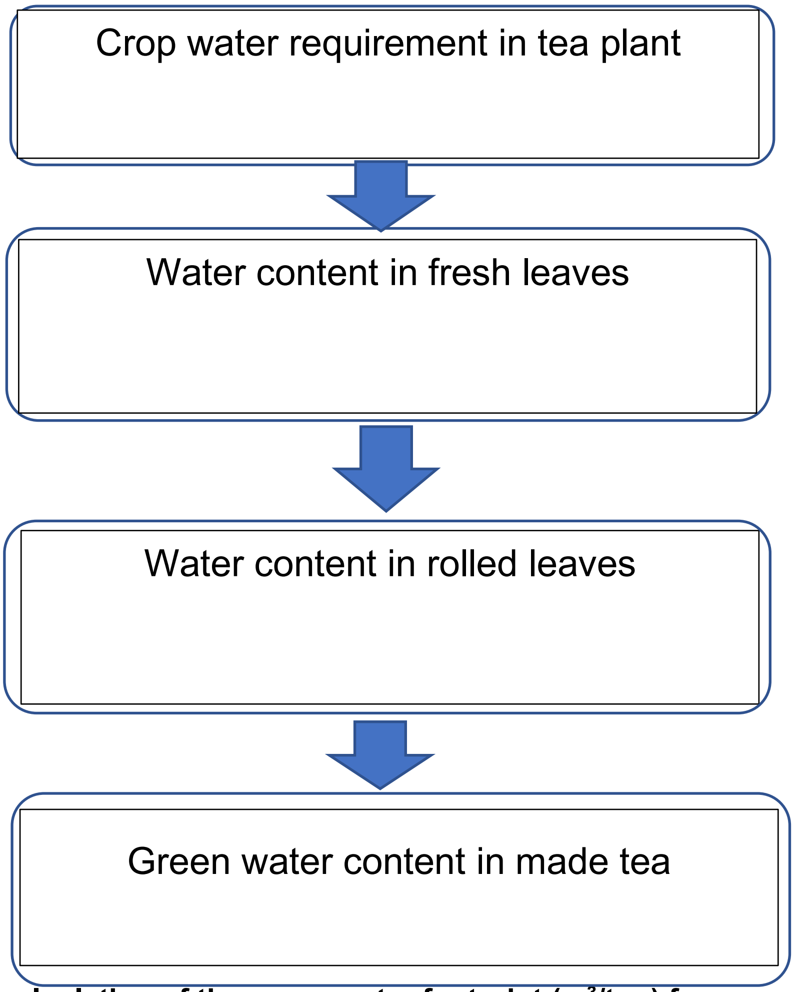


**Figure 3.1: Process steps in the calculation of the green water footprint ($m^3$/ton) for black tea production**

Figure 3.1 shows the process steps calculation of the green water footprint ($m^3$/ton) for black tea production. Based on desktop studies, the green tea component is done just after the rolled leaves process before made and oxidation. The weight reduction occurs in two steps in black tea production. These are withering, rolling and drying (oxidizing). In calculations (Jayasundra et al., 2016), a remaining fraction after withering and rolling of 0.53 (a ton of withered and rolled tea per ton of fresh leaves) and a remaining fraction after firing of 0.72 (a ton of black tea per ton of rolled leaves) are taken from field measurements.

From the total product, about 7% of tea was rejected as refused tea and then the total green water content in black tea is calculated in cubic meters per ton ($m^3$/ton). The water from Tshivhase-Mukumbani is from the mountain spring, boreholes, and the flowing river. The various sources are used to determine springs and used in humidifying and roller washing in the studied tea factories. The blue water footprint of black tea depends on the method of tea processing, e.g. use of boilers in tea drying will result in a higher blue water footprint in tea processing. The resulting quantity of blue water consumption was very low compared to the green water content conveyed from the fresh tea leaves. In this study, we will also investigate the possibility of pollutants such as nitrate from agrochemicals as reported in previous studies, which may be subjected to leaching in the production systems (Deurer et al., 2011; Green et al., 2010). Due to the difficulty of measuring nitrate leaching, most of the greywater footprint calculations in the literature were based on assumptions that 10% of the nitrogen applied as fertilizer was lost through leaching (Chapagain et al., 2006).

## 3.4. Results and discussions

This section covers the desktop results with data from the study site to generate projected results that will be validated by real data in the final report. Emphasis will be placed on the blue water footprint in the factory-processing plant.

### 3.4.1. Water footprint of a tea crop

According to Jayasundara et al. (2016), the green water content of fresh tea leaves is the volume of rainwater incorporated into the tea crop during the length of the growing period. However, the Mukumbani Tea Estate has established tea bushes that are not irrigated there. Since tea estates were not irrigated, the crop water requirement of the tea crop could be obtained fully from the effective rainfall that prevailed during the study period. Blue water footprint or the amount of water utilized for tea cultivation by the means of irrigation – either surface water or ground water – was not relevant, and it remains zero for Mukumbani Tea Estate. At Mukumbani, the annual rainfall varied across years with some years receiving more, while others received less than the minimum of 1 500 mm required for tea production (Figure 3.2). On average, the rainfall was less than the minimum (1 200 mm) required for tea production in one of every five years. Production of tea would be expected to be low in years with rainfall lower than the minimum requirement, due to moisture stress and in years of floods resulting from water erosion of top fertile soils and leaching of nutrients, especially nitrogen.

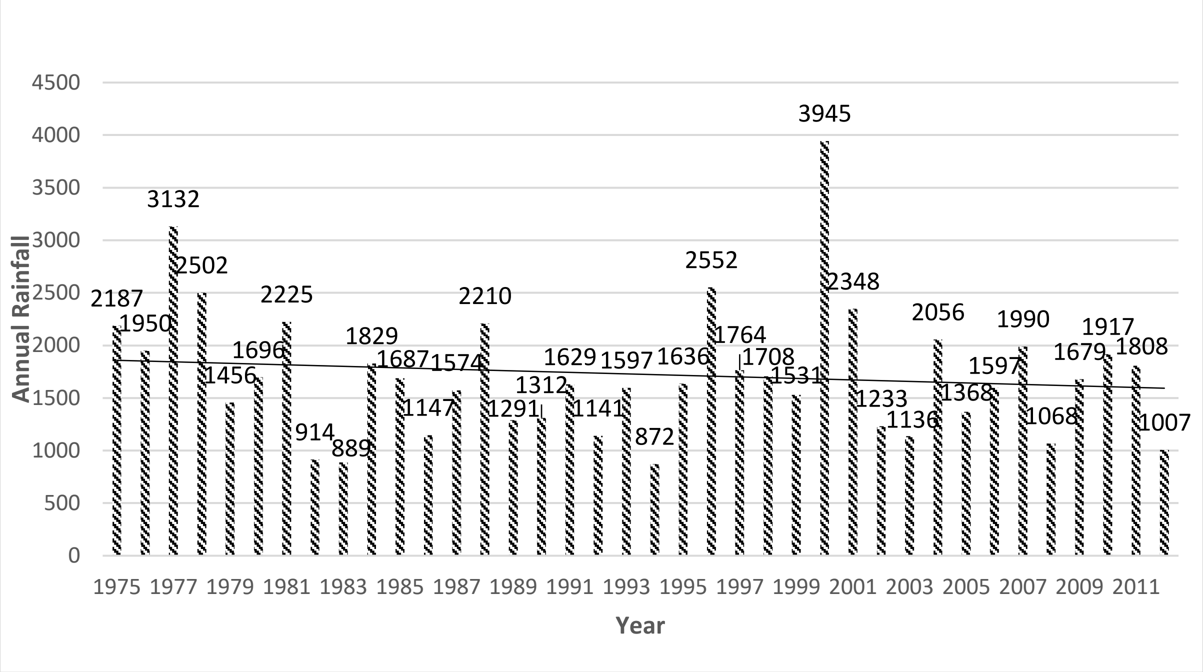


**Figure 3.2: Annual rainfall distribution for Tshivhase Tea Estate for the period 1975-2012 (Tshivhase Weather Data, 2012)**

Higher tea yields were obtained where the total yearly precipitations were also higher than normal. The total precipitation and tea production increased consecutively from the previous years, and a good correlation occurred between the two parameters (Ahmed, Hossain, Rowson, Haque & Ahmed, 2015).

### 3.4.2. Production of green leaf

The average yield per hectare in the studied tea estates was lower than the average land productivity of tea estates in Sri Lanka, which Chapagain and Hoekstra reported in year 2007. At the study site, the green leaf was 350 kg/ha to 380 kg/ha for clonal established at the Mukumbani site. Similarly, the yield per ha for the seedling variety established at the Tshivhase site was 360 kg/ha to 390 kg/ha. The Labor Unit (LU) per hectare was 12 for clonal and 14 for seedling variety. Therefore, it was recommended to adopt suitable crop and land management practices in the tea estates to improve land productivity.

Production of green leaf was higher during the summer months of December to mid-February and continued to be higher during the autumn months of mid-February to April. On the contrary, the production turned out to be lower for the winter months of May to July and continued to be low in the spring months of August to mid-October and in the early summer months of mid-October to November (Table 3.2).

**Table 3.2: Monthly tea production at Tshivhase Estate (Tshivhase Production Data, 2018)**

| | Green leaf kg (Estate) | Kg/ha |
|---|---:|---:|
| **January** | 456 906,00 | 424,24 |
| **February** | 357 703,00 | 332,13 |
| **March** | 405 152,00 | 376,19 |
| **April** | 296 716,00 | 275,50 |
| **May** | 125 339,00 | 116,38 |
| **June** | 18 841,00 | 17,49 |
| **July** | 0 | 0,00 |
| **August** | 0 | 0,00 |
| **September** | 22 068,00 | 20,49 |

| | Green leaf kg (Estate) | Kg/ha |
|---|---:|---:|
| **October** | 90 663,00 | 84,18 |
| **November** | 121 722,00 | 113,02 |
| **December** | 310 365,00 | 288,18 |
| **Total/Annum** | **2 205 475,00** | **2 047,79** |

The results suggest higher rainfall in summer compared to the winter months. Also, the yield of green leaf seems to be influenced by rainfall.

### 3.4.3. Water footprint for black tea production

Figure 3.1 shows the process calculation of the green water footprint ($m^3$/ton) for black tea production. Based on the results by Jayasundra et al. (2016), weight reduction occurs in two steps in black tea production. These are withering, rolling, and drying (oxidizing). In calculations, a remaining fraction after withering and rolling of 0.53 (a ton of withered and rolled tea per ton of fresh leaves) and a remaining fraction after the firing of 0.72 (a ton of black tea per ton of rolled leaves) were taken from field measurements.

From the total products, 7% of tea was rejected as refused tea and then the total green water content in black tea was 12 784.55 $m^3$/ton. Further, the blue water footprint of black tea production was 65.79 $m^3$/ton. Water is obtained from the springs and used in humidifying and roller washing in the studied tea factories. The blue water footprint of black tea depends on the method of tea processing, e.g. use of boilers in tea drying will result in a higher blue water footprint in tea processing.

The resulting quantity of blue water consumption based on desktop research was very low compared to the green water content conveyed from the fresh tea leaves. Further, leaks should be avoided in the water distribution lines which carry water into humidifiers and roller washing at the factory. There is always a potential to reduce the blue water component in the black tea product.

### 3.4.4. The greywater footprint of tea production

Previous studies identified that nitrate was the major pollutant in agrochemicals subjected to leaching in crop production systems (Deurer et al., 2011). Therefore, in this study nitrogen fertilizer application rate was considered based on the fertilizer application rates to the tea estates. The annual nitrogen application rate (6.8 kg/ha) was calculated based on the replacement ratio. Due to the difficulty of measuring nitrate leaching, most of the greywater footprint calculations in the literature were based on assuming that 10% of the nitrogen applied as fertilizer is lost through leaching (Chapagain et al., 2006). The annual greywater footprint of tea cultivation was 73 $m^3$/ton for tea cultivation. It means 73 $m^3$ volume of water is required to dilute the pollution load generated during the tea cultivation. The study site does not fertilize its tea bushes, which will significantly reduce the volume of water to dilute the pollutants' load. The virtual water content of black tea produced by the study area was 12 923.34 $m^3$/ton/year, which was a higher value compared to the values available in the literature (Jayasundra et al. (2016).

This might be due to the lower land productivity in the tea plantations and the incorporation of both blue and greywater footprints into the calculation.

## 3.5. Botanical products

Plants have been used through the ages to meet basic human needs (fuel, shelter, food, medicine, cosmetics and other). The use of a plant for a specific use such as medicine is normally related to the chemical properties of the plant. The chemical profile of plant parts dictates their usefulness for nutritional or medicinal purposes. Traditionally, plants were used in unaltered form be it being eaten, chewed, snuffed, or applied externally, with a variety of dosages or infusions developing over time.

Due to variations in the concentrations of chemical compounds in individual plants, the use of unaltered plant materials as phytomedicines is limited to experienced traditional healers who know how to adjust dosages. Over-dosage may cause illness or death, and under-dosage may render the plant ineffective (van Wyk & Wink, 2015). Modern phytomedicines are carefully manufactured and standardized to ensure safety and efficacy and are available as specialized extracts and tablets. Sometimes extracts are manipulated to increase the concentration of desired compounds while eliminating or reducing unwanted substances. Modern dosage forms for phytomedicines include about 29 widely used forms, such as capsules, extracts, infusions, liniments, lotions, syrups and tinctures (van Wyk & Wink, 2015).

The U.S. Pharmacopeia describes botanical extracts as preparations of botanical origin with liquid, solid and semisolid consistency. The products obtained by extraction are fluid extracts, powdered extracts, semisolid extracts, and tinctures. The extraction practice includes complete or partial separation from other components with the aid of water, alcohol, alcohol-water mixtures, or other suitable solvents. The process involves the removal of the desired constituents from the plant matter, the evaporation of all or nearly all the solvent, and the adjustment of the residual fluids, masses or powders to the prescribed standards. Extracts with no added inert substances and no processing beyond the extraction are called native extracts. Methods of extraction include percolation on, maceration, and preparations which include fluidextracts, powdered extracts, or semisolid extracts (U.S. Pharmacopeia).An extract can also be described as a mixture of soluble chemical compounds, separated from the unwanted fibrous and non-soluble portion of a crude drug using water or alcohol. The extract may be liquid/viscous, dried/powdered, or soft (extract evaporated until a soft mass is produced). Volatile oils are also regarded as extracts.

Instant tea is a dried herbal extract mixed with a suitable filler or carrier such as lactose, sucrose, or maltodextrin. A carrier increases bulk, reduces viscosity, and improves solubility. Spray drying was most often used, where a concentrated infusion of the herb was sprayed into a heated column with carrier particles (van Wyk & Wink, 2015). In terms of global trade, extracts, essences and concentrates from coffee, tea, or maté are categorized under Harmonised System (HS) code 2101. Vegetable (botanical) saps and extracts are categorized under HS code 1302, and antioxidant extracts under HS code 130219 (Other vegetable saps and extracts) – (WCO, 2012). Essential oils, resinoids, and terpenic by-products are categorized under HS 3301, and odoriferous mixtures as raw materials under HS code 3302. The main botanical extracts for consideration have always been:

a) Green tea (*C. sinensis*) extract as liquid and/or powder (‘native’ extracts, sold as bulk ingredients into high volume markets)

b) Black tea (*C. sinensis*) extract as liquid and powder ('native' extracts, sold as bulk ingredients into high-volume markets).

## 3.6. Methodology

### 3.6.1. Green tea extract specifications

Fresh leaves of *C. sinensis* were harvested using the same procedure as that used for black tea production (two top leaves and a bud). The fresh leaves were used on the same day to produce dried green tea extract at the pilot tea extract facility at Tshivhase Tea Estate according to the following procedure:

(i) Extraction with heated water in a jacketed extraction tank
(ii) Filtration through 100-micron filter and ultra-filtration membrane
(iii) Concentration using a reverse osmosis membrane
(iv) Drying the concentrate to a powder using a spray dryer.

Table 3.3 indicates the change in total polyphenol content (TPC) in green tea extract across the different production processes.

**Table 3.3: Analysis of total polyphenol content of green tea extract during different production stages**

| Green tea | Liquid extract | Liquid filtrate | Liquid concentrate | Spray dried powder |
|---|---|---|---|---|
| % Total polyphenol content (TPC) | 4.2% | 54.5% | 9.9% | 21.3% |

In 2015, analyses of six quality indicators of green tea extract were conducted and the results are listed in Table 3.4. The dried extract was analysed for TPC, free radical scavenging activity, antioxidant activity, moisture content, solubility and particle size. Total polyphenol content and antioxidant analyses were done using a UV-visible spectrophotometer.

**Table 3.4: Values for quality indicators for Tshivhase green tea extract**

| Indicator (Green tea extract) | Average | Minimum | Maximum |
|---|---|---|---|
| Total polyphenol content (%) | 21.3 | 19.4 | 25.8 |
| Free radical scavenging activity (%) | 4.1 | -2.0 | 11.0 |
| Antioxidant activity (%) | 13.0 | 11.0 | 18.0 |
| Average solubility (%) | 64.4 | 61.3 | 67.3 |
| Moisture content (g/100 g) | 7.6 | 7.0 | 7.9 |
| Particle size (PM10) % | 92.5 | 78.0 | 100.0 |
| Particle size (D10) µm | 1.5 | 1.1 | 2.0 |
| Particle size (D50) µm | 3.2 | 1.8 | 5.4 |
| Particle size (D90) µm | 7.6 | 2.9 | 15.1 |

## 3.7. Black tea extract

Black tea produced at Mukumbani Tea Factory was used to produce dried black tea extract at the pilot tea extract facility at Tshivhase Tea Estate. The tea was produced according to ISO standard 3720:2011. Samples of the made tea were used to produce the extract according to the following procedure:

(i) Extraction with heated water in a jacketed extraction tank
(ii) Filtration through a 100-micron filter and ultra-filtration membrane
(iii) Concentration using a reverse osmosis membrane
(iv) Drying the concentrate to a powder using a spray dryer.

The production of dried tea extracts in general includes four main processes, described in Table 3.5.

**Table 3.5:Description of general extract production processed and suitable equipment**

| Processing stage | Description | Suitable equipment |
|---|---|---|
| Extraction/brewing | Mixing of raw material and solvent in pre-determined ratios to extract soluble solids into solvent, and separating the spent raw material from the extract | Brewing vessel<br>Counter current extractor<br>Spinning cone column |
| Filtration | Straining out of all particles greater than 100 kiloDalton (kD), so the extract contains only dissolved solids | Ultrafiltration (UF) membrane system<br>Clarifying centrifuge |
| Concentration | Removing a large percentage of the water from the filtrate to concentrate the extract and reduce time and energy needed for drying | Reverse osmosis (RO) membrane system<br>Rising or falling thin film evaporator<br>Centritherm evaporator |
| Drying | Removing most of the water from the concentrate to produce a powdered product with a specified maximum moisture content and soluble solids | Spray dryer<br>Freeze dryer |
| Packaging | Collection of liquid or dried extract and packaging in suitable containers for controlled storage and shipping – the dried powder is packaged in vacuum-sealed plastic containers | Vacuum sealer (for bags) |

## 3.8. Results and discussions

### 3.8.1. Water footprint-production cycles and outputs

The production cycles, outputs, and capacity of the pilot extract facility are based on the efficacy of the equipment used in terms of extraction of soluble solids, concentration, and drying. The extraction vessel operates on a batch cycle, whereas the rest of the equipment works on a continuous cycle. From July 2014, the pilot facility was utilized to produce dried extracts from fresh green, dried black and dried rooibos tea leaves. The processing conditions for production cycles for the three types of tea are summarised in Table 3.6.

**Table 3.6: Processing conditions for the production of extracts from green, black and rooibos tea**

| Processing parameters | Average values (GTE) | Average values (BTE) | Average values (RTE) |
|---|---:|---:|---:|
| Weight of leaves (kg) | 104 | 35 | 32 |
| The volume of water (l) | 1 000 | 1 000 | 1 000 |
| Extraction temperature (˚C) | 60 | 60 | 64 |
| Extraction time (minutes) | 45 | 45 | 45 |

Table 3.7 describes the values measured for several parameters during the production of black, green and rooibos tea extracts, up to April 2015. The values for black and rooibos tea extract are averages of two production cycles each, and the values for green tea extract are averages of 34 production cycles.

Green tea leaves were collected from many different blocks on the estates and included leaves from seedling tea (a mixture of different blocks) as well as five different clones. In addition, during several production cycles, only a portion of the total concentrate was spray dried during the first day of the cycle (due to staff working hours), causing the remainder to stand overnight and resulting in deterioration of the extract. Therefore, the average percentage of the concentrated spray dried about what was collected is less than 100% for all three extract types. On average, 13% of the concentrate was discarded.

**Table 3.7: Average values of specific parameters measured for black, green, and rooibos tea extract**

| Parameter | Average (GTE) | Average (BTE) | Average (RTE) | Average (all) |
|---|---|---|---|---|
| UF/RO time (hours) | 4 | 6 | 4 | 5 |
| Concentrate collected (kg) | 55 | 63 | 41 | 53 |
| Concentrate spray dried (kg) | 48 | 46 | 39 | 44 |
| % of total concentrate processed | 89 | 75 | 96 | 87 |
| Total spray drying time (hours) | 15 | 17 | 13 | 15 |
| Outlet temperature (degrees Celsius) | 95 | 97 | 96 | 96 |
| Average pump rate (rpm) | 38 | 41 | 36 | 38 |
| Spray dryer water evaporation rate (kg/hr) | 3.2 | 2.78 | 3 | 3 |
| Powder moisture content (%) | 3.5 | 2.9 | 3.3 | 3.2 |
| Total powder (kg) | 0.22 | 0.14 | 0.15 | 0.17 |
| % yield (dry weight of powder/weight of leaves used) | 0.21 | 0.39 | 0.48 | 0.36 |

The percentage yields (dry weight of powder/weight of leaves used) were very low for all three types of extract (average 0.36%). In comparison, during laboratory-based production, a 7% yield for dried green tea extract was recorded. Tea contains about 300 to 450 g/kg extractable solids; however, the yield in a production scale set-up for instant tea extract is expected to be less (around 200 g/kg or 20%). The yield can be increased by varying processing conditions such as pH, the temperature of extraction, re-extraction of spent leaves, etc. For example, the effect of pH on tea solids extraction from black tea indicated a significant improvement (to around 290 g/kg at pH 2-11) (Liang & Xu, 2001). A different study on the effects of water-to-leaf ratio, temperature, and extraction time indicated maximum yields of about 32% after 120 minutes at 90˚C (Chandini, Rao, & Subramanian, 2011).

A balance needs to be kept between the intensity of extraction conditions (and total solids yield) and the quality (polyphenols content) of the extract. In the context of this study, a soluble solids yield (dry weight of powder/weight of leaves used) of 7% is taken as a benchmark for expected extractable solids yield for dried tea extract.

### 3.9. Seasonal patterns of botanical extract production

The production of extracts commenced in July 2014. During 34 green tea extract production cycles between July 2014 and May 2015, a general downward trend in the production of powder (kg) was observed (Figure 3.3). Generally, the green tea extracts production cycles showed a general downward trend in the production of powder (kg) from spring (September, October, November), summer (December, January, February), autumn (March, April, May), to winter (June, July, August). The yield of tea extracts in dry weight of powder per leaf mass was 0.067%.

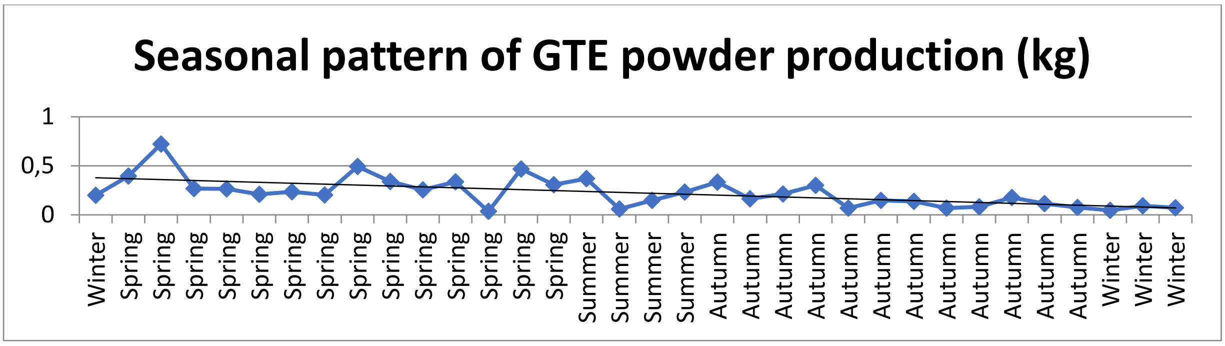


**Figure 3.3: Trend in GTE powder production over four seasons (winter 2014 to winter 2015)**

Due to the number of variations in production conditions (including different clones used), more experiments with leaves from one block need to be conducted to confirm if this trend is due to seasonal variation in the leaf content. One green tea extract production cycle was set up to trace, calculate and measure the flow/loss of extract between each processing step. Where possible, the liquid remaining in each tank was decanted and weighed. Table 3.8 describes the changes in liquid (kg) between each step, the loss of liquid during each step (remaining behind in break tanks and pipes) and the total amount of liquid concentrate collected.

From 45 kg of concentrate, 0.072 kg of powder (solids yield of 0.067%) was produced. The outcome of 1 004 kg of liquid extract is summarized as follows:

a) 380 kg (38%) of the original liquid extract was lost through inefficiencies in pumping all liquid from the break tanks or out of the piping systems
b) 579 kg of liquid and solids (58%) was calculated as waste from the UF and RO systems (suspended or insoluble solids and clean water suitable for recirculation)
c) 45 kg of liquid (5%) was collected as a concentrate ready for spray drying.

**Table 3.8: Calculation of weight changes between each step of the production process for green tea extract**

| Process – green tea extraction | Weight (kg) | Balance (kg) | Balance as % of liquid extract without leaves |
|---|---:|---:|---:|
| Water added to brew tank (BT) | 1 000 | 1 000 | |
| Leaves added to BT | 104 | 1 104 | |
| Waste leaves removed from extract | -100 | 1 004 | 100.0% |
| Extract remaining in BT (due to pump protection) | -16 | 988 | 98.5% |
| Extract pumped to UF break tank | | 988 | 98.5% |
| Extract remaining in UF break tank (due to pump protection) | -192 | 797 | 79.4% |
| Filtrate pumped through UF membrane to RO break tank | | 797 | 79.4% |
| Filtrate remaining in RO break tank (due to pump protection) | -63 | 734 | 73.1% |
| Filtrate remaining in UF pipes | -66 | 668 | 66.5% |
| Concentrate pumped through RO system | | 668 | 66.5% |
| Concentrate remaining in RO pipes | -43 | 624 | 62.2% |
| RO reject water | -579 | 45 | 4.5% |

| Process – green tea extraction | Weight (kg) | Balance (kg) | Balance as % of liquid extract without leaves |
|---|---|---|---|
| Concentrate collected in RO break tank and spray dried | | 45 | 4.5% |
| Powder spray dried (kg) | 0.072 | 0.072 | 0.007% |
| Solids in powder (moisture 4.2%) | -0.003 | 0.069 | 0.007% |
| **Yield (dry weight of powder/leaf mass)** | **0.067%** | | |

Table 3.9 lists the average time requirements for each part of the production cycle in the pilot facility. Most of the equipment works on a continuous cycle (excluding the brew tank). The low average water evaporation rate (WER) of the spray dryer (3 kg/h) caused drying times (average 15 hours) to be too long to fit into production cycles based on normal working hours, with the result that any concentrate left over would ferment and become too thick (viscous) to spray dry.

**Table 3.9: Time requirements for each part of the production cycle (pilot facility)**

| **Process** | **Average hours required** | **Maximum capacity** |
|---|---|---|
| Weighing of fresh/dry leaves | 1 | 142 kg fresh leaves |
| Loading of extraction vessel | 0.5 | |
| Extraction | 0.75 | 1 000 litres |
| Pumping to ultrafiltration break tank | 1 | |
| Ultrafiltration and reverse osmosis | 4 | 700 l/hr |
| Pumping to spray dryer break tank | 1 | |
| Spray drying | 15 | 3 kg/hour water evaporation rate |
| **Total** | **23.25** | |

## 3.10. Conclusions

The tea crop at Tshivhase-Mukumbani is dependent on rainwater and not irrigation; water footprint of the crop solely depends on the green water footprint. On average, the rainfall was less than the minimum (1 200 mm) required for tea production in one of every five years. There is a potential to reduce water usage from the production of leafy green tea through processing and packaging. The seedling variety and some clones are tolerant to drought and do not need irrigation. The use of technology can also reduce the factory water usage during processing. The blue water footprint of black tea depends on the method of tea processing, e.g. use of boilers in tea drying will result in a higher blue water footprint in tea processing.

# Chapter 4 THE VULNERABILITY OF THE TEA PRODUCTION SYSTEM TO CLIMATE CHANGE/EXTREMES

## 4.1 Introduction

In most countries where tea is produced, the crop provides the main income source for millions of farmers in high-lying and mountain areas, is an important tax revenue source for local governments, and plays a pivotal role in the sustainable development of rural areas (Wei & Li, 2014). Since tea plant cultivation is very sensitive to extreme climate events, understanding the influence of unfavourable climate events on tea production is crucial. The purpose of this study was to conduct a broad literature evaluation that covers pertinent topics, namely: (1) description of the tea plant, consumption, and global production, (2) environmental requirement for tea production (edaphic factors, climate requirement and effect of climate change), and ultimately (3) the influence of rainfall on tea production. Based on the literature, an attempt was made to propose strategies for mitigating the adverse effect of low rainfall. New technologies to monitor vegetation including tea estates are proposed, with opportunities available to be employed in this current study.

## 4.2 Methodology

### 4.2.1 Study area.

Tshivhase Tea Estate is in the Limpopo Province of South Africa, specifically under the Thulamela Municipality of Vhembe District (Figure 4.1). The tea estate is made up of two farms: Tshivhase Farm located at 30.314: 30.367 E and -22.968: -22.994 S and Mukumbani Farm at 30.386: 30.437 E and -22.904: -22.940 S. A road (Route R523 connecting Thohoyandou with Makhado Town) cuts through the Tshivhase Farm, with a major portion of the farm to the south of the road, while Mukumbani Farm lies to the north. Tea production at Tshivhase Estate is rain-fed at Tshivhase Farm and supplementary irrigated at Mukumbani Farm.

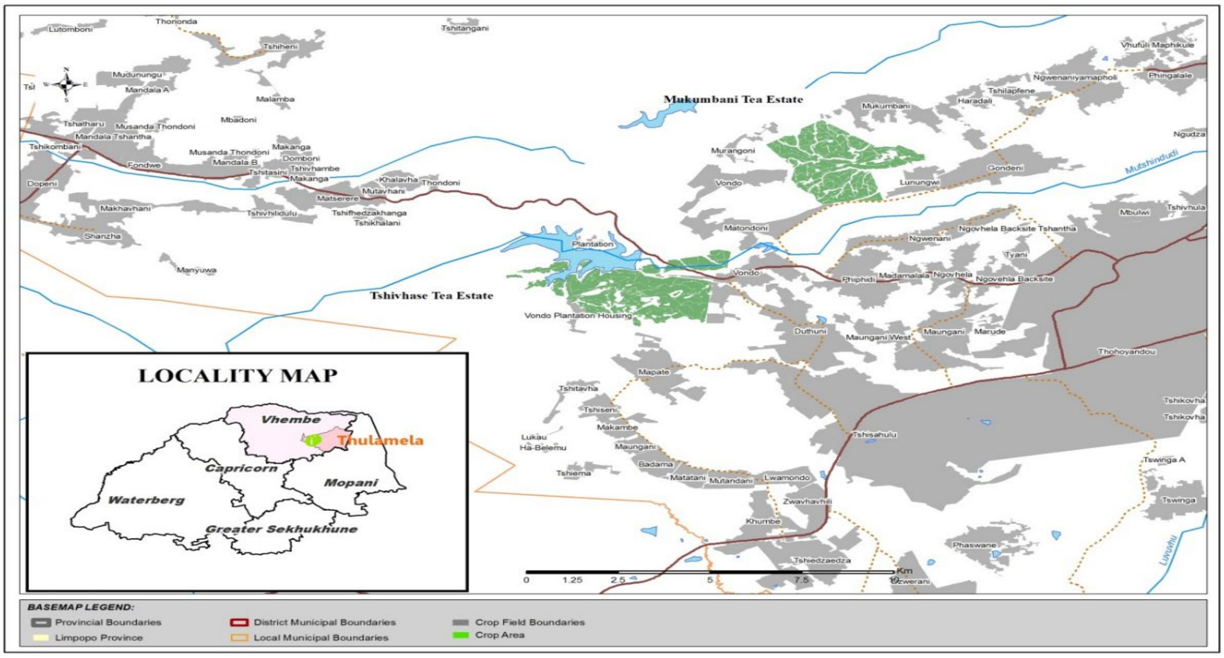


**Figure 4.1: Location of Tshivhase Tea Estate in Thulamela Municipality of Vhembe District, Limpopo Province, South Africa**
**(Source: LDARD, 2016)**

### 4.2.2 Research approach.

The study mainly followed a quantitative approach defined as an inquiry into a problem based on testing a theory made up of variables, measured with numbers and analysed, using statistical procedures to determine whether the predictive generalizations of the theory hold (Creswell, 2003; Leedy & Ormrod, 2010). Insights were developed on interactions among variables, and these were described through a complex holistic picture formed with words, thereby introducing some element of qualitative approach (Cresswell, 2003; Smith, 1983); thus, making the overall research approach somewhat mixed (Tashakkori & Teddlie, 1998; Hurmerinta-Peltomaki & Nummela, 2006; Leedy & Ormrod, 2010).

### 4.2.3 Research design.

As stated by Mouton (2001), research designs are techniques for collecting, analysing, interpreting and reporting data in research investigations. The research designs provide guidelines and instructions to be followed in addressing the research problem (Welman *et al.,* 2005), and such is necessary for the usefulness of research findings in developing general conclusions on similar challenges in different geographic areas (Egbu, 2007; Yin, 1989). Data was mainly obtained from records kept at the Tshivhase

Estate, and that included rainfall, green leaf (GL) yield, quantity, and quality of made tea (MT).

Rainfall data was for the period 1975 to 2012, while yield data was for 2007/2008 to 2016/2017, following the revitalization of the estate in 2006. Analysis of the influence of rainfall on tea production was based on averages for the variables for 12 months of the year. A lot of information was also obtained through a review of literature that focused mainly on scientific journals and books.

Records kept at the Tshivhase Estate provided mainly quantitative data while literature reviewed provided both quantitative and qualitative data. Quantitative data was captured and analysed through Excel spreadsheets. The data was used to generate summary tables and graphs of pertinent statistical analyses. The summary tables and graphs generated from the data were discussed, based on objective interpretations (Lee, 1999; Leedy & Ormrod, 2010). Qualitative data was summarised according to content and main themes addressed and discussed based on subjective interpretations.

### 4.2.4 Botanical extracts

#### *4.2.4.1 Green tea extract specifications*

Fresh leaves of C. sinensis were harvested using the same procedure as that used for black tea production (two top leaves and a bud). The fresh leaves were used on the same day to produce dried green tea extract according to the following procedure:

(i) Extraction with heated water in a jacketed extraction tank
(ii) Filtration through 100-micron filter and ultra-filtration membrane
(iii) Concentration using a reverse osmosis membrane
(iv) Drying the concentrate to a powder using a spray dryer.

#### *4.2.4.2 Black tea extract*

‘Made’ or fermented black tea produced at Mukumbani Tea Factory was used to produce dried black tea extract. The tea was produced according to ISO standard 3720:2011. Samples of the made tea were used to produce the extract according to the following procedure:

(i) Extraction with heated water in a jacketed extraction tank

(ii) Filtration through a 100-micron filter and ultra-filtration membrane
(iii) Concentration using a reverse osmosis membrane
(iv) Drying the concentrate to a powder using a spray dryer.

## 4.3 Results

### 4.3.1 Annual rainfall at Tshivhase Estate

The annual rainfall varied across years, with some years receiving more, while others received less than the minimum of 1 500 mm required for tea production (Figure 4.2). On average, the rainfall was less than the minimum (1 200 mm) required in one of every five years. Accordingly, for the 38-year period (1975 to 2012), some eight years had less rainfall than the minimum required for tea production. They were: 1982 (with rainfall of 914 mm), 1983 (889 mm), 1986 (1 147 mm), 1992 (1 141 mm), 1994 (872 mm), 2003 (1 136 mm), 2008 (1 068 mm) and 2012 (1 007 mm).

Also, there were some years in which very high rainfalls were received, with resulting floods; this was mainly in 1977 (3 132 mm) and 2000 (3 945 mm). Production of tea would be expected to be low in years with rainfall lower than the minimum requirement due to moisture stress and in years of floods resulting from water erosion of top fertile soils and leaching of nutrients, especially nitrogen.

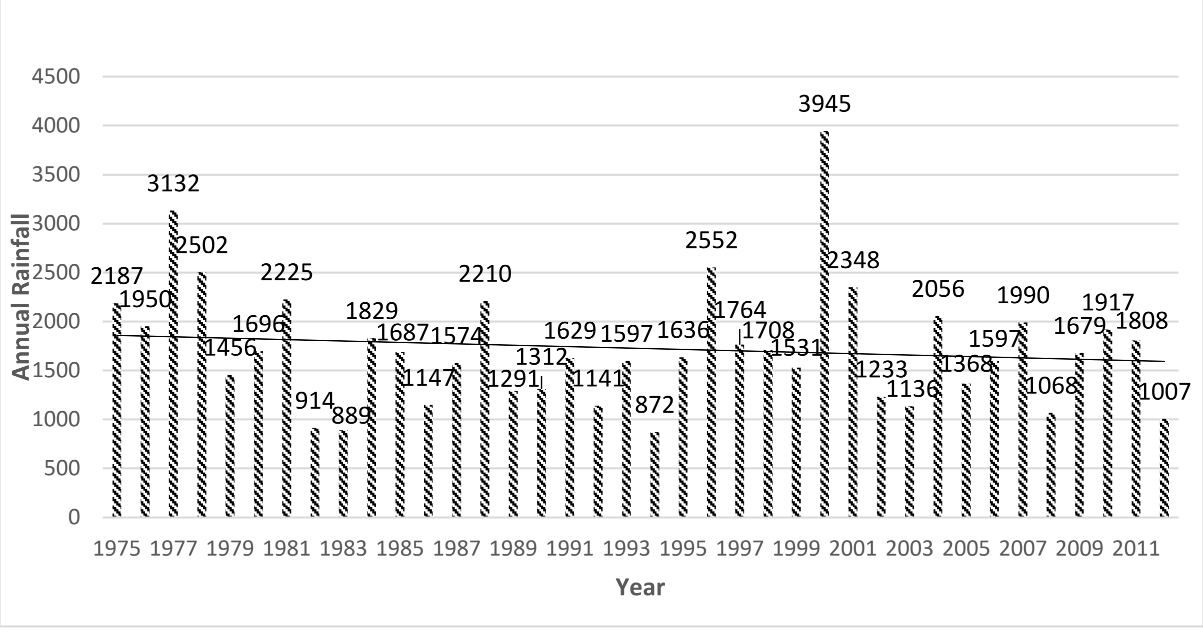


**Figure 4.2: Annual rainfall distribution for Tshivhase Tea Estate for the period 1975-2012 (Tshivhase Weather Data, 2012)**

The trend of rainfall at the Tshivhase Estate (see Figure 4.2) reveals a decline over time, and this is an issue of concern. While the tea estate has mostly received above-minimum rainfall for tea production, the situation may be expected to change over time with rainfall continuing to decline. Higher tea yields were obtained where the total yearly precipitations were also higher than normal.

The total precipitation and tea production increased consecutively from the previous years, and a good correlation occurred between the two parameters (Ahmed, Hossain, Rowson, Haque & Ahmed, 2015). The effect of declining rainfall could be exacerbated by increasing temperature conditions linked to global warming. As stated in Anju (2011), temperature has been steadily increasing over the years, with increases of 0.74 ±0.18°C or 1.33 ± 0.32° reported during the 20th century.

The decline of rainfall with time makes it necessary for the tea estate to have some coping strategies, and these may include the development of stress-tolerant varieties and the introduction of wastewater-conserving production practices. As alluded to in Indahsari and Kesumajaya (2016), without strategies for remedying the adverse effect of declining rainfall, the tea estate would abandon these bushes and focus on another agribusiness to generate income.

### 4.3.2 Monthly rainfall

Other than the total annual rainfall received, the monthly distribution of the rainfall is an important determinant of the yield and quality of tea produced. Tshivhase Estate is located in a summer rainfall area with more precipitations generally received during summer months and less during winter months. Rainfall at the Tshivhase Estate was higher (≥100 mm) in October to March (mostly summer) and lower (<100 mm) from April to September (mostly winter) – see Figure 4.3. The wettest months had mean rainfall of more than 300 mm each and were the summer months of January (340 mm) and February (327 mm). These two months contributed more than 20% of the annual rainfall, with January contributing 22.3%, while February contributed 21.4% .

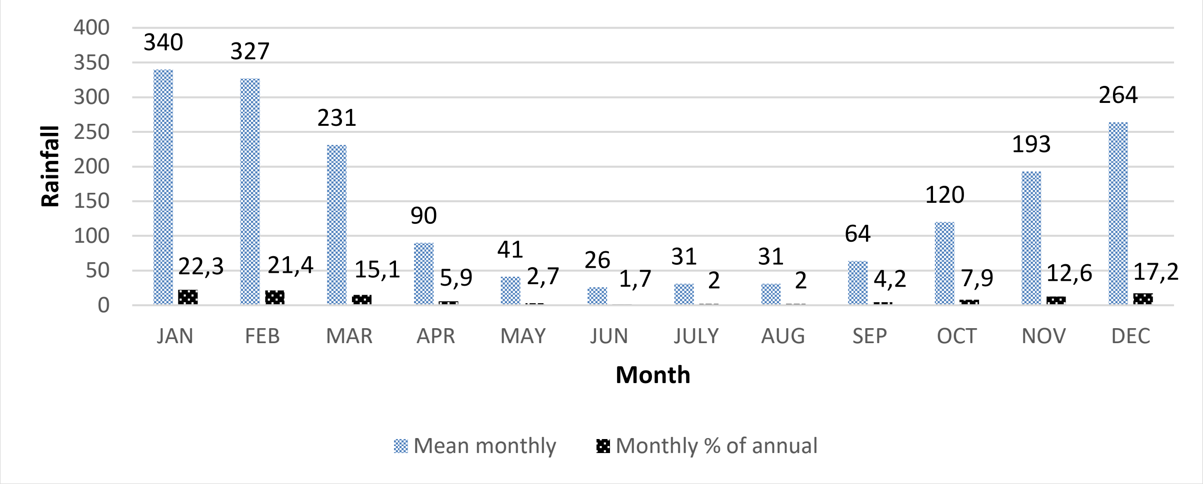


**Figure 4.3: Monthly rainfall distribution for Tshivhase Estate (Tshivhase Weather Data, 2012)**

The driest months had mean rainfall of ±30 mm each; they were the winter months of June (26 mm), July (31 mm) and August (31 mm). These (dry) months contributed ≤2% of the annual rainfall each. Similar trends were reported for Bangladesh where winter precipitation was the lowest and accounted for only less than 4% of the annual total precipitation (Farukh, Rahman, Sarker & Islam, 2020).

### 4.3.3 Tea production at Tshivhase Estate

Tea yield is determined by the area harvested and the weight of the tea leaves plucked. Two or three leaves and a bud are plucked, and the height of the canopy is maintained at an optimal level for plucking, the so-called 'plucking table', which is much lower than the level to which tea bushes would grow naturally. Tea bushes are plucked in 7 to 10-day cycles (Hajiboland, 2017).

Production of both GL and MT was higher during the summer months of December to mid-February and continued to be higher during the autumn months of mid-February to April. Conversely, the production turned out to be lower for the winter months of May to July and continued to be low in the spring months of August to mid-October and in the early summer months of mid-October to November (Table 4.1).

**Table 4.1: Monthly tea production at Tshivhase Estate (Tshivhase Production Data, 2018)**

| Month | Green leaf | | Made tea | | Made tea as % of green leaf |
|---|---|---|---|---|---|
| | kg (Estate) | Kg/ha | kg | Kg/ha | |
| **Jan** | 456 906,00 | 424,24 | 90 456,00 | 83,99 | 19,8 |
| **Feb** | 357 703,00 | 332,13 | 73 473,00 | 68,22 | 20,54 |
| **Mar** | 405 152,00 | 376,19 | 85 405,00 | 79,30 | 21,08 |
| **Apr** | 296 716,00 | 275,50 | 61 032,00 | 56,67 | 20,57 |
| **May** | 125 339,00 | 116,38 | 27 432,00 | 25,47 | 21,89 |
| **Jun** | 18 841,00 | 17,49 | 4 618,00 | 4,29 | 24,51 |
| **Jul** | 0 | 0,00 | 0 | 0,00 | 0 |
| **Aug** | 0 | 0,00 | 0 | 0,00 | 0 |
| **Sep** | 22 068,00 | 20,49 | 5 039,00 | 4,68 | 22,83 |
| **Oct** | 90 663,00 | 84,18 | 20 214,00 | 18,77 | 22,3 |
| **Nov** | 121 722,00 | 113,02 | 25 908,00 | 24,06 | 21,28 |
| **Dec** | 310 365,00 | 288,18 | 62 780,00 | 58,29 | 20,23 |
| **Total/ Annum** | **2 205 475,00** | **2 047,79** | **456 357,00** | **423,73** | |

The ratio of MT to GL (expressed as %) tended to decrease as time elapsed from spring through summer (September – 22.83%; October – 22.30%; November – 21.28%; December – 20.23%; January – 19.80%; February – 20.54%) and generally increased with time from autumn through winter (March – 21.08%; April – 20.57%; May – 21.89%; and June – 24.51%). With the results suggesting higher rainfall in summer compared to that of the winter months, the yield of GL, the quantity of MT processed, and indeed the ratio of MT per given quantity of GL seems to be influenced by rainfall.

Although higher rainfall was reported for Bangladesh compared to the Limpopo Province, lower tea yields of 1 015 kg/ha to 1 466 kg/ha were obtained (Rahman, 2022), compared to the average of 2 047,79 kg/ha observed for the Tshivhase Estate (Table 5.1). This could be a result of production practices used to produce the crop. As reported by Wijeratne, Anandacoomaraswamy, Amarathunga, Ratnasiri, Basnayake, and Kalra (2007), very high rainfall reduces sunlight's availability, which turns down photosynthesis, a probable cause of lower yields in Bangladesh. Similarly, excessive rain causes waterlogged conditions, which affects soil saturation and the plant's absorption capacity, which can also reduce crop yields. Another challenge associated with continuous rainfall is the prevention of plucking during peak harvesting time (Boehm, Cash, Anderson, Ahmed, Griffin, Robbat, Stepp, Han, Hazel, & Orians, 2016).

### 4.3.4 Influence on green leaf and made tea harvested at month of rainfall.

Tea growth and productivity are mainly controlled by water availability and, therefore, influenced by rainfall. Drought is responsible for a 14-20% reduction in yield and 6-19% mortality of tea plants (Cheruiyot, Mumera, Ng'etich, Hassanali, & Wachira, 2008). Although the total annual rainfall in most of the rain-fed growing areas was sufficient for tea production, its uneven distribution throughout the year often limited annual tea yield (Hajiboland, 2017).

As illustrated earlier (Figure 4.3), rainfall at Tshivhase Estate was highly uneven, with more rainfall occurring during summer months compared to that received during winter months, and this tended to limit tea yields. The R-values for tea harvested at months of rainfall (0-month lag from rainfall to harvesting) was 0.8634 (GL) and 0.8571 (MT), suggesting the occurrence of rather strong positive linear relationships between rainfall and tea production (Figure 4.4).

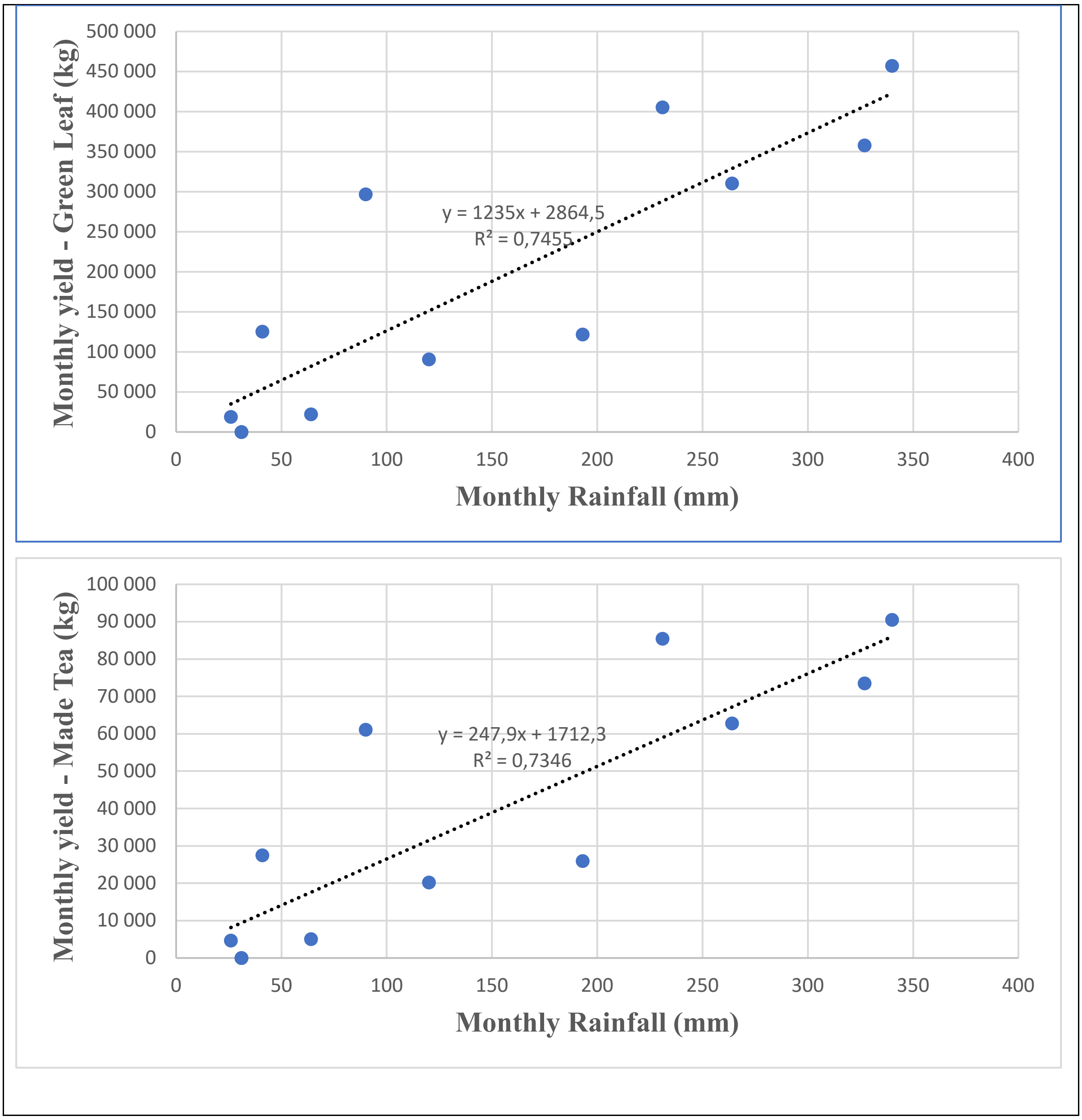


**Figure 4.4: Influence of monthly rainfall on green leaf and made tea yields at Tshivhase Tea Estate with rainfall and harvesting occurring in the same month**

The 95% critical value for sample correlation coefficient (degrees of freedom (df) = n-2 = 10) is ±0.576. The R-values for both GL (0.8634) and MT (0.8571) >0.576; hence, both R-values are statistically significant. The linear relationships between rainfall and the two production parameters (GL and MT) are therefore strong enough to use to model the relationship in the population and are represented by regression lines: Y = 1235x + 2864.5 (GL) and Y=247.9x + 1712.3 (MT) (Figure 4.4). The relationship between rainfall and tea production was perhaps shown by Li et al. (2022), who revealed that an increase in consecutive dry days (CDD) was associated with decreased annual tea yield. As reported by Li et al. (2022), the negative correlation of CDD with annual tea yield decreased with time.

Also important was the calculation of the coefficients of determination ($r^2$) that measure the extent to which variation in the dependent variables (GL and MT) can be accounted for by variation in the independent variable (rainfall). For GL, the $r^2$-value was 0.7455, indicating that 74.55% of the variation in GL yield can be accounted for by variation in rainfall, with the remainder (25.45%) accounted for by other variables. The $r^2$-value for MT was 0.7346, revealing that 73.46% of the variation in the quantity of MT can be accounted for by variation in rainfall.

The observation confirms the findings by Ahmed et al. (2015), who revealed that among the weather parameters of precipitation, temperature, humidity, evaporation and sunshine hours, precipitation plays the most important role in the development and growth of tea plants – and ultimately – yields per area. Rainfall at Tshivhase Estate had a strong influence on the production of tea when harvested in the month of the rainfall, both GL and MT.

### 4.3.5 Influence of rainfall on green leaf and made tea with 1-month lag from rainfall to tea harvesting.

A lag of 1-month from rainfall to harvesting increased the R-values from 0.8634 to 1.00 (GL) and from 0.8571 to 0.9600 (MT). The increase in the R-values suggests that the relationship between rainfall and production was stronger one month after rainfall, and this was probably a result of tea growth over that month. With the 95% critical values for sample correlation coefficient (df = 10) being ±0.576, the R-values for both GL (1.00) and MT (0.9600) > 0.576 were statistically significant. Accordingly, the relationship between rainfall and tea production is modelled by regression lines: $Y = 1365.3x – 16230$ (GL) and $Y=277.69x – 2651.3$ (MT) (Figure 4.5).

As would be expected, the time lag of 1-month from the occurrence of rainfall to tea harvesting also influenced the $r^2$-values. The $r^2$-value increased from 0.7455 (0-month lag) to 0.9112 (1-month lag) for GL and from 0.7346 to 0.9217 for MT, indicating that increased amounts of 91.12% and 92.17% of the variation in GL and MT respectively, can be accounted for by variation in rainfall. A 1-month lag from rainfall occurrence to tea harvesting allowed for some tea growth in response to rainfall, which was an expression of the influence of rainfall.

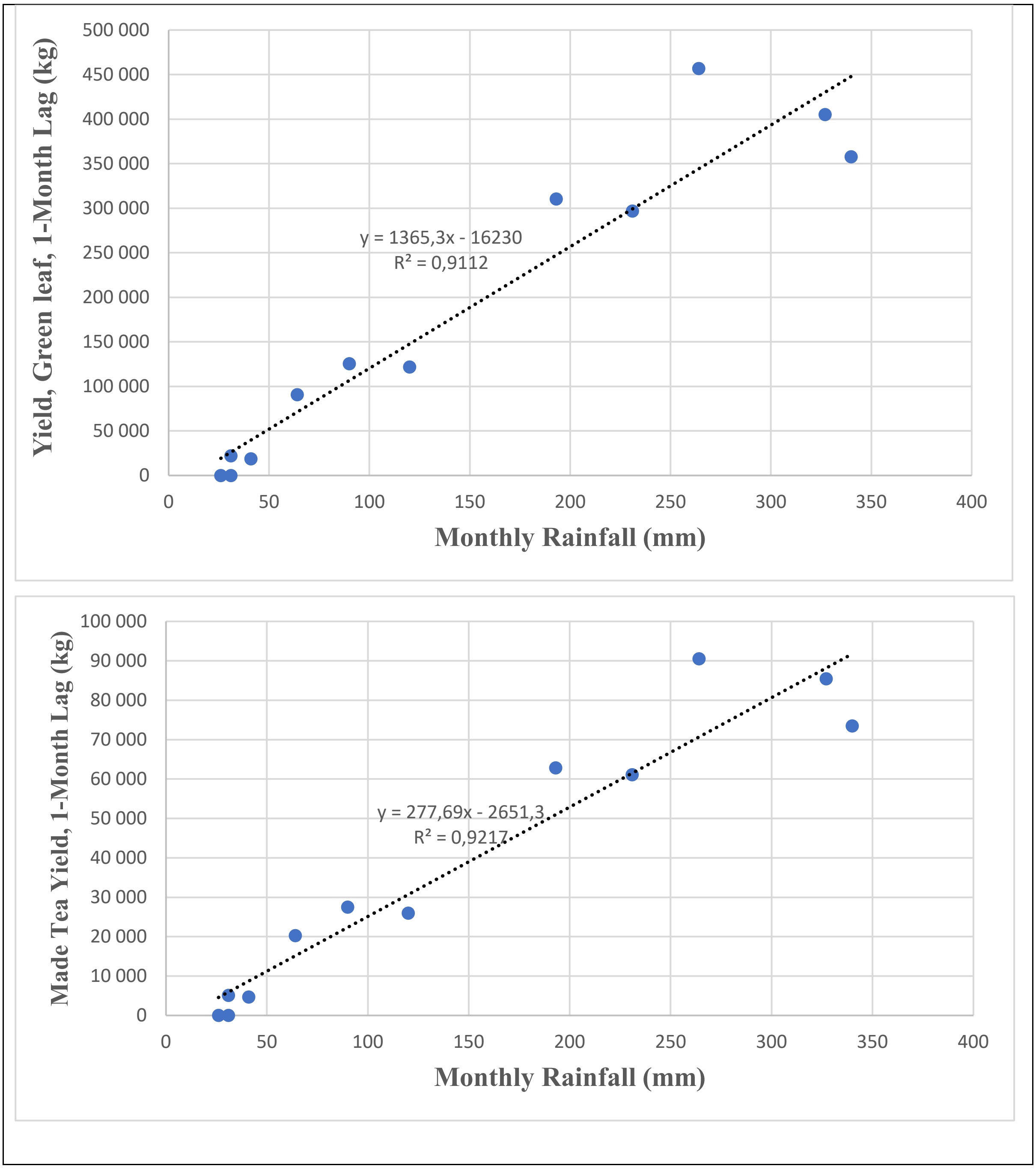


**Figure 4.5: Influence of monthly rainfall on green leaf and made tea yields at Tshivhase Tea Estate with 1-month lag from rainfall to harvesting**

Contrary to the situation with 0-month lag, the $r^2$-value of MT (92.12%) was slightly higher than that of GL (91.12%), suggesting that the 1-month lag resulted in an increase in MT per unit of GL. The increase of MT per unit of GL was probably a result of increased fiber associated with the 1-month growth or increased factory processing efficiency as the tea production season progressed.

### 4.3.6. Influence of rainfall on green leaf and made tea with 2-month lag from rainfall to tea harvesting and processing

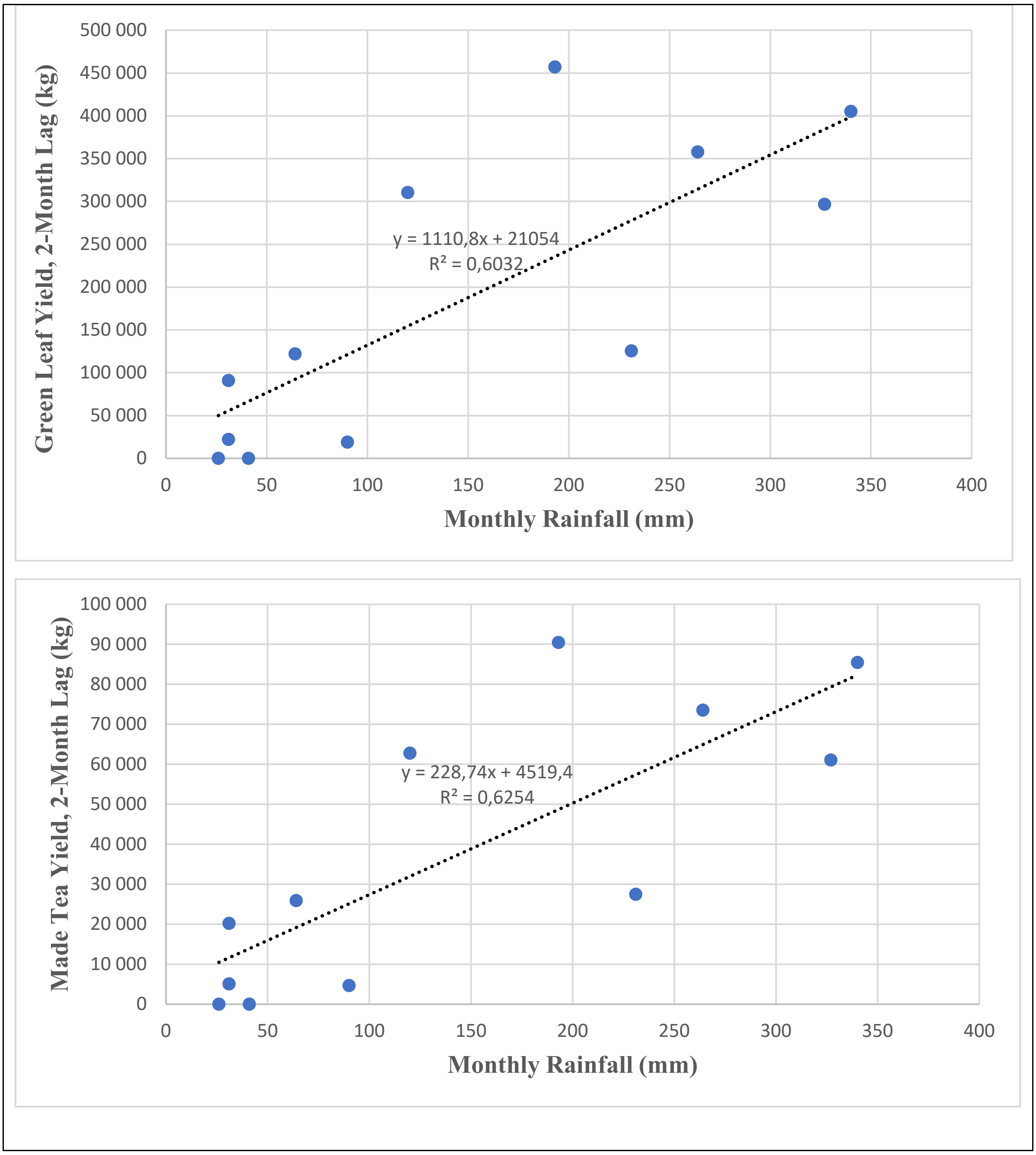


**Figure 4.6: Influence of monthly rainfall on green leaf and made tea yields at Tshivhase Tea Estate with a 2-month lag from rainfall to harvesting**

A 2-month lag from the occurrence of rainfall to the harvesting of GL tea decreased the R-values from 1.00 (for a 1-month lag) to 0.7766 for GL and from 0.9600 to 0.7908 for MT. With the 2-month lag, the R-values were in fact lower than even those with a 0-month lag, which were 0.8634 (GL) and 0.8571 (MT). The decrease in the R-values from a 1-month lag to a 2-month lag revealed a relative weakening of the relationship between rainfall and tea production two months after rainfall.

Based on the R-values, the relationships between rainfall and tea production (both GL and MT) were relatively weaker with a 2-month lag than even that with a 0-month lag. Effectively, the relationship between rainfall and tea yield was strongest with a 1-month lag from rainfall to harvesting, followed by a 0-month lag, and lastly that with a 2-month lag. With the 95% critical values for sample correlation coefficient (df = 10) still ±0.576, the R-values for both GL (0.7766) and MT (0.7908) remained statistically significant. Although the R-values revealed a relative weakening of the relationship between rainfall and tea production (both GL and MT) compared to a 0-month and 1-month lag, the linear relationship with a 2-month lag remained strong enough to use to model the relationship in the population.

With a 2-month lag from rainfall to harvesting, the relationships between the rainfall and tea production were modelled by regression lines: $Y = 1110x + 21054$ (GL) and $228.74x + 4519.4$ (MT) (Figure 4.6). The time lag of 2 months also influenced the $r^2$-values. For GL, the $r^2$-value decreased from 0.9112 (1-month lag) to 0.6032, suggesting that a reduced amount of 60.32% of the variation in GL yield can be accounted for by variation in rainfall. The $r^2$-value for MT also decreased from 0.9217 (1-month lag) to 0.6254. The $r^2$-values with a 2-month lag from rainfall to tea harvesting were in fact less than even those with a 0-month lag (0.7455 for GL and 0.7346 for MT).

Although the level of influence of rainfall on both GL and MT varied with time lag from the occurrence of rainfall, it was evident that a generally strong correlation occurred between rainfall and tea yield. The results supported the findings of Patra et al. (2013) in their study in Darjeeling (India), who observed a highly significant and positive association between the green leaf of tea and rainfall. A strong positive and significant correlation was found between green leaf yield and rainfall (r=0.78). As stated by Patra et al. (2013), the coefficient of determinants indicated that a high variation (61.4%) of green leaf yield was due to rainfall.

### 4.3.7. Botanical extracts

Green tea or fresh leaves from the plant *Camellia sinensis* are needed to produce green tea extract. To ensure high-quality leaves, the bud and two top leaves are the only parts of the growing stem tips that are used. The quality and polyphenol content are dependent on the age of the leaves used, the season harvested, the cultivation and harvesting practices, and the specific processes and equipment used for extract production. If not used immediately, the leaves must be stored under cool conditions.

In some instances, dried green tea may also be used for extract production. ISO 11287: 2011 describes green tea as tea produced by acceptable processes, including enzyme inactivation and commonly rolling or comminution and drying. The tender leaves, buds and shoots of the tea bush are used for making green tea.

**Figure 4.7: Pruning of tea leaves at Tshivhase Tea Estates, and shoots harvested for tea and extract production**

Black (made) tea was used to produce black tea extract. The tea should be produced by acceptable processes including withering, leaf maceration, aeration and drying. The tea must be made from the tender two top leaves and bud, from the species *C. sinensis*, according to ISO 3720:2011 standards (8 and 9).

**Figure 4.8: Withering of tea leaves and maceration processes at Mukumbani Tea Factory**

**Figure 4.9: Tea in the process of fermentation, and a sample of dried black tea produced at Mukumbani Tea Factory**

An inter-laboratory test on finely ground and instant green and black leaf tea (ISO standard 14502-1) indicated mean total polyphenol content as a percentage (mass fraction) on a dry matter basis as follows:

a) 24.5% for green leaf tea
b) 18.81% and 13.95% for black-leaf tea.

An inter-laboratory test on finely ground and instant green and black leaf tea (ISO standard 14502-2) indicated mean total catechin content as a percentage (mass fraction) on a dry matter basis as follows:

a) 12.30% and 15.70% for green leaf tea
b) 9.53% and 7.19% for black leaf tea (lightly fermented Darjeeling tea).

The chemical composition of fresh tea leaf typically has the following percentages by dry weight for some of the most important constituents (Punyasiri, 2011):

a) Flavanols (catechins) 17-30%
b) Flavonols and flavonol glycosides 3-4%
c) Leucoanthoyanins/Proanthocyanins 2-3%
d) Phenolic acid and depsides about 5%
e) Caffeine 3-4%
f) Volatile substances 0.01-0.02%.

The total polyphenol content in tea leaves is typical of the following (Punyasiri, 2011):
a) 35.8% in the bud
b) 35% in the first leaf
c) 27.9% in the second leaf
d) 23.1% in the third leaf
e) 15% in the stem.

**Table 4.2: Typical levels of individual polyphenols in fresh tea leaf**

| Polyphenol | Typical level (by dry weight) |
|---|---|
| Epigallocatechin gallate (EGCG) | 9-13 g/100 g |
| Epigallocatechin (EGC) | 3-6 g/100 g |
| Epicatechin gallate (ECG) | 3-6 g/100 g |
| Epicatechin (EC) | 1-3 g/100 g |
| Gallocatechin (GC) | 1-2 g/100 g |
| Catechin (C) | 1-2 g/100 g |
| Total catechins (sum of the above) | 18-32 g/100 g |
| Flavonols and their glycosides | 3-4 g/100 g |
| Leucoanthocyanins/Proanthocyanidins | 2-4 g/100 g |
| Phenolic acids | 4 g/100 g |
| **Total polyphenols (sum of all the above)** | **27-40 g/100 g** |

The polyphenol composition of the fresh tea leaf typically contains the levels of individual polyphenols by dry weight as listed in Table 4.. Green tea from Sri Lanka contained 7% total catechins, 11% total polyphenols and 32% water extract (TS) on a dry weight basis (Punyasiri, 2011).

**Table 4.3: Minimum specification sheet for green tea powder from Tshivhase Tea Estate**

<table>
<tr><th colspan="3">Specification sheet for green tea powder</th></tr>
<tr><td colspan="3"></td></tr>
<tr><td><b>Product name</b></td><td colspan="2">Green tea powder</td></tr>
<tr><td><b>Botanical name</b></td><td colspan="2">Camellia sinensis, Theaceae</td></tr>
<tr><td><b>Originating from</b></td><td colspan="2">Limpopo Province, South Africa</td></tr>
<tr><td><b>Extraction</b></td><td colspan="2">Spray dried</td></tr>
<tr><td><b>Important properties</b></td><td colspan="2">Strong antioxidant-healing, rejuvenating, natural preservative, anti-inflammatory</td></tr>
<tr><td><b># Chemical Abstracts Services (CAS) No.</b></td><td colspan="2">84650-60-2</td></tr>
<tr><td><b># EINECS (European Inventory of Existing Commercial Chemical Substances)</b></td><td colspan="2">283-519-7</td></tr>
<tr><td colspan="3">All percentages referred to in the text of the following information refer to the percentage of the total integrated peak area calculated directly from the chromatograms</td></tr>
<tr><td><b>Chemical component</b></td><td><b>Units</b></td><td><b>Value</b></td></tr>
<tr><td rowspan="2">Total polyphenol content</td><td>%</td><td>21.3</td></tr>
<tr><td>mg/g</td><td>1 065</td></tr>
<tr><td>Free radical scavenging activity</td><td>%</td><td>4.1</td></tr>
</table>

| Specification sheet for green tea powder | | |
|---|---|---|
| Antioxidant activity | % | 13 |
| Average solubility | % | 64.4 |
| Moisture content | g/100 g | 7.6 |
| Particle size (PM10) | % | 92.5 |
| Particle size (D10) | µm | 1.5 |
| Particle size (D50) | µm | 3.2 |
| Particle size (D90) | µm | 7.6 |

**Table 4.4 Minimum specification sheet for black tea powder from Tshivhase**

| Specification sheet for black tea powder 2015 | |
|---|---|
| | |
| **Product name** | Black tea powder |
| **Botanical name** | Camellia sinensis, Theaceae |
| **Originating from** | Limpopo Province, South Africa |
| **Extraction** | Spray dried |
| **Important properties** | Strong anti-oxidant-healing, rejuvenating, natural preservative, anti-inflammatory |
| **# CAS (Chemical Abstracts Service) No** | 84650-60-2 |
| **# EINECS (European Inventory of Existing Commercial Chemical Substances)** | 283-519-7 |

| **Specification sheet for black tea powder 2015** | | |
|---|---|---|
| All percentages referred to in the text of the following information, refer to the percentage of the total integrated peak area calculated directly from the chromatograms | | |
| **Chemical component** | **Units** | **Specification** |
| Identification: UV-Vis Spectrophotometer | | |
| Total polyphenol content | % | 16 |
| | mg/g | 798 |
| Free radical scavenging activity | % | -6 |
| Antioxidant activity | % | 11 |
| Average solubility | % | 69.7 |
| Moisture content | g/100 g | 7.3 |
| Particle size (PM10) | % | 92 |
| Particle size (D10) | µm | 2 |
| Particle size (D50) | µm | 4.1 |
| Particle size (D90) | µm | 9.4 |

Several studies were conducted on Tshivhase green and black tea extracts to obtain an understanding of the quality. There were differences in the methodologies used, and for purposes of comparison, the TPC and total flavanol values have been converted to mg/g.

**Table 4.5: Comparison of different TPC, flavanol, and antioxidant capacity analyses of Tshivhase tea extracts**

| Institution | Green/Black tea extract | Drying method used | Analysis method used | TPC (GAE mg/g) | Flavanols (mg/g) | Antioxidants (% Inhibition) |
|---|---|---|---|---|---|---|
| Biosciences study | GTE | Spray dried | - | 2.437 | 1.4 | - |
| CPUT study | GTE | Oven-dried | UV/vis Spectrophotometer | 0.00031 | 0 | - |
| | | Freeze-dried | | 0.099 | 0.1 | - |
| | BTE | Oven-dried | | 0.00012 | 0 | - |
| | | Freeze-dried | | 0.39 | 0.05 | - |
| LATS Bench study | GTE | | UV/vis Spectrophotometer | 16.7 | - | 70 |
| | BTE | | | 127.2 | - | 74 |
| Tshivhase Pilot Plant study | GTE | Spray dried | UV/vis Spectrophotometer | 990 | - | 13 |
| | BTE | | | 798 | - | 11 |

## 4.4 Discussions

### 4.4.1 Annual rainfall at Tshivhase Estate

The annual rainfall for the effective production of tea is around 1 500-2 000 mm (Kumar & Shruthi, 2014), which for optimum production is 2 500-3 000 mm, while the minimum requirement is estimated at 1 200 mm (Waheed et al., 2013). Based on rainfall data, the mean annual rainfall at Tshivhase Estate was 1 726 mm and was above the minimum requirement of 1 200 mm (Waheed et al., 2013) for tea production.

### 4.4.2 Influence of rainfall on tea production

With the rather high moisture requirement (≥1 200 mm, Waheed et al., 2013) for tea production, the crop would be expected to do well during the higher rainfall seasons compared to production during the lower rainfall seasons. The seasonal rainfall tends to be determined by that of individual months comprising that season; accordingly, the monthly yields of tea have gained interest in this study. The influence of rainfall on tea production was explained using Pearson's Coefficient of Correlation (r), which measures the strength and direction of the linear relationship between the two variables (Rice, 2007: 146). Correlation analysis is seldom used alone and is usually accompanied by regression analysis. The difference between correlation and regression lies in the fact that while a correlation analysis stops with the calculation of the correlation coefficient and perhaps a test of significance, a regression analysis goes ahead to express the relationship in the form of an equation and moves into the realm of prediction (Gogtay & Thatte, 2017). To estimate the proportion of change in the production of tea that may be accounted for the change in rainfall, the coefficient of determination ($r^2$) was used. Rainfall at Tshivhase Estate had a strong influence on the production of tea when harvested at the 0-month, 1-month, and 2-month lags from rainfall to harvesting, both GL and MT.

The correlations coefficient took a trend from 0.8634 at the 0-month lag, 1.00 at the 1-month lag, and 0.776 at the 2-month lag from rainfall for (GL). Similarly, the trend for MT was 0.8571 at a 0-month lag, 0.96 at 1-month, and 0.790 at a 2-month lag from rainfall. It was evident from the results that the relationship between rainfall and tea yield was strongest at a 1-month lag from rainfall to harvesting. The variation in GL yield was attributed to the variation in rainfall with an $r^2$ value of 0.745, 0.911, and 0.603 at a 0-month, 1-month, and 2-month lag from rainfall. Similarly, the variation in MT was due to the variation in rainfall with an $r^2$ value of 0.735 at a 0-month lag, 0.9217 at a 1-month lag, and 0.625 at a 2-month lag from rainfall for MT.

### 4.4.3 Influence of monthly rainfall on tea quality

Rainfall has some influence on the quality of tea produced (Gulati et al., 1996; Kottur et al., 2010). The rainfall influence may be exerted through the concentrations of compounds such as methylxanthine and polyphenolic catechin that vary with water availability (Ahmed et al., 2012; Ahmed et al., 2013; Lin et al., 2003), associated with the occurrence of rainfall. At the industrial level, the quality of tea may be described in terms of grades of the tea where grading is the process of evaluating products based on the condition of tea leaves.

Tea quality at Tshivhase Estate is described in terms of grade with the top quality referred to as primary grade, followed by secondary grade, and lastly, the off grade that is often excluded from the tea blended for sales. As was the case with the relationship between rainfall and tea production, the relationship between this climatic variable and the quality of tea was estimated by coefficients of correlation (r). The R-values for the quality of tea harvested ranged from 0.450 with a 0-month lag, 0.446 at a 1-month lag, and 0.407 at a 2-month lag between rainfall and harvesting. The r values indicated weak positive but non-significant linear relationships between rainfall and tea quality. Accordingly, linear relationships between rainfall and tea quality for a 0-month, 1-month, and 2-month lag from rainfall to tea harvesting were not all strong enough to use to model the relationship in the population. Contrary to assertions by Gulati et al. (1996) and Kottur et al. (2010), results in this study revealed that rainfall does not have a significant influence on tea quality, be it with a 0-month, 1-month, or 2-month lag between rainfall and harvesting.

### 4.4.4 Strategies to mitigate the effect of low rainfall.

Considering the socio-economic importance of the tea industry, it is important to implement adaptation measures in tea plantations, aiming at minimizing adverse impacts of climate, especially low rainfall conditions. The use of the adaptation strategies was regarded important for the effective production of tea under low rainfall conditions (Rahman, 2022). Such strategies include:

#### (a) Judicious selection of land for tea planting

For successful production of tea, it was deemed critical to select land for tea planting carefully (Patra et al., 2013). Proper selection of land is necessary for tea to adapt even under declining rainfall conditions (Ashardiono & Cassim, 2014).

For instance, the land selected should have access to water sources to allow for irrigation, be it surface or groundwater sources. Also, suitable land for tea production should have sufficiently deep soils with high water and nutrient retention.

### (b) Use of drought-tolerant cultivars

The use of drought-tolerant cultivars is important for mitigating the adverse effects of drought and extreme temperatures (Patra et al., 2013), and such would require the selection of extreme weather-resistant clones (Rokhmah, Wibowo & Supriadi, 2016). As affirmed by Ashardiono and Cassim (2014), the selection of tea cultivars that are drought-tolerant is important for the effective production of the crop under low rainfall conditions.

### (c) Planting of shade trees

The planting of shade trees on tea fields is important (Patra et al., 2013; Rokhmah, Wibowo & Supriadi, 2016), as this protects the crop plants from solar radiation (Rahman, 2022), thereby reducing moisture loss through evapotranspiration. Among the recommended shade trees were Silver Oak (*Grevillea robusta*), Calliandra (*Calliandra calothrysus*), Acacia (*Acacia pruinosa*) (Kalita, Das & Nath, 2014), Neem (*Azadirachta indica*), and Knotweed *(Bish kanthali)* (Rahman, 2022). Tea plants with shade (*A. chinensis* or *A. odoratisma*), which are well-managed in the dry season are reported to still have fresh grow because of the high soil moisture content.

### (d) Irrigation

Effective irrigation is an important strategy for lessening the adverse effect of low rainfall (Rokhmah, Wibowo & Supriadi, 2016), and this requires the abstraction of water from available water bodies such as rivers, dams, and groundwater resources. In affirmation of the importance of irrigation under low rainfall conditions, it was observed that the application of 2 225 and 1 610 $m^3ha^{-1}$ of water in two years of experimentation caused the production of harvestable shoots in summer to increase by 162 and 153 percent, respectively, as compared to rain-fed condition. Also, as the amount of irrigation water in the drip irrigation system increased, the fresh weight of shoots increased (Salimi, Gonbad & Shaigan, 2021). As stated by Salim et al. (2021), improvement in tea quality characteristics such as total polyphenols, caffeine, total ash and nitrogen percentage of shoots was also observed with the introduction of irrigation.

### (e) Use of other production practices

Important crop production practices would include but are not limited to intercropping, especially with young tea plantations (Patra et al., 2013). Intercropping would promote quicker land cover at the earlier stage of tea growth, thereby minimizing the development of weeds that could be problematic to the tea plants. As mentioned by Rokhmah et al. (2016), the pruning of tea plants should also be considered, together with the application of biofertilizers and potassium. In addition to the application of fertilizers, the use of organic matter and mulch before the dry season is recommended, as well as the control of pest  and diseases and weeds (Rahman, 2022; Roy, Barooah, Ahmed, Baruah, Prasad & Mukhopadhyay, 2019; Tuwei, Kaptich, Langat, Smith & Corley, 2008). Also, the application of compost and green manure helps maintain soil organic matter content in tea plantations (Wijerante & Chandrapala, 2014). The minimum specification sheet for black tea powder produced at Tshivhase Tea Estate is described in Table 4.7

Total polyphenol and antioxidant analyses were done using a UV-Visible Spectrophotometer. Based on a sample size of 1 g, the total polyphenol content was calculated at 798 mg/g GAE (a concentration of 16%).

## 4.5 Conclusions

To better manage and sustain the plantation of any crop, it is important to know and understand its ecological requirements for optimal growth. The ideal growth of tea requires acid soil, a humid tropical environment, and a high altitude free from frost. The 4.5-5.6 pH range and minimum rainfall of 1 200 mm year-1, but 2 500-3 000 mm year-1 were observed to be optimum for the growth of tea in a certain study. The soil conditions should be well-drained, deep and well-aerated with more than 2% organic matter for best tea growth. Tea growth is favoured by a temperature range of 20-30°C as well as a relative humidity of 80-90%. At least five hours a day of sunlight are important for the growth of tea. The study showed a basis for supplementary irrigation decision-making for the months of the year when rainfall declines. Though rainfall influenced the amount of green leaf production and manufactured tea, there was no significant correlation between rainfall and tea quality.

# Chapter 5 THE WATER FOOTPRINT OF TEA CROPS IN THE CONTEXT OF FUTURE CLIMATE CHANGE SCENARIOS

## 5.1 Introduction

Tea is one of the most consumed beverages in the world (Abudureheman *et al.,* 2022; Pan *et al.,* 2022; Wickham, 2014; and, Yang *et al.,* 1993). It is recognized as one of the important ancient hot drinks as it was first discovered in China in 2737 BC (Amin *et al.,* 2022). Presently, tea crop is cultivated all over the world, primarily in Asia and Africa, although it is commercially produced in more than sixty countries worldwide. The prime tea-producing countries are China (2 400 000 tons), India (900 000 tons), Kenya (305 000 Tons), Sri Lanka (300 000 tons), Turkey (175 000 tons), Indonesia (157 000 tons), Vietnam (117 000 tons) and Japan (89 000 tons).

Pan *et al.* (2022), infer that approximately three billion people across the globe drink tea. Such a high value (3 billion: 37.5%) suggests how significant tea is to human life. The high consumption of tea is intertwined with cultural beliefs (Maurya, 2022; Wang, 2011 and Fair & Barnitt, 1999), medicinal purposes (Pan *et al.,* 2022; Khan & Mukhtar, 2013; Namita, 2012), and traditions (Tulaboevna *et al.,* 2022; Pan *et al.,* 2022). These imply that the drink derives its importance from multiple perspectives.

Nonetheless, the dawn of climate change will adversely impact the production of tea (Muoki *et al.,* 2020; Nowogrodzki, 2019; Ahmed *et al.,* 2019). It is rather unfortunate that the landscape of tea as we know it will drastically change. Such alterations are rooted in the fact that the tea plantations are heavily dependent on climatological variables (Muench *et al.,* 2021; Muoki *et al.,* 2020). The world climatic observations suggest that there is a shift in the steady state of the global weather system (Ballew *et al.,* 2019). Such a shift manifests in many forms including a surge in temperature and rainfall patterns, which influences tea production, and climate change which bears the potential to reduce the yields, damage plants, and affect the quality of the tea produced (Alfonso *et al.,* 2021; Zandalinas *et al.,* 2021; Ballew *et al.,* 2019; Cavicchioli *et al.,* 2019). It is rather unfortunate that in many regions, tea plantations are already experiencing changes in temperature and rainfall patterns due to climate change (Muench *et al.,* 2021; Muoki *et al.,* 2020). In some areas, temperatures are rising, which can cause tea plants to grow more slowly and reduce their yield (Muench *et al.,* 2021; Muoki *et al.,* 2020). In other areas, rainfall patterns are becoming more unpredictable, leading to droughts or flooding that can damage tea plants (El Kasri *et al.,* 2021).

In view of the undesired realization of climate change and its associated phenomena, there is a need to project the climatic conditions from the historic trends and assess how they will impact tea production at a national level. Such undertakings may position the farmers and the authority to marginalize the exposure of the farmers to the impacts of climate change.

## 5.2 The study area

### 5.2.1 The location

According to the map in Figure 5.1, which depicts the study area, South Africa is located at the southern tip of the African continent. It is confined between 16 and 32° longitudes and, 22 and 34° latitudes. It is also one of the few countries with a unique geographical description in Africa. The country has a long coastline (2 948 km) which borders the Indian Ocean to the east and the Atlantic Ocean to the west. The country shares national borders with Namibia, Botswana, Zimbabwe, Mozambique and Eswatini in an easterly progression. The independent kingdom of Lesotho is wholly enclosed by South Africa in the eastern central plain.

Internally, South Africa is divided into nine provinces: KwaZulu-Natal, Northwest, Mpumalanga, Free State, Western Cape, Eastern Cape, Northern Cape (the largest), Gauteng (the smallest) and Limpopo. Geographically there are three primary regions in South Africa: an expansive central plateau, mountain ranges that surround the plateau to the west, south, and east, and finally, a narrow strip of low-lying land around the coast. The Central Plateau covers nearly two-thirds of the country.

It can be divided into high-lying areas (Upper Karoo, the Ghaap Plateau, and the Highveld) as well as depressions and basins (the Kalahari Basin, Cape Middleveld, Bushveld Basin, and the Middle Limpopo Valley). Perhaps the most impressive mountains in South Africa are the Drakensberg Mountains (Dragon's back). These peaks have been named part of a UNESCO World Heritage Site and they host South Africa's highest peak, Mafadi at 3 450 m, located on the South African/Lesotho border. The narrow coastal strip is known as the Lowveld, which varies in width from around 60 km to more than 200 km.

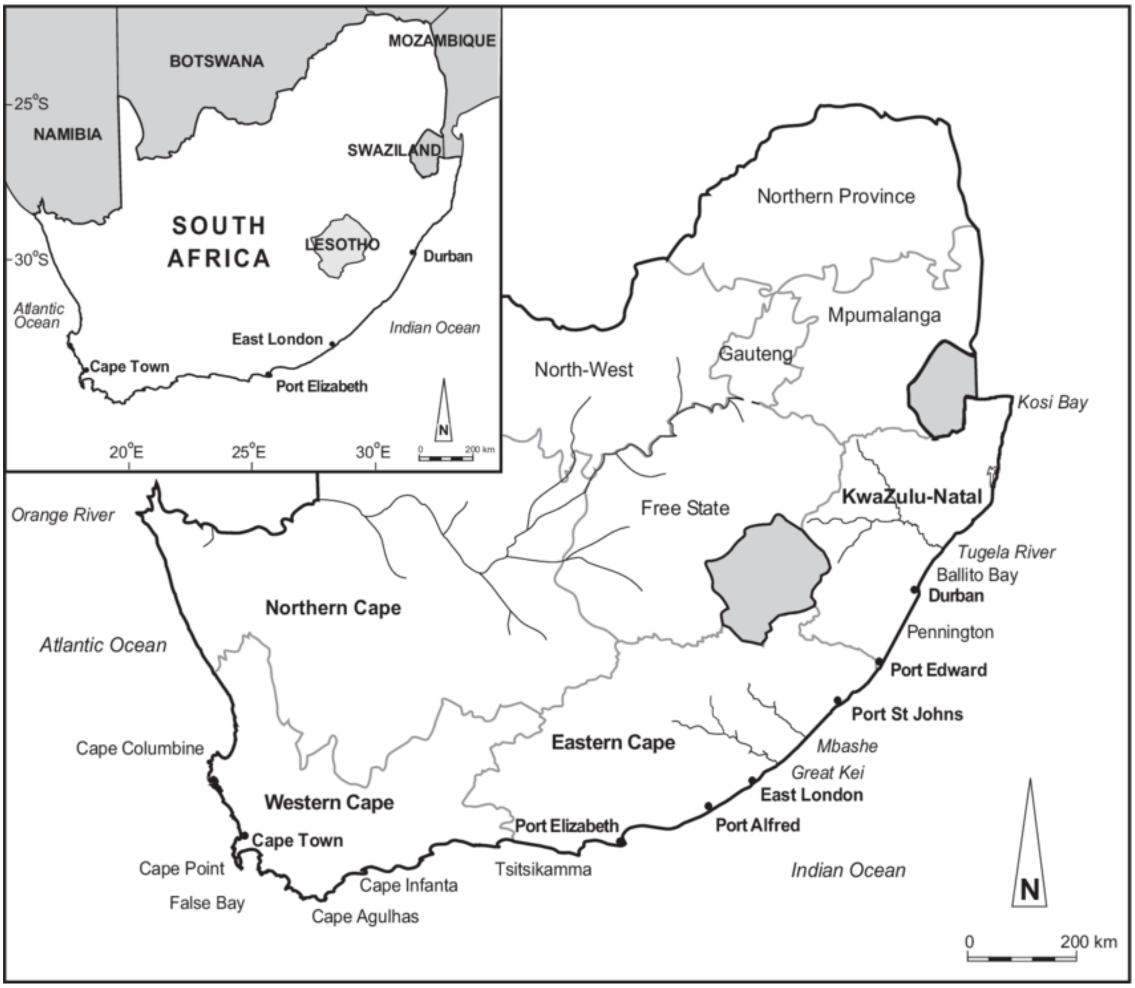


**Figure 5.1:The locality map of the study area in reference to the neighbouring countries and the geographical positioning (Harrison, 2002)**

### 5.2.2 Climatic landscape

South Africa is attributed to spatially variable climatic conditions. Such variability is a result of distinct topography, geography, and location. Subsequently, the country is divided into nine main climatic zones (Mediterranean, desert, boreal, temperate, tropical, alpine, subtropical, semi-arid, and sub-Antarctic), each exhibiting unique sets of climatological attributes (temperature and precipitation patterns). In this essay, we will provide a detailed description of each of these climatic zones. The first climatic zone in South Africa is the Mediterranean, which is found in the Western Cape province. This climate is characterized by mild, wet winters and hot, dry summers. The Western Cape receives most of its precipitation during the winter months, with an average rainfall of around 760 mm per year.

The coastal regions of the Western Cape, such as Cape Town, are known for their mild, oceanic temperatures, which average around 18°C during the winter and 25°C during the summer. The vegetation in this region is typically characterized by fynbos, a type of vegetation that is adapted to the Mediterranean climate.

The second climatic zone is the desert climate, which is found in the Northern Cape province. This climate is characterized by hot, dry summers and mild, wet winters. The Northern Cape receives very little precipitation, with an average rainfall of around 400 mm per year. The Karoo region, which is located in the central and eastern parts of the Northern Cape, is one of the most arid regions in the country, with annual rainfall as low as 100 mm. The vegetation in this region is typically characterized by succulents and other drought-resistant plants.

The third climatic zone is the boreal climate, which is found in the Eastern Cape province. This climate is characterized by cool, wet winters and hot, dry summers. The Eastern Cape receives most of its precipitation during the winter months, with an average rainfall of around 1 200 mm per year. The province is known for its cool, oceanic temperatures, which average around 16°C during the winter and 27°C during the summer. The vegetation in this region is typically characterized by hardwood forests and ferns. The fourth climatic zone is the tropical climate, which is found in the northeastern part of the country, around the city of Durban. This climate is characterized by hot, humid summers and mild, wet winters.

The KwaZulu-Natal province, where Durban is located, receives most of its precipitation during the summer months, with an average rainfall of around 1 000 mm per year. The vegetation in this region is typically characterized by tropical rainforests. The fifth climatic zone is the temperate climate, which is found in the eastern part of the country, around the city of Gqeberha. This climate is characterized by mild, wet winters and hot, dry summers.

The Eastern Cape province, where Port Elizabeth is located, receives most of its precipitation during the winter months, with an average rainfall of around 760 mm per year. The vegetation in this region is typically characterized by hardwood forests and ferns. The sixth climatic zone is the alpine climate, which is found in the Drakensberg Mountains. This climate is characterized by cold, wet winters and hot, dry summers.

The Drakensberg Mountains receive most of their precipitation during the winter months, with an average rainfall of around 800 mm per year.

The temperatures in the alpine climate zone are also much cooler than the surrounding areas, with average temperatures ranging from 5°C to 15°C. The vegetation in this region is typically characterized by ferns, mosses, and alpine plants. The seventh climatic zone is the subtropical climate, which is found in the Eastern Cape province, around the city of Makhanda. This climate is characterized by mild, wet winters and hot, dry summers. The Eastern Cape province, where Grahamstown is located, receives most of its precipitation during the winter months, with an average rainfall of around 760 mm per year. The vegetation in this region is typically characterized by hardwood forests and ferns.

The eighth climatic zone is the semi-arid climate, which is found in the central and northern parts of the country. This climate is characterized by hot, dry summers and mild, wet winters. The Karoo region, which is located in the central and eastern parts of the Northern Cape, is one of the most arid regions in the country, with annual rainfall as low as 100 mm. The vegetation in this region is typically characterized by succulents and other drought-resistant plants.

The ninth and final climatic zone is the sub-Antarctic climate, which is found on Prince Edward Island and Marion Island. This climate is characterized by cool, wet summers and cold, dry winters. The temperatures in this region are much cooler than the surrounding areas, with average temperatures ranging from 5°C to 10°C.

## 5.3 Tea crop climate requirements

Tea is a crop that is grown in many countries around the world, with the largest producers being China, India, Sri Lanka, Kenya and Vietnam. The cultivation of tea requires specific climatic conditions that are suitable for the growth and development of the plants. Therefore, this section is directed to discuss the climatic requirements of tea crops (Pandey *et al.,* 2021; Shah & Pate, 2016; Shoubo, 1989; Carr, 1972).

### 5.3.1 Temperature

Tea is a tropical or subtropical crop that requires warm and humid conditions. The optimal temperature range is between 15 and 25°C. The ideal temperature for tea growth is around 20-22°C. High temperatures above 27°C can cause leaf damage and reduce yield. Temperatures below 15°C can also affect the growth and development of tea plants, causing leaf yellowing and reduced productivity.

### 5.3.2 Rainfall

Tea is a crop that requires a significant amount of rainfall – approximately 2 000-3 000 mm per year. In areas with low rainfall, irrigation is necessary to maintain crop productivity. The timing of rainfall is also important, with tea plants requiring consistent rainfall throughout the growing season to promote healthy growth and development.

### 5.3.3 Humidity

Tea is a crop that requires high humidity to grow and develop. The optimal humidity for tea cultivation is around 70-80%. Low humidity can cause leaf dryness, leaf curl and reduced productivity. In areas with low humidity, irrigation can be used to increase humidity levels around the plants.

### 5.3.4 Sunlight

Tea plants require a significant amount of sunlight to grow and develop. The best sunlight intensity for tea cultivation is around 4-5 hours per day. However, in areas with high sunlight intensity, shading is necessary to prevent leaf scorch and reduce leaf damage.

### 5.3.5 Soil

Tea is a crop that requires well-drained, fertile soil with a pH range of 5.5 to 6.5. The soil should be rich in organic matter and have a good balance of nutrients. In addition, tea plants are sensitive to soil compaction, so it is important to avoid over-fertilization and to maintain good soil structure.

## 5.4 Predictive variables for tea suitability

South Africa is a country located at the southern tip of the African continent, with a diverse climate ranging from desert to tropical (Mani *et al.,* 2021; Ziervogel *et al.,* 2014). The country is highly vulnerable to the impacts of climate change, which are expected to increase in the coming decades (Chersich *et al.,* 2018; Dube *et al.,* 2016; Rust & Rust, 2013). In this report, we will discuss the projected climatic conditions of

South Africa, including changes in temperature, precipitation, and extreme weather events – and how these phenomena will impact tea production.

### 5.4.1 Observed temperature.

To understand the variation in the climatic landscape, a point of reference was established for comparison purposes. Subsequently, the mean annual temperature for the period ranging between 1900 and 2000 was established (Figure 5.2).

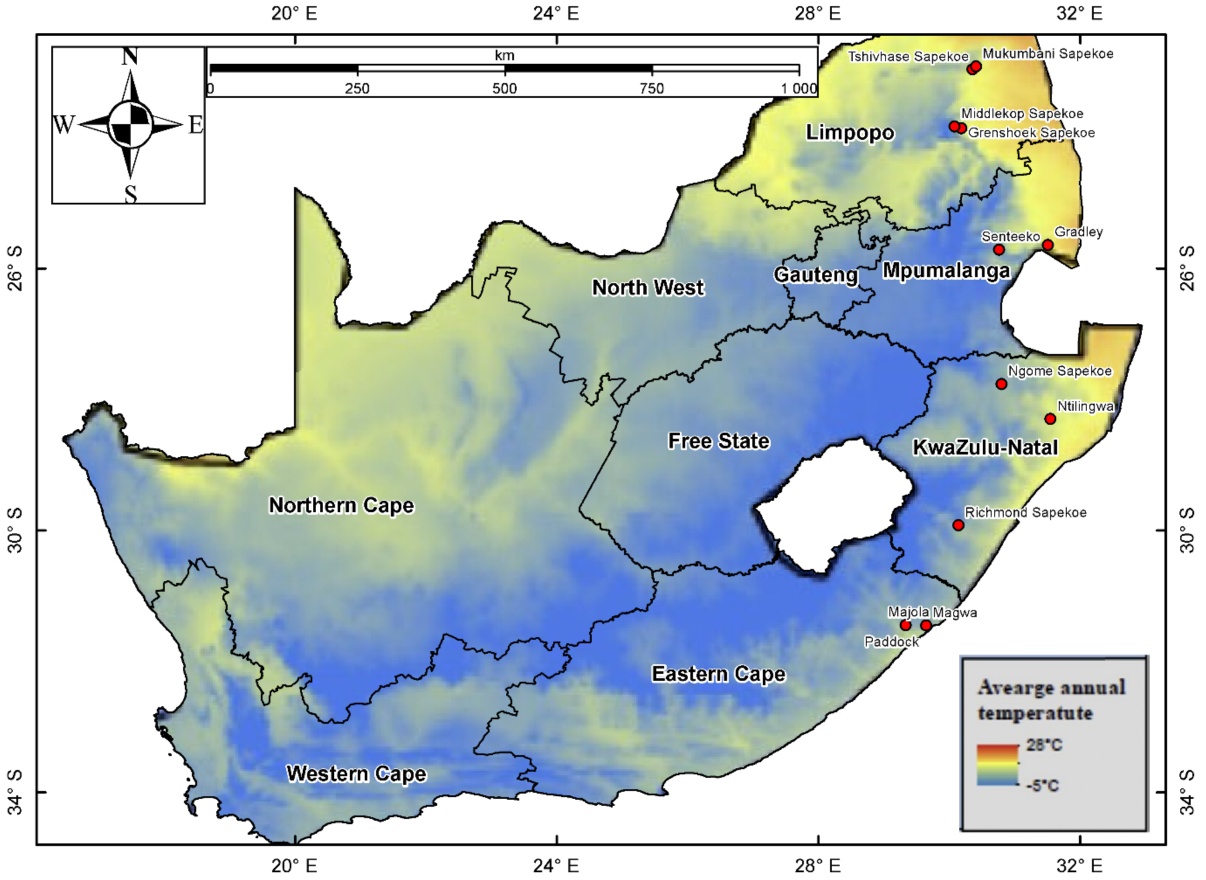


**Figure 5.2:The mean annual temperature of the period ranging from 1900-2000 (Mafongoya, 2017)**

According to Figure 5.2, the mean annual temperature in the country ranged between -5°C and 28°C. When considering that the optimal temperature range for tea is between 15°C and 25°C, almost the entirety of the country may be deemed ideal for tea production in terms of temperature. Only a few portions exhibit mean annual values that exceed 25°C that are spatially constrained to the northern and the northeastern part of the country. It is also worth noting that the areas matching such parts are the Kruger National Park in the eastern section of the country. While all the tea estates in the country appear to be positioned on the upper side of the temperatures, it is logical, especially when considering that the maximum values are not far off from the required range.

According to the same map, a significant proportion of the map covers Mpumalanga, Free State, Gauteng, the western part of Mpumalanga, Kwazulu-Natal, Eastern Cape, Western Cape and the eastern part of the Northwest and Western Cape. These areas are attributed to power mean annual temperatures to support the production of tea plants. Areas that are attributed with the mean annual temperatures that are below 15°C hinder the growth and development of tea plants.

### 5.4.2 Projected temperatures

Figure 5.3 indicates the projected mean annual temperatures for the year 2050. The projected temperatures were extrapolated based on the monitoring observations data between 1900 and 2000. The map suggests that the mean annual temperatures in the country would have increased from the initial observation data to the projected date (from 28°C to 31°C), which reflects a giant increase of 3°C over the period.

The map also indicates that the yellow color is encroaching on the eastern part of the country. Most of the areas that were light blue in Figure 5.2 are getting overwhelmed by the prominent yellow color in Figure 5.3. Such a sharp change is visible in Limpopo, Mpumalanga, Kwazulu-Natal and the Eastern Cape. However, these increments may not hint anything alarming about the fate of tea production just yet. South Africa is expected to experience significant temperature changes in the coming decades, with both warming and cooling trends projected. Currently, the country is already experiencing an average temperature increase of 0.2°C per decade, with the highest temperature increases projected for the interior and high-elevation areas.

By the end of the century, the average temperature is projected to increase by 1.8°C to 5.2°C, depending on the emissions scenario. In addition, higher temperatures can also affect the quality of tea leaves, leading to lower levels of catechins, the compounds that give tea its unique flavor and health benefits. These temperature changes are expected to have significant impacts on South Africa's climate, including changes in precipitation patterns and increased frequency of extreme weather events.

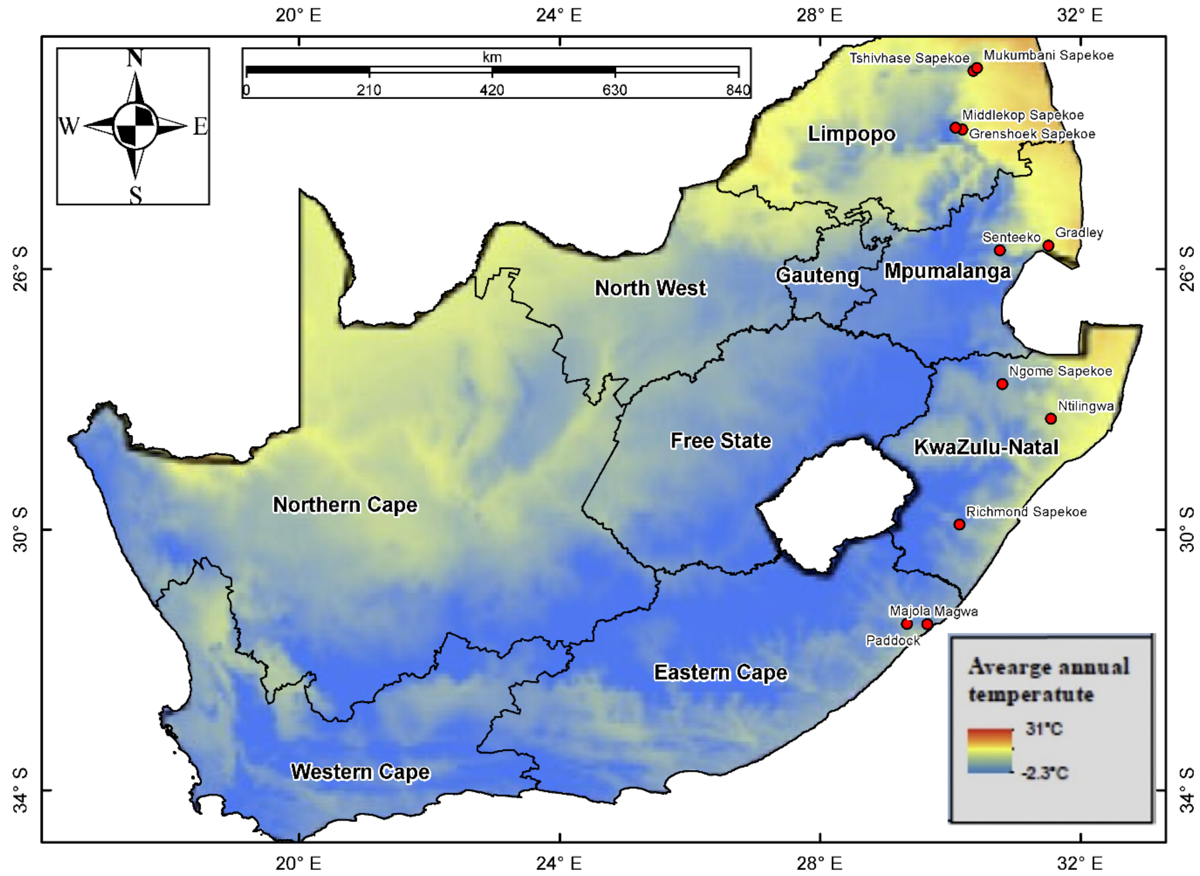


Figure 5.3: The projected mean annual temperature for 2050 ((Mafongoya, 2017)

### 5.4.3 Precipitation

Figure 5.4 depicts a map illustrating the mean annual precipitation from the period ranging from 1900 to 2008. The map was overlain with the prominent tea plantations in the country. The map indicates that there is a significant spatial trend in the rainfall in South Africa. The maximum amount of rainfall of up to 2 700 mmpa occurs in the eastern part of the country as a belt that transects through Limpopo, Mpumalanga, KwaZulu-Natal, and the northern part of the Eastern Cape.

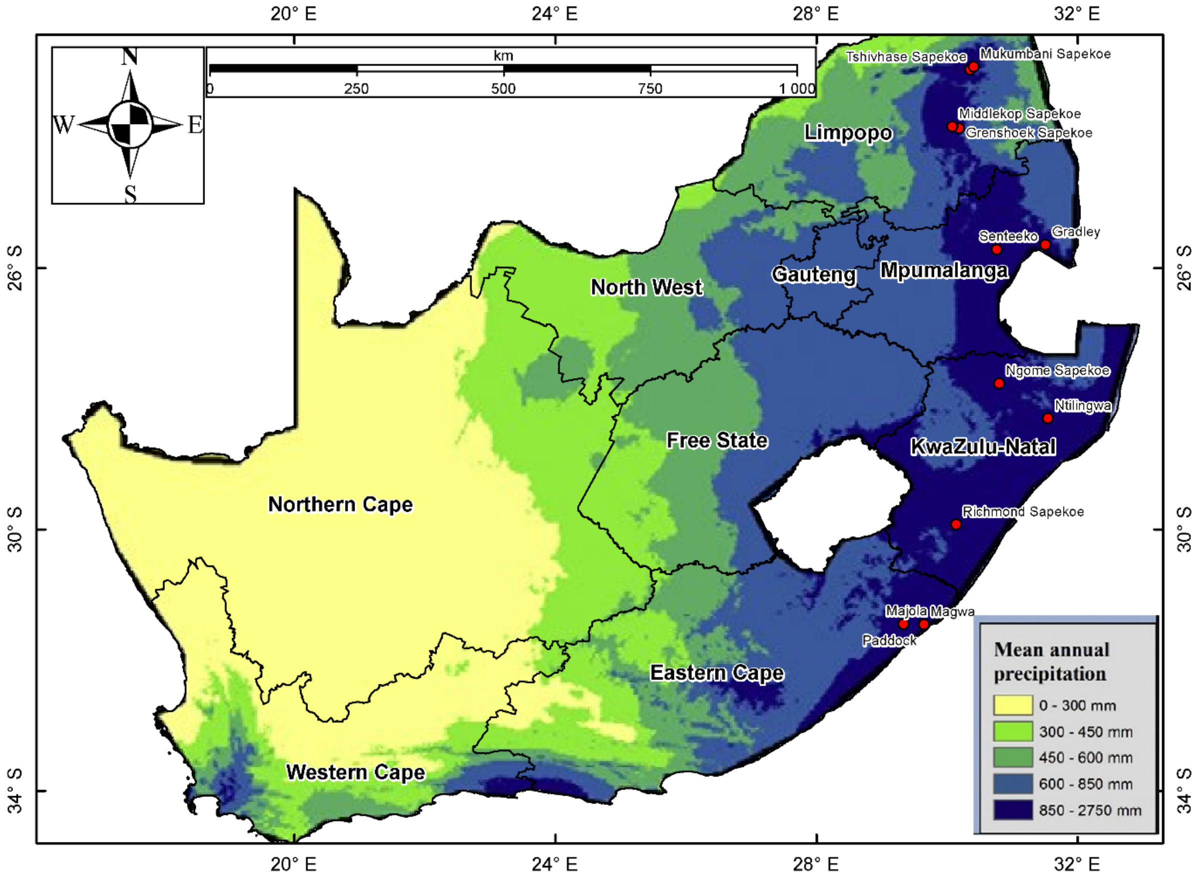


**Figure 5.4: The mean annual precipitation of South Africa from 1900-2008 (Mafongoya, 2017)**

The precipitation drastically decreases from the eastern part of the country to the west. According to Figure 5.4, the country may be sectionalized into five distinct precipitation districts, each exhibiting a unique range of precipitation values. Class 1 is depicted by the navy-blue color on the map; it is spatially restricted to the eastern side of the country and conforms to the optimal rainfall areas. All the tea estates adhere to this rainfall area. This is not surprising because tea requires a comparatively high mean annual precipitation in the range of 2 000-3 000 mmpa. The confinement of the tea estates in this region is due to the ideal precipitation the transverse receives and the limited surface water resources in the country, which deems rainfall as the only dependable water resource. Some areas are marked by the blue color that depicts the optimal rainfall zones. These areas are situated westward of the first class. They have a mean annual precipitation ranging between 600-850 mmpa. The westward projection reveals a decrease in rainfall to the minimum precipitation of about 300 mmpa on the most westerly part of the country which corresponds to the Northern Cape.

### 5.4.4 Projected precipitation for the country

The map in Figure 5.5 indicates the projected precipitation for South Africa in the year 2050. At a surface value glance, the past precipitation trends (1900-2008) and the projected (2050) appear to be the same. However, that is not necessarily the case. The maximum annual precipitation for Figure 6.4 was 2 750 mmpa; meanwhile, the projected value is 2 610 mmpa (Figure 5.5). This suggests that over the course of the decade, 140 mmpa would be shed. While it can be argued that such a value is not much, it actually is, especially when taking into account the fact that South Africa is a water-scarce country. The mean annual precipitation in the country stands at 700 mmpa, which is lower than the global average of 850 mmpa. Any drop in precipitation could have a detrimental effect on the country, particularly on the tea plantations – as the country is already lacking sufficient precipitation to suffice such operation.

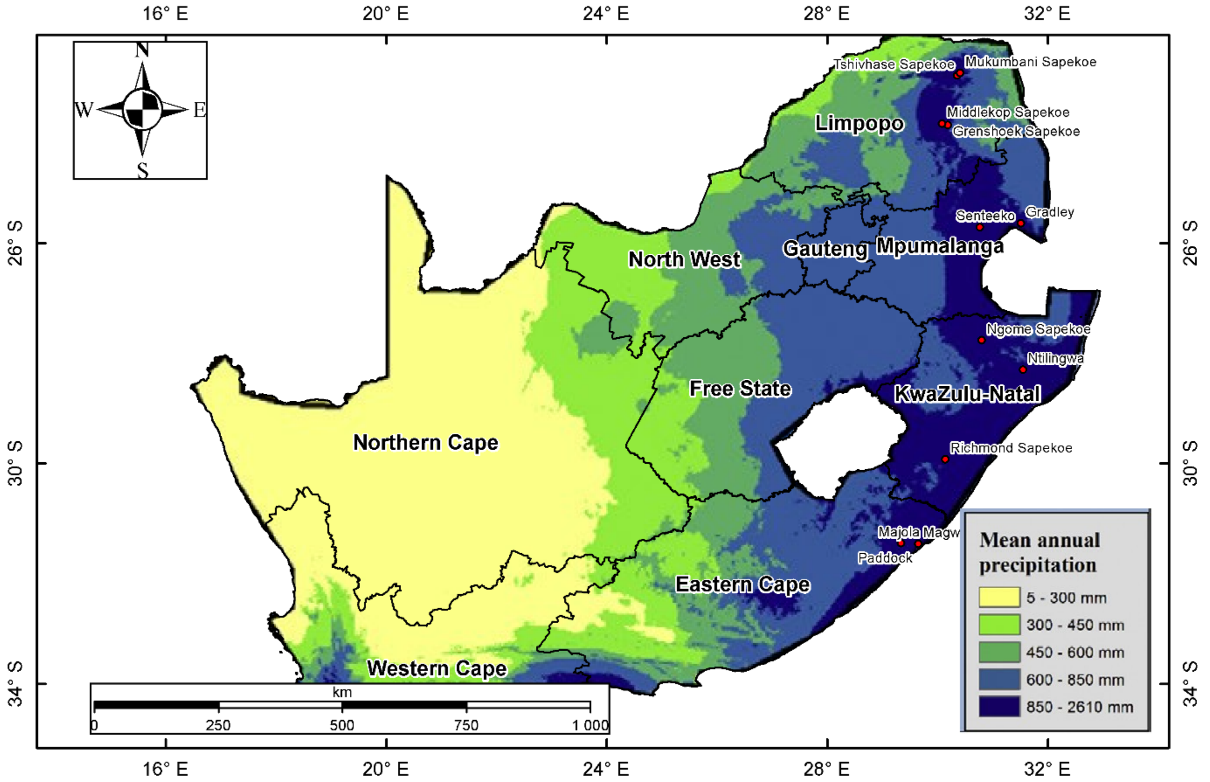


**Figure 5.5: The projected mean annual precipitation for South Africa in 1950 (Mafongoya, 2017)**

While the tea plantations are still conforming to the optimal precipitation areas that the country experiences, the amount of precipitation would drop slightly, which is a cause for concern. The tea crop requires a mean annual precipitation of between 2 000-3 000 mmpa. The prime and potential area receives a little less rainfall than the requirement of tea.

However, this will only worsen as the temperatures indicate that there is a gradual increase beyond the requirement range of the tea plant. When the temperatures increase, the demand for water resources also spikes to mitigate the impact of temperature on the crop. In the context of South Africa, the temperature increase is inversely proportional to the precipitation. This implies that the additional water resource that is necessitated by the escalating temperatures will not be catered for. If there is a shortage of precipitation to sustain tea plantations, the farmers always resort to irrigation. However, South Africa has limited surface water resources and most of the resources from such water bodies is already over-allocated. Therefore, it is highly unlikely that the growing demand could be accommodated. Ultimately, there will be constriction of the tea production – that is, after increased temperature and reduction in precipitation.

### 5.4.5 Impact of climate change on tea

South Africa is also expected to experience changes in precipitation patterns in the coming decades (Thornton *et al.,* 2014; Dai, 2011; Kotir, 2011, Brown *et al.,* 2014), with both wetter and drier conditions projected. The country is already experiencing an increase in annual precipitation, with the highest increases projected for the western coastal regions (Thornton *et al.,* 2014; Dai, 2011; Kotir, 2011, Brown *et al.,* 2014). By the end of the century, the average precipitation is projected to increase by 10% to 20%, depending on the emissions scenario (Adhikari *et al.,* 2015; New *et al.,* 2001; Partridge *et al.,* 1997).

In addition to changes in temperature and precipitation, South Africa is also expected to experience an increase in the frequency and intensity of extreme weather events such as heatwaves, droughts, floods and storms (Nhemachena *et al.,* 2020; Kusangaya *et al.,* 2014; Ziervogel *et al.,* 2014). These events can have significant impacts on the production of tea (Roy *et al.,* 2020; Muoki*et al.,* 2020). For instance, heat waves are becoming more common and intense (Libonate *et al.,* 2022; Van Der Walt *et al.,* 2022); meanwhile, droughts are also becoming more frequent and severe. These events are a firm cause for concern for tea production in South Africa.

## 5.5 How climate change will affect the tea production

One of the most significant impacts of climate change on tea production is the temperature change. The highlands where tea is grown in South Africa are already cooler than the surrounding areas, but rising temperatures are expected to affect tea production in several ways.

Earlier springs and later falls can affect the growth and development of tea plants, and higher temperatures can increase the incidence of pests and diseases, which can reduce yields and quality of tea. In addition, higher temperatures can also affect the timing of tea harvests, which can impact the availability and quality of tea.

Another notable impact of climate change on tea production is the change in precipitation. South Africa is already experiencing an increase in annual precipitation, with the highest increases projected for the western coastal regions. However, the increase in precipitation is not evenly distributed across the country, and some regions are experiencing droughts and water scarcity. Excessive rainfall can lead to waterlogging and soil erosion, which can reduce soil fertility and quality. On the other hand, reduced rainfall can lead to water scarcity and reduced yields. Heat waves can lead to reduced growth and development of tea plants, while droughts can lead to water scarcity and reduced yields. Floods can also damage tea plants and infrastructure, while storms can damage tea fields and cause soil erosion.

## 5.6 Conclusion

In conclusion, climate change is expected to have significant impacts on tea production in South Africa, and these impacts are likely to be felt in the coming decades. The change in temperature, precipitation and extreme weather events are expected to affect the growth and development of tea plants, the timing of tea harvests, and the quality and quantity of tea produced. To reduce the impacts of climate change on tea production, farmers and producers must adopt sustainable practices and technologies, and policymakers must support climate-friendly tea production and adaptation.

# Chapter 6 ECONOMIC TRADE-OFFS ON WATER-ENERGY-TEA-EXTRACTS-ENVIRONMENT NEXUS

## 6.1 Introduction

The paper reviewed the literature and analysed data, with the main aim of demonstrating the linkages between the WEF nexus with the Sustainable Development concept based on the Tshivhase Tea Estate Case Study. The review adopted the framework developed by Biggs et al. (2015), which articulated their perspective on the connectedness of the WEF nexus and community livelihood.

The concept of the water-energy-food interrelationships was developed in the international community because of climate change and social changes, including population growth, globalization, economic growth, urbanization, growing inequalities and social discontent. These issues are putting more pressure on water, energy and food resources, presenting communities with an increasing number of trade-offs, and potential conflicts among these resources that have complex interactions.

The demand for water, energy, and food is estimated to increase by 40%, 50%, and 35%, respectively by 2030 (USNIC). ***In motivating this study, the aim will be to seek solutions to reduce the high costs of inputs (water, energy, labour and other consumables), in producing (black and green) tea coupled with the botanical extract.*** The most important, though intangible, product will be the sustainable greening of the environment, which comes with the slopes of tea estates that are covered with leafy, green tea plants. The Research Framework, though with a focus on water-footprint, will enable the researchers to inculcate the concept of the water-energy-food-environment nexus. Figure 6.1 shows an adaptation of Endo et al. (2015) dynamics of the WEF nexus under the Research Institute for Humanity and Nature Water-Energy-Food Nexus (RIHN WEFN) project. The diagram can be used preliminarily as a frame to illustrate the prevailing set-up at the Tshivhase-Mukumbani Tea Estate.

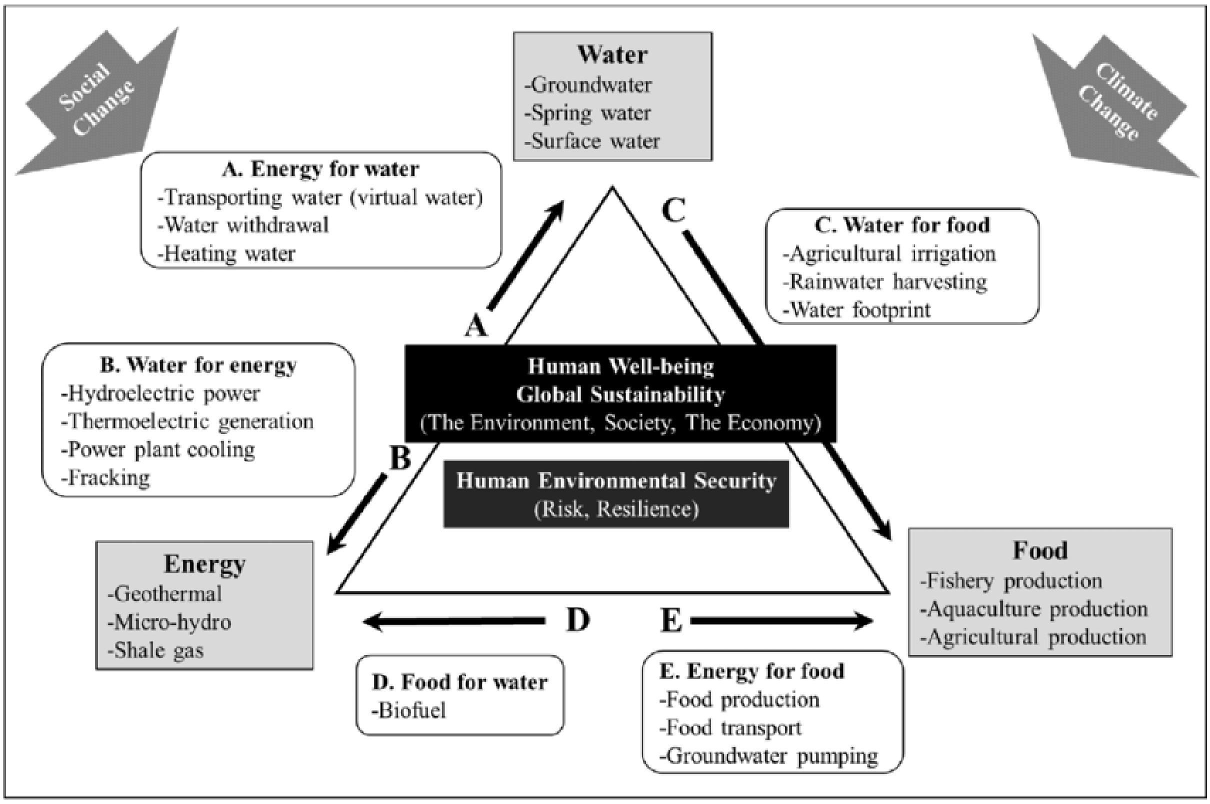


**Figure 6.1: Dynamics of the WEF nexus under the Research Institute for Humanity and Nature Water-Energy-Food Nexus (RIHN WEFN) project**

The project was developed as part of the countrywide production of tea in South Africa which started in 1964. The tea industry was supported by the government and later by the Industrial Development Corporation (IDC) as one of the "mass employers in the rural areas" and the strategy worked with absorption rates of over 1 000 workers on a 500-ha farm or estate. The effect of democracy in 1994, globalization and SADC Trade Protocols on agribusiness enterprises was massive and left many agribusinesses battling to remain profitable. De-investments in South African black tea production started when black tea became unprofitable in South Africa, due to some or all the following points identified by Sapekoe (Pty) Ltd at the time. These were: (a) high worker minimum wage rates, (b) no protection against tea imports from SADC, (c) high production cost structure, (*due to labour wages, electricity, and inputs costs*), (d) the strong rand against the US Dollar, (e ) land claims on tea estates, and lastly, (f) it emerged that the United Kingdom directors were not happy with RSA tea estates' bottom line. At a local level, the tea estate is part of the Tshivhase Tribal Authority based on Apartheid Legislation of separate development. The estate is currently under LEDA with no Lease Agreement or clear partnership agreement between the agency

LEDA and the Tshivhase Tribal Authority. It is surrounded by villages with a growing number of residential stands.

At peak production, they benefit from temporal work opportunities from picking to processing tea. In our previous work (Nesamvuni et al., 2014), we articulated the aspects of the Tshivhase tea competitiveness.

### 6.1.1 Climate change

Climate change is one of the most influential phenomena in tea production. According to Marx et al. (2017), climate is one of the controlling factors in agriculture, since most crops are responsive to their surrounding climatic conditions. Tea depends greatly on climate for optimal growth; hence, changes in climatic conditions affect tea production (Gunathilaka et al., 2017).

#### *6.1.1.1 Rainfall*

As revealed by Kumar and Shruthi (2014), the effective production of tea requires a high annual rainfall of around 1 500-2 000 mm. The essence of rainfall for the optimal production of tea was affirmed by Ochieng et al. (2016), who emphasized the importance of adequacy and consistency of rainfall. Other than yield, rainfall was revealed to have some influence on the quality of tea produced (Kottur et al., 2010). Annual rainfall of 2 500-3 000 mm is considered ideal. The annual rainfall at Tshivhase-Mukumbani Tea Estate was 1 758 mm, well above the minimum requirement for tea production. The distribution of the rainfall was rather uneven, as reported in our previous work (Nesamvuni et al., 2022). The Tshivhase-Mukumbani Tea Estate is situated in a micro-climatic area. It was noted that half (51.1%) of the rainfall at Tshivhase-Mukumbani Tea Estate was received in the first quarter (January to March) of the calendar year. This followed one-third (32.8%) of the rainfall received in the preceding quarter (fourth quarter, October to December). The second (April to June) and third (July to September) quarters of the year shared the remaining 16.1% of the rainfall. Improvement of soil moisture for increased tea production at the Tshivhase-Mukumbani Tea Estate may be achieved through the introduction or improvement of irrigation at the Tshivhase and Mukumbani Farms, respectively.

#### *6.1.1.2 Temperature*

The ideal temperature for tea production is 18-25°C with a minimum recommended temperature of 13°C (average for the coldest month) and a maximum of 30°C (average for the warmest month) (Waheed et al., 2013). Temperatures at Tshivhase-Mukumbani Tea Estate are lower in winter, and this results in tea plants becoming dormant. Excessively high summer temperatures may result in wilting of tea leaves, especially at the Tshivhase Farm without irrigation. Not much can be done to change the temperatures for tea production at the estate.

## 6.2 Aspects of the WEF nexus

### 6.2.1 Water

In the production of tea (black, green, and botanical extracts), water is at the centre of the production system from irrigation to processing of both black and green tea, and the production of botanical extracts. In the context of the framework Figure 6.1, the tea estate makes use of surface water that gets harvested and stored in a small dam located on the west of the estate at Mukumbani Tea Estate for partial irrigation. There is also limited use of underground water to augment the water resources. On the eastern side of Mukumbani, the Lunwenwe tributary flows past the tea estate to the river Tshinane. It feeds and supplies the community with water to produce vegetable and field crops along the river. Tea production at the Tshivhase Farm is rain-fed; this portion of the estate lies adjacent to the Vondo Dam, a strategic water reservoir in the Mutshindudi River that supplies water to Thohoyandou and neighbouring areas.

### 6.2.2 Energy

The form of energy being used includes petrol, diesel, electricity, and firewood for the processing of black tea. The use of firewood (mainly blue gum and pine trees) creates a close relationship with the environment. Energy is also closely associated with the use of water to produce food (black, green, and botanical extracts). The tea plantations themselves cover over 14 567 ha of land, which create a good greening project for the environment. After picking the tea there is an urgent need to transport the tea leaves from the rest of the Tshivhase-Mukumbani estate to the factory at Mukumbani.

Energy is required in the following steps of tea processing in a dynamic relationship to dry the tea leaves.

(a) In withering of leaves from the field – From the distribution header, steam is delivered through a 150 m x 100 mm diameter steam supply line to the withering radiators. This high-pressure steam supply line, capable of delivering 6 000 kg of steam at a pressure of 8 bars, is in place to serve the 80 high-efficiency steam radiators. The line is run from the main distribution header and sub-divided down-stream into two to separate the upper from lower deck troughs through appropriate pressure reduction stations for regulation.

(b) Coupled with radiators is a 65 mm diameter condensate recovery line that runs through twin Ogden pump units located at the lower eastern end of the withering shed and back to the boilers' feed water tank.

(c) Rolling section – The energy source is electricity to run the rollers to cut the tea into a fine texture before fermentation.

(d) Drying section – At the drying section, where 70% moisture is driven out under continuous hot air blasting at an average of 140°C on the units' feed-end and a constant manometer setting of 1.5 units, the 3 726 kg of withered leaf/h charge at the CTCs is converted into 1 200 kg of black made tea at a moisture content of 3%, each MCCLOY drier yielding 600 kg/h.

(e) Drying section – Coupled with the driers are two steam boilers with a generation capacity of 6 000 kg of steam at 10 bar and about 180°C each. For drying purposes, only about 4 000 kg of steam is needed, and therefore, only one of these units is run at a time. A second boiler is often engaged on wet days when withering requires some heat to drive away excess moisture. It is worth noting that, after the installation of the new 3-pass high-efficiency boilers, the fire-wood consumption has dropped significantly from the initial average of 0.54 $m^3$/100 kg of made tea last season to 0.21 $m^3$/100 kg of made tea this season, which is an improvement of 100+%.

(f) Value adding – The energy needed here is electricity.

## 6.3 Livelihood security of the community

Central to the challenge of sustainable production of tea at Tshivhase is the livelihood security of the community around the tea estate. The linkages between the water-energy-food-environment (WEFE), with the added environmental aspects of forest harvesting and community livelihood become crucial.

The framework by Biggs et al. (2015) talks about **Environment Livelihood Security (ELS)** defined as a concept that seeks a balance between natural resource supply and human demand on the environment to promote sustainability. It is conceptualized that ELS is impacted by livelihood and environmental pressures.

Livelihood pressures include population growth and urbanization, whereas environmental pressure is due to climate change and natural hazards. It is our contestation that the said pressures are at play at the Tshivhase Tea Estate. The estate is surrounded by growing residential areas and community amenities coupled with the impact of climate change (manifested as droughts and high temperatures) and natural hazards such as fires (Nesamvuni et al., 2014).

The debate on the long-standing term ‘sustainable development’ and its associated frameworks in relation to the moving target of the Sustainable Development Goals (SDGs), is ongoing. The SDGs oblige signatory countries to have new action targets designed to achieve sustainable water use, energy use and agricultural practices, as well as enhance more inclusive economic development (Biggs et al., 2015; United Nations, 2014). In closing the gap of the current debate on sustainable development, the term ‘livelihood’ will be part of the adopted model by Biggs et al. (2015). The next section will describe the model from the Sustainable Livelihood perspective.

## 6.4 Water-energy-food nexus approaches – a review

The Sustainable Development Goals (SDGs, UN 2015) set the measure for the global community to effectively manage water, energy, and food resources for sustainable outcomes. The WEF nexus has been conceptualized for ease of understanding the complex connections among numerous resource ecosystems. The biggest challenge with the complex interaction of major resources which are central to development is the methods of analysis.

However, many scholars have employed the WEF nexus concept in policy settings (Keairns et al., 2016). Several of these authors (Bazilian et al., 2011, Wolfe et al., 2016, Foran, 2015) reiterated that the WEF nexus was system-based, interconnected, and interdependent. According to Kurian (2017), the main aim of such a system is to **(a) amplify the combined effect of water energy and food, (b) minimize trade-offs, (c) improve the efficiency of the combined use of the resources, and (d) internalize social and environmental impacts.**

Beyond the initial focus to establish the interconnectedness of the WEF nexus, modifications were made that integrated the effects and impacts of environmental, economic, political and social aspects (Lawford et al., 2013). To attain sustainable outcomes, WEF nexus methods need to assess nexus impacts and effects on human livelihoods, and the influence of institutions in improving resource governance, predominantly at community level (Biggs et al., 2015). The WEF nexus assessments are frequently conducted at regional or national levels, due to the availability of data or national-level policy goals or metrics (Miralles & Wilhelm. 2016). However, Chang et al. (2016), indicated that there is a need for a balance of top-down and bottom-up approaches to address a multiplicity of platforms and scales. Some nexus research has focused on dual-sector interactions, e.g. water-food or water-energy. The drawback to the nexus concept is that water resources are central as compared to energy and food, which then renders nexus analysis inherently weak to enhance coordination of policies across resource sectors (Smajgl et al., 2016).

The interlinkages and interdependence among the WEF nexus cannot be overemphasized. For purposes of analysis, there is a need for the three sectors to be assessed together, equally, and in an integrated manner. This will enhance our understanding and trade-offs between sectors for better developmental outcomes in socio-political contexts (Chang et al., 2016, Miralles-Wilhelm., 2016, Smajgl et al., 2016).

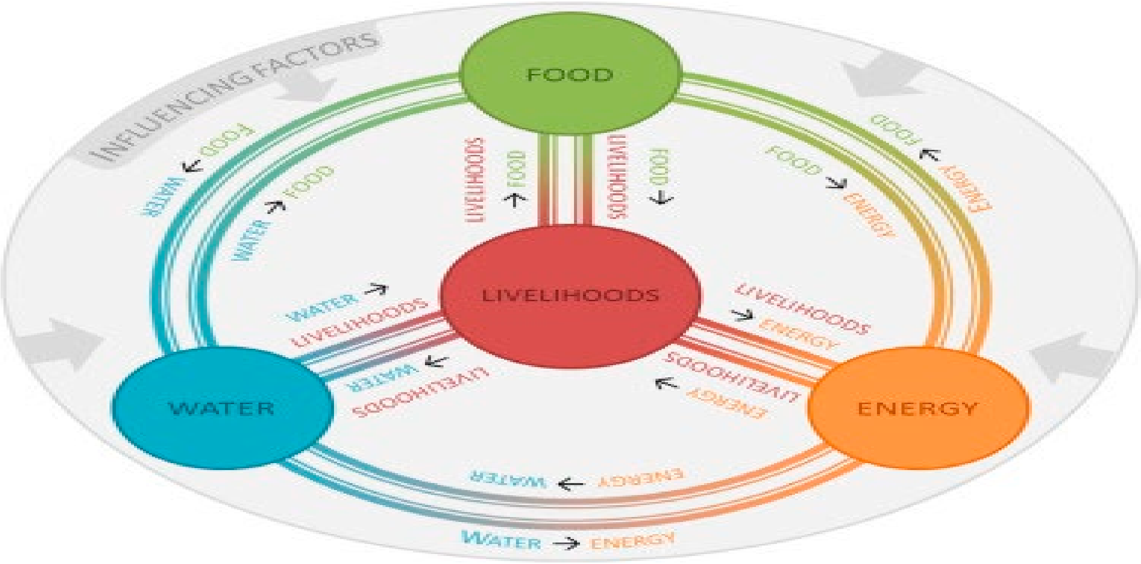


**Figure 6.2: The notion of ELS conceptualizes the links between water, energy, food, and livelihoods which need balance to achieve a sustainable system.**

External influencing factors such as climate change, population growth, and governance can all impact attaining ELS (Biggs et al., 2015). Three areas have been identified for the use of the WEF nexus, mainly as an analytical tool, a conceptual framework, and discourse (Keskinen et al., 2016). As an **analytical tool**, a nexus analysis systematically uses quantitative and/or qualitative methods to understand interactions among water, energy, and food systems. As a **conceptual framework**, the nexus approach leverages an understanding of WEF linkages to promote coherence in policymaking and enhance sustainability (Figure 6.2). Lastly, as a **discourse**, the nexus concept can be used for problem framing and promoting cross-sectoral collaboration (Keskinen et al., 2016).

### 6.5 The background to nexus thinking.

'Nexus thinking' was first considered by the World Economic Forum (2011) to encourage the close links between the use of resources to provide basic and worldwide rights to food, water, and energy security. The World Economic Forum (2011) presented the nexus framework from a securities viewpoint (water-energy-food security); successive versions have taken on various facets with alternative components, such as water resources as a central component (Hoff, 2011), land use-water-energy (Howells et al., 2013) and food as an essential component with land-water-energy linkages (Ringler et al., 2013). Nexus thinking is promoted as an improvement to the current and often sector-specific governance of natural resource use.

The one challenge of natural resource use, especially water, is that it may lead to the depletion of reserves and increased climate risk without a reasonable amount equal to the benefits (Hoff, 2011; Rockström et al., 2009). A good example is in northwest India, where intensive agriculture has been driven by government policies to support national food welfare. The side-effect of these policies has degraded ecosystems without increasing levels of food security (Aggarwal et al., 2004; Pritchard et al., 2013). The best approach is to combine environmental and social frameworks with measurable targets, for the purposes of achieving sustainable development goals (Biggs et al., 2015; Griggs et al., 2013). For purposes of this review, we adapted the approach by Biggs et al. (2015), who incorporated an explicit focus on livelihoods and livelihood dynamics within nexus framings to capture bottom-up approaches and local opportunities for sustainable development (Figure 6.2).

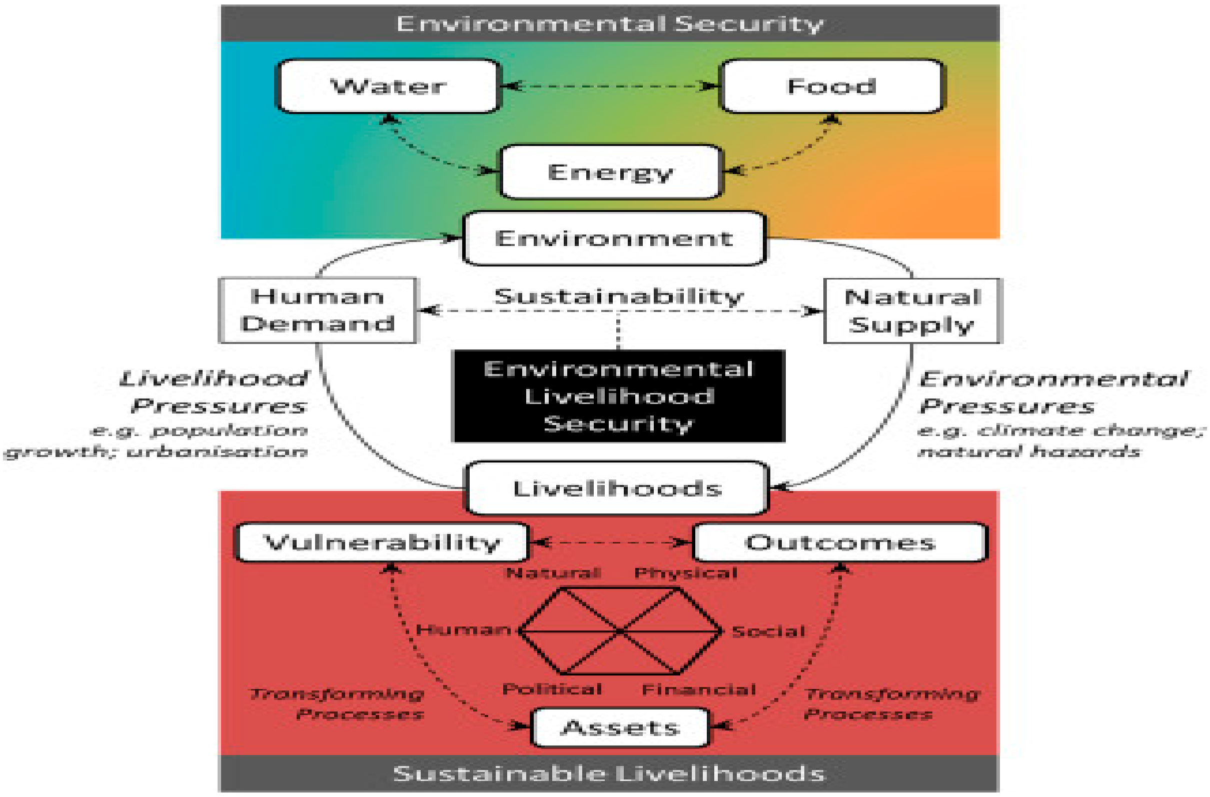


**Figure 6.2:** The conceptual framework for investigating ELS combines concepts of the water-energy-food-climate nexus with the capitals of the sustainable livelihoods framework to achieve a sustainable balance between natural supply and human demand to ensure 'environmental livelihood security' (Biggs et al., 2014).

Nexus frames consider key issues in food, water and energy security through a sustainability focus, to forecast and protect against potential risks of future insecurity. Livelihood pressures impact on the resources (Figure 6.2) due to population growth and urbanization. Environmental pressure also impacts negatively on the sustainability of the resources coming in the form of climate change (drought, high temperatures) and natural hazards. We will adopt Figure 6.2 to construct our own practical model that combines livelihood security and the nexus framework. Key to the new framework will be the fact that livelihood security is not only driven by the availability of resources but also by access to resources, the capacity to exploit them, as well as dynamics of social power relations and the strength of institutions (Ericksen, 2008; Pritchard et al., 2013). The inclusion of a complete concept of ‘livelihoods’ within existing nexus framings would integrate the other factors that control security with the drivers of resource availability.

Such an approach would also build upon and complement prior applications of the Sustainable Livelihood Approaches in the sectors of water (Nicol, 2000), forestry (Warner, 2000), natural resource management (Pound et al., 2003), agriculture (Carswell, 1997), river basin management (Cleaver and Franks, 2005), and fisheries (Allison and Ellis, 2001).

### 6.5.1 Integrating sustainable livelihoods and nexus approaches

A thought leadership review has been done by Biggs et al. (2015) on the integration of sustainable livelihood and nexus approaches. There are clear interactions between the SLA and nexus approaches regarding sustainable development. Both consider socio-ecological pressures, governance, the environment (in terms of resource access through natural capital in the SLA), and security (environmental and economic security in the nexus; livelihood security in the SLA) (e.g. World Economic Forum, 2011; Hoff, 2011). To date, the nexus literature has not explicitly identified how water-energy-food securities are interlinked with livelihoods to enhance water-energy-food security at the livelihood level. The water-energy-food nexus (FAO, 2014) situates a nexus approach to natural resource use within the context of social needs and economic development, specifically in the context of reducing poverty, sustainable agriculture and ecosystems and food security.

## 6.6 Environmental livelihood security

ELS was first developed by Biggs et al. (2014), referring to the challenges of maintaining global food security and universal access to freshwater and energy. The main purpose is to (a) sustain livelihoods and promote inclusive economic growth, and (b) sustain key environmental ecosystems to function, even under extreme and variable climatic conditions. The term was conceived to address a lack of consideration of ‘livelihoods’ within nexus frameworks, which is essential to ensure water, energy, and food security for sustainable development and livelihoods. The ELS of a system is met when a balance is achieved between human demand on the environment and environmental impacts on humans (Figure 6.2).

In this way, the theoretical underpinning of ELS draws upon the concepts of environmental security and human (livelihood) security (Biggs et al., 2014). In addition, the desire to achieve sustainable systems places the concepts of sustainable development and sustainable livelihoods at the centre of ELS (Biggs et al., 2015). The conceptual grounding of ELS to develop a framework that can be applied to a system assists in identifying sustainable solutions for future development.

## 6.7 The environmental livelihood security framework

Incorporating sustainable livelihoods with the WEF nexus entails the identification of the interconnections between these securities, as well as the assets of human populations and the natural environment. Figure 6.2 demonstrates the integrated model with livelihood around the linkages of the WEF nexus. Livelihood is now at the centre of the wheel driven by the balance of available and accessible resources. Central to the drivers of livelihood is the water (surface, groundwater, and spring water) which can provide for food through **irrigation**, rainwater harvesting and water footprint. Water can also be important for energy through **hydroelectric power**, thermoelectric generation, power plant cooling, and fracking.

The same can be true for energy (micro-hydro, **electricity**, **diesel**, shale gas) for food in the form of **food production, food processing, food transport and groundwater pumping**; also, energy for water in the form of **transporting water** (virtual water), water withdrawal, and **heating water**. Lastly in this exercise is food (fisheries, aquaculture, and agricultural production) – for energy you get biofuel and biodiesel. Similarly, food for water could be food produced with plenty of stored water in the form of watermelons and their varieties. This is well demonstrated in Figure 6.1.

This is further shown by Figure 6.3, which recognizes the interdependence between water and livelihoods: (a) water is needed to support livelihood activities such as fisheries or irrigated agriculture, and (b) livelihood activities and capital may contribute to (or deplete) the conservation of water supplies and access (e.g. physical capital (infrastructure) may permit more efficient water extraction and transportation, and financial capital (public or private funds) may help in implementing more sustainable practices in water use or purchase access to alternative supplies).

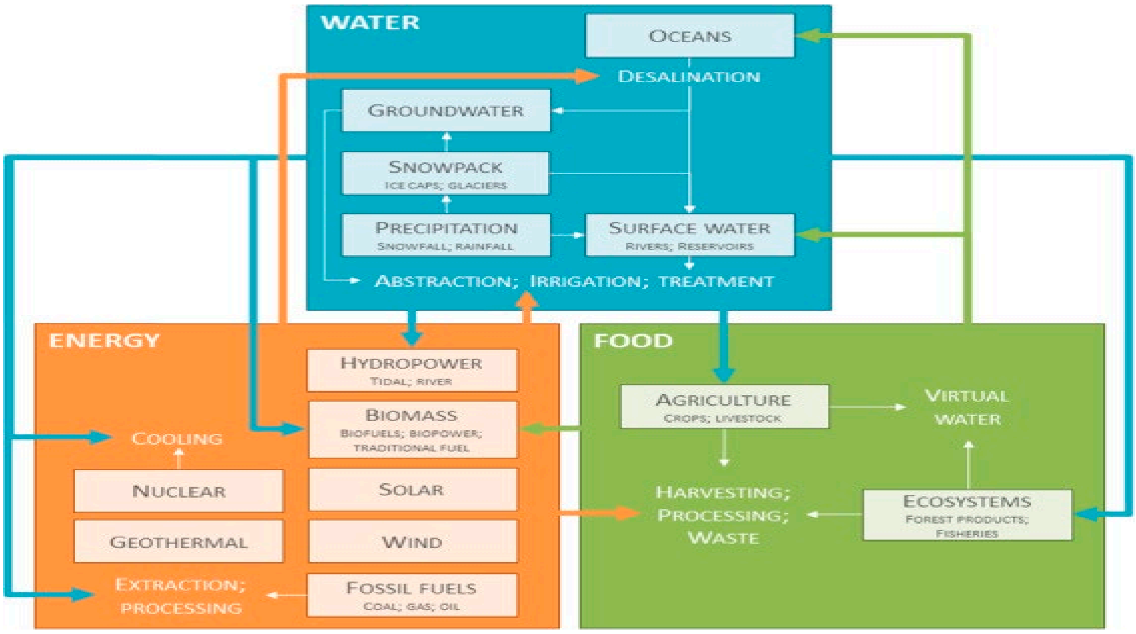


**Figure 6.3: The environmental nexus system defines the major flows within and between water, energy and food systems**

The external influences or pressures acting upon all internal linkages within this system are population dynamics and climate change or hazards. To achieve ELS in any ecosystem, these linkages need to remain balanced and resilient under external pressures or influences (Biggs et al., 2015). Figure 6.4 indicates the internal (livelihoods-water-energy-food) and external (influencing) factors that need consideration for attaining ELS. Through quantifying such factors, the system can be used to promote sustainable development by balancing sustainable activities within livelihoods and the environment.

The framework must fundamentally explain system dynamics and, through identifying synergies and trade-offs, capture system feedback such as the direction and pace that ELS may transition across spatial and temporal scales. This may assist in the process of identifying whether the ELS of any particular system is in dynamic equilibrium, has multiple equilibriums (such as impoverished and environmentally degraded components as well as wealthy and environmentally sustainable components), or is linearly increasing or declining in a general sense. While this capacity resonates with systems thinking theory (see Enfors, 2013; Tittonell, 2014), the framework provides a more integrative approach to monitoring and evaluating sustainable development across multiple spatial and temporal scales, while still ensuring that the focus of people-centred livelihoods remains at its core. In this way, the approach may contribute to achieving more general targets such as the SDGS in a more holistic and equitable manner and can also be applied at smaller scales.

**Figure 6.4: Fundamental internal (livelihoods-water-energy-food) and external (influencing) factors that need consideration for attaining ELS (Biggs et al., 2015)**

### 6.7.1 Study area.

Tshivhase Tea Estate is in the Limpopo Province of South Africa, specifically within the Thulamela Municipality of Vhembe District (Figure 6.5). The tea estate is made up of two farms: Tshivhase Farm located at 30.314: 30.367 E and -22.968: -22.994 S and Mukumbani Farm at 30.386: 30.437 E and -22.904: -22.940 S. A road (Route R523 connecting Thohoyandou with Makhado Town) cuts through the Tshivhase Farm, with a major portion of the farm to the south of the road, while Mukumbani Farm lies to the north. Tea production at Tshivhase Estate is rain-fed at Tshivhase Farm and supplementary irrigated at Mukumbani Farm.

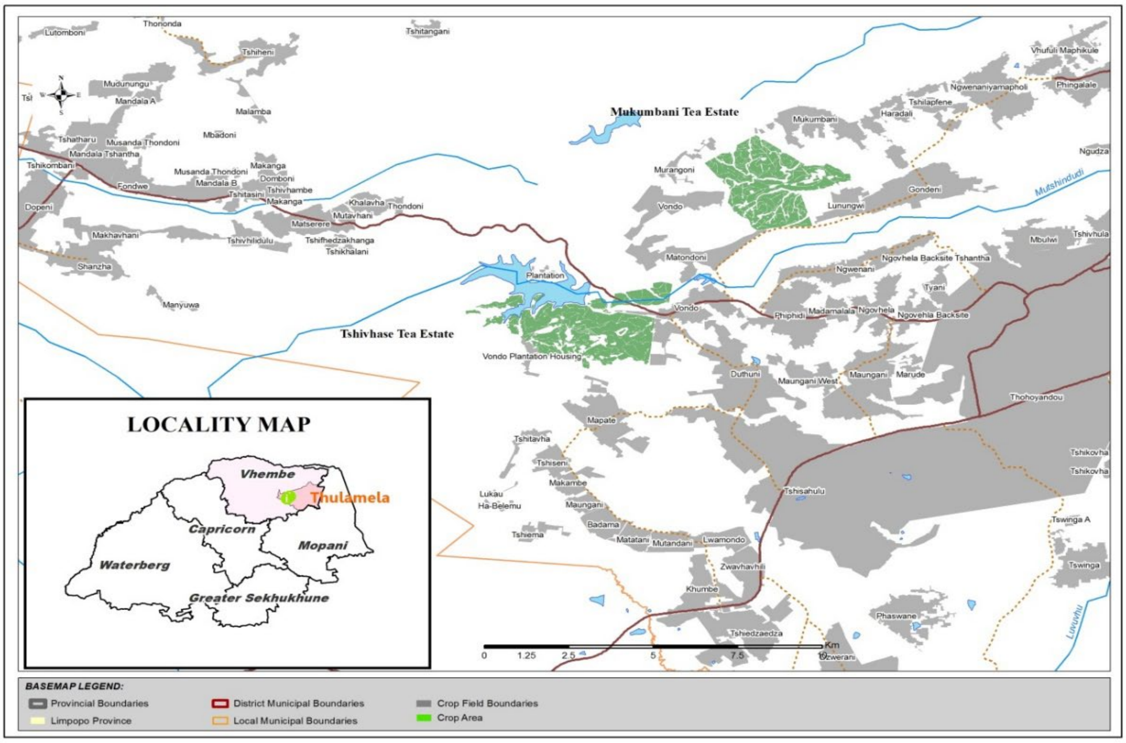


**Figure 6.5: Location of Tshivhase Tea Estate in Thulamela Municipality of Vhembe District, Limpopo Province, South Africa**
**(Source: LDARD, 2016)**

### 6.7.2 Research design.

As stated by Mouton (2001), research designs are techniques for collecting, analysing, interpreting and reporting data in research investigations. The research designs provide guidelines and instructions to be followed in addressing the research problem (Welman *et al.,* 2005); such is necessary for the usefulness of research findings in developing general conclusions on similar challenges in different geographic areas (Egbu, 2007; Yin, 1989).

Data was mainly obtained from records kept at the Tshivhase Estate (2007-2023) and that included rainfall, green leaf (GL) yield, quantity and quality of made tea (MT), moisture loss, wood and electricity used in processing tea. A lot of information was also obtained through a review of literature that focused mainly on scientific journals and books. Records kept at the Tshivhase Estate provided mainly quantitative data while literature reviewed provided both quantitative and qualitative data. Quantitative data was captured and analysed through Excel spreadsheets. The data was used to generate summary tables and graphs of pertinent statistical analyses. The summary tables and graphs generated from the data were discussed based on objective interpretations (Lee, 1999; Leedy & Ormrod, 2010). Qualitative data was summarised according to content and main themes addressed and was discussed based on subjective interpretations.

## 6.8 Results water-energy-food-environment nexus

Three areas have been identified for the use of the WEF nexus, mainly as an analytical tool, a conceptual framework, and discourse (Keskinen et al., 2016). The main emphasis of the report will be on an **analytical tool.** That is a nexus analysis that systematically uses quantitative and/or qualitative methods to understand the interactions among water, energy, and food systems. In this scenario, it will be a factory analysis in the main. However, the WEF nexus is also used as a **conceptual framework.** The nexus approach leverages an understanding of WEF linkages to promote coherence in policymaking and enhance sustainability. Lastly, as a **discourse**, the nexus concept can be used for problem framing and promoting cross-sectoral collaboration (Keskinen et al., 2016).

### 6.8.1 The conceptualized model

The conceptual framework for ELS which combines concepts of the water-energy-food-environment nexus with the natural capitals of the sustainable livelihood's framework is shown in Figure 6.7. Timber in this model is the main base on which there should be livelihood security. The water component is mainly supplied through rain surface water. The energy is supplied by electricity, wood from timber – mainly Eucalyptus. The food component is the production of tea (black, green and botanical extracts). Livelihood pressures include population growth and urbanization which create a demand for made tea. The environmental pressures include climate change and natural disasters. In context, the tea industry has continued to expand, coupled with a critical need to improve the energy utilization required to produce tea. The following factors have a contribution: (a) the energy utilization in the tea sector has increased in recent years and will continue to do so, due to a growing global tea consumption and an increasing production capacity, (b) the environmental impact; the increasing use of firewood will result in severe deforestation, (c) rapid population growth will increase the demand for firewood and (d) the electrical power is expensive and becoming unreliable in South Africa and many developing tea producing countries.

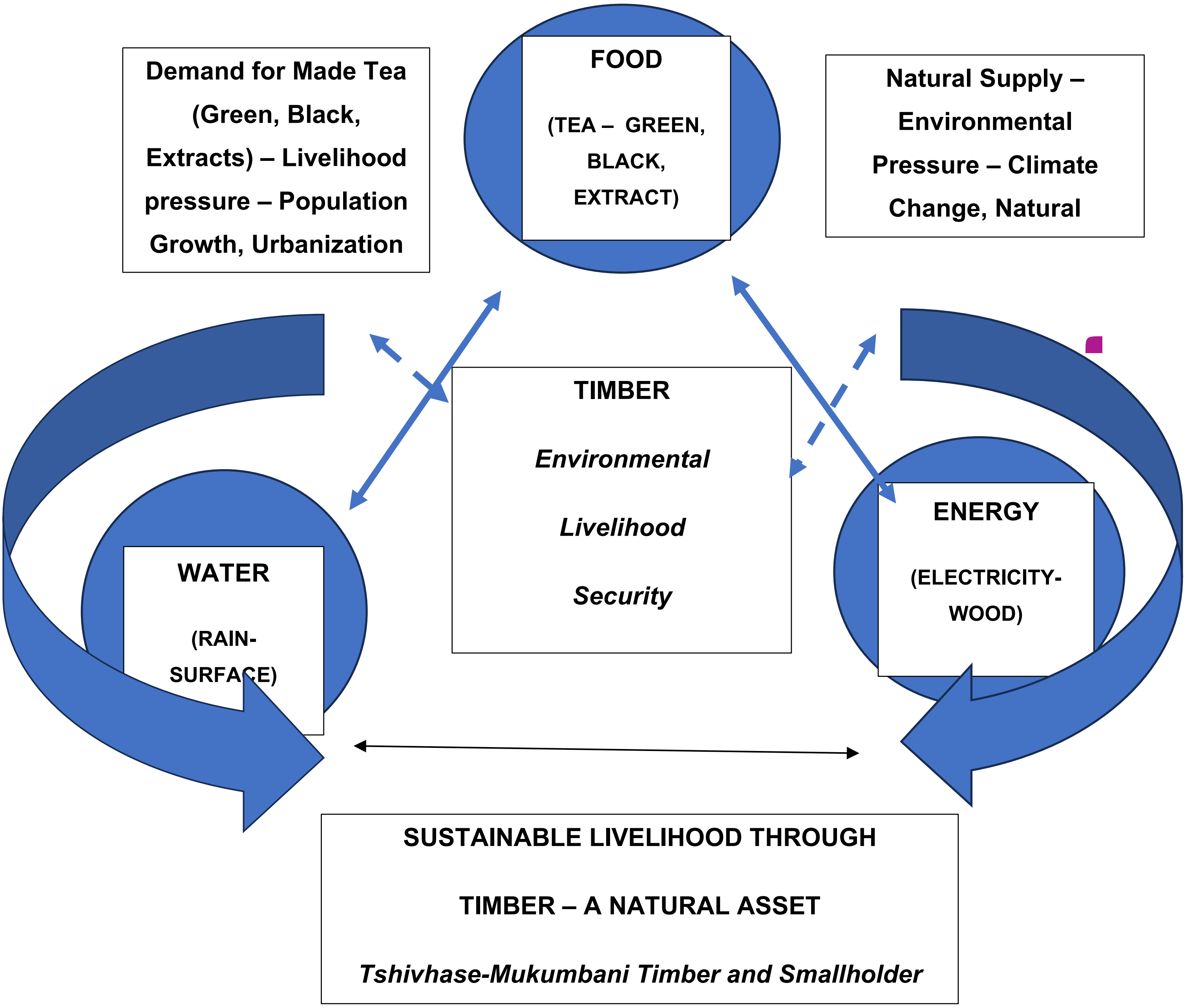


**Figure 6.7: The conceptual framework for environmental livelihood**

## 6.9 Seasonal variations of major attributes of W-E-F-E nexus

This section reports the seasonal variations in major attributes of the water-energy-food-environmental nexus. The model has been explained in section 5.1. which articulates the base of the Environmental Livelihood Security as a concept. In our model in the context of tea production, the environmental component is represented in the main wood of eucalyptus timber. This has been supplied from its own production at the Tshivhase-Mukumbani estates. To enhance community sustainability, there were seasons when the timber was supplied by a community of smallholder timber producers. This section will, for our purposes, only focus on the amount and energy generated from timber.

In a separate chapter, the matter of water has been dealt with fully. In this deliverable, the concept of water will be focused on moisture loss in tea processing. The energy components consist of electricity and energy generated from timber – or wood. For purposes of this work, wood energy is not normally quoted in kWh, but is expressed in kWh to give a total energy consumption in electrical equivalent. The food component will be the made tea in the main, though there will be a separate chapter focusing on the green and botanical extract products.

Figure 6.8 shows the total green leaf (kg), total made tea (kg), moisture loss (kg) and electrical usage (kWh) per month of tea production. The total green leaf (kg), total made tea (kg), moisture loss (kg) and electrical usage (kWh) increased in varying scales from the first month of production in September to the peak in December, then decreased per month to the end of the season in May.

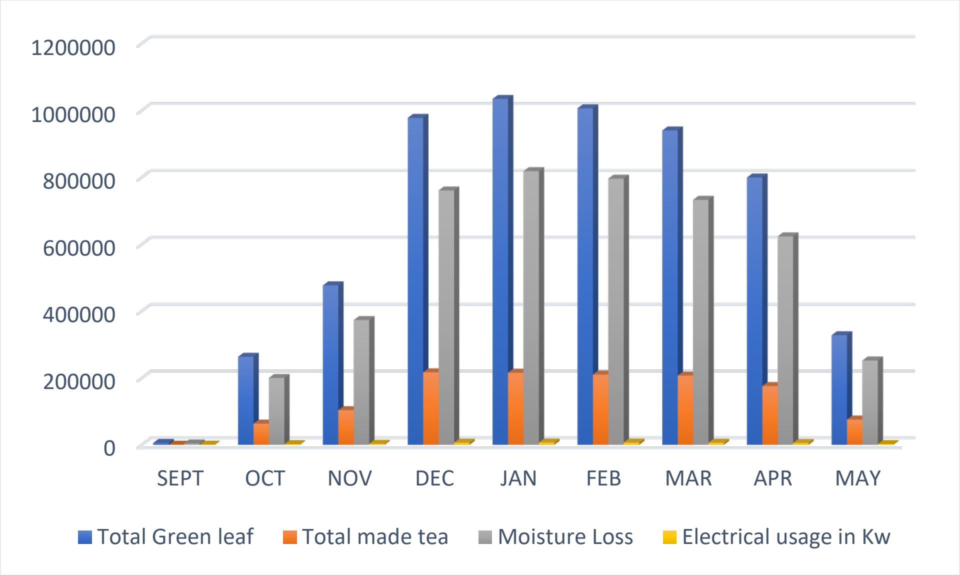


**Figure 6.8: Total green leaf (kg), total made tea (kg), moisture loss (kg) and electrical usage (kWh) per month of tea production**

Figure 6.9 indicates the energy in kWh from the wood used and electrical usage in Kw per month of tea production. The amount of energy in kWh used in tea production increased from October at 12 262 610.64 Kw to 88 749 807.51 in February, decreasing every month to May. Electricity usage also took a similar trend but a peak in January with 6942.13. The trend of wood used in kilogram was similar to the estimate of energy in kWh generated from wood. In a study done by Kumar and Pou (2016), the total energy consumption in tea manufacturing was found to be 4.2-8.5 kWh/kg of made tea. Thus, the total energy consumption (5 kWh/kg of tea) for manufacturing 1 197 million kg of tea from 564 000 ha tea plantation in India (during 2014-2015) was 5.985×109 kWh.

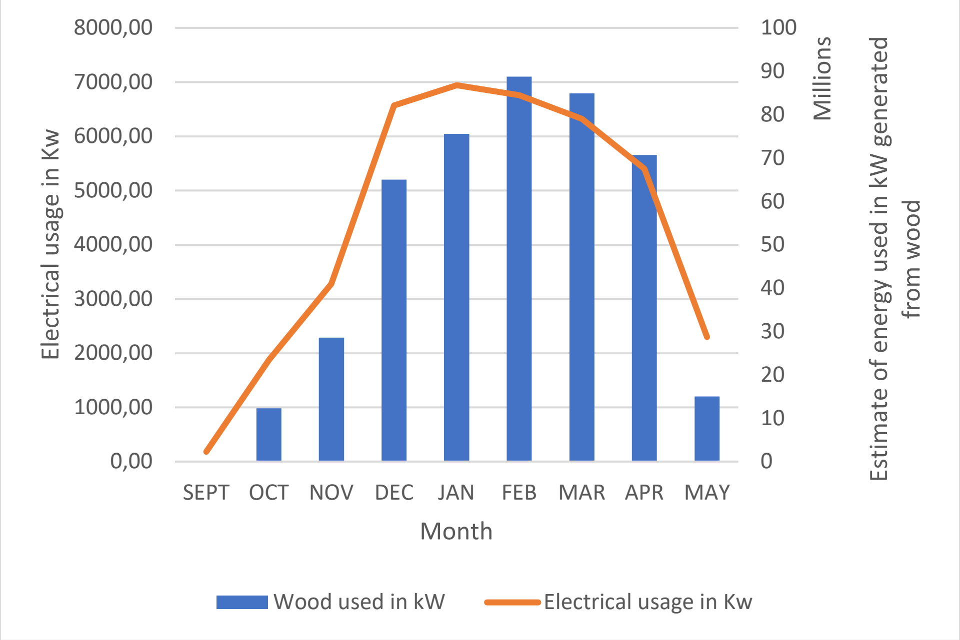


**Figure 6:9 Energy in (kWh) from wood used and electrical usage (kWh) per month of tea production**

## 6.10 Trends of major attributes of W-E-F-E nexus

Figure 6.10 demonstrates the trend of total green leaf production decreasing over 17 years. The variation in total leaf production (41%) could be well explained by differences in years. However, the total leaf production increased from 2007 to the highest level of 7 264 260 kg in the year 2011 to a sudden decrease in 2012. This was followed by another sharp increase in 2014 and then a decrease over the years to 2023.

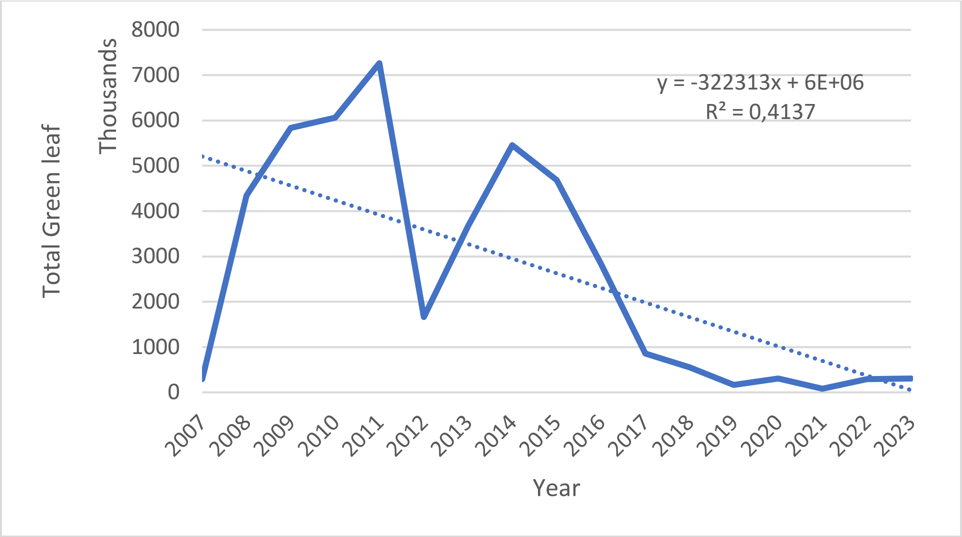


**Figure 6.10: Trend of total green leaf in kg over the 17 years of production (2007-2023)**

Figure 6.11 demonstrates the trend of total made tea decreasing over 17 years. The variation in total made tea (41%) could be well explained by differences in years. However, the total leaf production increased from 2007 to the highest level of 1 535 292 kg in the year 2010 to a sudden decrease in 2011. This was followed by another sharp increase in 2014 and then a decrease over the years to 2023.

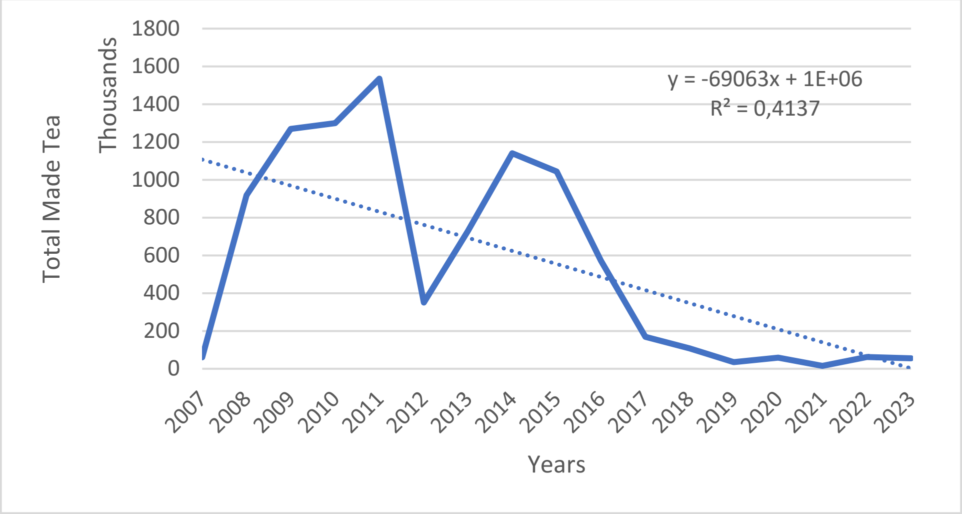


**Figure 6.11: Trend in total made tea kg over the 17 years of production (2007-2023)**

Figure 6.12 shows the trend of total made tea decreasing over 17 years. The variation in total made tea (34%) could be well explained by differences in years. The first phase of production indicates an increase from 2007 to 2011 with a moisture loss of 5 728 968 kg. Overall moisture loss increased from 2007 to the highest level of 7 729 126 kg to a sudden decrease in 2013. This was followed by a sharp decrease from 2014 over the years to 2023.

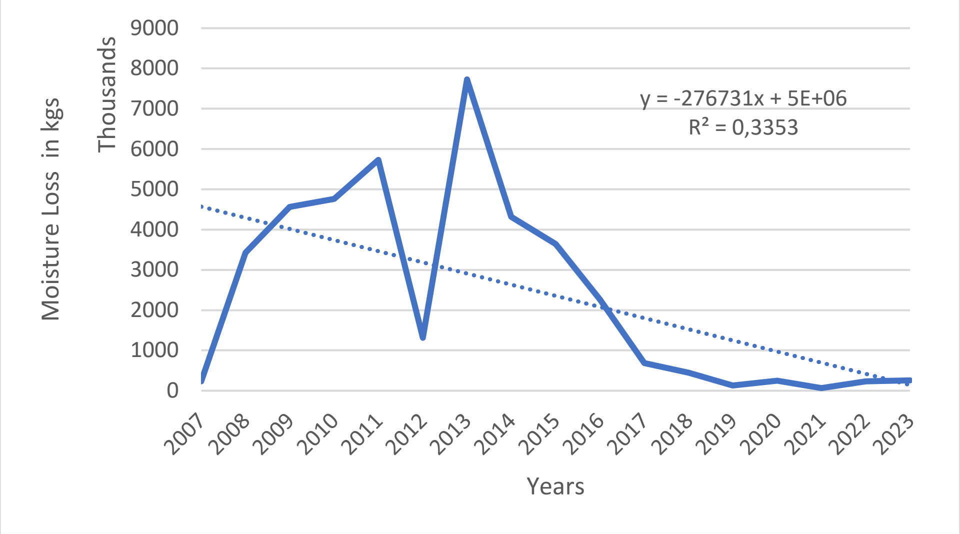


**Figure 6.12: Trend in moisture loss over 17 years of tea production (2007-2023)**

Figure 6.13 shows the trend of wood (kg) decreasing over the 17 years. The variation in total made tea (37%) could be well explained by differences in years. The first phase of production indicates an increase from 2007 to 2011 with wood used to the amount of 1 203 876.216 kg. Also, there was a sharp decrease in 2012 to an increase in 2014 of 901 074.48 kg of wood used. This was followed by a sharp decrease from 2014 over the years to 2023. The study done by Irakoze (2017) reported that in 2015, the annual tea production at the Ijenda factory was 1 891 952 kg and the **annual wood usage** was about 2 666 805 kg. Comparable research was done by Taulo and Sebitosi (2015), who indicated that green leaf consumption in the studied factories ranged from 4.19 to 6.33 kg green leaf/kg made tea (MT), with an average of 4.96 kg per kg of made tea.

Their study also compared 4.5 and 4.66 kg of green leaf for tea factories in Kenya and Sri Lanka, respectively. Average wood consumption in Malawian tea factories is 3.35 kg/kg made tea and specific water consumption ranges from 1.92 to 8.32 kg/kg MT.

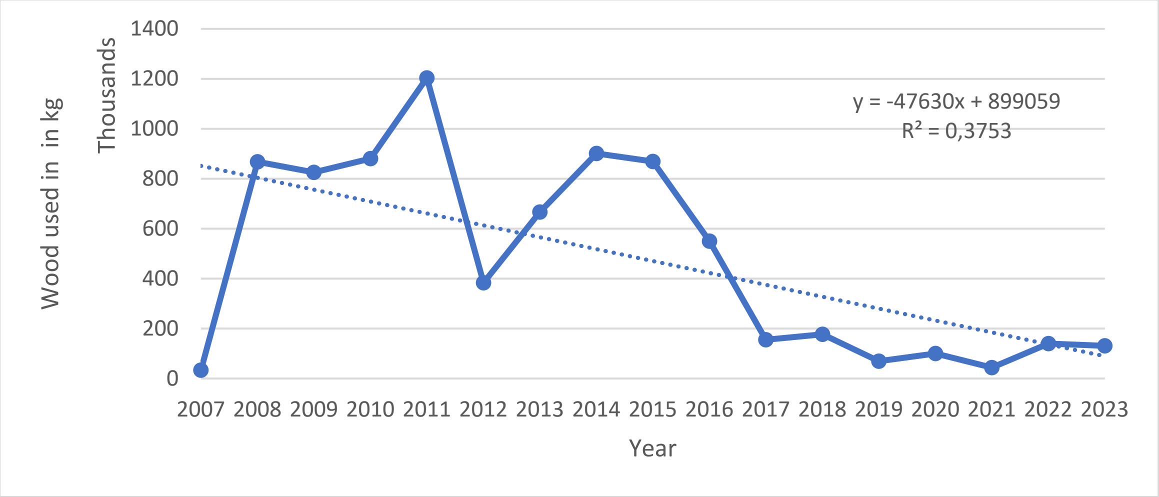


**Figure 6.13: Trend of wood used (kg) over the 17 years of tea production (2007-2023)**

Figure 6.14 shows the trend of energy used from wood (kWh) decreasing over the 17 years. The variation in total made tea (35%) could be well explained by differences in years. The first phase of production indicates an increase from 2007 to 2011 with energy used from wood to the amount of 863 881 872.6 kg. Also, there was a sharp decrease in 2012 to an increase in 2014 of 540 555 223.5 kg of energy used from wood. This was followed by a sharp decrease from 2014 over the years to 2023.

In the work done by Kumar et al. (2021), assuming a specific fuel wood consumption of 1.5 kg of fuel wood per kg of made tea, the estimated consumption of fuel wood by the tea industry was about 489 000 tons per year, approximately 1.7 million m$^3$. Of the total fuel wood demand for processing, (about 60% – which was 293 000 tons per year), was accounted for by bought-leaf factories.

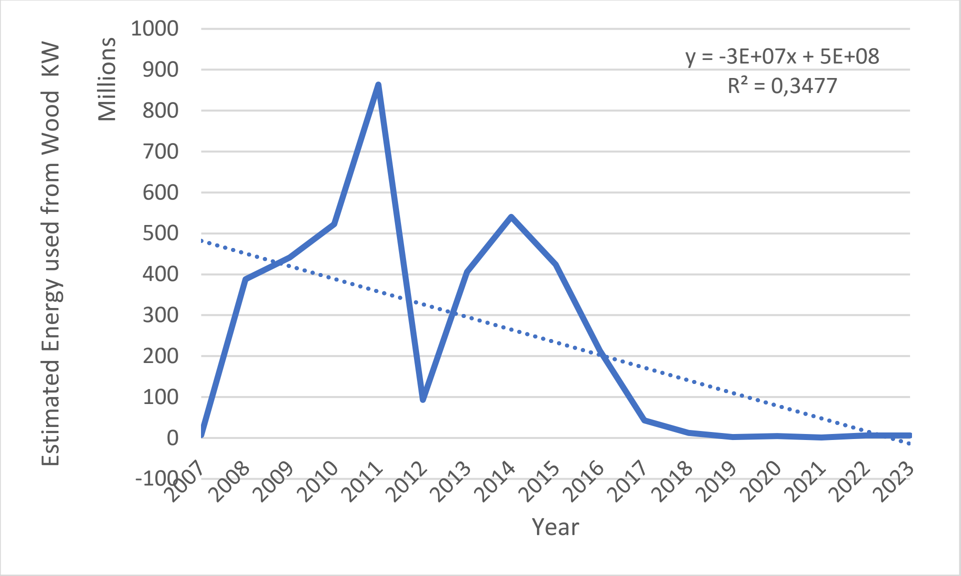


Figure 6.14: Trend of energy used from wood (kWh) over the 17 years (2007-2023)

## 6.11 Relationship of major attributes of W-E-F-E nexus

Figure 6.15 shows the relationship between energy from wood (kWh) and total made tea (kg). The correlation between energy used from wood and made tea was high ($R^2 = 0.94$). The amount of energy used from wood increased with the amount of made tea. The rate of increase was 475.65 per thousand kg of made tea.

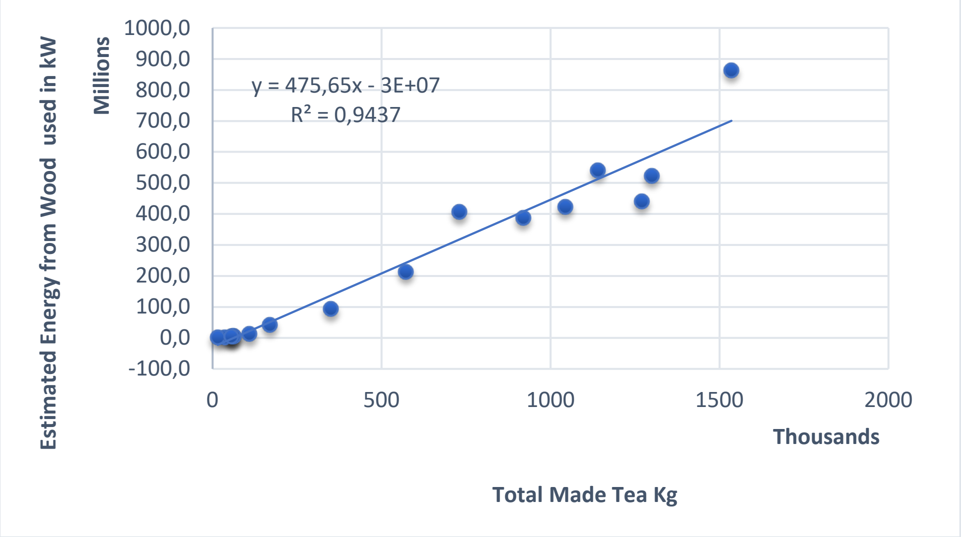


Figure 6.15: Relationship between energy from wood (kWh) and total made tea (kg)

Figure 6.16 shows the relationship between electrical usage (kWh) and total made tea (kg). The correlation between electrical usage and made tea was very high ($R^2 = 0.99$). The amount of electrical usage increased with the amount of made tea. The rate of increase was 0.031 per thousand kg of made tea.

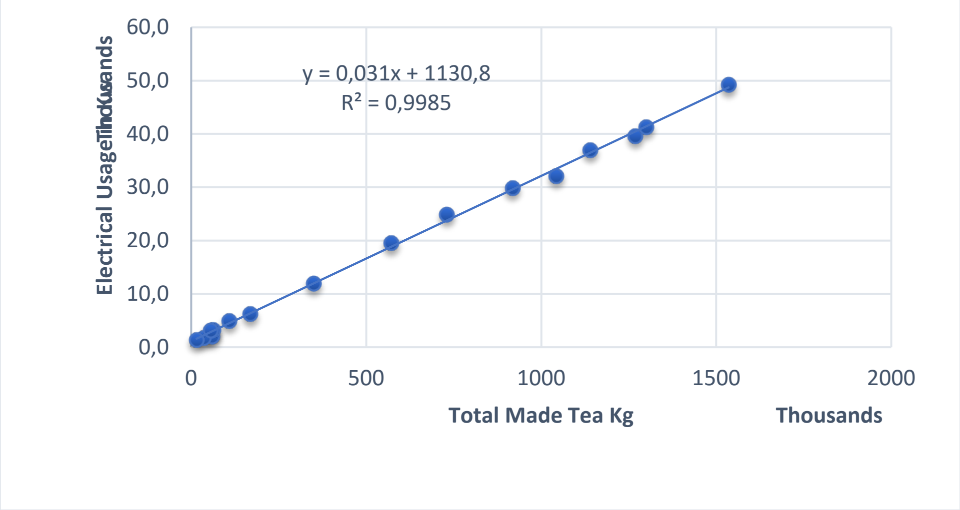


Figure 6.16: Relationship between electrical usage (kWh) and total made tea (kg)

Figure 6.17 shows the relationship between moisture loss (kg) and estimated energy from wood (kWh). The correlation between moisture loss (kg) and estimated energy from wood (kWh) was high ($R^2 = 0.79$). The amount of moisture loss (kg) increased with the energy from wood. The rate of increase was 0.0081 per unit of energy from wood.

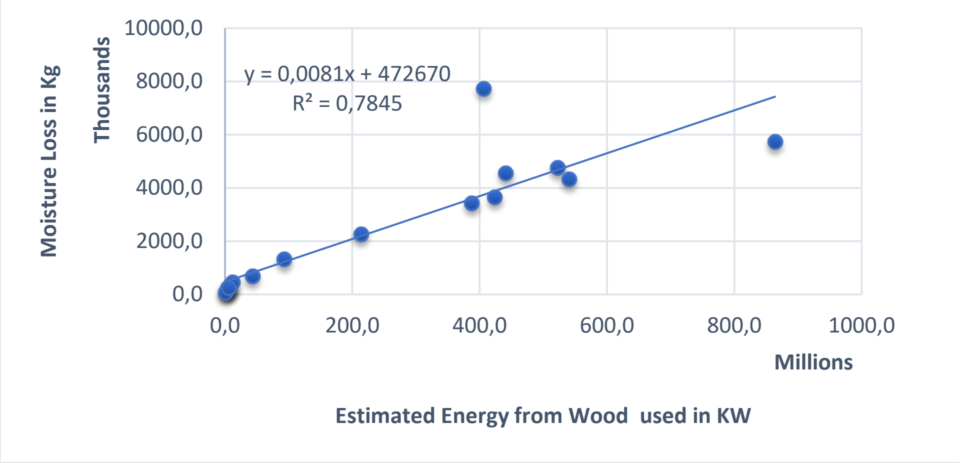


Figure 6.17: Relationship between moisture loss (kg) and estimated energy from wood (kWh)

Figure 6.18 shows the relationship between moisture loss and electrical usage (kWh). The correlation between moisture loss and electrical usage and made tea was high ($R^2$ = 0.76). The amount of moisture loss increased with the amount of electrical usage. The rate of increase was 125.21 per unit of electrical usage in kWh.

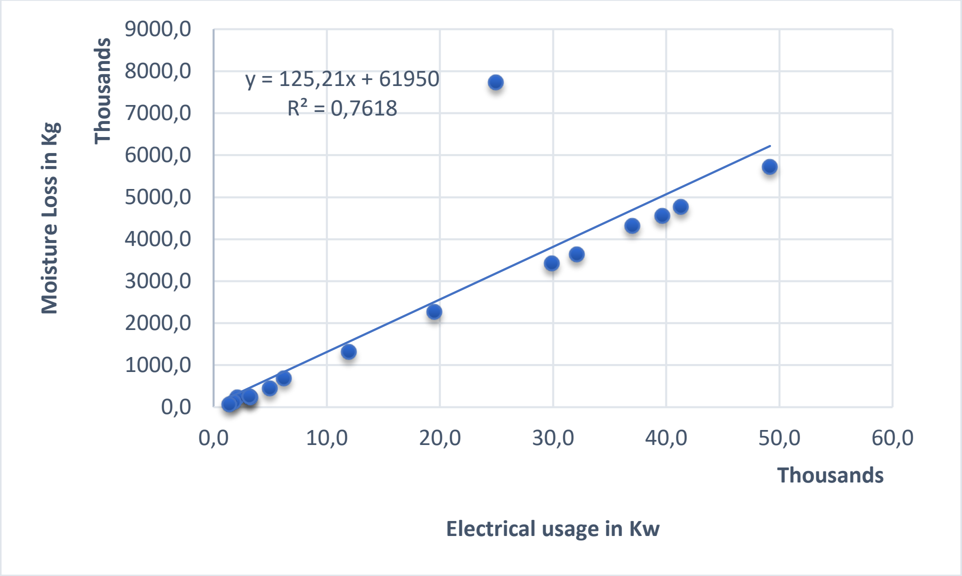


**Figure 6.18: Relationship between electrical usage (kWh) and total made tea (kg)**

## 6.12 Conclusions

The eradication of poverty is the predominant target of the United Nations as per the Sustainable Development Goals (SDG). Sustained poverty eradication is also a key goal of sustainable livelihood approaches in recognition that ensuring the livelihoods of communities is central to breaking the poverty cycle. Water, energy and food security are significant pivotal elements to decrease poverty, by safeguarding enough resources for sustaining and improving livelihoods in equitable ways. It is crucial that we simultaneously preserve ecosystems for sustaining healthy natural environments and ecosystems through the provision of services for livelihoods (MEA, 2005). Energy accounts for about 30% of the tea processing factories' operational costs, with electricity accounting for 17%. At least 70% of the tea factories rely on wood-fired steam boilers to generate heat. According to the Kenya Tea Development Agency (KTDA), the reliance on wood fuel has helped the factories to save up to 60% of energy use when compared to the use of furnace oil.

Therefore, the plan for tea processing factories should be to acquire land with exotic trees for wood fuel, which should be coupled with land for indigenous trees for conservation. In the context of Tshivhase-Mukumbani Tea Estate, a collaboration between smallholder timber producers should be fostered to enhance livelihood security for these communities. This will be an opportunity for smallholder timber farmers to earn extra income. There is also a need to focus on alternative energy sources for tea processing such as solar, and wind energy. The Tshivhase-Mukumbani Estate is still grid-connected to electricity. However, the petroleum-based fuels to supply energy for tea processing to the tea factory have become very expensive. The use of timber for energy was intensive for the tea estates – though from their own timber farm. The negative impacts of the use of timber in addition to domestic wood requirements may lead to more trees being harvested for fuel, leading to reduced forest cover – an environmental sustainability issue. This will be a threat to the sustainability of wood as a source of energy and also poses a challenge to environmental conservation as it may result in increased soil erosion and associated risks of reduced water quality.

# Chapter 7 ASSESSMENT OF LONG-TERM RELATIONSHIP BETWEEN REMOTELY SENSED-DERIVED INDICES AND THE STANDARDIZED PRECIPITATION INDEX (SPI) IN THE TEA PLANTATION: A CASE STUDY OF MUKUMBANI TEA ESTATE, LIMPOPO PROVINCE

## 7.1 Introduction

Tea is the second most consumed beverage globally (after water), with an estimated 7.09 billion kg of tea consumed globally in 2023 alone (Statista, 2024). The availability of tea to support the growing global population is dependent upon optimal tea growth conditions and minimal environmental hazards, such as drought and floods.

Sadly, the persistent rate of climate change continues to threaten the ideal growth and sustainability of tea plantation in developing countries. The tea species (*Camellia sinensis*) is an evergreen woody shrub that is cultivated mainly in the tropical, subtropical and the Mediterranean climatic zones of the world (Das et al., 2021; Hajiboland, 2017). As a rainfed crop, tea production is highly affected by changes in soil moisture availability, temperature, and any sudden environmental stress. For example, it has been reported in some previous studies that high-temperature stress can result in a reduction of chlorophyll content in plant leaves, causing detrimental effects on photosynthesis in tea plants and, in severe cases, causing irreversible damage to photosynthetic protein (Chen et al., 2022).

One of the measures for assessing moisture availability or lack thereof is an index called the standardized precipitation index (SPI). The SPI describes the amount of precipitation over a certain period in a normalized scale. It has been widely used for the detailed assessment of drought conditions by many recent and former researchers (Goheer et al., 2023; Mlenga et al., 2017; McKee et al., 1993). For example, Parida et al. (2023) applied remote sensing techniques to evaluate the dynamics of tea plantations in Assam in India. Additionally, Thi et al. (2023) characterized the spatiotemporal drought pattern and its vegetation responses in North-West Africa for the years between 1981 and 2020. In this study, it was found that the SPI-3 showed the highest correlation with the vegetation response to drought, especially in dry season. The seasonal variations of SPI are largely attributed to the seasonal precipitation patterns and the groundwater table. Therefore, it becomes necessary to correlate the SPI with the vegetation parameters and temperatures to aid our understanding of the potential impact of climate variability on tea plantation.

Satellite remote sensing has been used as an alternative and reliable approach to quantify drought hazards in different regions of the world. For example, the spectral indices such as the Normalized Difference Vegetation Index (NDVI), the normalized difference water index (NDWI), the land surface temperature (LST) and vegetation condition index (VCI) have been used widely to quantify drought effects across different seasons and years (Al Shoumick et al., 2023; Karnieli et al., 2010). In these studies, correlations were made between the remotely sensed-derived indices and drought sensitivity of a given area, with such correlations made under primarily meteorological and agricultural drought categories (Thi et al., 2023).

However, studies on the spatiotemporal variations of the SPI in the tea plantation are very limited, owing to the geographic location of countries where *C. sinensis* is optimally grown (Tibpromma et al., 2021). Given this background, this study aimed to assess the long-term relationship between the SPI and optical remotely sensed-derived indices along the seasonal gradient in the Mukumbani Tea Estate in South Africa.

## 7.2 Methods

### 7.2.1 Study area.

The study was conducted on Mukumbani Tea Estate which is located in the northern part of South Africa. The estate is located at the geographic coordinates of 30.408366° E and 22.917606° S in the Thulamela local municipality, in the subtropical environment, which receives an annual rainfall of about 1 758 mm (Nesamvuni et al., 2021). The Mukumbani tea estate receives much of its rainfall during summer (November to February), while the lowest rainfall is usually observed in winter months (June to August) (Durowoju et al., 2019). The study area is situated at an elevation of approximately 806 m (Figure 7.1).

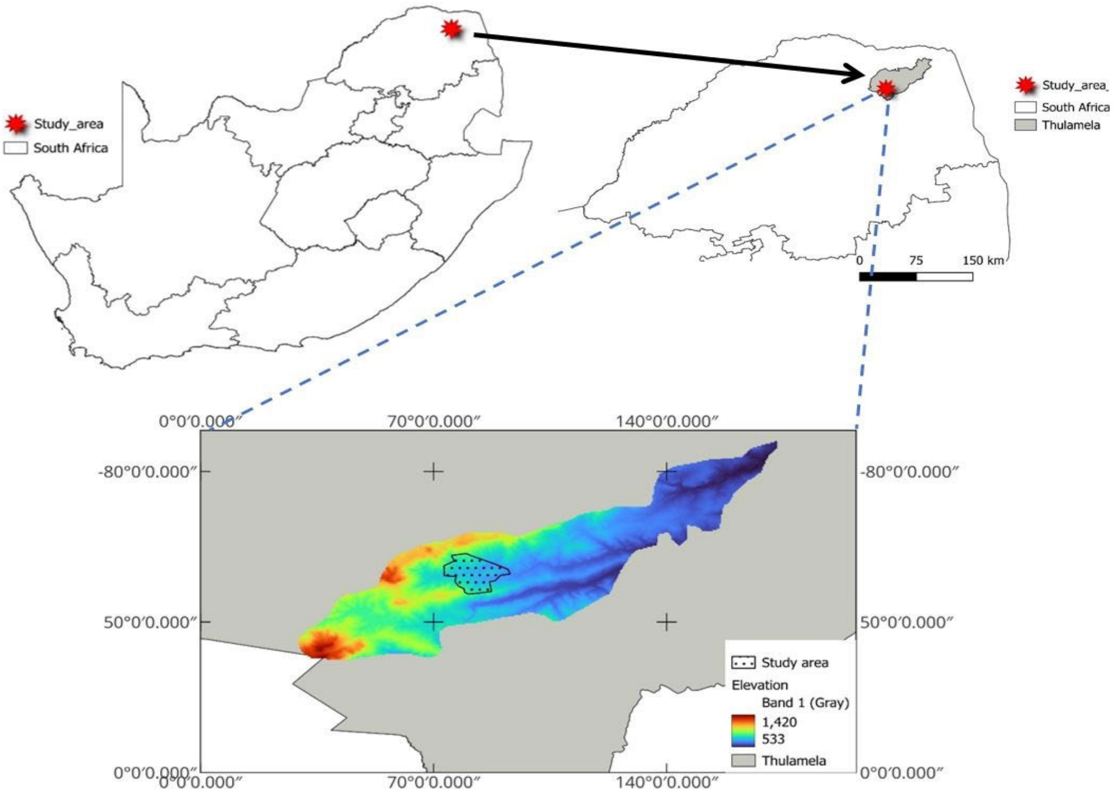


**Figure 7.1: Location of the study area in Limpopo province, South Africa**

### 7.2.2 Data acquisition

#### *7.2.2.1 Temperature and SPI data*

The temperature data was acquired from the Power Data Access Viewer which contains meteorology and solar-related parameters (https://power.larc.nasa.gov/data-access-viewer/). The drought pattern was analysed using the Standardized Precipitation Index (SPI). The SPI is one of the most widely used indices for assessing the magnitude and duration of drought events developed by Mckee et al. (1993) (Senamaw et al., 2021). The SPI was determined using annual precipitation data from the 1987-2022 period obtained from the Power Data Access Viewer. The equations (1) and (2) were used to derive the SPI (Khosrvi et al., 2017):

$$SPI = \frac{\mathrm{p}_i - \mathrm{p}}{\mathrm{S}}$$ eq. (1)

and

$$S = \sqrt{\frac{\sum_1^i (p_i - p)^2}{n}}$$ eq. (2)

where: $\mathrm{p}_i$ rainfall of the given period, S= standard deviation, $p$ =average rainfall of the period, and *n* = number of data in a single period.

### *7.2.2.2 Satellite data acquisition and pre-processing*

Landsat imageries were used in this study. Traditionally, the Landsat sensor has a spatial resolution of 15 m (panchromatic), 30 m (multispectral), and 100 m thermal bands. The satellite imagery was obtained from the United States Geological Survey's Earth Explorer website (https://earthexplorer.usgs.gov/ ). For this study, only the 30 m multispectral bands were utilized to assess possible association with the climatic variables and trends.

The spectral bands used included the red (0.66 µm), the near-infrared (0.80 µm), and the shortwave infrared (1.65 µm) used to derive the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI). Table 7.1 shows the computations of the indices.

**Table 7.1: Selected vegetation indices derived from Landsat data**

| Index | Equation | References |
|---|---|---|
| NDVI | $\mathrm{NDVI} = \left(\frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}\right)$ | Sellers (1985) |
| NDWI | $\mathrm{NDWI} = \left(\frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}\right)$ | Xu (2006) |

### 7.2.3 Data analysis

The analysis of variance (ANOVA) was applied on each of the variables, namely. the SPI, NDVI, NDWI and temperature. The purpose of this analysis was to assess the time-series variations of these climate-vegetation variables across four seasons and to quantify potential drought event on the Mukumbani Tea Estate. The threshold of statistically significant variation of each variable was set at $p < 0.05$. The ANOVA analysis was conducted in R statistical software using the tidyverse package (Wickham et al., 2019). In addition to the ANOVA, a correlation analysis was conducted between the SPI and other variables to assess both the nature and strength of association between variables. This was undertaken using the corrplot package embedded in the R statistical software (Wei and Simko, 2021). The correlations were assessed in order to predict the SPI through Landsat-derived variables and the surface temperature.

The linear regression takes the form as indicated in equation (3):

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \beta_n x_n + \varepsilon \qquad \text{eq. (3)}$$

where $y_i$ is the output variable, $\beta_0$ is the intercept, $\beta_n$ is the estimate (coefficient) of the variable $x_n$ and $\varepsilon$ is an error term. The linear models were calibrated from seasonal datasets and the stepwise variable selection was utilized to choose the optimum variables for a given model.

The Aikaike's Information Criterion (AIC) was used to determine which variables to include in the model – in which case the model with the lowest AIC was selected as the final one (Moi et al., 2021; Yamashita et al., 2009). Mapping of potential SPI distribution was done in Quantum GIS software (QGIS Development Team, 2023).

## 7.3 Results

Figure 7.2 shows results of the SPI plotted according to seasons. The autumn SPI and winter SPI show a relatively stable trend than both summer and spring SPI. The year 2007 was characterized by very lower than normal SPI in both summer and spring months. The ANOVA results suggest that there were significant differences between the mean NDWI in autumn and in winter (*p* = 0.0084 and *p* = 0.0476 respectively) (Table 7.2).

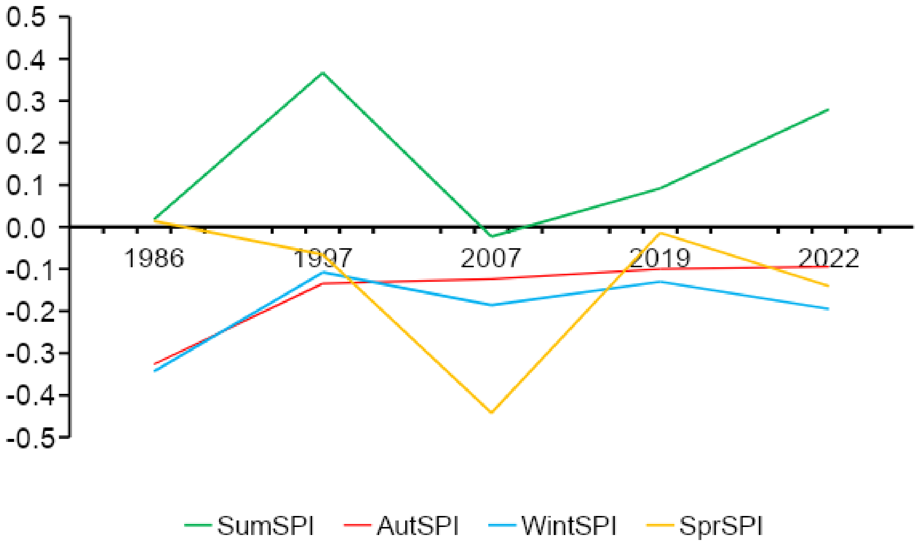


**Figure 7.2 Seasonal SPI trends over time on the Mukumbani Tea Estate**

Table 7.2: ANOVA results of the selected climate-vegetation measures

| Period | Season | SPI | NDVI | NDWI | Temperature |
|---|---|---|---|---|---|
| 1987-2022 | Summer | 0.782 | 0.419 | 0.599 | 0.284 |
| | Autumn | 0.072 | 0.644 | **0.0084 *** | 0.969 |
| | Winter | 0.322 | 0.811 | **0.0476 *** | 0.288 |
| | Spring | 0.742 | 0.111 | 0.647 | 0.323 |

Values with bold and asterisks indicate statistical significance at $p < 0.05$

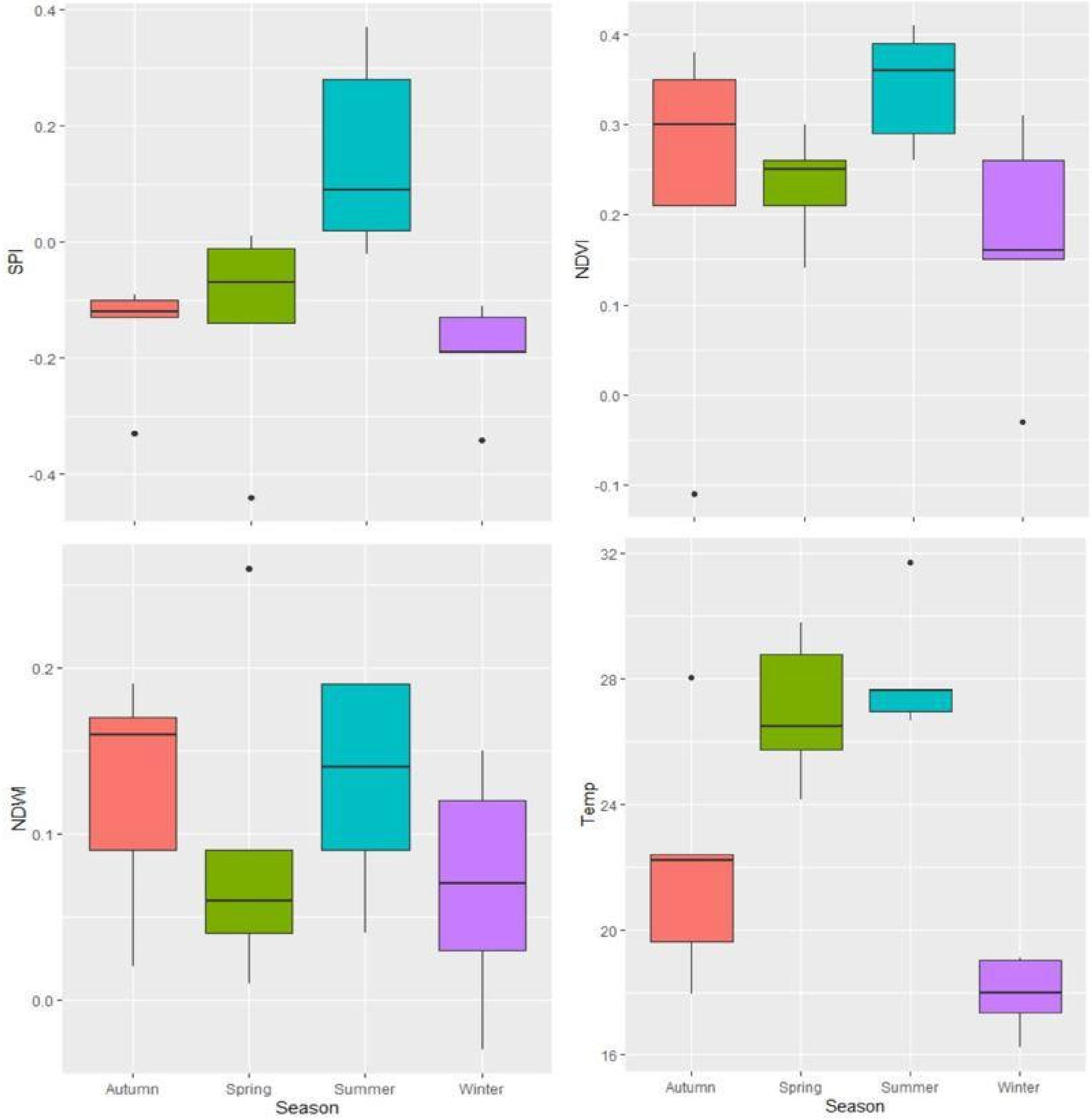


Figure 7.3: Seasonal variations of four variables. The black dots indicate the outliers.

Generally, the highest SPI values were observed for the summer months while the winter months, as expected, exhibited lower SPI values (Figure 7.3). The largest variation among the variables is observed from temperatures between summer and winter seasons, while the SPI between autumn and spring exhibited lower variation.

The seasonal correlations between the SPI and individual climate-vegetation (tea plant) variables are indicated in Figure 7.4. The autumn correlation analysis revealed that the SPI and NDWI are strongly and positively correlated in the period between 1987 and 2022 (*r* = 0.91) while the weakest correlation existed between NDVI and NDWI (*r* = 0.05). For the spring season, the NDVI and temperatures exhibited a strong and positive correlation (r = 0.94) while the strongest and positive correlation in summer was between NDVI and NDWI (*r* = 0.99). Conversely, the NDVI and temperature exhibited strong negative correlation with each other for the winter season across the study period.

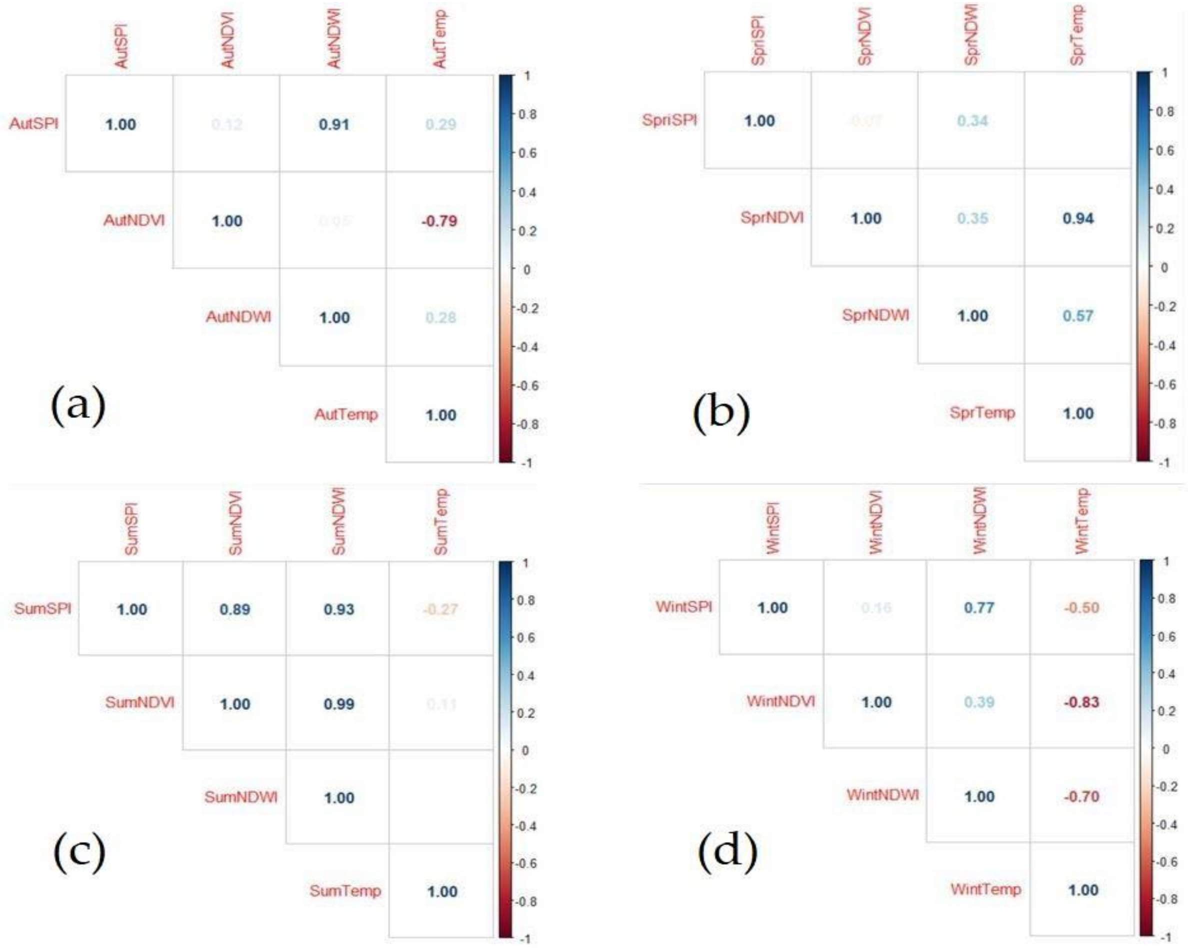


**Figure 7.4: The autumn (a), spring (b), summer (c) and winter (d) correlations between the SPI and climate-vegetation variables**

The results of the stepwise linear regression modelling are summarized in Table 7.3. The autumn SPI model was found to be the only significant one in this study (*p* = 0.032), while the highly insignificant model was found to be for the spring SPI prediction (*p* = 0.965).

**Table 7.3: Summary of regression models used in the study**

| **Season** | **Model** | **$R^2$** | **p-value** |
|---|---|---|---|
| Autumn | SPI = -0.31642 + (1.28905 * NDWI) | 0.83 | 0.032* |
| Spring | SPI = 0.95748 + (1.03437 * NDVI) + (1.12016 * NDWI) + (-0.05301 * Temperature) | 0.18 | 0.965 |
| Summer | SPI = 0.48102 + (2.41169 * NDWI) + (-0.02298 * Temperature) | 0.94 | 0.060 |
| Winter | SPI = -0.25768 + (0.96582 * NDWI) | 0.59 | 0.130 |

## 7.4 Discussion

The results of the analysis indicated that the SPI in the Mukumbani Tea Estate varies greatly between the seasons. This trend is exhibited by the differences between 1986 and 2007, even though the tea estate is located in the subtropical environment. The SPI trends in this study support the observation that in 2007, South Africa in general experienced droughts, and the Mukumbani Tea Estate was not spared this climate change effect (Verschuur et al., 2021). Interestingly, the study area did not experience extreme climatic episodes regarding any potential drought conditions (SPI <-2). In previous studies, it has been observed that the longer-term SPI between years does not generally detect extreme wet events between 0 and 1.99 (Al-Kilani et al., 2021). For shorter periods of monitoring of droughts/wetness in an agricultural field such as the Mukumbani Tea Estate, it becomes important to assess variables that relate to soil moisture changes, since these are relevant to parameters such as stream flow changes and groundwater levels (Zhao et al. 2018). The SPI has demonstrated correlations with remote sensing variables (NDVI, NDWI) and temperatures that vary with seasons. The NDWI exhibited very strong positive correlations with SPI during summer, while weaker correlations were generally observed during spring months. This is not surprising since the NDWI is a surrogate for vegetation moisture content which is directly proportional to the soil wetness, and by association, the positive SPI (Ahmad et al., 2021).

Interestingly, the winter season has shown a strong negative correlation between the SPI and temperature, which suggests that the increase in surface temperature results in decreasing levels of the SPI, and the persistent temperature increase could result in higher drought levels.

The linear models used in this study yielded no statistical significance, except for the autumn model where the NDWI was the sole predictor of the SPI. This further emphasizes the importance of assessing variables that are related to tea plantation species canopies and/or soil moisture, which could contribute immensely to our understanding of climate change in subtropical environments. Figure 7.5 shows the distribution of the SPI mapped for autumn and winter months combined between 1987-2022. The models somewhat predicted the positive SPI, and did not predict the negative SPI accurately, although in this study the negative SPI were a bit closer to a 0, indicating moderately dry conditions in the tea estate. The inability of the employed variables to map the lower SPI present a challenge, which should be looked at in the future studies that aim to explore the remote sensing datasets for the SPI and drought/wetness estimation, especially in the subtropical environment.

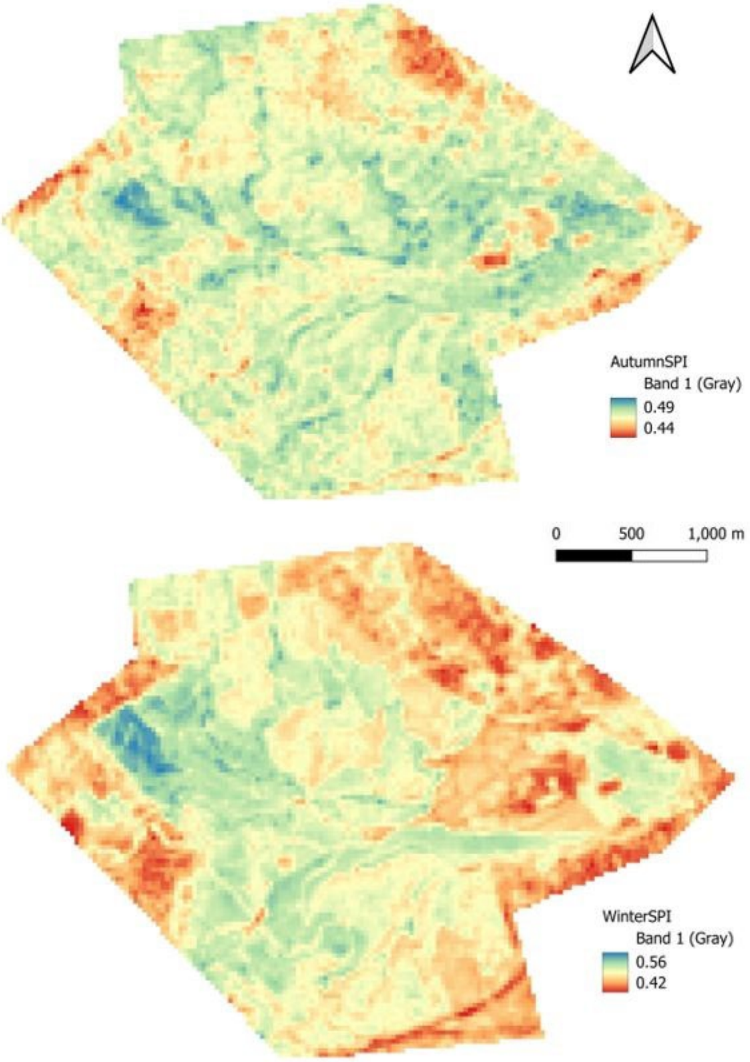


**Figure 7.5: Predicted autumn (top) and winter (bottom) SPI**

## 7.5 Conclusions

The study aimed to assess the long-term relationship between the SPI and various indices derived from optical remote sensed-derived vegetation indices. The following conclusions were drawn from the current study:

7.5.1. The NDWI was highly correlated to the autumn SPI (*r* = 0.91) throughout the study period. The highest SPI correlation was observed with the NDWI in summer (0.93). This thus emphasizes the importance of surface and vegetation moisture for quantification of drought in the tea estate.

7.5.2. The lowest correlation was observed between the SPI and temperature during spring season (r = 0.01).

7.5.3. In general, the autumn and winter NDWI were significantly different for years between 1987-2022.

7.5.4. Only the autumn model for predicting the SPI in the tea estate was statistically significant (p = 0.032) and this model incorporated NDWI as the sole predictor variable. This further emphasizes the importance of vegetation moisture as an indicator of potential drought conditions in the tea plantation.

7.5.5. The year 2007 has shown lower SPI readings, suggesting that Mukumbani Tea Estate also suffered the effects of climate change.

# Chapter 8 POLYPHENOLIC CONTECT FROM SOUTH AFRICAN GREEN TEA (CAMELLIA SINENSIS)

## 8.1 Introduction

Green tea, extracted from the unfermented dried leaves of the *Camellia sinensis* (L.) O. Kuntze plant has been consumed for centuries due to its refreshing taste, as well as its potential health benefits. However, beyond its popularity as a beverage, green tea leaves possess a wealth of phytochemical compounds that can be extracted and utilized in various products, most notably antioxidant health supplements. This study reports on the levels of various polyphenolic antioxidant components found in South African green tea from four different Mukumbani tea farm tea clones, with Tea Research Foundation (TRF) codes SFS150, PC81, SFS204, and BB35, sampled at three different times between mid-November and mid-December 2023. The components studied for the above-mentioned purpose fall into three main categories:

**Polyphenols**: The Pinnacle of Green Tea Chemistry: At the core of green tea's therapeutic properties are polyphenols, a group of plant-derived compounds rich in antioxidants. Within this category, catechins are the most important group of compounds, with epigallocatechin gallate (EGCG) standing out as the most potent. Catechins contribute not only to the distinctive bitterness of green tea but also to its health-promoting properties. Understanding the variations in catechin composition among different green tea varieties is crucial for determining the potential therapeutic benefits, such as its antioxidant properties.

**Caffeine and L-theanine**: Balancing Act in the Brew: Green tea contains significant amounts of caffeine, albeit in lower amounts compared to coffee. The interplay between caffeine and another essential component, L-theanine, is jointly partially responsible for the unique alertness and calmness experienced by green tea drinkers. While caffeine stimulates the central nervous system, L-theanine is known to induce a sense of relaxation, offering an equilibrium that gives green tea both refreshing and calming effects.

**Flavonoids**: Beyond Catechins: Beyond catechins, green tea contains a large number of polyphenolic flavonoids, a diverse class of compounds also known for their potent antioxidant properties. Quercetin, kaempferol and myricetin derivatives and glycosidebound forms are notable flavonoids found in green tea, each contributing significantly to the overall antioxidant capacity of green tea extracts.

**Other components** found in green tea are vitamins and minerals, and volatile components (chiefly terpenes) that give green tea its characteristic aroma. These were not included in the study at this stage because, although they undoubtedly add to the overall therapeutic value of green tea extracts, they are not unique to green tea, and generally have very little effect on its specific therapeutic antioxidant properties.

A key requirement for accessing the market for nutraceutical green tea extracts is to concentrate on the development of fully characterized and standardized green tea, with known (high) polyphenol content, low theaflavin, and a balanced L-theanine/caffeine content. This report, designating the polyphenol content of available South African green tea clones on Mukumbani Tea Farm thus represents the first step in this direction.

### 8.2. Method

Dried green tea samples, prepared with the sampling handling protocol provided, that specifically cancels the antioxidant reducing "browning" effects that polyphenol oxidase (PPO) has on the tea, were supplied from the Mukumbani tea plantation. An amount of 2 g of each sample was accurately weighed into a 50 ml centrifuge tube and extracted for one hour with 20 ml extraction solvent (50% methanol/50% water containing 1% formic acid) with vortexing and ultrasonication.

The sample was then centrifuged to separate undissolved solids from the extract. After centrifugation, the clear supernatant was diluted 10 times more with the extraction solvent and transferred into a glass vial for HPLC-MS analysis. For each sample 1 µl was injected into the HPLC column (Waters Acquity HSS T3 2.1 x 150 mm, 1.8 µm) and subjected to gradient elution, starting with water (containing 0,1% formic acid), gradually changing to 44% acetonitrile (also containing 0,1% formic acid) over a period of 13 minutes, and finally washing the column to remove all of the sample with 100% acetonitrile (also containing 0,1% formic acid). The column flow rate was 0,3 mL/min throughout. All column effluent was led first to a Waters Acquity PDA acquiring UV absorption data from 230 to 499 nm. The UV absorption values at 272 nm were used to quantify the caffeine concentrations against a standard calibration curve. After passing through the PDA, the flow was directed to a Cyclic IMS mass spectrometer set to scan from 100 to 1 500 m/z in electrospray negative mode.

Data was collected simultaneously in Functions 1 and 2, allowing the unfragmented and fragmented mass spectra for each compound to be collected in MSe mode. Compounds measured using MS were quantified relative to a known epigallocatechin gallate (EGCG) concentration. Data was processed using MSDIAL and MSFINDER (RIKEN Center for Sustainable Resource Science: Metabolome Informatics Research Team, Kanagawa, Japan) with searching against a host of databases to yield a series of identifications for each compound, together with their peak heights and relative concentrations.

## 8.3. Results

Figure 8.1 below, shows an example of a typical TIC (total ion chromatogram) obtained by the above-mentioned HPLC analysis. Table 8.1. to Table 8.4 below, contain mg/kg (ppm) concentrations of each of the components identified in the green tea extracts of the various commercial clones of *C. sinensis* investigated. Table 8.4 lists a synopsis of the average values of each clone, as well as global average values for each component. The concentrations listed refer to the amount of these compounds in the dried plant material mass, i.e. the values already take the dilution factor from the extraction solvent into account. The most important polyphenolic compounds in the analysis are listed in bold font.

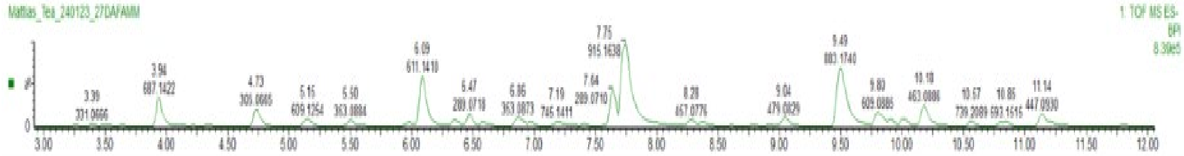
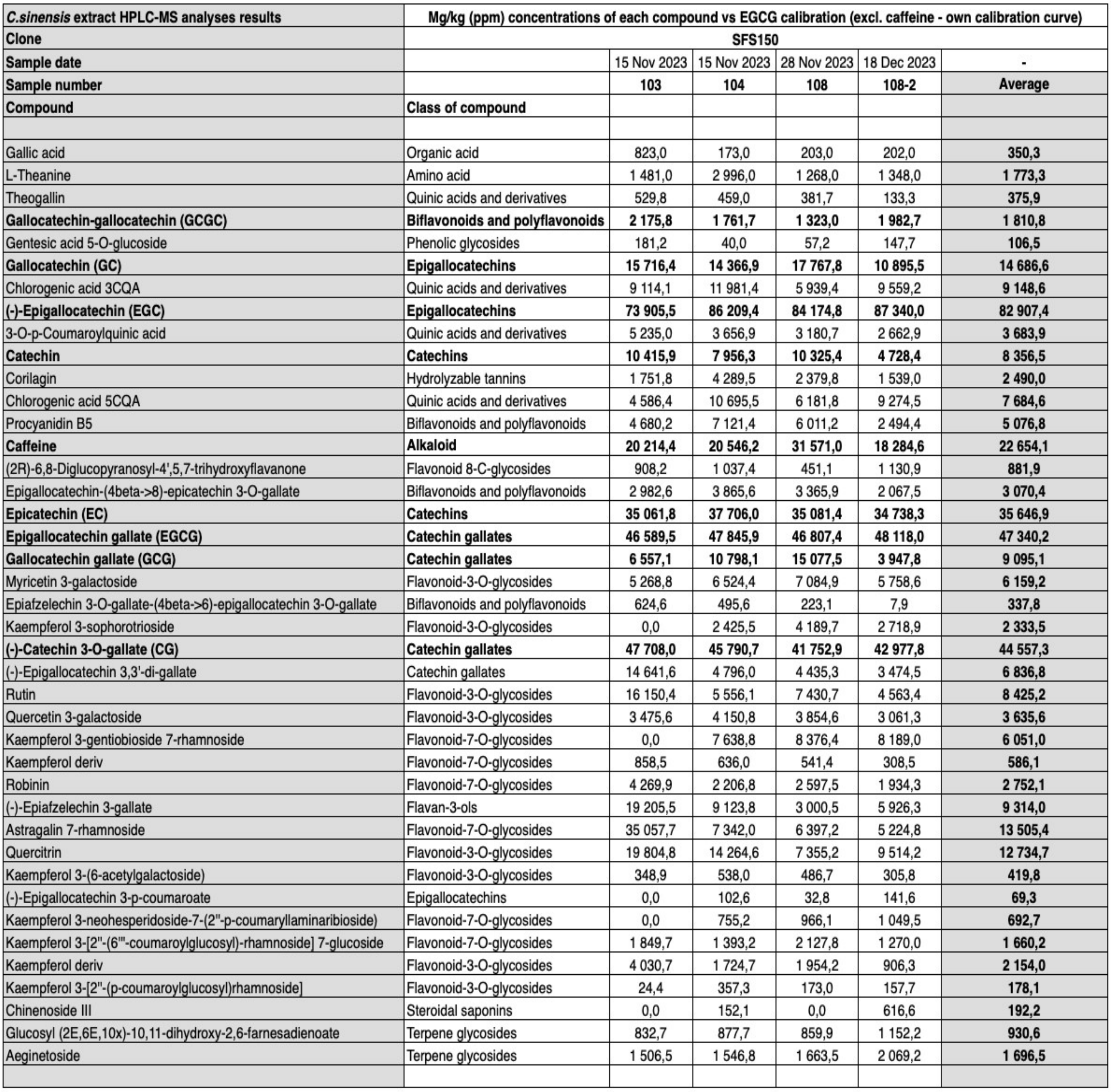


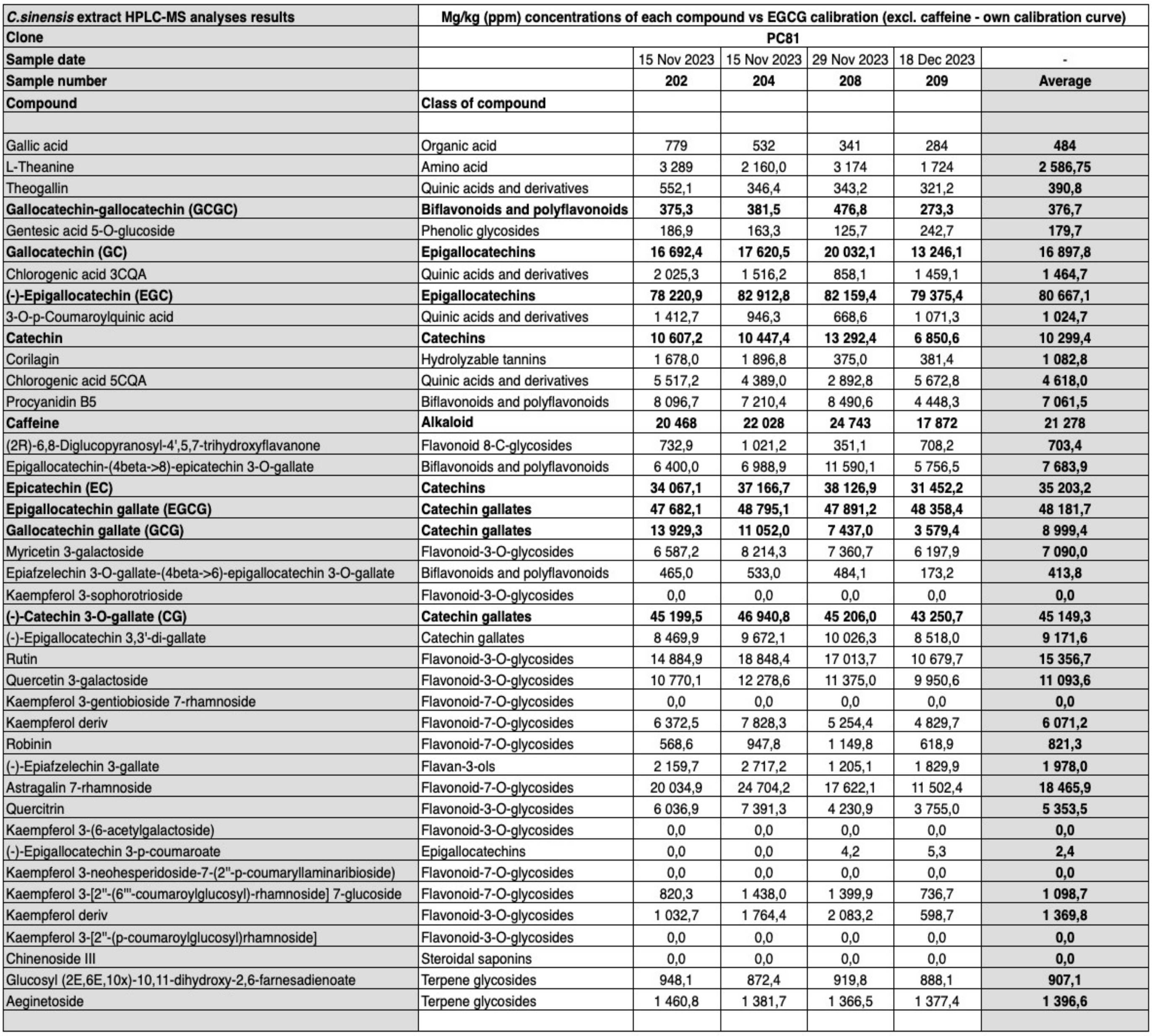
**Figure 8.1: Potential moringa products flowchart**

### Table 8.1: HPLC-MS values for compounds identified in C. sinensis clone SFS150



| ***C.sinensis* extract HPLC-MS analyses results** | **Mg/kg (ppm) concentrations of each compound vs EGCG calibration (excl. caffeine - own calibration curve)** | | | | | |
|---|---|---|---|---|---|---|
| **Clone** | **SFS150** | | | | | |
| **Sample date** | | 15 Nov 2023 | 15 Nov 2023 | 28 Nov 2023 | 18 Dec 2023 | - |
| **Sample number** | | **103** | **104** | **108** | **108-2** | **Average** |
| **Compound** | **Class of compound** | | | | | |
| | | | | | | |
| Gallic acid | Organic acid | 823,0 | 173,0 | 203,0 | 202,0 | **350,3** |
| L-Theanine | Amino acid | 1 481,0 | 2 996,0 | 1 268,0 | 1 348,0 | **1 773,3** |
| Theogallin | Quinic acids and derivatives | 529,8 | 459,0 | 381,7 | 133,3 | **375,9** |
| **Gallocatechin-gallocatechin (GCGC)** | **Biflavonoids and polyflavonoids** | **2 175,8** | **1 761,7** | **1 323,0** | **1 982,7** | **1 810,8** |
| Gentesic acid 5-O-glucoside | Phenolic glycosides | 181,2 | 40,0 | 57,2 | 147,7 | **106,5** |
| **Gallocatechin (GC)** | **Epigallocatechins** | **15 716,4** | **14 366,9** | **17 767,8** | **10 895,5** | **14 686,6** |
| Chlorogenic acid 3CQA | Quinic acids and derivatives | 9 114,1 | 11 981,4 | 5 939,4 | 9 559,2 | **9 148,6** |
| **(-)-Epigallocatechin (EGC)** | **Epigallocatechins** | **73 905,5** | **86 209,4** | **84 174,8** | **87 340,0** | **82 907,4** |
| 3-O-p-Coumaroylquinic acid | Quinic acids and derivatives | 5 235,0 | 3 656,9 | 3 180,7 | 2 662,9 | **3 683,9** |
| **Catechin** | **Catechins** | **10 415,9** | **7 956,3** | **10 325,4** | **4 728,4** | **8 356,5** |
| Corilagin | Hydrolyzable tannins | 1 751,8 | 4 289,5 | 2 379,8 | 1 539,0 | **2 490,0** |
| Chlorogenic acid 5CQA | Quinic acids and derivatives | 4 586,4 | 10 695,5 | 6 181,8 | 9 274,5 | **7 684,6** |
| Procyanidin B5 | Biflavonoids and polyflavonoids | 4 680,2 | 7 121,4 | 6 011,2 | 2 494,4 | **5 076,8** |
| **Caffeine** | **Alkaloid** | **20 214,4** | **20 546,2** | **31 571,0** | **18 284,6** | **22 654,1** |
| (2R)-6,8-Diglucopyranosyl-4',5,7-trihydroxyflavanone | Flavonoid 8-C-glycosides | 908,2 | 1 037,4 | 451,1 | 1 130,9 | **881,9** |
| Epigallocatechin-(4beta->8)-epicatechin 3-O-gallate | Biflavonoids and polyflavonoids | 2 982,6 | 3 865,6 | 3 365,9 | 2 067,5 | **3 070,4** |
| **Epicatechin (EC)** | **Catechins** | **35 061,8** | **37 706,0** | **35 081,4** | **34 738,3** | **35 646,9** |
| **Epigallocatechin gallate (EGCG)** | **Catechin gallates** | **46 589,5** | **47 845,9** | **46 807,4** | **48 118,0** | **47 340,2** |
| **Gallocatechin gallate (GCG)** | **Catechin gallates** | **6 557,1** | **10 798,1** | **15 077,5** | **3 947,8** | **9 095,1** |
| Myricetin 3-galactoside | Flavonoid-3-O-glycosides | 5 268,8 | 6 524,4 | 7 084,9 | 5 758,6 | **6 159,2** |
| Epiafzelechin 3-O-gallate-(4beta->6)-epigallocatechin 3-O-gallate | Biflavonoids and polyflavonoids | 624,6 | 495,6 | 223,1 | 7,9 | **337,8** |
| Kaempferol 3-sophorotrioside | Flavonoid-3-O-glycosides | 0,0 | 2 425,5 | 4 189,7 | 2 718,9 | **2 333,5** |
| **(-)-Catechin 3-O-gallate (CG)** | **Catechin gallates** | **47 708,0** | **45 790,7** | **41 752,9** | **42 977,8** | **44 557,3** |
| (-)-Epigallocatechin 3,3'-di-gallate | Catechin gallates | 14 641,6 | 4 796,0 | 4 435,3 | 3 474,5 | **6 836,8** |
| Rutin | Flavonoid-3-O-glycosides | 16 150,4 | 5 556,1 | 7 430,7 | 4 563,4 | **8 425,2** |
| Quercetin 3-galactoside | Flavonoid-3-O-glycosides | 3 475,6 | 4 150,8 | 3 854,6 | 3 061,3 | **3 635,6** |
| Kaempferol 3-gentiobioside 7-rhamnoside | Flavonoid-7-O-glycosides | 0,0 | 7 638,8 | 8 376,4 | 8 189,0 | **6 051,0** |
| Kaempferol deriv | Flavonoid-7-O-glycosides | 858,5 | 636,0 | 541,4 | 308,5 | **586,1** |
| Robinin | Flavonoid-7-O-glycosides | 4 269,9 | 2 206,8 | 2 597,5 | 1 934,3 | **2 752,1** |
| (-)-Epiafzelechin 3-gallate | Flavan-3-ols | 19 205,5 | 9 123,8 | 3 000,5 | 5 926,3 | **9 314,0** |
| Astragalin 7-rhamnoside | Flavonoid-7-O-glycosides | 35 057,7 | 7 342,0 | 6 397,2 | 5 224,8 | **13 505,4** |
| Quercitrin | Flavonoid-3-O-glycosides | 19 804,8 | 14 264,6 | 7 355,2 | 9 514,2 | **12 734,7** |
| Kaempferol 3-(6-acetylgalactoside) | Flavonoid-3-O-glycosides | 348,9 | 538,0 | 486,7 | 305,8 | **419,8** |
| (-)-Epigallocatechin 3-p-coumaroate | Epigallocatechins | 0,0 | 102,6 | 32,8 | 141,6 | **69,3** |
| Kaempferol 3-neohesperidoside-7-(2''-p-coumaryllaminaribioside) | Flavonoid-7-O-glycosides | 0,0 | 755,2 | 966,1 | 1 049,5 | **692,7** |
| Kaempferol 3-[2''-(6'''-coumaroylglucosyl)-rhamnoside] 7-glucoside | Flavonoid-7-O-glycosides | 1 849,7 | 1 393,2 | 2 127,8 | 1 270,0 | **1 660,2** |
| Kaempferol deriv | Flavonoid-3-O-glycosides | 4 030,7 | 1 724,7 | 1 954,2 | 906,3 | **2 154,0** |
| Kaempferol 3-[2''-(p-coumaroylglucosyl)rhamnoside] | Flavonoid-3-O-glycosides | 24,4 | 357,3 | 173,0 | 157,7 | **178,1** |
| Chinenoside III | Steroidal saponins | 0,0 | 152,1 | 0,0 | 616,6 | **192,2** |
| Glucosyl (2E,6E,10x)-10,11-dihydroxy-2,6-farnesadienoate | Terpene glycosides | 832,7 | 877,7 | 859,9 | 1 152,2 | **930,6** |
| Aeginetoside | Terpene glycosides | 1 506,5 | 1 546,8 | 1 663,5 | 2 069,2 | **1 696,5** |
| | | | | | | |

### Table 8.2.: HPLC-MS values for compounds identified in C. sinensis clone PC81



| ***C.sinensis* extract HPLC-MS analyses results** | **Mg/kg (ppm) concentrations of each compound vs EGCG calibration (excl. caffeine - own calibration curve)** | | | | | |
|---|---|---|---|---|---|---|
| **Clone** | **PC81** | | | | | |
| **Sample date** | | 15 Nov 2023 | 15 Nov 2023 | 29 Nov 2023 | 18 Dec 2023 | - |
| **Sample number** | | **202** | **204** | **208** | **209** | **Average** |
| **Compound** | **Class of compound** | | | | | |
| | | | | | | |
| Gallic acid | Organic acid | 779 | 532 | 341 | 284 | **484** |
| L-Theanine | Amino acid | 3 289 | 2 160,0 | 3 174 | 1 724 | **2 586,75** |
| Theogallin | Quinic acids and derivatives | 552,1 | 346,4 | 343,2 | 321,2 | **390,8** |
| **Gallocatechin-gallocatechin (GCGC)** | **Biflavonoids and polyflavonoids** | **375,3** | **381,5** | **476,8** | **273,3** | **376,7** |
| Gentesic acid 5-O-glucoside | Phenolic glycosides | 186,9 | 163,3 | 125,7 | 242,7 | **179,7** |
| **Gallocatechin (GC)** | **Epigallocatechins** | **16 692,4** | **17 620,5** | **20 032,1** | **13 246,1** | **16 897,8** |
| Chlorogenic acid 3CQA | Quinic acids and derivatives | 2 025,3 | 1 516,2 | 858,1 | 1 459,1 | **1 464,7** |
| **(-)-Epigallocatechin (EGC)** | **Epigallocatechins** | **78 220,9** | **82 912,8** | **82 159,4** | **79 375,4** | **80 667,1** |
| 3-O-p-Coumaroylquinic acid | Quinic acids and derivatives | 1 412,7 | 946,3 | 668,6 | 1 071,3 | **1 024,7** |
| **Catechin** | **Catechins** | **10 607,2** | **10 447,4** | **13 292,4** | **6 850,6** | **10 299,4** |
| Corilagin | Hydrolyzable tannins | 1 678,0 | 1 896,8 | 375,0 | 381,4 | **1 082,8** |
| Chlorogenic acid 5CQA | Quinic acids and derivatives | 5 517,2 | 4 389,0 | 2 892,8 | 5 672,8 | **4 618,0** |
| Procyanidin B5 | Biflavonoids and polyflavonoids | 8 096,7 | 7 210,4 | 8 490,6 | 4 448,3 | **7 061,5** |
| **Caffeine** | **Alkaloid** | **20 468** | **22 028** | **24 743** | **17 872** | **21 278** |
| (2R)-6,8-Diglucopyranosyl-4',5,7-trihydroxyflavanone | Flavonoid 8-C-glycosides | 732,9 | 1 021,2 | 351,1 | 708,2 | **703,4** |
| Epigallocatechin-(4beta->8)-epicatechin 3-O-gallate | Biflavonoids and polyflavonoids | 6 400,0 | 6 988,9 | 11 590,1 | 5 756,5 | **7 683,9** |
| **Epicatechin (EC)** | **Catechins** | **34 067,1** | **37 166,7** | **38 126,9** | **31 452,2** | **35 203,2** |
| **Epigallocatechin gallate (EGCG)** | **Catechin gallates** | **47 682,1** | **48 795,1** | **47 891,2** | **48 358,4** | **48 181,7** |
| **Gallocatechin gallate (GCG)** | **Catechin gallates** | **13 929,3** | **11 052,0** | **7 437,0** | **3 579,4** | **8 999,4** |
| Myricetin 3-galactoside | Flavonoid-3-O-glycosides | 6 587,2 | 8 214,3 | 7 360,7 | 6 197,9 | **7 090,0** |
| Epiafzelechin 3-O-gallate-(4beta->6)-epigallocatechin 3-O-gallate | Biflavonoids and polyflavonoids | 465,0 | 533,0 | 484,1 | 173,2 | **413,8** |
| Kaempferol 3-sophorotrioside | Flavonoid-3-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| **(-)-Catechin 3-O-gallate (CG)** | **Catechin gallates** | **45 199,5** | **46 940,8** | **45 206,0** | **43 250,7** | **45 149,3** |
| (-)-Epigallocatechin 3,3'-di-gallate | Catechin gallates | 8 469,9 | 9 672,1 | 10 026,3 | 8 518,0 | **9 171,6** |
| Rutin | Flavonoid-3-O-glycosides | 14 884,9 | 18 848,4 | 17 013,7 | 10 679,7 | **15 356,7** |
| Quercetin 3-galactoside | Flavonoid-3-O-glycosides | 10 770,1 | 12 278,6 | 11 375,0 | 9 950,6 | **11 093,6** |
| Kaempferol 3-gentiobioside 7-rhamnoside | Flavonoid-7-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Kaempferol deriv | Flavonoid-7-O-glycosides | 6 372,5 | 7 828,3 | 5 254,4 | 4 829,7 | **6 071,2** |
| Robinin | Flavonoid-7-O-glycosides | 568,6 | 947,8 | 1 149,8 | 618,9 | **821,3** |
| (-)-Epiafzelechin 3-gallate | Flavan-3-ols | 2 159,7 | 2 717,2 | 1 205,1 | 1 829,9 | **1 978,0** |
| Astragalin 7-rhamnoside | Flavonoid-7-O-glycosides | 20 034,9 | 24 704,2 | 17 622,1 | 11 502,4 | **18 465,9** |
| Quercitrin | Flavonoid-3-O-glycosides | 6 036,9 | 7 391,3 | 4 230,9 | 3 755,0 | **5 353,5** |
| Kaempferol 3-(6-acetylgalactoside) | Flavonoid-3-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| (-)-Epigallocatechin 3-p-coumaroate | Epigallocatechins | 0,0 | 0,0 | 4,2 | 5,3 | **2,4** |
| Kaempferol 3-neohesperidoside-7-(2''-p-coumaryllaminaribioside) | Flavonoid-7-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Kaempferol 3-[2''-(6'''-coumaroylglucosyl)-rhamnoside] 7-glucoside | Flavonoid-7-O-glycosides | 820,3 | 1 438,0 | 1 399,9 | 736,7 | **1 098,7** |
| Kaempferol deriv | Flavonoid-3-O-glycosides | 1 032,7 | 1 764,4 | 2 083,2 | 598,7 | **1 369,8** |
| Kaempferol 3-[2''-(p-coumaroylglucosyl)rhamnoside] | Flavonoid-3-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Chinenoside III | Steroidal saponins | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Glucosyl (2E,6E,10x)-10,11-dihydroxy-2,6-farnesadienoate | Terpene glycosides | 948,1 | 872,4 | 919,8 | 888,1 | **907,1** |
| Aeginetoside | Terpene glycosides | 1 460,8 | 1 381,7 | 1 366,5 | 1 377,4 | **1 396,6** |
| | | | | | | |

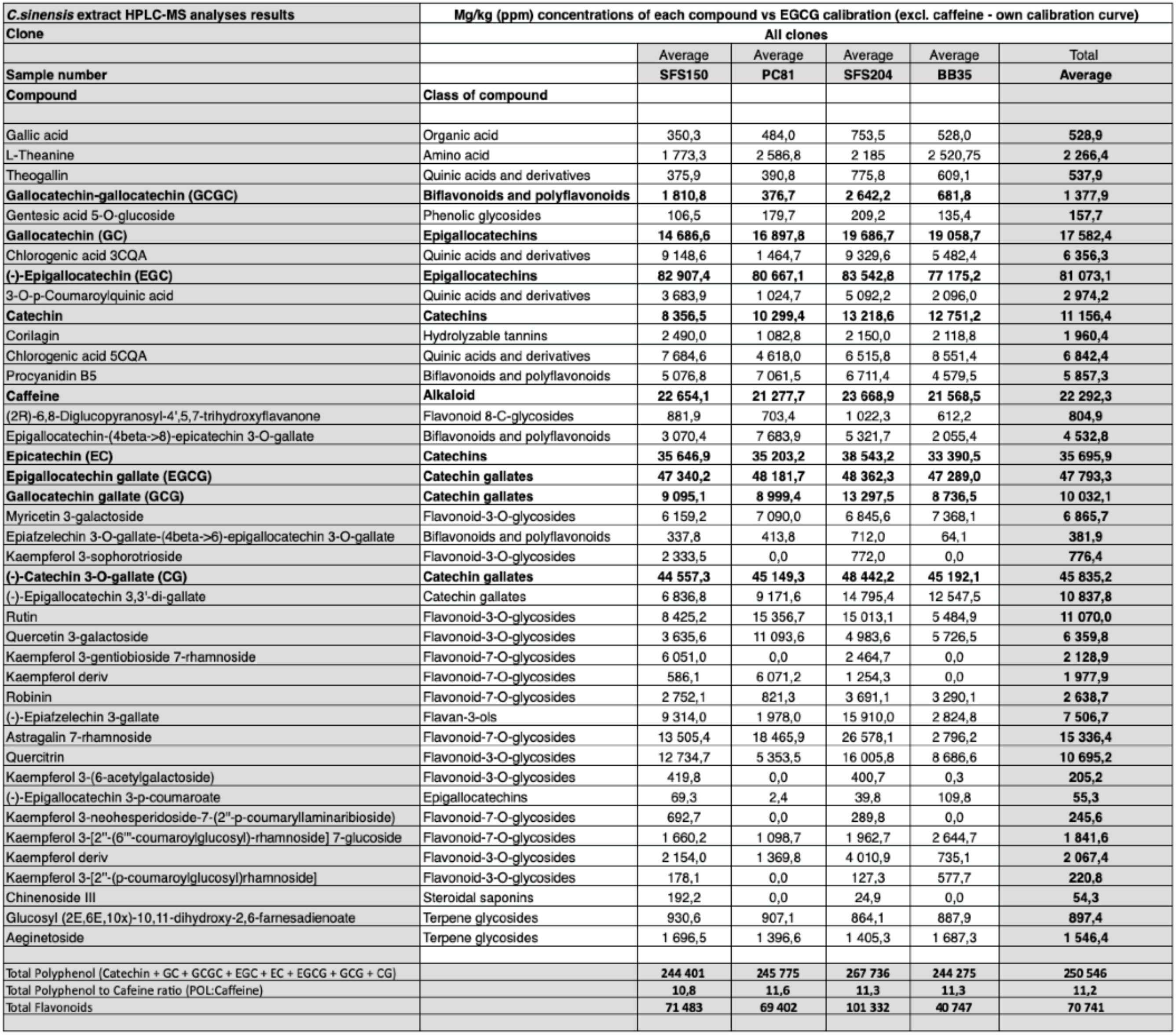
## Table 8.3.: HPLC-MS values for compounds identified in C. sinensis clone SFS204

| ***C.sinensis* extract HPLC-MS analyses results** | **Mg/kg (ppm) concentrations of each compound vs EGCG calibration (excl. caffeine - own calibration curve)** | | | | | |
|---|---|---|---|---|---|---|
| **Clone** | **SFS204** | | | | | |
| **Sample date** | | 15 Nov 2023 | 15 Nov 2023 | 28 Nov 2023 | 18 Dec 2023 | - |
| **Sample number** | | **303** | **304** | **307** | **308** | **Average** |
| **Compound** | **Class of compound** | | | | | |
| | | | | | | |
| Gallic acid | Organic acid | 832 | 1 451 | 507 | 224 | **753,5** |
| L-Theanine | Amino acid | 1 946 | 3 443 | 2 392 | 959 | **2 185** |
| Theogallin | Quinic acids and derivatives | 553,3 | 1 321,7 | 863,6 | 364,8 | **775,8** |
| **Gallocatechin-gallocatechin (GCGC)** | **Biflavonoids and polyflavonoids** | **1 848,7** | **2 853,5** | **3 023,7** | **2 842,9** | **2 642,2** |
| Gentesic acid 5-O-glucoside | Phenolic glycosides | 31,4 | 375,9 | 228,1 | 201,3 | **209,2** |
| **Gallocatechin (GC)** | **Epigallocatechins** | **14 080,6** | **23 104,9** | **22 296,8** | **19 264,5** | **19 686,7** |
| Chlorogenic acid 3CQA | Quinic acids and derivatives | 10 864,1 | 9 676,4 | 7 334,1 | 9 444,0 | **9 329,6** |
| **(-)-Epigallocatechin (EGC)** | **Epigallocatechins** | **84 810,4** | **84 941,4** | **81 696,9** | **82 722,7** | **83 542,8** |
| 3-O-p-Coumaroylquinic acid | Quinic acids and derivatives | 2 648,0 | 6 343,1 | 4 909,4 | 6 468,2 | **5 092,2** |
| **Catechin** | **Catechins** | **7 260,1** | **16 345,7** | **17 212,6** | **12 056,1** | **13 218,6** |
| Corilagin | Hydrolyzable tannins | 3 864,4 | 2 658,6 | 1 050,2 | 1 026,9 | **2 150,0** |
| Chlorogenic acid 5CQA | Quinic acids and derivatives | 7 784,7 | 7 814,6 | 3 130,1 | 7 333,7 | **6 515,8** |
| Procyanidin B5 | Biflavonoids and polyflavonoids | 3 763,0 | 10 847,3 | 6 747,0 | 5 488,3 | **6 711,4** |
| **Caffeine** | **Alkaloid** | **21 799,4** | **31 395,8** | **24 757,4** | **16 723,0** | **23 668,9** |
| (2R)-6,8-Diglucopyranosyl-4',5,7-trihydroxyflavanone | Flavonoid 8-C-glycosides | 1 222,5 | 1 427,5 | 437,0 | 1 002,1 | **1 022,3** |
| Epigallocatechin-(4beta->8)-epicatechin 3-O-gallate | Biflavonoids and polyflavonoids | 2 714,0 | 7 332,7 | 6 412,9 | 4 827,0 | **5 321,7** |
| **Epicatechin (EC)** | **Catechins** | **36 291,8** | **41 041,1** | **38 340,7** | **38 499,1** | **38 543,2** |
| **Epigallocatechin gallate (EGCG)** | **Catechin gallates** | **47 400,3** | **48 782,9** | **48 644,1** | **48 622,1** | **48 362,3** |
| **Gallocatechin gallate (GCG)** | **Catechin gallates** | **12 204,7** | **24 604,6** | **11 945,4** | **4 435,2** | **13 297,5** |
| Myricetin 3-galactoside | Flavonoid-3-O-glycosides | 7 554,5 | 7 995,1 | 6 019,9 | 5 813,0 | **6 845,6** |
| Epiafzelechin 3-O-gallate-(4beta->6)-epigallocatechin 3-O-gallate | Biflavonoids and polyflavonoids | 467,7 | 1 172,4 | 783,1 | 424,6 | **712,0** |
| Kaempferol 3-sophorotrioside | Flavonoid-3-O-glycosides | 3 088,0 | 0,0 | 0,0 | 0,0 | **772,0** |
| **(-)-Catechin 3-O-gallate (CG)** | **Catechin gallates** | **45 752,9** | **49 274,6** | **49 277,5** | **49 463,7** | **48 442,2** |
| (-)-Epigallocatechin 3,3'-di-gallate | Catechin gallates | 4 692,2 | 19 380,9 | 21 676,0 | 13 432,7 | **14 795,4** |
| Rutin | Flavonoid-3-O-glycosides | 6 457,4 | 21 562,2 | 16 827,4 | 15 205,5 | **15 013,1** |
| Quercetin 3-galactoside | Flavonoid-3-O-glycosides | 4 344,4 | 7 754,8 | 3 596,2 | 4 239,0 | **4 983,6** |
| Kaempferol 3-gentiobioside 7-rhamnoside | Flavonoid-7-O-glycosides | 9 858,8 | 0,0 | 0,0 | 0,0 | **2 464,7** |
| Kaempferol deriv | Flavonoid-7-O-glycosides | 640,8 | 3 429,7 | 352,4 | 594,3 | **1 254,3** |
| Robinin | Flavonoid-7-O-glycosides | 2 540,5 | 5 001,6 | 3 960,8 | 3 261,7 | **3 691,1** |
| (-)-Epiafzelechin 3-gallate | Flavan-3-ols | 9 449,6 | 19 769,2 | 15 290,2 | 19 131,1 | **15 910,0** |
| Astragalin 7-rhamnoside | Flavonoid-7-O-glycosides | 8 219,1 | 41 455,3 | 32 013,2 | 24 624,8 | **26 578,1** |
| Quercitrin | Flavonoid-3-O-glycosides | 15 202,0 | 22 070,3 | 14 410,9 | 12 340,1 | **16 005,8** |
| Kaempferol 3-(6-acetylgalactoside) | Flavonoid-3-O-glycosides | 672,1 | 398,5 | 350,6 | 181,7 | **400,7** |
| (-)-Epigallocatechin 3-p-coumaroate | Epigallocatechins | 110,6 | 43,2 | 0,0 | 5,5 | **39,8** |
| Kaempferol 3-neohesperidoside-7-(2''-p-coumaryllaminaribioside) | Flavonoid-7-O-glycosides | 1 159,3 | 0,0 | 0,0 | 0,0 | **289,8** |
| Kaempferol 3-[2''-(6'''-coumaroylglucosyl)-rhamnoside] 7-glucoside | Flavonoid-7-O-glycosides | 1 602,1 | 2 110,6 | 2 059,1 | 2 079,2 | **1 962,7** |
| Kaempferol deriv | Flavonoid-3-O-glycosides | 1 764,9 | 5 527,7 | 4 889,1 | 3 862,0 | **4 010,9** |
| Kaempferol 3-[2''-(p-coumaroylglucosyl)rhamnoside] | Flavonoid-3-O-glycosides | 400,6 | 97,5 | 4,8 | 6,5 | **127,3** |
| Chinenoside III | Steroidal saponins | 99,7 | 0,0 | 0,0 | 0,0 | **24,9** |
| Glucosyl (2E,6E,10x)-10,11-dihydroxy-2,6-farnesadienoate | Terpene glycosides | 858,1 | 857,1 | 860,9 | 880,1 | **864,1** |
| Aeginetoside | Terpene glycosides | 1 389,9 | 1 403,6 | 1 424,0 | 1 403,9 | **1 405,3** |
| | | | | | | |

## Table 8.4.: HPLC-MS values for compounds identified in C. sinensis clones BB35

| ***C.sinensis* extract HPLC-MS analyses results** | **Mg/kg (ppm) concentrations of each compound vs EGCG calibration (excl. caffeine - own calibration curve)** | | | | | |
|---|---|---|---|---|---|---|
| **Clone** | **BB35** | | | | | |
| **Sample date** | | 15 Nov 2023 | 15 Nov 2023 | 28 Nov 2023 | 19 Dec 2023 | - |
| **Sample number** | | **402** | **405** | **407** | **409** | **Average** |
| **Compound** | **Class of compound** | | | | | |
| | | | | | | |
| Gallic acid | Organic acid | 483 | 862 | 500,0 | 267 | **528** |
| L-Theanine | Amino acid | 2 705 | 3 248 | 2 632 | 1 498 | **2 520,75** |
| Theogallin | Quinic acids and derivatives | 570,0 | 913,1 | 541,0 | 412,5 | **609,1** |
| **Gallocatechin-gallocatechin (GCGC)** | **Biflavonoids and polyflavonoids** | **502,6** | **595,4** | **760,6** | **868,5** | **681,8** |
| Gentesic acid 5-O-glucoside | Phenolic glycosides | 88,4 | 98,4 | 85,5 | 269,4 | **135,4** |
| **Gallocatechin (GC)** | **Epigallocatechins** | **14 058,9** | **15 599,3** | **22 171,9** | **24 404,6** | **19 058,7** |
| Chlorogenic acid 3CQA | Quinic acids and derivatives | 4 533,8 | 4 955,9 | 4 623,8 | 7 816,1 | **5 482,4** |
| **(-)-Epigallocatechin (EGC)** | **Epigallocatechins** | **72 220,0** | **70 511,8** | **78 691,2** | **87 277,8** | **77 175,2** |
| 3-O-p-Coumaroylquinic acid | Quinic acids and derivatives | 1 828,3 | 1 989,2 | 1 772,4 | 2 794,0 | **2 096,0** |
| **Catechin** | **Catechins** | **8 929,7** | **9 831,1** | **14 520,5** | **17 723,2** | **12 751,2** |
| Corilagin | Hydrolyzable tannins | 2 661,0 | 2 755,4 | 1 429,8 | 1 628,9 | **2 118,8** |
| Chlorogenic acid 5CQA | Quinic acids and derivatives | 6 809,2 | 7 719,5 | 5 554,6 | 14 122,5 | **8 551,4** |
| Procyanidin B5 | Biflavonoids and polyflavonoids | 3 075,0 | 3 837,9 | 4 107,9 | 7 297,1 | **4 579,5** |
| **Caffeine** | **Alkaloid** | **19 880,6** | **21 342,7** | **21 622,1** | **23 428,5** | **21 568,5** |
| (2R)-6,8-Diglucopyranosyl-4',5,7-trihydroxyflavanone | Flavonoid 8-C-glycosides | 572,3 | 472,3 | 268,9 | 1 135,3 | **612,2** |
| Epigallocatechin-(4beta->8)-epicatechin 3-O-gallate | Biflavonoids and polyflavonoids | 1 442,1 | 1 675,1 | 1 763,5 | 3 341,0 | **2 055,4** |
| **Epicatechin (EC)** | **Catechins** | **29 763,6** | **29 409,2** | **34 317,0** | **40 072,2** | **33 390,5** |
| **Epigallocatechin gallate (EGCG)** | **Catechin gallates** | **46 672,7** | **46 893,9** | **47 302,5** | **48 286,8** | **47 289,0** |
| **Gallocatechin gallate (GCG)** | **Catechin gallates** | **4 917,5** | **13 329,3** | **9 447,4** | **7 252,0** | **8 736,5** |
| Myricetin 3-galactoside | Flavonoid-3-O-glycosides | 6 073,9 | 6 239,8 | 8 043,0 | 9 115,7 | **7 368,1** |
| Epiafzelechin 3-O-gallate-(4beta->6)-epigallocatechin 3-O-gallate | Biflavonoids and polyflavonoids | 77,1 | 99,4 | 0,0 | 80,0 | **64,1** |
| Kaempferol 3-sophorotrioside | Flavonoid-3-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| **(-)-Catechin 3-O-gallate (CG)** | **Catechin gallates** | **44 500,6** | **43 811,9** | **44 714,2** | **47 741,5** | **45 192,1** |
| (-)-Epigallocatechin 3,3'-di-gallate | Catechin gallates | 11 576,7 | 11 877,7 | 11 783,8 | 14 952,0 | **12 547,5** |
| Rutin | Flavonoid-3-O-glycosides | 5 423,7 | 5 157,0 | 5 883,3 | 5 475,6 | **5 484,9** |
| Quercetin 3-galactoside | Flavonoid-3-O-glycosides | 5 112,7 | 4 881,1 | 6 437,6 | 6 474,7 | **5 726,5** |
| Kaempferol 3-gentiobioside 7-rhamnoside | Flavonoid-7-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Kaempferol deriv | Flavonoid-7-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Robinin | Flavonoid-7-O-glycosides | 3 628,3 | 3 941,7 | 2 994,6 | 2 595,8 | **3 290,1** |
| (-)-Epiafzelechin 3-gallate | Flavan-3-ols | 2 847,2 | 2 731,5 | 2 137,1 | 3 583,3 | **2 824,8** |
| Astragalin 7-rhamnoside | Flavonoid-7-O-glycosides | 3 230,9 | 3 259,0 | 2 887,5 | 1 807,3 | **2 796,2** |
| Quercitrin | Flavonoid-3-O-glycosides | 10 174,7 | 10 174,1 | 8 088,2 | 6 309,4 | **8 686,6** |
| Kaempferol 3-(6-acetylgalactoside) | Flavonoid-3-O-glycosides | 0,0 | 1,1 | 0,0 | 0,0 | **0,3** |
| (-)-Epigallocatechin 3-p-coumaroate | Epigallocatechins | 0,0 | 0,0 | 0,0 | 439,2 | **109,8** |
| Kaempferol 3-neohesperidoside-7-(2''-p-coumaryllaminaribioside) | Flavonoid-7-O-glycosides | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Kaempferol 3-[2''-(6'''-coumaroylglucosyl)-rhamnoside] 7-glucoside | Flavonoid-7-O-glycosides | 2 682,9 | 2 489,6 | 2 752,6 | 2 653,6 | **2 644,7** |
| Kaempferol deriv | Flavonoid-3-O-glycosides | 792,7 | 855,9 | 1 113,3 | 178,5 | **735,1** |
| Kaempferol 3-[2''-(p-coumaroylglucosyl)rhamnoside] | Flavonoid-3-O-glycosides | 689,5 | 642,2 | 746,9 | 232,3 | **577,7** |
| Chinenoside III | Steroidal saponins | 0,0 | 0,0 | 0,0 | 0,0 | **0,0** |
| Glucosyl (2E,6E,10x)-10,11-dihydroxy-2,6-farnesadienoate | Terpene glycosides | 895,6 | 867,9 | 903,4 | 884,8 | **887,9** |
| Aeginetoside | Terpene glycosides | 1 751,0 | 1 729,7 | 1 737,3 | 1 531,5 | **1 687,3** |
| | | | | | | |

## Table 8.5: Average HPLC-MS values for compounds identified in all C. sinensis clone samples



| ***C.sinensis* extract HPLC-MS analyses results** | **Mg/kg (ppm) concentrations of each compound vs EGCG calibration (excl. caffeine - own calibration curve)** | | | | | |
|---|---|---|---|---|---|---|
| **Clone** | **All clones** | | | | | |
| | | Average | Average | Average | Average | Total |
| **Sample number** | | **SFS150** | **PC81** | **SFS204** | **BB35** | **Average** |
| **Compound** | **Class of compound** | | | | | |
| | | | | | | |
| Gallic acid | Organic acid | 350,3 | 484,0 | 753,5 | 528,0 | **528,9** |
| L-Theanine | Amino acid | 1 773,3 | 2 586,8 | 2 185 | 2 520,75 | **2 266,4** |
| Theogallin | Quinic acids and derivatives | 375,9 | 390,8 | 775,8 | 609,1 | **537,9** |
| **Gallocatechin-gallocatechin (GCGC)** | **Biflavonoids and polyflavonoids** | **1 810,8** | **376,7** | **2 642,2** | **681,8** | **1 377,9** |
| Gentesic acid 5-O-glucoside | Phenolic glycosides | 106,5 | 179,7 | 209,2 | 135,4 | **157,7** |
| **Gallocatechin (GC)** | **Epigallocatechins** | **14 686,6** | **16 897,8** | **19 686,7** | **19 058,7** | **17 582,4** |
| Chlorogenic acid 3CQA | Quinic acids and derivatives | 9 148,6 | 1 464,7 | 9 329,6 | 5 482,4 | **6 356,3** |
| **(-)-Epigallocatechin (EGC)** | **Epigallocatechins** | **82 907,4** | **80 667,1** | **83 542,8** | **77 175,2** | **81 073,1** |
| 3-O-p-Coumaroylquinic acid | Quinic acids and derivatives | 3 683,9 | 1 024,7 | 5 092,2 | 2 096,0 | **2 974,2** |
| **Catechin** | **Catechins** | **8 356,5** | **10 299,4** | **13 218,6** | **12 751,2** | **11 156,4** |
| Corilagin | Hydrolyzable tannins | 2 490,0 | 1 082,8 | 2 150,0 | 2 118,8 | **1 960,4** |
| Chlorogenic acid 5CQA | Quinic acids and derivatives | 7 684,6 | 4 618,0 | 6 515,8 | 8 551,4 | **6 842,4** |
| Procyanidin B5 | Biflavonoids and polyflavonoids | 5 076,8 | 7 061,5 | 6 711,4 | 4 579,5 | **5 857,3** |
| **Caffeine** | **Alkaloid** | **22 654,1** | **21 277,7** | **23 668,9** | **21 568,5** | **22 292,3** |
| (2R)-6,8-Diglucopyranosyl-4',5,7-trihydroxyflavanone | Flavonoid 8-C-glycosides | 881,9 | 703,4 | 1 022,3 | 612,2 | **804,9** |
| Epigallocatechin-(4beta->8)-epicatechin 3-O-gallate | Biflavonoids and polyflavonoids | 3 070,4 | 7 683,9 | 5 321,7 | 2 055,4 | **4 532,8** |
| **Epicatechin (EC)** | **Catechins** | **35 646,9** | **35 203,2** | **38 543,2** | **33 390,5** | **35 695,9** |
| **Epigallocatechin gallate (EGCG)** | **Catechin gallates** | **47 340,2** | **48 181,7** | **48 362,3** | **47 289,0** | **47 793,3** |
| **Gallocatechin gallate (GCG)** | **Catechin gallates** | **9 095,1** | **8 999,4** | **13 297,5** | **8 736,5** | **10 032,1** |
| Myricetin 3-galactoside | Flavonoid-3-O-glycosides | 6 159,2 | 7 090,0 | 6 845,6 | 7 368,1 | **6 865,7** |
| Epiafzelechin 3-O-gallate-(4beta->6)-epigallocatechin 3-O-gallate | Biflavonoids and polyflavonoids | 337,8 | 413,8 | 712,0 | 64,1 | **381,9** |
| Kaempferol 3-sophorotrioside | Flavonoid-3-O-glycosides | 2 333,5 | 0,0 | 772,0 | 0,0 | **776,4** |
| **(-)-Catechin 3-O-gallate (CG)** | **Catechin gallates** | **44 557,3** | **45 149,3** | **48 442,2** | **45 192,1** | **45 835,2** |
| (-)-Epigallocatechin 3,3'-di-gallate | Catechin gallates | 6 836,8 | 9 171,6 | 14 795,4 | 12 547,5 | **10 837,8** |
| Rutin | Flavonoid-3-O-glycosides | 8 425,2 | 15 356,7 | 15 013,1 | 5 484,9 | **11 070,0** |
| Quercetin 3-galactoside | Flavonoid-3-O-glycosides | 3 635,6 | 11 093,6 | 4 983,6 | 5 726,5 | **6 359,8** |
| Kaempferol 3-gentiobioside 7-rhamnoside | Flavonoid-7-O-glycosides | 6 051,0 | 0,0 | 2 464,7 | 0,0 | **2 128,9** |
| Kaempferol deriv | Flavonoid-7-O-glycosides | 586,1 | 6 071,2 | 1 254,3 | 0,0 | **1 977,9** |
| Robinin | Flavonoid-7-O-glycosides | 2 752,1 | 821,3 | 3 691,1 | 3 290,1 | **2 638,7** |
| (-)-Epiafzelechin 3-gallate | Flavan-3-ols | 9 314,0 | 1 978,0 | 15 910,0 | 2 824,8 | **7 506,7** |
| Astragalin 7-rhamnoside | Flavonoid-7-O-glycosides | 13 505,4 | 18 465,9 | 26 578,1 | 2 796,2 | **15 336,4** |
| Quercitrin | Flavonoid-3-O-glycosides | 12 734,7 | 5 353,5 | 16 005,8 | 8 686,6 | **10 695,2** |
| Kaempferol 3-(6-acetylgalactoside) | Flavonoid-3-O-glycosides | 419,8 | 0,0 | 400,7 | 0,3 | **205,2** |
| (-)-Epigallocatechin 3-p-coumaroate | Epigallocatechins | 69,3 | 2,4 | 39,8 | 109,8 | **55,3** |
| Kaempferol 3-neohesperidoside-7-(2''-p-coumaryllaminaribioside) | Flavonoid-7-O-glycosides | 692,7 | 0,0 | 289,8 | 0,0 | **245,6** |
| Kaempferol 3-[2''-(6'''-coumaroylglucosyl)-rhamnoside] 7-glucoside | Flavonoid-7-O-glycosides | 1 660,2 | 1 098,7 | 1 962,7 | 2 644,7 | **1 841,6** |
| Kaempferol deriv | Flavonoid-3-O-glycosides | 2 154,0 | 1 369,8 | 4 010,9 | 735,1 | **2 067,4** |
| Kaempferol 3-[2''-(p-coumaroylglucosyl)rhamnoside] | Flavonoid-3-O-glycosides | 178,1 | 0,0 | 127,3 | 577,7 | **220,8** |
| Chinenoside III | Steroidal saponins | 192,2 | 0,0 | 24,9 | 0,0 | **54,3** |
| Glucosyl (2E,6E,10x)-10,11-dihydroxy-2,6-farnesadienoate | Terpene glycosides | 930,6 | 907,1 | 864,1 | 887,9 | **897,4** |
| Aeginetoside | Terpene glycosides | 1 696,5 | 1 396,6 | 1 405,3 | 1 687,3 | **1 546,4** |
| | | | | | | |
| Total Polyphenol (Catechin + GC + GCGC + EGC + EC + EGCG + GCG + CG) | | **244 401** | **245 775** | **267 736** | **244 275** | **250 546** |
| Total Polyphenol to Cafeine ratio (POL:Caffeine) | | **10,8** | **11,6** | **11,3** | **11,3** | **11,2** |
| Total Flavonoids | | **71 483** | **69 402** | **101 332** | **40 747** | **70 741** |
| | | | | | | |

## 8.4. Discussion

The above-listed results show that the green tea extracts obtained from the supplied plant material samples mostly contain the expected complex mixture of polyphenolic, flavonoid, and catechin/ epicatechin phytochemicals usually found in green tea. These are present either in their free forms (e.g. catechin and epicatechin), glycosidically bound (e.g. quercitrin 3-galactoside), or as gallate esters (e.g. gallocatechin gallate). Total catechin values appear to be excellent, but there are some key differences between this data and published results.

Whereas EGCG is generally the catechin mostly found in green tea extracts, the current analyses found higher concentrations of EGC in all the samples, with EGCG only coming in second place. Also, values for catechin, EC and CG are all higher than usually reported. Due to time/budget constraints, this data could not be verified in the current analytical campaign. Ideally, these results should be confirmed by analysis of the current samples against known standards of all the catechins identified, to confirm or correct the results and peak attributions given here. Although the specific identity of the individual catechins is thus not certain, *there is nevertheless no doubt that all the compounds identified as catechins or catechin esters are true of this class of compound (catechin/polyphenols), and that the total polyphenol values obtained in these extracts are indeed very high [avg. 25,05% (w/w%)].*

When comparing individual clones, *C. sinensis* SF204 consistently produced extracts with the highest polyphenolic, catechin, flavonoid, and caffeine levels. Variances in concentrations of individual components in samples from the same clones taken on different dates show no recognizable trends. Reasons for these variations are unclear but are likely to be the result of a multitude of variable factors, such as weather conditions, time of day of sample collection, homogeneity of sample collection (part of the plant, e.g. tip leaves vs. base leaves), small variations in PPO enzyme deactivation procedure, sample age at time of analysis, and homogeneity of sample selection for analysis (i.e. samples were not milled and mixed prior to analysis).

Caffeine is present within the expected literature reported range for green tea extracts [2-5% (w/w%)] and shows that the chosen method of PPO enzyme deactivation does not decrease it significantly. Other methods of PPO deactivation, such as blanching, is known to decrease caffeine levels by up to 50%. Despite the relatively high caffeine values (compared to blanched green tea samples), the total polyphenol-to-caffeine ratio in the current extracts remains very good at ±11:1 (due to high overall polyphenol content). Free gallic acid is present only in modest amounts, especially when the amount of gallate esters present in the extracts are considered and serves as an indication that little to no hydrolysis of the samples took place during sample preparation, PPO enzyme deactivation, or during extraction. Similarly, the absence of any obvious theaflavin compounds in these analyses indicates that PPO enzyme deactivation by microwave radiation, as described in the sample preparation protocol provided previously, worked excellently.

The predominant amino acid found in *C. sinensis* is L-theanine, which may comprise >50% of the total free amino acids or 1-2% of the dry weight of tea. L-theanine mainly contributes to the aroma of green tea extracts and is known to give it a sweetish savoury "umami" type aroma. Whereas L-theanine's calming effect is well appreciated by green tea drinkers worldwide, its presence in green tea extracts prepared for nutraceutical application (i.e. highest possible polyphenol content), is not required as such. In this case, the low overall free L-theanine levels, as found here, are an indication that little proteolytic breakdown of proteins took place during PPO enzyme deactivation and sample preparation, which is an indication of the success of the sample preparation protocol and suggests that preservation of catechins by PPO deactivation was indeed successful. It should, however, be stressed that free L-theanine analysis could not be quantified very accurately with the current analytical method. This part of the analysis should thus ideally be performed with dedicated amino acid analytical procedures and standards to confirm this preliminary result.

Flavonols are also an important group of bioactive components in green tea extract and contribute significantly to its antioxidant properties. Flavonols are mainly present in their glycosylated forms, as well as to a lesser extent, in their non-glycosylated forms. Quercetin, kaempferol, and myricetin are the non-glycosylated moieties of the major flavonols found in green tea and were all present in the current samples, mainly in glycosylated form. In general, total flavonols (including their glycosides) in green tea usually constitute between 2% and 3% of the weight of dried tea leaves. The average value of 7,07% (w/w%) of the weight of the dried tea found in the current samples therefore represents an unusually high number and indicates that this plant material is likely to exhibit excellent anti-oxidant properties. As with the catechins tea clone, SF204 yielded significantly higher amounts of total flavonoids when compared to the other clones. SF204 yielded a total flavonol content of 10,13% (w/w%), compared to clone BB35, which yielded only a total of 4,07% (w/w%) flavonols.

## 8.5. Conclusion

Green tea extracts were successfully prepared and analysed by HPLC-MS methods. Although some uncertainties and inconsistencies remain in the complex analytical data, which would require the acquisition of a range of analytical standards to clear up completely.

The results of these analyses indicate that the extracts prepared and analysed here undoubtedly contained higher than normal total catechin and flavonoid concentrations. From this data, all the plant material investigated – and tea clone SFS204 – which consistently yielded the highest concentrations of polyphenolic catechins and flavonoids (and caffeine) levels, would very likely make suitable candidates as raw materials for the preparation of high-quality green tea extracts for application in the nutraceutical markets.

The overall high catechin compound concentrations (catechin, GC, GCGC, EGC, EC, EGCG, GCG, and CG) found in all the samples, combined with the absence of theaflavins, low free L-theanine, and normal caffeine concentrations, indicate that the PPO enzyme deactivation and sample preparation method employed was very effective in deactivating PPO, whilst preserving polyphenols, proteins and caffeine in the plant material studied.

# Chapter 9 CONCLUSIONS AND RECOMMENDATIONS

## 9.1 Background

The study contributed to easing the challenge of the tea industry within the country, regionally, and worldwide. There is a consensus that at global level, the tea industry continues to find it increasingly difficult to make ends meet, caught between rising costs and stagnant or declining prices. The practical option available to the industry is in the realm of cost reduction. The water footprint, linked with the water-energy-food and environment nexus lends itself well as an approach to reduce cost; also, with its contribution to sustainable livelihood and environmental livelihood approaches. These approaches can enhance competitiveness and efficient use of both water, energy and environmental resources. The focus here was not only on labour competitiveness, but also on the other production factors that are involved in the growing, manufacturing and marketing of tea. The understanding was that production practices that do not take the well-being of the environment into account, coupled with the expectation of higher profits, can lead to the deterioration of natural resources; also, the trade-offs in the use of linked natural resources-water and environment – for the competitiveness of tea.

## 9.2 The conceptual framework

The conceptual framework for environmental livelihood security (ELS), which combines concepts of the water-energy-food-environment nexus with the natural capitals of the sustainable livelihood framework is shown in Figure 9.1. Timber supplied through pine and blue gum (Eucalyptus) trees was shown to be the highest risk for ELS. The manufacturing of tea demands all forms of energy supply from diesel, electricity and timber. The water component was mainly supplied through rain-surface water. The food component is the production of tea (black, green and botanical extracts). Livelihood pressures include population growth and urbanization, which create a demand for made tea. The environmental pressures include climate change and natural disasters. In context, the tea industry in countries where they continued with production saw a critical need to improve the energy utilization required.

The following factors make a contribution: (a) the energy utilization in the tea sector has increased in recent years and will continue to do so, due to a growing global tea consumption and an increasing production capacity, (b) the environmental impact – the increasing use of firewood will result in severe deforestation, (c) rapid population growth will increase the demand for firewood and (d) the electrical power is expensive and becoming unreliable in South Africa and many developing tea producing countries.

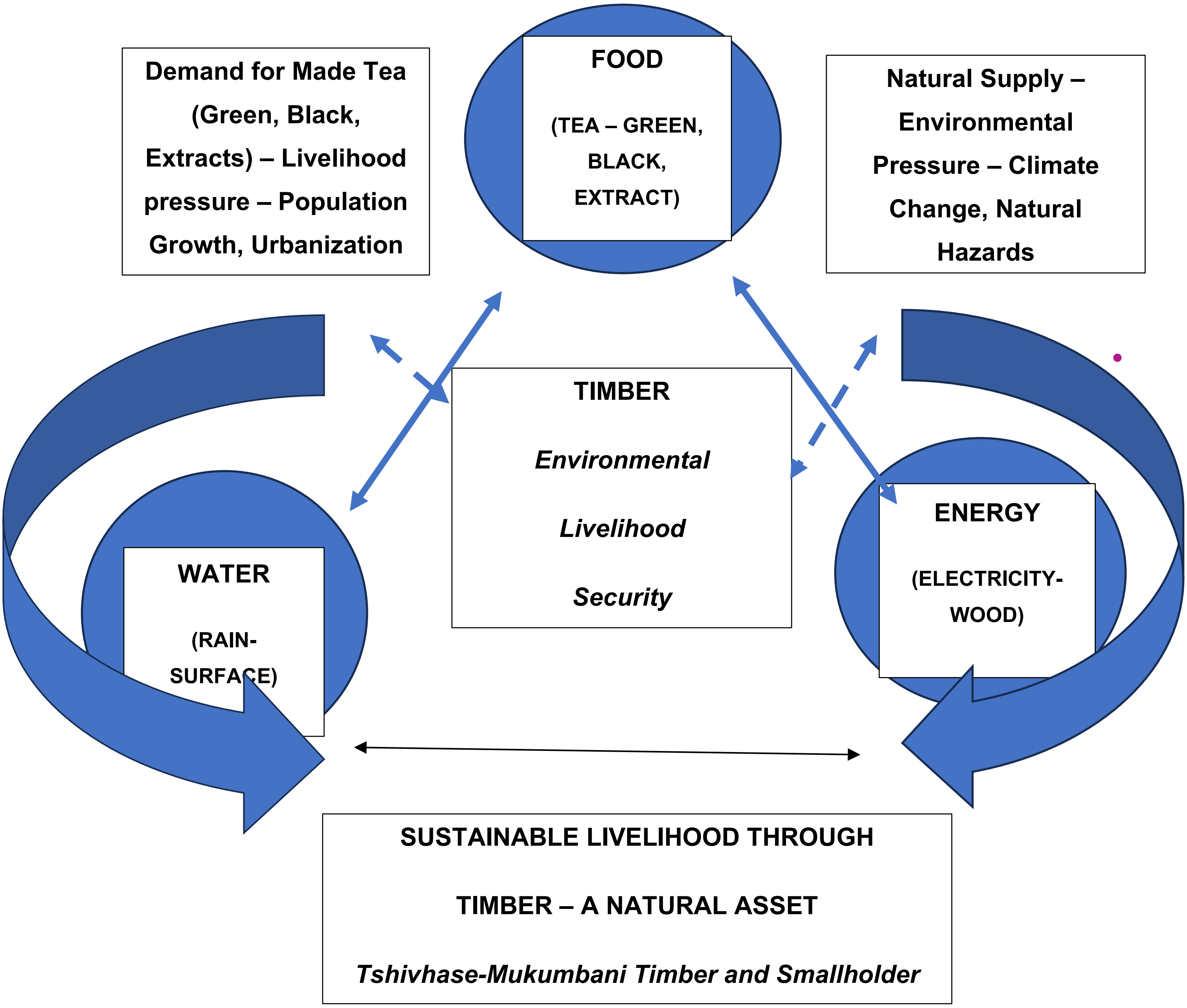


**Figure 9.1: The conceptual framework for environmental livelihood security (ELS) which combines concepts of the water-energy-food-environment nexus with the natural capitals of the sustainable livelihood's framework**

## 9.3 Competitiveness in the context of the tea industry

A comprehensive review was done to study the tea industry and recommend some of the strategies to be considered, using the case of Tshivhase-Mukumbani. The study, based on desktop review, concluded that the prospects of tea production in South Africa, specifically in Limpopo Province, will in the long run depend on international competitiveness. At present, the cost of producing tea in South Africa is very high compared to the major tea producing countries such as Kenya, Malawi, Tanzania, Sri Lanka and India. The increase in the cost of production of tea in South Africa has made the tea industry unviable, with slight fluctuations in the international price of tea. Studying the total chain of production and alternative products from tea can assist in making tea economically and socially sustainable.

## 9.4 The water footprint for tea and its botanical extract

The tea crop at Tshivhase-Mukumbani is dependent on rainwater and not irrigation; water footprint of the crop depends solely on the green water footprint. On average, the rainfall was less than the minimum (1 200 mm) required for tea production in one of every five years. There is a potential to reduce water usage from the production of leafy green tea to processing and packaging. The use of technology can also reduce the factory water usage during processing. The seedling variety and some clones are tolerant to drought and do not need irrigation. The blue water footprint of black tea depends on the method of tea processing; e.g. use of boilers in tea drying will result in a higher blue water footprint in tea processing.

## 9.5 The vulnerability of the tea production system to climate change/extremes

To better manage and sustain the plantation of any crop, it was important to know and understand its ecological requirements for optimal growth. The study confirmed that the ideal growth of tea requires acid soil, a humid tropical environment and a high altitude free from frost. The 4.5-5.6 pH range and minimum rainfall of 1 200 mm year-1, but 2 500-3 000 mm year-1 were observed to be optimum for the growth of tea in a certain study. The soil conditions should be deep, well-drained and well-aerated with more than 2% organic matter for optimal tea growth. Tea growth is favoured by a temperature range of 20-30°C as well as a relative humidity of 80-90%. At least five hours a day of sunlight are important for the growth of tea.

The study showed a basis for supplementary irrigation decision-making for the months of the year when rainfall declines. Though rainfall influenced the amount of green leaf production and manufactured tea, there was no significant correlation between rainfall and tea quality.

## 9.6 The water footprint of tea crops in the context of future climate change scenarios

Climate change is expected to have significant impacts on tea production in South Africa, and these impacts are likely to be felt in the coming decades. The change in temperature, precipitation and extreme weather events are expected to affect the growth and development of tea plants, the timing of tea harvests, and the quality and quantity of tea produced. To mitigate the impacts of climate change on tea production, farmers and producers must adopt sustainable practices and technologies, and policymakers must support climate-friendly tea production and adaptation.

## 9.7 Economic trade-offs on water-energy-tea-extracts-environment nexus

The review of the literature indicated that energy accounts for about 30% of the tea processing factories' operational costs, with electricity accounting for 17%. At least 70% of the tea factories rely on wood-fired steam boilers to generate heat. According to the Kenya Tea Development Agency (KTDA), the reliance on wood fuel has helped the factories to save up to 60% of energy use when compared to the use of furnace oil. Therefore, the plan for tea processing factories should be to acquire land with exotic trees for wood fuel, which should be coupled with land for indigenous trees for conservation. In the context of Tshivhase-Mukumbani Tea Estate – a collaboration between smallholder timber producers should be fostered to enhance livelihood security for these communities.

This will be an opportunity for smallholder timber farmers to earn extra income. There is also a need to focus on alternative energy sources for tea processing such as solar and wind energy. The Tshivhase-Mukumbani Estate is still grid-connected to electricity. However, the petroleum-based fuels to supply energy for tea processing to the tea factory have become very expensive. The use of timber for energy was intensive for the tea estates – though from their timber farm.

The negative impacts of the use of timber in addition to domestic wood requirements may lead to more trees being harvested for fuel, leading to reduced forest cover – an environmental sustainability issue. This will be a threat to the sustainability of wood as a source of energy, and also poses a challenge to environmental conservation, as it may result in increased soil erosion and associated risks of reduced water quality.

## 9.8 Assessment of long-term relationship between remotely sensed-derived indices and the standardized precipitation index (SPI) in the tea plantation: A case study of Mukumbani Tea Estate, Limpopo Province

The study sought to assess the long-term relationship between the SPI and various indices derived from optical remote sensed-derived vegetation indices. The following conclusions were drawn from the current study:

- The NDWI was highly correlated to the autumn SPI ($r = 0.91$) throughout the study period. The highest SPI correlation was observed with the NDWI in summer (0.93). This thus emphasizes the importance of surface and vegetation moisture for quantification of drought in the tea estate.
- The lowest correlation was observed between the SPI and temperature during the spring season ($r = 0.01$).
- In general, the autumn and winter NDWI were significantly different for the years between 1987-2022.
- Only the autumn model for predicting the SPI for the tea estate was statistically significant ($p = 0.032$), and this model incorporated NDWI as the sole predictor variable. This further highlights the importance of vegetation moisture as an indicator of potential drought conditions on the tea plantation.
- The year 2007 has shown lower SPI readings, suggesting that Mukumbani Tea Estate also suffered the effects of climate change.

## 9.9 Potential value-added products and polyphenolic content from South African green tea (Camellia Sinensis) and Moringa (Moringa Oleifera)

There are significant opportunities for tea extracts and value-added products. Meeting the market requirements for value-added botanical extracts is essential to capitalise on the opportunities identified in the previous study. By focusing on product quality, certification, customization, regulatory compliance, supply chain efficiency, competitive pricing and effective marketing strategies, the commercial-scale production facility can successfully enter and flourish in the targeted food, beverage, and cosmetic markets. Continual monitoring of market trends and evolving customer preferences will be critical to sustaining market relevance and achieving long-term success.

### 9.9.1 Green tea

The tea extract market presents a promising landscape with abundant opportunities for companies, particularly in the realms of cosmetics and functional foods/nutraceuticals. Incorporating tea extracts into skincare and haircare products can provide numerous benefits, such as antioxidant protection, hydration, anti-inflammatory properties, and UV defence. Moreover, tea extracts have found their way into functional foods and nutraceuticals, offering advantages such as energy boost without caffeine-related side effects, support for weight loss efforts, enhancement of heart health, and strengthening of the immune system. These applications, coupled with the growing demand for health-conscious and natural ingredients, as well as the increasing popularity of functional foods, contribute to the continued expansion of the tea extract market. Companies that recognize and seize these opportunities are poised to flourish in this dynamic and thriving industry, catering to the rising consumer preference for products that promote well-being and embrace the potential of tea's health benefits.

#### *9.9.1.1 Opportunities to use tea extracts in a variety of cosmetics include:*

- Skincare products: help improve skin health. For example, green tea extract has been shown to help reduce wrinkles and age spots.
- Haircare products: help improve hair health. For example, black tea extract has been shown to help reduce hair loss and to improve hair growth.
- Makeup products: help improve the look of skin and hair. For example, matcha tea extract can be used to add a natural green tint to makeup products.

#### *9.9.1.2 Opportunities to use tea extracts in a variety of functional foods and nutraceuticals include:*

- Energy drinks: help provide a sustained source of energy
- Pre-workout supplements: help improve performance and endurance
- Dietary supplements: help improve overall health and well-being.

#### *9.9.1.3 The following approach is recommended for the tea extract market:*

- Develop new and innovative products that use tea extracts. There are several ways to do this. For example, tea extracts can be used to create new flavours for beverages, food and dietary supplements. They can also be used to create new textures for cosmetics and personal care products.
- Expand into new markets. The tea extract market is a global one, and there are opportunities for expansion into new markets. For example, businesses can extend into Asia, Latin America and Africa.
- Partner with other businesses – to develop new products and expand into new markets. For example, partnering with beverage companies to develop new tea-flavoured drinks; or partnering with cosmetics companies to develop new tea-infused cosmetics.
- The tea extract market is growing, with a lot of potential. Businesses that can develop new and innovative products and expand into new markets will be successful in this arena.
- In addition to the recommendations above, one should also focus on the following:
    - Quality control: Tea extracts should be of high quality and free of contaminants
    - Safety: Tea extracts should be safe for human consumption
    - Sustainability: Tea extracts should be produced sustainably.

### 9.9.2 Recommendations

Seven recommendations were suggested based on the results of the study. These recommendations were in the form of strategies which included the following:

- The industry needs a dedicated differentiation strategy that will give focus to tea production of specialty quality. Chapter 9 results indicate the potential of the markets and the consideration of novel products.
- Expansion of own tea brands emphasizing originality and distinctive attributes, such as chemical-free tea, single estate low caffeine and catechin-rich tea.
- Promote the demand for green tea extract, powdered tea and tailor-made products for the growing demand for specialty products

- Establishment of partnerships with proven tea-producing companies such as Rooibos Limited, which produces green tea extract for the food industry
- Promote the tea estates as organic production and promote organic certification
- Recapitalization of the tea estates to improve production efficiencies and investment in modern technology, with the possibility of developing a small-scale sector of out-growers
- Efficiency of resource utilization could also mean the adoption of new business models by diversification into growing other agricultural products.

# Chapter 10 REFERENCES

Adhikari, U., Nejadhashemi, A.P., and Woznicki, S.A., 2015. Climate change and eastern Africa: a review of the impact on major crops. *Food and Energy Security, 4(2), 110-132.*

Adjei-Mensah, K. and Kusimi, J.M. 2020. Dwindling water supply and its socio-economic impact in Sekyere Kumawu District in Ashanti Region of Ghana: public opinion on the role of climate change. GeoJournal, 85: 1355-1372. https://doi.org/10.1007/s10708-019-10026-0.

Aggarwal, P.K., Joshi, P.K., Ingram, J.S.I., Gupta, R.K., 2004. Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. Environ. Sci. Policy 7, 487-498.

Ahammed, D. K. M. 2012. Investment for Sustainable Development of Bangladesh Tea Industry – An Empirical Study. Proceedings of BEA XVIII Biennial Conference, Paper No. 9, Bangladesh, September 2012, 12-16.

Ahmad U, Alvino A., Marino S., 2021. A Review of Crop Water Stress Assessment Using Remote Sensing. Remote Sensing,**13**: 4155

Ahmed, I., Hossain, A., Rowson, A., Haque, D. M. Z., Miah, M. L., and Ahmed, T. 2015. Effect of Precipitation on Yield and Crop Distribution of Tea. Journal of Global Bioscience, 4, 2304-2314.

Ahmed, S., Griffin, T. S., Kraner, D., Schaffner, M. K., Sharma, D., and Hazel, M., 2019. Environmental factors variably impact tea secondary metabolites in the context of climate change. *Front. Plant Sci. 10:939*. doi: 10.3389/fpls.2019.00939.

Ahmed, S., Griffin, T., Cash, S.B., Han, W.Y., Matyas, C., Long, C., Orians, C.M., Stepp, J.R., Robbat, A. and Xue, D., 2018. Global Climate Change, Ecological Stress, and Tea Production. In: Han, W.Y., Li, X., Ahammed, G. (eds) Stress Physiology of Tea in the Face of Climate Change (pp 1-23). Springer, Singapore.

Ahmed, S., Orians, C., Griffin, T., Buckley, S. and Unachukwu U. 2013. Effects of water availability and pest pressures on tea (Camellia sinensis) growth and functional quality. AoB Plants. DOI 10.1093/aobpla/plt054

Ahmed, S., Peters, C.M., Chunlin, L., Meyer, R. and Unachukwu, U. 2012. Biodiversity and phytochemical quality in indigenous and state-supported tea management systems of Yunnan, China. *Conservation Letters 5(6): 28-36.*

Ali, M., Uddin, M.N., Mobin, M.N. and N. Saha, N., 2014. Effects of Microclimatic Parameter on Tea Leaf Production in Different Tea Estates, Bangladesh. *J. Environ. Sci. & Natural Resources,*7(1): 183-188, 2014 ISSN 1999-7361

Al-Kilani M.R., Rahbeh M., Al-Bakri J., Tadesse T., and Knutson C. 2021. Evaluation of Remotely Sensed Precipitation Estimates from the NASA POWER Project for Drought Detection over Jordan. Earth Systems and Environment, **5**: 561-573.

Allison, E., Ellis, F., 2001. The livelihoods approach and management of small-scale fisheries. Mar. Policy 25, 377-388.

Anju, A., 2011. Effect of Global Warming on Climate Change, Flora, and Fauna. *Journal of Ecophysiology and Occupational Health 11: 161-174.*

Ashardionoa F., Cassimb M. 2015. Adapting to Climate Change: Challenges for Uji Tea Cultivation. *International Journal Sustainable Future for Human Security*, 3(1):32-36

Baffes, J. 2003. Tanzanian Tea Sector Constraint and Challenges, Washington DC: World Bank

Barman, A., Nath, A., Thakur, D. (2020). Identification and characterization of fungi associated with blister blight lesions of tea (Camellia sinensis L. Kuntze) isolated from Meghalaya, India. *Microbiological Research*, 240 (2020):126561

Biggs, E.M., Boruff, B., Bruce, E., Duncan, J.M.A., Duce, S., Haworth, B.J., Horsley, J., Curnow, J., Neef, A., McNeill, K., Pauli, N., Van Ogtrop, F., Imanari, Y., 2014. Environmental Livelihood Security in South-East Asia and Oceania: a nexuslivelihoods approach for spatially assessing change. In: IWMI-CGIAR White Paper International Water Management Institute, Colombo, Sri Lanka, Online at: hhttp://www.iwmi.cgiar.org/publications/other-publication-types/ environmental-livelihood-security-south-east-asia-oceania/i (accessed October 2014).

Biggs, E.M., Bruce, E., Boruff, B., Duncan, J.M.A., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow J., Haworth, B., Duce, S., Imanari, Y. 2015. Sustainable development and the water-energy-food nexus: A perspective on livelihoods. Environmental Science & Policy 54: 389-397.

Biggs, E.M., Gupta, N., Saikia, S.D., and Duncan, J.M.A., 2018. The tea landscape of Assam: multi-stakeholder insights into sustainable livelihoods under a changing climate *Environ. Sci. Policy 82: 9-18*

Boehm, R., Cash, S.B., Anderson, B.T., Ahmed, S., Griffin, T.S., Robbat, A., Stepp, J.R., Han, W.Y., Hazel, M., and Orians, C.M., 2016. Association between empirically estimated monsoon dynamics and other weather factors and historical tea yields in China: Results from a yield response model, *Climate*, 4: 20.

Bore, J.K. and Nyabundi, D.W., 2016. Impact of climate change on tea and adaptation strategies. Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea (Rome: Food and Agriculture Organization of the United Nations) pp 45-60 ((http://www.fao.org/3/ai5743e.pdf)).

Brown, P., Daigneault, A., Gawith, D., Aalbersberg, W., Comley, J., Fong, P., Morgan, F., 2007. Evaluating Ecosystem-Based Adaptation for Disaster Risk Reduction in Fiji. Landcare Research, New Zealand Online at hhttp:// www.landcareresearch.co.nz/__data/assets/pdf_file/0004/77341/ Fiji_disaster_risk_reduction.pdfi (accessed October 2014).

Cao, J., Zhao, Y., Li, Y., Deng, H.J., Yi, J., and Liu, J.W., 2006. Fluoride levels in various black tea commodities: Measurement and safety evaluation. Food and Chemical Toxicology, 44: 1131-1137.

Carnazzi S. 2014. The Challenges of the Tea Industry: Environmental and Social Sustainability. Expo net.

Carswell, G., 1997, ‘Agricultural intensification and sustainable rural livelihoods: a think piece’, IDS (Institute of Development Studies), Working Paper 64, Brighton: IDS

Chandini, S. K., Rao, L. J., & Subramanian, R. 2011. Influence of extraction conditions on polyphenols content and cream constituents in black tea extracts. International Journal of Food Science & Technology 46, 879-886.

Chang, K. and Brattlof, M., 2015. Socio-economic implications of climate change for tea producing countries, Market and Policy Analyses of Raw Materials, Horticulture and Tropical (RAMHOT) Products Team, Food and Agriculture Organization of the United Nations (FAO).

Chapagain, A. A. 2012. Water footprint: Help of hindrance? Water alternatives (3 ed., Vol. 5).

Chapagain, A. K., Hoekstra, A. Y., and Savenije, H. H. G. 2006. Water saving through international trade of agricultural products, Hydrol. Earth Syst. Sci., 10, 455-468, https://doi.org/10.5194/hess-10-455-2006.

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G., and Gautam, R. 2006. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton-producing countries, Ecol. Econ., 60(1), 186-203.

Chapagain, A.K. and Hoekstra, A.Y. 2007. The water footprint of coffee and tea consumption in the Netherlands. Journal of ecological economics,Vol:64.pp109-108.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water Footprints of Nations. Value of Water Research Report Series, vol. 16. UNESCO-IHE, Delft, the Netherlands. Available at www.waterfootprint.org.

Chatterjee, D.N. 2005: Review of ILO/UNFPA/Indian Tea Association Family Welfare Education Project in Dooars, India.

Chen, J.H., Tang, M., Jin X.Q., Li H, Chen L.S., Wang Ql, Sun A.Z., Yi Y., Guo F.Q. 2022. Regulation of Calvin-Benson Cycle Enzymes under High Temperature Stress. aBIOTECHNOLOGY **3**: 65-77.

Chen, L., Xu, B., Zhao, C., Duan, D., Cao, Q., and Wang, F.2021. Application of Multispectral Camera in Monitoring the Quality Parameters of Fresh Tea Leaves. *Remote Sensing*, 13: 3719

Chen, J., Liu, Q., and Gao, L. 2019. Visual Tea Leaf Disease Recognition Using a Convolutional Neural Network Model. *Symmetry*, 11:343.

Cheruiyot, E.K., Mumera, L.M., Ng’Etich, W.K., Hassanali, A. and Wachira, F. 2010. High fertilizer rates increase susceptibility of tea to water stress. *Journal of Plant Nutrition, 33:115-129.*

Cheruiyot, E.K., Mumera, L.M., Ng'etich, W.K., Hassanali, A. and Wachira, F.N., 2008. Threshold soil water content for growth of tea [*Camellia sinensis*(L.) O. Kuntze]. Tea 29: 29-38.

Cheserek, B. C., Elbehri, A., & Bore, J., 2015. Analysis of links between climate variables and tea production in the recent past in Kenya. *Donnish Journal of Research in Environmental Studies*, *2*(2), 5-17.

Cho, D. 1994. A dynamic approach to internal competitiveness: A case of Korea. Journal of Far Eastern Business 1 (1): 17-36

Cho, D.S and Moon, H.C. 2002. From Adam Smith to Michael Porter. Evolution of competitiveness Theory World Scientific, Singapore, New Jersey, London, Hong Kong.

Cleaver, F., and Franks, T. 2005. How institutions elude design: river basin management and sustainable livelihoods. Alternative Water Forum, Bradford Centre for International Development, Bradford.

Creswell, J.W. 2003. Research Design: Qualitative, Quantitative and Mixed Methods Approaches (2nd Ed), Thousand Oaks, CA: Sage Publications.

Creswell, J.W. and V.L. Plano Clark . 2007. Designing and Conducting Mixed Methods Research, Thousand Oaks, CA: Sage Publications.

DAFF (Department of Agriculture, Forestry and Fisheries), 2016. Black tea production guideline. Directorate Communication Services, Pretoria, South Africa.

DAFF. (2015). A Profile of The South African Black Tea Market Value Chain.

Das A.C, Noguchi R., Ahamed T. 2021. An Assessment of Drought Stress in Tea Estates Using Optical and Thermal Remote Sensing. Remote Sensing, **13(14)**: 2730. https://doi.org/10.3390/rs13142730.

de Costa, W.J., Mohotti, A., Wijeratne, M., 2007. Ecophysiology of tea. Braz. J. Plant Physiol. 19: 299-332.

de Silva L.D.S.M. (2007). The effects of soil amendments on selected properties of tea soils and tea plants (*Camellia sinensis L.)* in Australia and Sri-Lanka. Ph.D. dissertation, James Cook University, Australia.

de Silva, R.L. 1994. Statistical references: Productivity improvement of tea plantations in Sri Lanka, World Bank.

de Silva, S., Johnston, R., Senaratna Sellamuttu, S. 2014. Agriculture, irrigation and poverty reduction in Cambodia: policy narratives and ground realities 396 E.M. Biggs et al. / Environmental Science & Policy 54 (2015) 389-397 compared. In: Working Paper: AAS-2014-13CGIAR Research Program on Aquatic Agricultural Systems, Penang, Malaysia. DFID (Department for International Development), 2001. Sustainable Livelihoods Guidance Sheets. Department for International Development, London.

Department of Agriculture , F. a. (n.d.). www.daff.gov.za. Retrieved April 07, 2015, from http://www.daff.gov.za/daffweb3/Branches/Agricultural-Production-Health-Food-Safety/Food-Import-Export-Standards/WTO-SPS-Co-ordination

Deurer, M., Green, S.R., Clotheir, B.E. and Movat, A. 2011. Can product water footprint indicate the hydrological impact of primary production. Journal of hydrology.

Dhau I., Adam E., Mutanga O., Ayisi K., Abdel-Rahman E.M., Odindi J., Masocha M. 2018. Testing the capability of spectral resolution of the new multispectral sensors on detecting the severity of grey leaf spot disease in maize crop. *Geocarto International* , 33(11): 1223-1236.

Duncan J.M., Saikia S.D., Gupta N., Biggs E.M., 2016. Observing climate impacts on tea yield in Assam, India. *Appl. Geogr. 77: 64-71.*

Durowoju O.S, Odiyo J.O, Ekosse G.I.E. 2019. Determination of isotopic composition of rainwater to generate local meteoric water line in Thohoyandou, Limpopo Province. South Africa. Water SA **45(2)**:183-189.

Dutta R., Stein A., Bhagat A.M. 2011. Integrating satellite images and spectroscopy to measuring green and black tea quality. *Food Chemistry*, 127: 866-874

Dutta, R. 2014. Climate change and its impact on tea in Northeast India. Journal of Water and Climate Change 5: 625-632.

Dutta, R., Smaling, E.M.A., Bhagat, R.M., TolpekinVand Stein, A. 2012. Analysis of factors that determine tea productivity in north-eastern India: a combined statistical and modelling approach. *Exp. Agric. 48: 64-84*

Edwin E. R., Ashokraj S., Radhakrishnan B. 2018. Detection of blister blight disease in tea using smartphone and image processing technique. Newsletter 28. UPASI Tea Research Foundation, Coimbatore, India.

Egbu, A. 2007. The Impact of Land Use Planning on Urban Land Markets in Sub-Saharan Africa: A Case Study of Nigeria. Unpublished Ph.D. Thesis, School of Engineering and Build Environment, University of Wolverhampton, Wolverhampton – United Kingdom

Endo, A.; Burnett, K.; Orencio, P.M.; Kumazawa, T.; Wada, C.A.; Ishii, A.; Tsurita, I.; Taniguchi, M. 2015. Methods of the Water-Energy-Food Nexus. *Water* 7, 5806-5830. https://doi.org/10.3390/w7105806

Enfors, E. 2013. Social-ecological traps and transformations in dryland agroecosystems: using water system innovations to change the trajectory of development. Global Environ. Change 23, 51-60.

Eric, R.S., Li, X., Kfoury, N., Morimoto, J., Han, W.Y., Ahmed, S., Sean, B.C., Griffin, T.S., Stepp, J.R., Robbat, and Orians, C.M. 2019. Interactive effects of drought severity and simulated herbivory on tea *(Camellia sinensis)* volatile and non-volatile metabolites. *Environmental and Experimental Botany*, 157: 283-292.

Ericksen, P.J. 2008. Conceptualizing food systems for global environmental change research. Global Environ. Change 18, 234-245.

Esterhuizen, D. 2006. An inquiry into the competitiveness of the South African agribusiness sector. PHD-thesis, University of Pretoria, Pretoria.

FAO (Food and Agriculture Organization of The United Nations), 2014. FAOSTAT: Available online at http://www.fao.org/faostat/en/#data/QC; cited on 10 Oct 2017.

FAO (Food and Agriculture Organization of The United Nations), 2015. World tea production and trade: Current and future development. Available online at http://www.fao.org/3/a-i4480e.pdf; cited on 10 Oct 2017.

FAO (Food and Agriculture Organization of The United Nations), 2016. Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea. FAO, Rome, Italy.

FAO. 1995. Documents for the 11th Session of the Intergovernmental Group on Tea, Rome. Government of Sri Lanka (1980): Tea Master Plan.

FAO. 2002. Analytical Framework: Sustainable Livelihoods. Food and Agriculture Organization of the United Nations Accessed at hhttp://fao.org/docrep/007/ j2602e02.htmi (accessed 17 March 2014).

FAO. 2003. Technical conversion factors for agricultural commodities. Available online: [www.fao.org/fileadmin/templates/ess/documents/methodology/tcf.pdf]. Rome: Food and Agriculture Organization.

FAO. 2003a. CROPWAT model. Website: http://www.fao.org/ag/AGL/aglw/cropwat.htm

FAO. 2003b. CLIMWAT database. Website: http://www.fao.org/ag/AGL/aglw/climwat.stm

FAO. 2003c. FAOSTAT database. Website: http://apps.fao.org

FAO. 2008. The Livelihood Assessment Tool-Kit: Analysing and Responding to the Impact of Disasters on the Livelihoods of People. Food and Agriculture Organization of the United Nations, Rome.

FAO. 2012. Mutually Acceptable Mechanism on Integrated Use of Water Resources in Central Asia: Application of the Scenario Approach. Food and Agriculture Organization of the United Nations, Rome.

FAO. 2014. The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture. Food and Agriculture Organization of the United Nations, Rome.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., and Basra, S.M.A., 2009. Plant drought stress: effects, mechanisms, and management *Agron. Sustain. Dev.* ***29:*** *185-212.*

Farukh, M., Rahman, M., Sarker, S. and Islam, M. 2020. Impact of Extreme Precipitation Intensity on Tea Production in the North-East of Bangladesh. *American Journal of Climate Change*, **9**, 441-453. doi: 10.4236/ajcc.2020.94028.

Freebairn, J. 1986. Implications of wages and industrial policies on competitiveness of Agricultural Expert Industries. Paper presented at the Australian Agricultural Economics Society Policy Forums. Canberra

Gesimba, R.M., Langat, M.C., Liu, G. and Wolukau, J.N. 2005. The tea industry in Kenya: The challenges and positive developments. Journal of Applied Sciences, 5(2): 334-336

Ghazali M.F., Wikantika K., Tridawati A., Harto A.B. 2020. Spectral analysis for phenological studies of leaves and fruits development in coffee plantation in Gunung Puntang: a preliminary result. *IOP Conference Series: Earth and Environmental Science*, 500(012024): doi:10.1088/1755-1315/500/1/012024.

Gogtay, N.J., and Thatte, U.M., 2017. Statistics for researchers: Principles of correlation analysis. Journal of the Association of Physicians of India, 65: 78-81.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockstrom, J., Ohman, M.C., Shyamsundar, P., Steffan, W., Glaser, G., Kanie, N., Noble, I. 2013. Sustainable development goals for people and planet. Nature 495, 305-307.

Gulati, A., Ravindranath, S.D. 1996. Seasonal variations in the quality of Kangra tea (Camellia sinensis) (L.) in Himachal Pradesh. J Sci Food Agr 71:231-236.

Gunathilaka, R.P.D.; Smart, J.C.R. and Fleming, C.M. 2017. The impact of changing climate on perennial crops: The case of tea production in Sri Lanka. Climate Change, 140: 577-592.

Hajiboland R. 2017. Environmental and nutritional requirements for tea cultivation. Folia Horticulture, 29: 199-220.

Hao X, Zhang W, Zhao F, Liu Y, Qian W, Wang Y, Wang L, Zeng J, Yang Y and Wang X 2018. Discovery of Plant Viruses from Tea Plant (Camellia sinensis (L.) O. Kuntze) by Metagenomic Sequencing. *Frontiers in Microbiology*, 9:2175

Hayakawa S., Ohishi T., Miyoshi N., Oishi Y., Nakamura Y., and Isemura M. 2020. Anti-cancer effects of green tea epigallocatchin-3-gallate and coffee chlorogenic acid. *Molecules*, 25 (19):4553

Ho, C.T., Lin, J.K., Shahidi, F., 2009. Tea and Tea Products: Chemistry and Health-Promoting Properties. CRC press, Taylor & Francis group, Boca Raton, FL, USA.

Hoekstra, A., and Chapagain, A. 2007. Water footprint of nations: Water use by people as a function of their consumption pattern. Water Resources Management, 21, 35-48.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series, vol. 11. UNESCO-IHE, Delft, the Netherlands.

Hoff, H., 2011. Understanding the Nexus: Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm.

Hong, N.B. and Yabe, M., 2015. Resource use efficiency of tea production in Vietnam: Using Translog SFA Model. Journal of Agricultural Science, 7(9): 160-172.

Hossain, S., Mou, R.M., Hasan, M.M., Chakraborty, S., and Razzak, A. 2018. IEEE 14th International Colloquium on Signal Processing & its Applications (CSPA 2018)

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerstro¨m, R., Alfstad, R., Gielen, D., Rogner, H., Fischer, G., van Velthuizen, H., Wiberg, D., Young, C., Roehrl, A., Mueller, A., Steduto, P., Ramma, I. 2013. Integrated analysis of climate change, land-u H se, energy and water strategies. Nat. Clim. Change 3, 621-626.

Huang Y., Jiang H., Wang W. 2022. Research on Tea Tree Growth Monitoring Model Using Soil Information. *Plants*, (11)3:262

Hurmerinta-Peltomaki I, Nummela, N. 2006. Mixed methods in international business research: A value-added perspective. Management International Review, 46(4): 439-459.

ILO. 2007. International Labor Organization (2007): Global Employment Trends Brief, http://www.ilo.org/public/english/employment/strat/download/gerbo7en.pdf

Indahsari, G. and Kesumajaya, D., 2016. The Effect of Global Warming on Tea Production. Case Study of PTPN XYZ in Indonesia. European Scientific Journal December 2016 /SPECIAL/ edition ISSN: 1857-7881 (Print) e – ISSN 1857-7431

IPCC, 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds., *Cambridge University Press, Cambridge, United Kingdom* and New York, N.Y.

Irakoze, A. 2017. Analysis of potential energy savings for black tea drying process. Case study: IJENDA Tea Factory. Master's Programme in Energy Systems Engineering at Uppsala University and the Swedish University of Agricultural Sciences.

ISMEA. 1999. Institute of Mathematical and Economical Sciences Applied. The European Agro-food system and the challenge of global competition. Rome.

ISO. 2005. International Standard ISO 14502-1 Determination of substances characteristic of green and black tea – Part 1: Content of total polyphenols in tea – Colorimetric method using Folin-Ciocalteu reagent. Geneva: International Organization for Standardization.

Jayasundara, J.M.D.M., Ranundeniya, R.M.N.S., and Lakmali, W.A.S. 2016. Water Footprint Assessment of Black Tea; A Case Study from Nuwara Eliya District, Sri Lanka., 15th Agricultural research symposium.

Jin, J. Q., Liu, Y. F., Ma, C. L., Ma, J. Q., Hao, W. J., and Xu, Y. X., 2018. A novel F3'5'H allele with 14 bp deletion is associated with high catechin index trait of wild tea plants and has potential use in enhancing tea quality. J. Agric. Food Chem. 66, 10470-10478. doi: 10.1021/acs.jafc.8b04504

Jing N.N., Liu X.X., Jin M.L., Yang X.B., Hu X., Li C.Y., Zhao, K. 2020. Fubrick tea attenuates high-fat diet induced fat deposition and metabolic disorder by regulating gut microbiota and caffeine metabolism. *Food Function*, 11 (8):6971-6986

Kalita, R.M., Das, A.K. and Nath, A.J., 2014. Comparative study on growth performance of two shade trees in tea agroforestry system. *Journal of Environment Biology,* **35:** 699-702.

Karmokar, B.C., Ullah, M.S., Siddiquee, K., and Alam, R.K. 2015. Tea Leaf Diseases Recognition using Neural Network Ensemble. *International Journal of Computer Applications*, 114(17):0975-8887

Karnieli A, Agam N., Pinker R.T, Anderson M., Imhoff M.L., Gutman G.G, Panov N., Golberg A. 2010. Use of NDVI and Land Surface Temperature for Drought Assessment: Merits and Limitations. Journal of Climate, 23(3): 618-633.

Kattelus, M., Mizanur Rahaman, M., Varis, O. 2014. Myanmar under reform: emerging pressures on water, energy, and food security. Nat. Resour. Forum 38, 85-98.

Kfoury, N., Morimoto, J., Kern, A., Scott, E.R., Orians, C.M., Ahmed, S., Griffin, T., Cash, S.B., Stepp, J.R., Xue, D, Long, C. and Robbat, A., 2018. Striking changes in tea metabolites due to elevational effects. *Food Chemistry*, 264: 334-341.

Khan, S., Khan, M.A., Hanjra, M.A., Mu, J., 2009. Pathways to reduce the environmental footprints of water and energy inputs in food production. Food Policy 34, 141-149. MEA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being. World Resources Institute, Washington, DC.

Khosrvi, H., Haydarl, E., Shekoohizadegan, S., Zareie, S. 2017. Assessment of the Effect of Drought on Vegetation in Desert Area using Landsat Data. The Egyptian Journal of Remote Sensing and Space Sciences, **20(1):** S3-S12.https://doi.org/10.1016/j.ejrs.2016.11.007

Khumalo, T., Chasomeris, M., Munapo, E., Adeyeye, O. 2015. The South African tea industry: challenges and business strategies. Environmental Economics, 6 (4): 133-142

Kotikot, S.M., Flores, A., Griffin, R.E., Nyaga, J., Case, J.L., Mugo, R., Sedah, A., Adams, E., Limaye, A. and Irwin, D.E., 2020. Statistical characterization of frost zones: Case of tea freeze damage in the Kenyan highlands *Int. J. Appl. Earth. Obs. Geoinformation. 84 101971*

Kottur, G., Venkatesan, S., Kumar, R.S.S. and Murugesan, S., 2010. Influence of seasons on biochemical parameters of green shoots and quality parameters of made tea under south Indian conditions. J. Biosci Res 1(2): 74-82.

Kumar, K. R., Dashora, K., Krishnan, N., Sanyal, S., Chandra, H., Dharmaraja, S., Kumari, V. 2021. Feasibility assessment of renewable energy resources for tea plantation and industry in India – A review Renewable and Sustainable Energy Reviews. 145: 11083

Kumar, S. and Pou, J. 2016. Assessment of Bio-Energy Potential In Tea Industries Of India. Asian Journal of Agriculture and Rural Development. 6(5), 83-89

Kumar, A., Manjunath, K.R., Bala, R., Sud, R.K., Singh, R.D. and Panigrahy, S. 2013. Field hyperspectral data analysis for discriminating spectral behavior of tea plantations under various management practices. International Journal of Applied Earth Observation and Geoinformation, 23:352-359

L'Amyx 2003. 'Tea history and legend'. Website: http://www.lamyx.com/tealegend.html

LDA, 2008. Limpopo Department of Agriculture Report on the Rehabilitation of Tshivhase-Mukumbani Estates. Polokwane

Leedy, P.D, Ormrod, J.E 2010. Practical Research, Planning, and Design. 9th Edition. New Jersey, USA: Pearson Merrill Prentice Hall.

Li N., Zhang D., Li L., Zhang Y. 2017. Mapping the Spatial Distribution of Tea Plantations Using High-Spatiotemporal-Resolution Imagery in Northern Zhejiang, China. *Forests*, 10(856): 1-16.

Li, H., Liu, Z.W., Wu, Z.J., Wang, Y.X., Teng, R.M. and Zhuang, J., 2018. Differentially expressed protein and gene analysis revealed the effects of temperature on changes in ascorbic acid metabolism in harvested tea leaves. *Horticulture Research. 5: 65*

Li, S., Lu, J., Pope, E., Golding, N., Zhou, T., Li, F. and Duan, W., 2022. Influence of multi-timescale precipitation indices on primary tea production in Boashan, Yunnan, China. Environmental Research Communications 4: 025009. https://doi.org/10.1088/2515-7620/ac5087

Li, N, Zhang, D., Li, L., and Zhang, Y. 2019. Mapping the Spatial Distribution of Tea Plantations Using High-Spatiotemporal-Resolution Imagery in Northern Zhejiang, China. *Forests*, 10, 856

Li., X, Wei, J.P., Ahammed, G.J., Zhang, L., Li, Y., Yan, P., Zhang, L.P., and Han, W.Y., 2018. Brassinosteroids attenuate moderate high temperature-caused decline in tea quality by enhancing theanine biosynthesis in Camellia sinensis L. *Frontiers in Plant Science. 9: 1016*

Liang , Y., and Xu, Y. 2001. Effect of pH on cream particle formation and solids extraction yield of black tea. Food Chemistry 74, 155-160.

Lin, S. K., Lin, J., Liu, Q. L., Ai, Y. F., Ke, Y. Q., and Chen, C., 2014. Time-course photosynthesis and non-structural carbon compounds in the leaves of tea plants *(Camellia sinensis* L. O. Kuntze) in response to deficit irrigation. *Agric. Water Manag. 144, 98-106*. doi: 10.1016/j.agwat.2014.06.005.

Lin, Y., Tsai, Y., Tsay, J. and Lin J. 2003. Factors affecting the levels of tea polyphenols and caffeine in tea leaves. J Agric Food Chem 51: 1864-1873.

Lipton, M., 1991, 'Growing points in poverty research: labour issues', International Institute for Labor Studies Discussion Paper 66, Geneva: IILS.

Lou, W.P., Sun, K., Zhao, Y.M., Deng, S.R., and Zhou, Z.D. 2021. Impact of climate change on inter-annual variation in tea plant output in Zhejiang, China. *Int. J. Climatol. 41: 479-490*

M.A. Wijeratne, M.A., Anandacoomaraswamy, A., Amarathungal, M.K.S.L.D. , Ratnasiri, J., Basnayake, B.R.S.B., and Kalra, N. 2007. Assessment of impact of climate change on productivity of tea (Camellia sinensis L.) plantations in *Journal of the National Science Foundation of Sri Lanka Sri Lanka*,35:(2):119-126

Malahlela O.E, Cho M.A., Mutanga O. 2015. Mapping the occurrence of *Chromolaena odorata* (L.) in subtropical forest gaps using environmental and remote sensing data. *Biological Invasions*, 17: 2027-2042.

Mallik, P., and Ghosh, T., 2022. Impact of climate on tea production: a study of the Dooars region in India. *Theor Appl Climatol* **147**, 559-573. https://doi.org/10.1007/s00704-021-03848-x

Maritim, T. K., Kamunya, S. M., Mireji, P., Mwendia, V., Muoki, R. C., and Cheruiyot, E. K., 2015. Physiological and biochemical responses of tea (*Camellia sinensis* L. O. Kuntze) to water deficit stress. *J. Hortic. Sci. Biotechnol. 90, 395-400.* doi: 10.1080/14620316.2015.11513200

Marx, W., Haunschild, R. and Bornmann, L. 2017. Global warming and tea production – the bibliometric view on a newly emerging research topic. Climate, 5(46): 1-14. Doi:10.3390/cli5030046.

Mckee T.B, Nolan J, Kleist J. 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology.

Melican, N. 2004. Potential Production of High Quality Orthodox Tea in Rwanda, and Organizational Constraints at Kitabi and Mata Units, International Inc: ADAR Project.

Meru B.M. 2018. Use of GIS and Remote sensing in Tea mapping Monitor Tea Status and Forecast Yield: A Case Study at Tanuyen, Laichau, Vietnam. *Remote sensing*, 12: 1814.

Mlenga D.H., Jordaan A.J., Mandebvu B. 2017. Integrating Standard Precipitation Index and Normalised Difference Vegetation Index for near-real-time drought monitoring in Eswatini. Jàmbá,11(1): pp.1-9.

Moon, H.C., Rugman, A.M, and Verbeke, A. 1995. The generalised double diamond approach to international competitiveness. In Rugman, A.M (ed) Research in Global Strategic Management: *A review manual* 5: 97-114

Mouton, J., 2001. How to succeed in your Master's and Doctoral Studies. A South

Muoki, C.R., Maritim, T.K., Oluoch, W.A., Kamunya, S.M. and Bore, J.K., 2020. Combating Climate Change in the Kenyan Tea Industry. *Front. Plant Sci. 11:339*. doi: 10.3389/fpls.2020.00339

Muoki, R. C., Paul, A., and Kumar, S., 2012. A shared response of thaumatin like protein, chitinase and late embryogenesis abundant protein to environmental stresses in tea (*Camellia sinensis* L. O. Kuntze). *Funct. Intergr. Genomic. 12, 565-571*. doi: 10.1007/s10142-012-0279-y.

Nesamvuni, A.E., Tshikolomo, K. A., Nephawe, K.A., Topham, R.W., and Mpandeli, N. S. 2014. Employee Perception on Determinants of Tea Enterprise Competitiveness: A Case of Tshivhase-Mukumbani Estate in Limpopo Province of South Africa. International Journal of Agric. Extension 2(3): 193-203.

Nesamvuni, AE, Bokosi, J., Tshikolomo, K.A., Mpandeli, S.M., and Nesamvuni, C.N. 2022. Tea Value Chains Viability in Limpopo Province of South Africa: A Cost-benefit Analysis. In: Sustainable Agricultural Value Chain. Book edited by: Dr. Habtamu Alem. IntechOpen (ISBN: 978-1-83969-756-2)

Niinemets, Ü. 2015. Uncovering the hidden facets of drought stress: secondary metabolites make the difference. *Tree Physiology*, 36: 129-132.

Nowogrodzki, A., 2019. The changing seasons of tea. *Nature 566 S10-1*

Ochieng, J., Kirimi, L. and Mathenge, M. 2016. Effects of climate variability and change on agricultural production: The case of small scale farmers in Kenya. NJAS-Wageningen Journal of Life Science, 77: 71-78.

Ochieng, J., Kirimi, L. and Mathenge, M., 2016. Effects of climate variability and change on agricultural production: The case of small-scale farmers in Kenya. *NJAS-Wageningen Journal of Life Science, 77: 71-78.*

OXFORD ENGLISH DICTIONARY. 2002. Paperback Oxford English Dictionary, Oxford University Press.

Pandey A.K., Sinniah G.D., Babu A., and Tanti, A.2021. How the Global Tea Industry Copes with Fungal Diseases – Challenges and Opportunities. *Plant Disease*

Papalexiou, S. M., AghaKouchak, A., Trenberth, K. E., and Foufoula-Georgiou, E., 2018. Global, regional, and megacity trends in the highest temperature of the year: diagnostics and evidence for accelerating trends. *Earth Future 6, 71-79.* doi: 10.1002/2017EF000709

Parida, B.R, Mahato T, GHOSH S. 2023. Monitoring tea plantations during 1990-2022 using multi-temporal satellite data in Assam (India). Tropical Ecology,24:1-12. doi:10.1007/s42965-023-00304-x.

Patra, P.S., Bisen, J.S., Kumar, R., Choubey, M., Basu Mazumdar, A., Singh, M., and Bera, B., 2013. Effect of climate change on production of Darjeeling Tea: A case study in Darjeeling Tea Research & Development Centre, Tea Board, Kurseong. *Global Journal of Biology, Agriculture and Health Sciences, 2(4):174-180.* ISSN: 2319-5584.

Pervin M., Unno K., Ohishi T., Tanabe H., Miyoshi N., and Nakamura Y. 2018. Beneficial effects of green tea catechins on neurodegenerative diseases. *Molecules*, 23 (6): 1297

Petit, M and Gnaegy, S. 1994. Agricultural competitiveness and Global trade: Looking at the future of agriculture through a crystal ball. Paper delivered at the 21st International Conference of Agricultural Economics, Harare, Zimbabwe 22-29 August 1994.

Phan P., Chen, C., Xu, L., Chen, Z. (2020). Using Multi-Temporal MODIS NDVI Data to Monitor Tea Status and Forecast Yield: A Case Study at Tanuyen, Laichau, Vietnam. *Remote sensing*, 12:1814.

Pitts, E and Lagnevik, M. 1997. *What determines food industry competitiveness?* In: Traill, W.B & Pitts, E.(eds), Competitiveness in the food industry. Blackie Academic & Professional London.

Porter, M.E. 1998. The competitive advantage of nations London. McMillan

Porter, M.E. 2011. The competitive advantage of nations. New York: The Free Press.

Pritchard, B., Rammohan, A., Sekher, M., Parasuramn, S., Choithani, C., 2013. Feeding India: Livelihoods, Entitlements and Capabilities. Routledge, London.

QGIS Development Team (2023) QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org.

Rahman, M.M., 2022. Effect of Rainfall Pattern on the Tea Production in Bangladesh: An Analysis of Socio-economic Perspectives. *Journal of Agroforestry and Environment, 15(1):43-55. DOI:* *https://doi.org/10.55706/jae1507* 43

Ramadanningrum D.P., Kamal M., Sigit S.H. 2020. Image-based tea yield estimation using Landsat-8 OLI and Sentinel-2B images. *Remote Sensing Applications: Society and Environment*, 20:100424

Ramoelo A., Cho M.A., Mathieu R., Madonsela S., van de Kerchove R., Kaszta Z., and Wolff E. 2015. Monitoring grass nutrients and biomass as indicators of rangeland quality and quantity using random forest modelling and WorldView-2 data. *International Journal of Applied Earth Observation and Geoinformation*, 43: 43-54.

Rao, N.S., Carruthers, T.J.B., Anderson, P., Sivo, L., Saxby, T., Durbin, T., Jungblut, V., Hills, T., Chape, S. 2013. In: An economic analysis of ecosystem-based adaptation and engineering options for climate change adaptation in Lami Town, Republic of the Fiji Islands. A technical report by the Secretariat of the Pacific Regional Environment Programme, Apia, Samoa.

Raper R.L. 2005. Agricultural traffic impacts on soil. *Journal of Terramechanics*, 42(3-4): 259-280.

Rice, J.A., 2007. Mathematical Statistics and data analysis (Third Ed.). Brooks / Cole, Cengage Learning. Belmont, CA 94002-3098, USA.

Ringler, C., Bhaduri, A., Lawford, R. 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustainability 5, 617-624.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14, 32.

Rokhmah, D.N., Astutik, D. and Supriadi, H., 2022. *IOP Conf. Ser.: Earth Environ. Sci.* 1038 012015.

Rokhmah, D.N., Wibowo, N.A. and Supriadi, H., 2016. Tea plant cultivation for adaptation and mitigation of climate change *Innovation on Biotic and Abiotic Stress Management to Maintain Productivity of Spice Crops in Indonesia*, ed S.R. Djiwanti, H. Supriadi, A. Wahyudi, D. Wahyuno, H. Nurhayati, D.J. Bagyaraj and S.C. Kaushik (Jakarta: IAARD Press) p. 267.

Roy, S., Barooah, A.K., Ahmed, K.Z., Baruah, R.D., Prasad, A.K. and Mukhopadhyay, A., 2019. Impact of climate change on tea pest status in northeast India and effective plans for mitigation. *Acta Aecologica Sinica* 30, 1-11.

Royimani L., Mutanga O., Odindi J., Dube T., Matongera T.N. 2019. Advancements in satellite remote sensing for mapping and monitoring of alien invasive plant species (AIPs). *Physics and Chemistry of the Earth, Parts A/B/C*, 112: 237-245.

Ruan, J., Ma L., Shi, Y. and Han, W., 2003. Uptake of fluoride by tea plant (Camellia sinensis L) and the impact of aluminium. J Sci Food Agric., 83:1342-1348.

Rugman, A.M and D'Cruz, J,R. 1993. The double diamond model of international competitiveness: Canada's experience. *Management Review* 33 (2): 17-39.

Salimi, K.M., Gonbad, R.A. and Shaigan, S., 2021. Drip Irrigation, an Effective Method to Improve the Quantitative and Qualitative Characteristics of Tea Green Leaves in Water Stress Conditions. *Environ. Water Eng., 2022, 8(1), 63-78.* DOI: 10.22034/JEWE.2021.286256.1567.

Schepp, K. 2009. Strategy to adapt to climate change for Michimikuru tea farmers in Kenya. AdapCC Report. Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany. Available: http://adapcc.org/en/kenya.htm

Schepp, K. 2009. Strategy to adapt to climate change for Michimikuru tea farmers in Kenya. AdapCC Report. Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany. Available: http://adapcc.org/en/kenya.htm

Sciona (2003) 'Storm in a teacup'. Website: http://www.sciona.com/coresite/nutrition/articles/storm_teacup.htm

Sekiyama,A., Sato, K., Shimada, Fujikawa, T. 2020. Monitoring The Growth and Quality of Japanese Green Tea by UAV Imagery. *Agro for International Journal*, 5(2):27-34

Sellers P.J. 1985. Canopy reflectance, photosynthesis, and transpiration. International Journal of Remote Sensing, 6: 1335-1372.

Senamaw. A, Addisu, S, .Suryabhagavan, KV. 2021. Mapping the spatial and temporal variation of agricultural and meteorological drought using geospatial techniques, Ethiopia. Environmental Systems Research, 10(15).https://doi.org/10.1186/s40068-020-00204-2.

Shah, M., Fischer, G., and van Velthuizen, H., 2008. Food security and sustainable agriculture: the challenges of climate change in Sub-Saharan Africa. *International Institute for Applied*

Sharples, J.A. 1990. Cost of production and productivity in analysing trade and competitiveness. *American Journal of Agricultural Economics* 72: 1278-1282

Shoubo H. 1989. Meteorology of the tea plants in China: A review. *Agricultural and Forest Meteorology*, 47: 19-30.

Singhal, G, Bansod, B., Mathew, L., Goswami, J., Choudhury, B.U., Raju, P.L.N. 2019. Chlorophyll estimation using multi-spectral unmanned aerial system based on machine learning techniques. *Remote Sensing Applications: Society and Environment*, 15:100235

Sivaram, B. 1992. A handbook on family health and welfare in plantations, ILO – Geneva. Available from http://www.ilo.ch/public/english/dialogue /proasia3.htm

Sivaram, B. 1994. Productivity improvement and labour relations in the tea industry in South Asia, ILO. 100th Session of International Labor Conference. ILO – Geneva. Available from http://www.ilo.ch/public/english/dialogue /proasia2.htm

Smith J.K. 1983. Quantitative versus ,qualitative research: An attempt to clarify the issue. Educational Researcher, 12: 6-13.

STATISTA. Consumer Goods & FMCG. Non-alcoholic Beverages. Volume of tea consumption worldwide from 2012 to 2025. Accessed on: 11-01-2024, at: https://www.statista.com/statistics/940102/global-tea-consumption/#:~:text=In%202022%2C%20global%20consumption%20of,7.4%20billion%20kilograms%20by%202025.&text=Tea%20is%20the%20second%20most,in%20the%20world%2C%20after%20water.

Stilo. F., Tredici, G., Bicchi, C., Robbat, A. Jr, Morimoto, J. and Cordero, C. 2020. Climate and processing effects on tea (Camellia sinensis L. Kuntze) metabolome: accurate profiling and fingerprinting by comprehensive two-dimensional gas chromatography/time-of-flight mass spectrometry. *Molecules. 25 2447* Sustainability challenges in uji tea cultivation. *Procedia Environmental Sciences,* **20:** 823-831

Tang G.Y., Meng X., Gan R.Y., Zhao C.N., Liu Q., Feng Y.B., Li S., Wei X.L., Atanasov A.G., Corke H., Li H.B. 2019. Health functions and related molecular mechanisms of tea components: an update review. *International Journal of Molecular Sciences*, 20 (24):6196

Tanton T.W. 1992.Tea crop physiology. pp 173-199

Tashakkori, A. and Teddlie, C. 1998. Mixed Methodology: Combining Qualitative and Quantitative Approaches, Thousand Oaks CA: Sage Publications.

Tea Board of Bangladesh, India and Sri Lanka 2010: Tea statistics.

Thi, N.Q, Govind, A, Le, M., Linh, N.T., Ahn, T.T.M, Hai N.K., Ha T.V. 2023. Spatiotemporal characterization of droughts and vegetation response in Northwest Africa from 1981 to 2020. The Egyptian Journal of Remote Sensing and Space Sciences, 26(3): 393-401.

Tibpromma S., Dong Y., Ranjitkar S., Schaefer D.A, Karunarathna S.C, Hyde K.D, Jayawardena R.S, Manawasinghe I.S, Bebber D.P, Promputtha I, Xu J, Mortimer P.E., Sheng J. 2021. Climate-Fungal Pathogen Modeling Predicts Loss of Up to One-Third of Tea Growing Areas. Frontiers in Cellular and Infection Microbiology, **11**:610567. doi: 10.3389/fcimb.2021.610567

TRFK (Tea Research Foundation of Kenya), 2002. Tea Growers' Handbook. 5th ed. Kijabe Printing Press, Kijabe, Kenya.

Tuwei, G., Kaptich, F.K.K., Langat, M.C., Smith, B.G. and Corley, R.H.V., 2008. Effects of grafting on tea 2: Drought tolerance. *Experimental Agriculture,* **44:** 4 537.

Twinings(2003b)'Tea production'. Website:http://www.twinings.com/en_int/tea_production/tea_prod.html.

Twinings. 2011. History of South African tea. http://www.twinings.com/en int/world of tea/southafrica prof.html

U.S. Pharmacopeia. (n.d.). Botanical Extracts. Retrieved 07 23, 2015, from www.pharmacopeia.cn: http://www.pharmacopeia.cn/v29240/usp29nf24s0_c565.html

UNESCO. (2003). Water for People, Water for Life: The United Nations World Water Development Report. Oxford: UNESCO Publishing, Paris/ Berghahn Books.

United Nations. 2012. The future we want. In: Resolution 66/288. Rio + 20 United Nations Conference on Sustainable Development. UN General Assembly, Rio de Janeiro, Brazil.

United Nations. 2014. Introduction and Proposed Goals and Targets on Sustainable Development for the Post 2015 Development Agenda. United Nations Online at hhttp://sustainabledevelopment.un.org/content/ documents/4528zerodraft12OWG.pdfi (accessed September 2014).

van Wyk, B.-E., & Wink, M. 2015. Phytomedicines, herbal drugs & plant poisons. Pretoria: Briza Publications.

Verschuur J., Li S., Wolski P., Otto F.E.L. 2021. Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. Scientific Reports, 11: 3852.

Waheed, A., Hamid F. S., Ahmad, H., Aslam, S., Ahmad, N., Akbar A. 2013. Different climatic data observation and its effect on tea crops. J. Mater. Environ. Sci. 4 (2): 299-308 I am running a few minutes late; my previous meeting is running over.

Wang, Y., Li, Y., Wang, J.H., Xiang, Z., Xi, P.Y. and Zhao, D.G., 2021. Physiological changes and differential gene expression of tea plants (Camellia sinensis (L.) Kuntze) under cold stress. *DNA and Cell Biology, 40: 906-920*

WCED, 1987. Our Common Future. World Commission on Environment and Development, Oxford.

WCO. 2012. HS Nomenclature 2012 Edition. Retrieved 07 26, 2015, from World Customs Organization: http://www.wcoomd.org/en/topics/nomenclature/instrument-and-tools/hs_nomenclature_2012/hs_nomenclature_table_2012.aspx

Wei T, Simko V. 2021. R package 'corrplot': Visualization of a Correlation Matrix. (Version 0.92), https://github.com/taiyun/corrplot.

Wei, L. and Li, J., 2014. Analysis for effects of social capital and human capital of agricultural industry cluster on farmers' income. *Issues in Agricultural Economy, 12: 41-47.*

Welman, C., Kruger, F. and Mitchell, B., 2005. Research Methodology, 3rd Edition. Oxford, Cape Town, South Africa.

Wesumperuma, D.; Gooneratne, W.; Fernando, N.A. 1985. Labor absorption in the plantation crop sector of Sri Lanka.

Wickham, H., Averick, M., Bryan, J., Chang, W., Mcgowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., … Yutani, H. 2019. Welcome to the tidyverse. Journal of Open Source Software, 4(43): 1686.

Wijeratne, M.A. and Chandrapala, L., 2014. Climatic variations in tea growing regions and vulnerability of tea plantations to climate change. *Proceedings of the 228th experiments and extension forum* p. 8-19

Wijeratne, M.A., 1996. Vulnerability of Sri Lanka tea production to global climate change. Water, Air, and Soil Pollution, 92: 87-94.

Wijeratne, M.A., Anandacoomaraswamy, A., Amarathunga, M.K.S.L.D., Ratnasiri, J., Basnayake, B.R.S.B. and Kalra, N. 2007. Assessment of impact of climate change on productivity of tea (Camellia sinensis L.) plantations in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka*, 35: 119-126.

Wirabudi, A.A., Munadi, R., and Rusdinar, Angga. 2019. Design Autonomous Drone Control for Monitoring Tea Plantation Using Dynamic Programming and Kruskal. *e-Proceeding of Engineering*,6(1): 1620

World Economic Forum (WEF), 2011. Water Security: The Water-Food-Energy-Climate Nexus. World Economic Forum, Washington DC.

Worley, T. 1996. PNW Agricultural Trade: Comparative advantage and competitiveness are fundamental web page: http://ag.arizona.edu/ AREC/ WEMC/PAPER/PNWAG TRADE.html.

WWAP (United Nations World Water Assessment Programme). 2015. The United Nations World Water Development Report 2015: Water for a Sustainable World. UNESCO, Paris.

Xu, H. 2006. Modification of normalized difference water index (NDWI) to enhance open water features in remotely sensed imagery. International Journal of Remote Sensing, **27(14):**3025-3033.

Yamashita T, Yamashita K, Kamimura R. 2007. A Stepwise AIC Method for Variable Selection in Linear Regression, Communications in Statistics – Theory and Methods, 36(13): 2395-2403, DOI: 10.1080/03610920701215639.

Yashin, A.Y., Nemzer, B.V., Combet-Aspray, E. and Yashin, Y.I., 2015. Determination of the chemical composition of tea by chromatographic methods: a review*. J. Food Res. 4: 56-87.*

Yemane, M., Chandravanshi, B.S. and Wondimu, T., 2008. Levels of essential and non-essential metals in leaves of the tea plant (Camellia sinensis L.) and soil of Wushwush farms, Ethiopia. Food Chemistry, 107: 1236-1243.

Yin, R. K. 1989. Case study research: Design and methods. London: Sage Publications.

Zhang M., Zhang X., Ho, C.T., Huang Q.R. Chemistry and health effect of tea polyphenol (-)-epigallocatechin 3-o-(3-o-methyl) gallate. *Journal of Agricultural and Food Chemistry*, 67 (19):5374-5378

Zhang Q, Wan, B, Cao, Z., Zhang, Q and Wang, D. 2021. Exploring the Potential of Unmanned Aerial Vehicle (UAV) Remote Sensing for Mapping Plucking Area of Tea Plantations. *Forests*, 12:121

Zhang Y.T., Li Q., Xing H., Lu, X.F., Zhao L.S., Qu K.K., Bi K.S.2013. Evaluation of antioxidant activity of ten compounds in different tea samples by means of an on-line HPLC-DPPH assay. *Food Research International*, 53 (2):847-856,

Zhang, L., Zhang, H., , Chen, Y., Dai, S., Li, X., Imou, K., Liu, Z., and Li, M. 2019. Real-time monitoring of optimum timing for harvesting fresh tea leaves based on machine vision. *International Journal Agricultural and Biological Engineering*, 12:1

Zhao C.N., Tang G.Y., Cao S.Y., Xu X.Y., Gan R.Y., Liu Q., Mao Q.Q. , Shang A., and Li H.B.2019.Phenolic profiles and antioxidant activities of 30 tea infusions from green, black, oolong, white, yellow, and dark teas .*Antioxidants,* 8 (7):215

Zhao Q., Chen Q., Jiao M., Wu P., Gao X., Ma M., Hong Y. 2018. The temporal-spatial characteristics of drought in the Loess Plateau using the remote-sensed TRMM precipitation data from 1998 to 2014. Remote Sensing, 10(6):838

Zhu J., Pan Z., Huang P., Sun J., Qin F., and Liu Z. 2019.An Improved Multi-temporal and Multi-feature Tea Plantation Identification Method Using Sentinel-2 Imagery. *Sensors*, 19:2087.

# ANNEXURE 1 PUBLICATIONS AND CAPACITY BUILDING REPORT

## CAPACITY BUILDING REPORT AND PUBLICATIONS

### 1. Introductions

The project was designed to build capacity throughout the value chain to completion. Postdoctoral students were involved in planning, data collection, and workshops to draft papers and publications. The following postdoctoral students were part of the project (Khuthadzo Ndwambi, Jutas Mavhungu, and Alissa Terblanché). The three doctoral students (Nembambula Fhulufhedzani, Maele Lebogang Merium, and Ranwedzi Ndivhuwo are at the stage of data collection for their specific projects. One Masters student, Livhuwani Nthangeni, is also at the level of data collection.

### 2. Student Capacity Building

2.1. **Nembambula Fhulufhedzani (PhD)** – Has registered for her second year at UFS. Her proposal has been accepted with the finalization of the Ethical clearance matters. She has contributed to one proceeding paper at an international conference. She was awarded the NRF Bursary for 2024. Overall her study is at data collection.

2.2. **Maele Lebogang Merium (PhD)** – Has registered for her second year at UFS. Her proposal has been accepted with the finalization of the Ethical clearance matters. She has finalised her Literature Review and ready for Data Collection. She was awarded the AGRI-SETA Bursary for 2023-2025. She was also awarded the GreenMatter Scholarship through WRC and Nedbank. She currently busy with the development of the data collection instrument.

2.3. **Ranwedzi Ndivhuwo (PhD)** – Has registered for his second year at UFS. His proposal has been accepted with the finalization of the Ethical clearance matters. He has finalized his Literature Review and Methods Chapters ready for Data Collection. He has contributed to one published paper. He currently busy with the development of the second paper.

2.4. **Livhuwani Nthangeni (Masters Rural Development)** – She is registered for her second year. Done the proposal and the Ethical Clearance. She is at the state of data collection.

## 3. Community Empowerment

The project was centred at the Tshivhase-Mukumbani Tea Estate. The community was very central to the main objective of being empowered. The project collaborating with the Limpopo Economic Development Agency, Provincial Departments of Agriculture and Rural Development, Limpopo Department of Economic Affairs, Environment and Tourism, University of Venda, and The Tshivhase Tribal Authority developed a turnaround strategy for the project. The strategy was submitted to the Member of the Executive Council for implementation. By the time of writing this report, the final consultations on the model of disposal to the community were being finalized.

## 4. Publications

4.1. Nesamvuni, AE, Bokosi, J., Tshikolomo, K.A., Mpandeli, S.M., and Nesamvuni, C.N. 2022. Tea Value Chains Viability in Limpopo Province of South Africa: A Cost-benefit Analysis. In: Sustainable Agricultural Value Chain. Book edited by: Dr. Habtamu Alem. IntechOpen (ISBN: 978-1-83969-756-2)

4.2. Malahlela, O.E., Nembambula, F., and Nesamvuni, A.E. 2024. Assessment Of Long-Term Relationship Between Remotely Sensed-Derived Indices And The Standardized Precipitation Index (Spi) In The Tea Plantation: A Case Study Of Mukumbani Tea Estate, South Africa. 5th International Conference on Agriculture, Food Security and Safety (Agrofood 2024). ISBN 978-955-3450-00-5. Bangalore, India.

## 5. Conclusions

The project achieved its major objectives in terms of:

5.1. Creating a Centre of Excellence with standing networks of academics in SMME, HEI, Science Councils, Government and Farmers

5.2. Human Capital Development: with three Doctoral Students

5.3. Dissemination of Knowledge: One paper will contribute to the conference proceedings with Fhulufhedzani Nembambula as co-author

5.4. Developing policy briefs based on the chapters done for support of government initiatives.