Check for updates

Received: 11 December 2023 | Accepted: 20 June 2024

DOI: 10.1002/uar2.20073

Urban Agriculture & Regional Food Systems OPEN ACCESS

ORIGINAL ARTICLE

Investigating the influence of varying water regimes on the growth and development and nutritional water productivity of bush tea (*Athrixia phylicoides* DC.)

Muneiwa Rumani[1] | **Tafadzwanashe Mabhaudhi**[2,3] | **Takudzwa Mandizvo**[1] | **Anza-Tshilidzi Ramabulana**[4] | **Ntakadzeni Edwin Madala**[5] | **Maanea Lonia Ramphinwa**[6] | **Lembe Samukelo Magwaza**[7,8] | **Fhatuwani Nixwell Mudau**[1]

[1]School of Agricultural Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa

[2]Centre of Transformative Agricultural and Food Systems, University of KwaZulu-Natal, Pietermaritzburg, South Africa

[3]Centre on Climate Change and Planetary Health, London School of Hygiene and Tropical Medicine, London, UK

[4]Department of Nutrition, Faculty of Health Sciences, University of Venda, Thohoyandou, South Africa

[5]Department of Biochemistry and Microbiology, Faculty of Sciences, Agriculture and Engineering, University of Venda, Thohoyandou, South Africa

[6]Department of Plant and Soil Science, Faculty of Sciences, Agriculture and Engineering, University of Venda, Thohoyandou, South Africa

[7]Department of Food Systems and Development, Faculty of Natural and Agricultural Sciences, University of Free State, Bloemfontein, South Africa

[8]Plant Science Laboratory, Cranfield University, Cranfield, UK

Correspondence
Muneiwa Rumani and Fhatuwani Nixwell Mudau, School of Agricultural Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa.
Email: muneiwaabigail@gmail.com and mudauf@ukzn.ac.za

Assigned to Associate Editor Zhanyou Xu.

Funding information
Water Research Commission, Grant/Award Number: C2020/2021-00420

Abstract

Bush tea (*Athrixia phylicoides* DC.) is an indigenous shrub of South Africa known for its medicinal properties. However, due to a lack of comprehensive information to develop suitable irrigation management strategies, the cultivation of bush tea is currently limited to small-scale operations. Considering this limitation, the current research investigated the effect of water regimes on the growth and development, yield, and nutrient content along with its nutritional water productivity (NWP) under field conditions. The treatment consisted of a crop water requirement (ET_a) of 100%, 30%, and the control (stress) in a complete randomized block design (CRBD). Each treatment was replicated three times to ensure robustness and accuracy of the findings. Results demonstrated that the highest gravimetric moisture content readings were found in the control treatment and the lowest in the 100% treatment. Conversely, the 30% ET_a treatment significantly ($p < 0.05$) impacted bush tea's growth, development, productivity, and NWP. However, it was observed that the 100% ET_a treatment resulted in a higher biomass yield (259.1 kg/ha) compared to the 30%

Abbreviations: CRBD, complete randomized block design; ET_a, crop water requirement; ET_o, reference evapotranspiration; NWP, nutritional water productivity; SWC, soil water content; WUE_i, intrinsic water use efficiency; WUE_{inst}, instantaneous water-use efficiency.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.
© 2024 The Author(s). *Urban Agriculture & Regional Food Systems* published by Wiley Periodicals LLC on behalf of American Society of Agronomy and Crop Science Society of America.

ET_a treatment (171.2 kg/ha) and control (stress) (68.2 kg/ha). The water productivity exhibited notable differences across the varying water regimes. These findings contribute valuable insights for developing appropriate irrigation management strategies to overcome existing limitations in the scale of bush tea production. The research lays the groundwork for future studies and practical applications aimed to foster the sustainable cultivation of bush tea in South Africa.

1 | INTRODUCTION

Bush tea (*Athrixia phylicoides* DC.) is a perennial, aromatic, indigenous shrub cultivated in South Africa, well-regarded for its traditional use as an herbal tea and medicinal herb (Lerotholi et al., 2017; Tshikhudo et al., 2019). The plant is known to possess pharmacological properties, and its leaves and stems are rich in bioactive compounds that hold significant medicinal value, including the treatment of heart disease, headaches, and infected wounds (Lobo et al., 2010; Mudau et al., 2007). Additionally, its compounds have been associated with potential benefits in managing high blood pressure, infected throats, and blood purification (Rakuambo et al., 2009). Notably, the edible parts of the plant contain notable levels of polyphenols, tannins, antioxidants, quercetin, and flavonoids, contributing to its therapeutic significance (Tshivhandekano et al., 2018). Despite its valuable attributes, bush tea plants are still primarily gathered from the wild, prompting efforts for their domestication and commercialization (Lerotholi et al., 2017; Reichelt et al., 2012).

Current research has emphasized the influence of cultural practices, mineral nutrition (Mudau et al., 2007; Tshivhandekano et al., 2018), pruning (Mohale et al., 2018), and environmental conditions (Ramphinwa, McHau, et al., 2022; Tshivhandekano et al., 2018) on the growth, development, and quality of the bush tea plant. Bush tea has exhibited some water stress tolerance compared to other tea cultivars; hence, the investigation into the impact of varying water regimes on its production and quality remains limited (Ponmurugan et al., 2016). Water is considered a crucial resource for promoting vegetative growth and reproductive stages, particularly in arid and semi-arid regions, where fluctuations in rainfall can significantly affect plant growth and quality (Chivenge et al., 2015; Rostamza et al., 2011). Prior research has highlighted the influence of water stress on various plant species, indicating its significance in plant biomass, leaf area, and secondary metabolite production (Chiappero et al., 2019).

Environmental conditions significantly impact the growth and development of bush tea. Furthermore, Ramphinwa et al. (2022) found that the application of shade nets in tea cultivation areas has been documented to enhance tea leaf quality through increased amino acid concentration, decreased catechin content, and prevention of flavonoid accumulation, ultimately leading to improved plant growth and productivity. Bush tea is harvested from the wild and while the domestication of this crop is now critical due to its commercial potential, the investigation into the impact of varying water regimes on its growth, development, and yield is imperative. Therefore, the main objective of this study was to assess the response of bush tea to different water regimes, particularly focusing on plant growth, development, and yield.

2 | MATERIALS AND METHODS

2.1 | Plant material, site description, and experimental design

A field experiment was conducted from spring to summer season in the year 2022 at the Controlled Environment Research Unit (CERU), located at the University of KwaZulu-Natal (UKZN) in Pietermaritzburg, South Africa (29°37′ S; 30°16′ E). The region experiences an annual rainfall of 400 mm, with 45% occurring during rainy days from June to August, typical of its humid, sub-tropical climate. Temperature fluctuations are significant, ranging from a maximum of 33°C during summer to a minimum of around 26°C in winter. The soil from the experimental site was sampled randomly at the beginning of the trial from a depth of 0–30 cm using a soil auger. Thereafter, the soil samples were then submitted to the Institute for Commercial Forestry Research (ICFR) Analytical and Research Laboratory to determine chemical and physical properties. The type of soil at the experimental site is predominantly characterized as loam (Table 1). The bush tea stem cuttings used in the study were sourced from the Agricultural Research Council (ARC) in Nelspruit, Mpumalanga province, South Africa (25°.4518′ S, 30°.9697′ E). Thereafter, two propagation media, sand and pine bark, were randomly assigned to seedling trays with 5 × 3 × 4.5 cm (width, breadth, and depth) cells. Cuttings were treated with Seradix No. 2 and planted in trays with a 2:1 ratio of pine bark to sand, each containing 45 cuttings. The trays were initially placed in shade netting and later transferred to a greenhouse, with irrigation adjusted based on solar radiation and plant size to maintain soil moisture. Bush tea plants were transplanted to the experimental field 80 days after the cuttings were set (Maedza, 2015).

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

The experiment was laid out in a complete randomized block design (CRBD) with three treatments (100%, 30%, and control [stress] of crop water requirement [ET_a]), replicated three times. The total plot area was 100 m^2, and the plant population was kept at 6944.44 plants/ha. The size of the individual plots was 10 m × 10 m. Each plot consisted of two plant rows, 1.2 m and 0.75 m (inter- and intra-row spacing), giving a total of 12 plants per plot. Weeding was done by hand prior to crop establishment and then weekly until the crop reached full maturity. The irrigation schedule was determined by the daily ET_a from the product of normal tea (unshaded) crop factors (Table 2), and the monthly average reference evapotranspiration (ET_o) was determined daily throughout the experimental period, enabling an accurate timely response to the plant's water needs. The on-site automatic weather station of the Discipline of Agrometeorology was used to collect the evapotranspiration reference data. All treatments were irrigated to reach field capacity before starting the treatments. This practice was adopted to minimize potential losses from evaporation and drainage and to ensure that the soil maintained adequate moisture levels during the critical peak periods of the day (Table 2). As a result, the ET_a was calculated using Equation (1):

$$ET_a = ET_o \times K_c \quad (1)$$

2.2 | Data collection

Weather data were obtained from an automated weather station using honest observer by onset data logger sensors (Onset Computer Corporation) (Table 3). The data were measured during spring and summer cropping season, from August 30 to November 1, 2022. Daily meteorological data considered included minimum (T_{min}) and maximum (T_{max}), air temperature (°C), solar radiation, relative humidity rainfall, and reference evapotranspiration (mm) was calculated using the Food Agriculture Organization calculator. The soil water content was determined through gravimetric sampling. Six soil samples were collected at a depth of 30 cm from all water treatments in each plot and sealed in zip-lock bags to prevent moisture loss. Subsequently, the gravimetric water content was calculated using Equation (2):

$$(\theta g) = \left(\frac{\theta \text{wet} - \theta \text{dry}}{\theta \text{dry}}\right) \times 100\,\% \quad (2)$$

where θg is the Gravimetric moisture content (%), θwet is the wet soil (g), and θdry is the dry soil (g).

Equation (3) is used to calculate volumetric water content from gravimetric water content:

$$(\theta v) = \theta g \times \left(\frac{P\text{soil}}{P\text{water}}\right) \quad (3)$$

Core Ideas

- Bush tea is an indigenous shrub of South Africa known for its medicinal properties.
- Water serves as a fundamental component for the growth and development of medicinal plants, playing a crucial role.
- Bush tea and water management contribute to food security, offering potential nutritional and medicinal properties.

TABLE 1 Physical and chemical characteristics of soil in the field.

Clay (%)	Organic C (%)	pH (KCl)	P (cmol/kg)	Ca (cmol/kg)	K (cmol/kg)	Mg (cmol/kg)	Na (cmol/kg)	N (%)
21.1	2.70	5.20	15.75	8.16	0.68	1.49	0.05	0.19

TABLE 2 Crop water requirements of bush tea in response to varying water regimes.

K_c		ET_o (mm)	ET_a (mm)	Duration (days)	Total water applied (mm)
Initial	0.95	10.2	9.96	40	408
Mid-season	1.00	8.61	8.61	61	525.21
Late season	1.00	12.2	12.2	28	341.60
Water applied (ET_a)					
100%					1274.81
30%					382.44
0%					0

Note: K_c, crop factor based on Allen et al. (1998); ET_o, reference evapotranspiration; ET_a, crop water requirement, which was measured during the spring to summer season of the year 2022.

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 3 Rainfall and temperature data for the duration of the experimental period from the UKZN CERU field.

	Total	June	July	August	September	October	November
Rainfall (mm)	299	11	9	30	42	95	110
$Temp_{min}$ (°C)	90	10	9	30	11	13	16
$Temp_{max}$ (°C)	150	22	24	26	28	23	25

Note: $Temp_{min}$ and $Temp_{max}$ represent the minimum and maximum temperatures, respectively, recorded during the growing season.

where θv is the volumetric moisture content (%), θg is the gravimetric moisture content (%), Psoil is the bulk density of that given soil (g/cm^3), and Pwater is the water density (g/cm^3).

Crop water use was then determined using Equation (4):

$$ET_a = P \pm \Delta SWC \quad (4)$$

where ET_a is the actual evapotranspiration (mm), P is the precipitation (mm), and ΔSWC is the changes in soil water content (mm).

2.3 | Morphological measurements

Leaf gas exchange and chlorophyll measurements were measured using LI-6400 XT Portable Photosynthesis System (Licor Bioscience, Inc.) integrated with an infrared gas analyzer (IRGA) attached to a leaf chamber fluorometer (640040B, 2 cm^2 leaf area, Licor Bioscience, Inc.). Measurements were taken on the third half-fully formed leaf from the plant's tip between 08:30 a.m. and 11:30 a.m. by clamping the leaf inside the sensor head, with analysis conducted from the vegetative stage to harvesting (Figure 1), with three plants from each treatment, replicated three times.

2.4 | Yield

The assessment of yield included the measurement of biomass with the collection of bush tea samples taking place 119 days after planting. A comprehensive assessment of bush tea yield components was conducted by sampling three plants for each treatment. The measurements recorded on a plot basis included the yield, focusing on the fresh above-ground mass.

2.5 | Determination of water productivity

Water productivity was calculated using Equation (5):

$$WP = Y_a/ET_a \quad (5)$$

where WP is the water productivity (kg/m^3), Y_a is the biomass, and ET_a is the water applied based on crop water requirement.

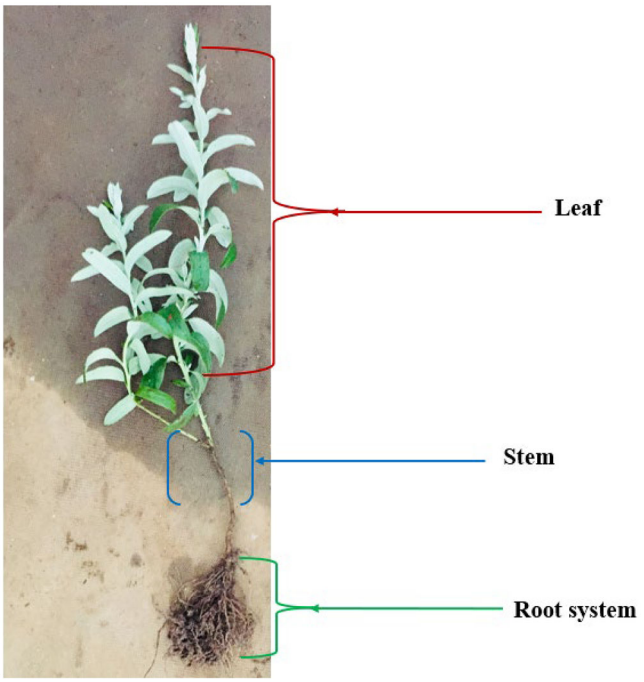

FIGURE 1 Bush tea plant at harvest.

2.6 | Determination of nutritional composition

The aerial parts of bush tea plant were freeze-dried using a model RV3 vacuum freeze drier (Edwards) immediately after yield determination to preserve nutrients and avoid further metabolic reactions. Thereafter, samples were ground using mortar and pestle and analyzed for nutritional content. The nutrients analyzed per dry matter basis included macro-nutrients (calcium [Ca], magnesium [Mg], and potassium [K]) and micro-nutrients (copper [Cu], zinc [Zn], iron [Fe], manganese [Mn], and sodium [Na]).

2.7 | Determination of nutritional water productivity (NWP)

Nutritional water productivity was calculated using Equation (6):

$$NWP = (Ya/ET_a) \times NC \quad (6)$$

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uaf2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

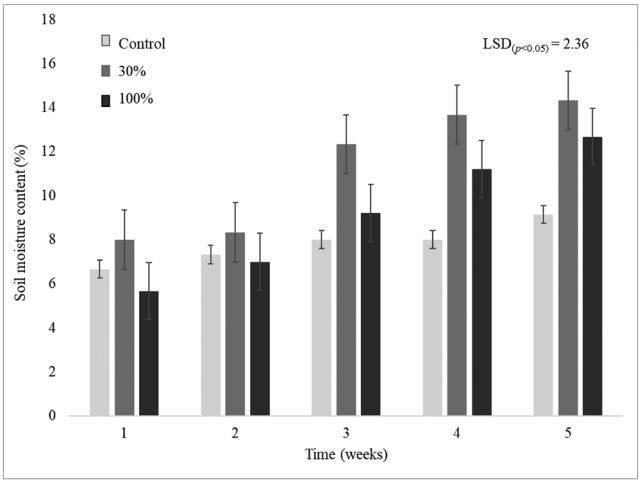

FIGURE 2 Soil water content (%) under varying water regimes of bush tea over 5-week period.

where NWP is the nutritional water productivity (nutrition/m^3 of water evapotranspired), *Ya* is the actual harvested yield (kg/ha), ET_a is the water applied based on crop water requirement (m^3/ha), and NC is the nutritional content (kg^{-1}).

2.8 | Statistical analysis

Data were subjected to analysis of variance using GenStat version 20 (VSN International). The least significant difference (LSD) was used to separate means at the 5% significance level.

3 | RESULTS AND DISCUSSION

3.1 | Soil water content

The data in Figure 2 displays the gravimetric sampling of soil water content (SWC) under different water regimes (ET_a levels) over 5 weeks. The results illustrate significant differences in soil moisture levels among the water treatments. Notably, the 30% ET_a water treatment exhibited the highest SWC, peaking at 15% during the study period, followed by the 100% ET_a treatment with a maximum of 12%, and the control group with a peak SWC of 9%. These findings underscore the critical role of soil water content in influencing various aspects of plant development, productivity, and soil temperature, as well as the overall water dynamics within the soil (Deutsch et al., 2010). Moreover, the presence of higher moisture content in the unsaturated root zone indicates that bush tea plants prefer moderately moist soil conditions rather than excessively wet environments (Choi & Jacobs, 2007). These observations may be attributed to the complex interplay of factors, such as soil texture and pore size distribution, which impact water depletion rates in different plant species (Gatabazi et al., 2022).

TABLE 4 Yield components of bush tea under varying water treatments (30% ET_a, 100% ET_a, and control).

Water treatments (ET_a)	Yield (kg/ha)	WP (kg/m^3)
Control	68.2a	0a
30%	171.2b	570.5b
100%	259.1c	259.1c
$LSD_{(p < 5\%)}$	7.91	8.33

Note: Water productivity (WP) represents the total biomass, including leaves. The yield and WP values are statistically significant according to the least significant difference (LSD) (5% level). Lowercase letters indicate the signficant differences.

3.2 | Yield

The study revealed significant differences in yield parameters, specifically in yield and water productivity (WP), among varying water treatments for bush tea plants (Table 4). The highest recorded yield was observed in the 100% water treatment, amounting to 259.1 kg/ha, surpassing the 30% treatment, which yielded 171.2 kg/ha. Conversely, the control treatment exhibited the lowest yield at 68.2 kg/ha. This reduction in yield under the control treatment could be attributed to water stress, a known factor limiting plant growth and crop yield across various agricultural settings (Gatabazi et al., 2022). These findings align with the observations made by Keshavarz Mirzamohammadi et al. (2021), who noted that water stress during the vegetative phase can impede cell division and expansion, ultimately leading to reduced plant growth and development.

Additionally, water-deficient plants tend to close stomata and restrict nutrient uptake in the root system, culminating in decreased dry matter accumulation (Keshavarz & Khodabin, 2019). Furthermore, drought-induced reductions in the leaf area index during the growing season can limit biological yield by diminishing photosynthetic rates (Yang et al., 2018). In terms of WP, water treatments also exerted a significant influence ($p < 0.05$). The 100% water treatment exhibited the highest WP, with a yield of 570.5 kg·ha, outperforming other treatments. These results are consistent with those presented by Rahil (2022), who emphasized the direct relationship between the volume of water applied and the observed results. This outcome was likely influenced by the full application of water in the 100% treatment. The current study's results are in line with those reported by Mabhaudhi et al. (2019) and Motsa et al. (2015), who employed similar water treatments in their research on sweet potato production.

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 5 Nutritional composition of bush tea under three water treatments (30% ET_a, 100% ET_a, and control).

Water treatments (ET_a)	Ca (mg/L)	Cu (mg/L)	Fe (mg/L)	K (mg/L)	Mg (mg/L)	Mn (mg/L)	Zn (mg/L)
Control	127.3a	0.207a	9.60a	137a	43.4a	2.133a	2.173a
30%	624.7c	2.433c	18.07c	1175.3c	817.0c	10.20c	7.933c
100%	422.0b	1.523b	13.60b	870.0b	501.0b	4.803b	3.40b
$LSD_{(p < 0.05)}$	4.5	0.23	2.3	1.78	1.73	1.60	6.90

Note: Lowercase letters indicate the signficant differences.
Abbreviation: LSD, least significant difference.

TABLE 6 Nutritional water productivity of bush tea under three water treatments (30% ET_a, 100% ET_a, and control).

Water treatments (ET_a)	NWP_Ca (mg/L)	NWP_Cu (mg/L)	NWP_Fe (mg/L)	NWP_K (mg/L)	NWP_Mg (mg/L)	NWP_Mn (mg/L)	NWP_Zn (mg/L)
Control	0a	0a	0a	0a	0a	0a	0a
30%	78,694c	317.9c	18.07c	1175.3c	817.0c	10.2c	1018.7c
100%	17,296b	62.8b	13.60b	870.0b	501.0b	4.80b	789.7b
LSD $_{(p < 0.05)}$	5.68	6.01	2.0	1.78	1.63	1.60	6.90

Note: NWP_ micro and macronutrients (ppm/mg/L): This denotes the analysis of variance concentration of micro- or macronutrients in milligrams per liter of water. The lowercase letters indicate the signficant differences.
Abbreviation: LSD, least significant difference; NWP, nutritional water productivity.

3.3 | Nutritional composition

The results indicated that the nutritional composition of bush tea plants was significantly influenced by the varying water regimes. Notably, the 30% ET_a treatment demonstrated the highest nutritional composition, with increased levels of essential elements such as Ca, Cu, Fe, K, Mg, Mn, and Zn compared to the 100% ET_a and water stress treatments (Table 5). The observed lower nutritional composition under water stress conditions could be attributed to the adverse effects of drought on nutrient uptake in plants, resulting in altered ion concentrations within plant tissues (Corell et al., 2012). These findings are consistent with the research of Gunes et al. (2006), who similarly reported decreased nutrient uptake and mineral nutrient concentrations in crops under drought stress conditions. In addition, the optimized water treatment level is approximately 88.09% ET_a. This means that, according to the quadratic regression model, the nutritional composition of bush tea (specifically, calcium concentration in parts per million) is predicted to be maximized when the water treatment level is around 88.09% of the reference evapotranspiration (ET_a) rate.

3.4 | Nutritional water productivity

The results obtained from the study demonstrate a significant difference in the micronutrient and macronutrient parameters, including Ca, Cu, Fe, K, Mg, Mn, and Zn, under varying water treatments (Table 6). Notably, the NWP_Ca (78694/m^3) was found to be higher under the 30% ET_a water treatment compared to the other treatments. The optimized water treatment level is approximately 54.44% ET_a. This means that, according to the quadratic regression model, the nutritional WP of bush tea (specifically, calcium concentration in parts per million per unit of water) is predicted to be maximized when the water treatment level is around 54.44% ET_a rate. These results provide valuable insights into the relationship between water treatment levels and both nutritional composition and nutritional WP of bush tea. They suggest that there exists an optimal water treatment level for maximizing these parameters, emphasizing the importance of water management in tea cultivation to achieve desired nutritional outcomes while optimizing water use efficiency. Similarly, the NWP_K (1175.3/m^3) was observed to be higher under the 30% ET_a treatment in comparison to the 100% ET_a (870.0/m^3) and stress conditions (0 mg/L). The interaction between NWP and micronutrients and macronutrients to water treatments was also found to be significantly different ($p < 0.01$). These results can be attributed to the varying responses of plants to water stress, influenced by the intensity and duration of the stress (Hosseinzadeh et al., 2018). Additionally, the findings align with previous observations on yield, WP, and nutritional content (Mabhaudhi et al., 2019), highlighting the potential of bush tea to provide nutrition even under limited water conditions.

3.5 | Leaf gas exchange and chlorophyll fluorescence measurements

The findings from this study reveal a significant effect of varying water regimes on the physiological parameters, including

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 7 Analysis of variance showing mean squares and significant tests for leaf gas exchange and chlorophyll fluorescence measurements of bush tea under three water treatments (30% crop water requirement (ET_a), 100% ET_a, and control).

Leaf gas exchange measurements									
Source of variance	***df***	g_s	T	A	C_i	A/C_i	C_i/C_a	WUE_i	WUE_{inst}
Water treatment	2	0.0672744**	99.730**	236.4336**	444,986.0**	1.37390**	86.49**	54.6706**	512.482**
Time	1	0.1734605**	614.302*	1679.5086**	628,587.7**	103.43761**	789.04**	1232.8113**	14,192.359**
Water treatment × time	2	0.0056122*	32.338*	70.7924**	24,220.3**	1.25047**	75.24**	5.4087**	222.444**
Residual	12	0.0005902	2.505	0.4742	828.5	0.03739	12.44	0.9491	3.111

Leaf gas exchange measurements								
Source of variance	***df***	**Fo**	F_m	F_v/F_m	Φ_{PSII}	**qP**	**qN**	**ETR**
Water treatment	2	212,670.4**	264,909**	0.0364162**	39.9027**	6.9390**	0.85000**	3487.627**
Time	1	395,624.4**	2004*	0.0799728*	1120.0131**	1.6563**	1.21607**	11,604,621**
Water treatment × time	2	55781.1*	584*	0.0142603*	3.4191**	0.1244**	0.84353**	1,722,146**
Residual	12	739.4	9033	0.0006282	0.3031	0.2717	0.01148	16,521

Abbreviations: A/C_i, CO_2 assimilation rate/intercellular CO_2 concentration; A, net CO_2 assimilation rate; C_i/C_a, ratio of intercellular and atmospheric CO_2; C_i, intercellular CO_2 concentration; *df*, degrees of freedom; ETR/*A*, relative measure of electron transport to oxygen molecules; ETR, electron transport rate; Fo, minimal fluorescence yield; F_v/F_m, maximum quantum efficiency of photosystem II photochemistry; g_s, stomatal conductance; qN; non-photochemical quenching; qP, photochemical quenching; T, transpiration rate; WUE_i, intrinsic water use efficiency; WUE_{inst}, instantaneous water-use efficiency; Φ_{PSII}, the effective quantum efficiency of PSII photochemistry.
* and ** denote significance at 5% and 1% probability levels, respectively; Ns, non-significant.

leaf gas exchange and chlorophyll fluorescence in bush tea (Tables 7 and 8). Photosynthetic rates were significantly influenced by varying water regimes, showing distinct differences among the treatments. Notably, the 30% ET_a treatment exhibited the highest rates, with A net photosynthetic rate values of 29.57 and 36.18 μmol $CO_2/m^2/s$ during weeks 1 and 2, respectively. Additionally, the 100% ETa treatment displayed improved photosynthetic rates, recording values of 22.79 and 26.80 μmol $CO_2/m^2/s$. In contrast, the control treatment exhibited the lowest photosynthetic rates, with values of 17.64 and 24.19 μmol $CO_2/m^2/s$ for weeks 1 and 2, respectively. These findings suggest that the 30% ET_a treatment provided the most conducive conditions for photosynthetic rate in bush tea, resulting in significantly higher rates compared to the control and 100% ET_a treatments. The results emphasize the plant's ability to efficiently utilize water, even under limited water conditions, thereby enhancing photosynthetic activity and fostering sustained growth and productivity.

Notably, the control treatment displayed significantly lower stomatal conductance (0.11 and 0.37 mmol/m^2/s) compared to the other water treatments. This reduction in stomatal conductance is often associated with water stress, which affects various physiological and metabolic processes, leading to decreased gas exchange and inhibited photosynthesis (Shao et al., 2008). These results align with previous observations on Citron melon production under stress conditions (Mandizvo et al., 2022), emphasizing the impact of reduced stomatal conductance and transpiration rate on water conservation and plant physiological functioning (Mandizvo et al., 2021). Moreover, the control (stress) treatment exhibited high water use efficiency, indicating that it efficiently utilized water through stress mechanisms such as reduced gas diffusion and transpiration rate. The 30% ET_a treatment displayed the highest water use efficiency indices (WUE_i) of 38.25 and WUE_{inst} of 113.4 compared to the 100% ET_a treatment with WUE_i of 34.19 and WUE_{inst} of 107.2. This suggests that the 30% ET_a treatment effectively maintained tissue water status, minimized water loss, and produced stable yields, highlighting the potential of bush tea crops to thrive even with limited rainfall. Furthermore, chlorophyll fluorescence measurements indicated a higher proportion of photosynthetic rate under the 30% ET_a treatment compared to other water treatments, which could be attributed to the relatively lower water received by the bush tea plants under stress conditions and full irrigation. These findings further support the idea that bush tea can thrive well under limited water conditions, even in water-scarce regions, as demonstrated in provinces like KwaZulu-Natal.

4 | CONCLUSION AND RECOMMENDATIONS

The result of the study highlights the significant influence of different water regimes on the growth and yield of bush tea plants. The highest yield was observed in plants subjected to 100% ET_a, with a subsequent decrease observed in those under 30% ET_a and water stress treatments. Noteworthy is the finding that the 30% ET_a treatment positively impacted soil water content, nutritional composition, and nutritional WP, highlighting the importance of optimizing water application

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 8 Means of leaf gas exchange and chlorophyll fluorescence measurements of bush tea under three water treatments (30% crop water requirement (ET_a), 100% ET_a, and control).

Leaf gas exchange measurements															
Week 1	**ET_a**	**g_s (mmol/m²/s)**	**T (mmol H_2O/m²/s)**	**A (µmol CO_2/m²/s)**	**C_i (µmol mol/m)**	**A/C_i (µmol/mol/m)**	**C_i/C_a**	**WUE_i (µmol (CO_2)/m²)**	**WUE_{inst} (µmol/mol)**	**Fo**	**F_m**	**F_v/F_m**	**Φ_{PSII}**	**qP**	**qN**	**ETR (µmol/e/m²/s)**
	Control	0.11a	29.27a	17.64a	229.31a	1.73a	0.27a	17.47a	41.94a	2573.0a	2233a	0.05a	15.59a	0.03a	0.95a	533a
	100%	0.38c	33.31c	29.57c	276.02c	3.43c	0.87c	21.63c	48.09c	2769.8c	2669c	0.30c	19.20c	2.20b	2.37a	981c
	30%	0.27b	30.74b	22.79b	254.31b	1.93b	0.71b	20.04b	46.31b	2641.2b	2444b	0.16b	17.86b	1.23ab	1.23a	849b
Leaf gas exchange measurements																
Week 2	**ET_a**	**g_s (mmol/m²/s)**	**T (mmol H_2O/m²/s)**	**A (µmol CO_2/m²/s)**	**C_i (µmol/mol m)**	**A/C_i (µmol/mol m)**	**C_i/C_a**	**WUE_i (µmol (CO_2)/m²)**	**WUE_{inst} (µmol/mol)**	**Fo**	**F_m**	**F_v/F_m**	**Φ_{PSII}**	**qP**	**qN**	**ETR (µmol/e/m²/s)**
	Control	0.37a	35.86a	24.19a	462.82a	7.06a	8.50a	32.35a	84.33a	2055.50a	2264a	0.22a	29.69a	0.83a	0.99a	1050a
	100%	0.53c	47.69b	36.18c	757.11c	7.17a	22.22c	38.25c	113.45c	2607.52c	2667b	0.78c	36.24c	2.94b	1.00b	3640c
	30%	0.45b	45.59b	26.80b	661.03b	7.25a	10.85b	34.19b	107.21b	2431.40b	2478ab	0.35b	34.04b	1.50ab	0.99a	2491b

Note: Varying lower-case letters within a column indicates significant differences among water treatments.

Abbreviations: A/C_i, CO_2 assimilation rate/intercellular CO_2 concentration; A, net CO_2 assimilation rate (µmol CO_2/m²/s); C_i/C_a, ratio of intercellular and atmospheric CO_2; C_i, intercellular CO_2 concentration; ETR, electron transport rate; Fo, minimal fluorescence yield; F_v/F_m, maximum quantum efficiency of photosystem II photochemistry; g_s, stomatal conductance; qN, non-photochemical quenching; qP, photochemical quenching; T, transpiration rate; WUE_i, intrinsic water-use efficiency; WUE_{inst}, instantaneous water-use efficiency; Φ_{PSII}, the effective quantum efficiency of PSII photochemistry.

in bush tea cultivation. Under control (stress) conditions, a decrease in stomatal conductance was noted, but water use efficiency increased, indicating the adaptability of bush tea to water-scarce environments. This emphasizes the plant's resilience and its potential to thrive in challenging conditions. The study underscores the crucial role of varying water regimes in influencing plant physiology, nutritional composition, leaf gas exchange, and chlorophyll fluorescence. The adaptability of bush tea to stress conditions suggests its potential as a valuable resource for food and nutritional security in arid regions. Future studies should delve into a more detailed analysis of nutritional WP and water use efficiency of bush tea. This is especially important under diverse water regimes and in varying environmental conditions. These in-depth investigations will contribute to a comprehensive understanding of the plant's adaptive mechanisms and shed light on potential it may offer. Such insights are crucial for advancing sustainable agriculture practices and promoting further research in the realm of natural products, ultimately contributing to the broader field of agriculture and enhancing our understanding of the plant's potential applications.

AUTHOR CONTRIBUTIONS

Muneiwa Rumani: Conceptualization; data curation; investigation; methodology; writing—original draft; writing—review and editing. **Tafadzwanashe Mabhaudhi**: Supervision; validation; writing—review and editing. **Takudzwa Mandizvo**: Formal analysis; validation; writing—review and editing. **Anza-Tshilidzi Ramabulana**: Formal analysis; validation; writing—review and editing. **Ntakadzeni Edwin Madala**: Formal analysis; supervision; validation; writing—review and editing. **Maanea Lonia Ramphinwa**: Conceptualization; formal analysis; validation; writing—review and editing. **Lembe Samukelo Magwaza**: Conceptualization; formal analysis; software; supervision; validation; writing—review and editing. **Fhatuwani Nixwell Mudau**: Formal analysis; supervision; validation; writing—review and editing.

ORCID

Muneiwa Rumani https://orcid.org/0000-0001-8956-2525

REFERENCES

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration-guidelines for computing crop water requirements—FAO irrigation and drainage paper 56*. FAO.

Chiappero, J., del Rosario Cappellari, L., Alderete, L. G. S., Palermo, T. B., & Banchio, E. (2019). Plant growth promoting rhizobacteria improve the antioxidant status in Mentha piperita grown under drought stress leading to an enhancement of plant growth and total phenolic content. *Industrial Crops and Products*, *139*, 111553. https://doi.org/10.1016/j.indcrop.2019.111553

Chivenge, P., Mabhaudhi, T., Modi, A. T., & Mafongoya, P. (2015). The potential role of neglected and underutilized crop species as future

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

crops under water scarce conditions in Sub-Saharan *Africa*. *International Journal of Environmental Research and Public Health*, *12*, 5685–5711. https://doi.org/10.3390/ijerph120605685

Choi, M., & Jacobs, J. M. (2007). Soil moisture variability of root zone profiles within SMEX02 remote sensing footprints. *Advances in Water Resources*, *30*(4), 883–896. https://doi.org/10.1016/j.advwatres.2006.07.007

Corell, M., Garcia, M. C., Contreras, J. I., Segura, M. L., & Cermeño, P. (2012). Effect of water stress on *Salvia officinalis* L. bio productivity and its bio element concentrations. *Communications in Soil Science and Plant Analysis*, *43*(1-2), 419–425. https://doi.org/10.1080/00103624.2012.641811

Deutsch, E. S., Bork, E. W., & Willms, W. D. (2010). Soil moisture and plant growth responses to litter and defoliation impacts in Parkland grasslands. *Agriculture Ecosystems and Environment*, *135*(1-2), 1–9. https://doi.org/10.1016/j.agee.2009.08.002

Gatabazi, A., Marais, D., Steyn, M., Araya, H., Du Plooy, C., Ncube, B., & Mokgehle, S. (2022). Effect of water regimes and harvest times on yield and phytochemical accumulation of two ginger species. *Scientia Horticulturae*, *304*, 111353. https://doi.org/10.1016/j.scienta.2022.111353

Gunes, A., Cicek, N., Inal, A., Alpaslan, M., Eraslan, F., Guneri, E., & Guzelordu, T. (2006). Genotypic response of chickpea (*Cicer arietinum* L.) cultivars to drought stress implemented at pre-and post-anthesis stages and its relations with nutrient uptake and efficiency. *Plant Soil and Environment*, *52*(8), 368–376. https://doi.org/10.17221/3454-PSE

Hosseinzadeh, S. R., Amiri, H., & Ismaili, A. (2018). Evaluation of photosynthesis, physiological, and biochemical responses of chickpea (*Cicer arietinum* L. cv. Pirouz) under water deficit stress and use of vermicompost fertilizer. *Journal of Integrative Agriculture*, *17*, 2426–2437. https://doi.org/10.1016/s2095-3119(17)61874-4

Keshavarz, H., & Khodabin, G. (2019). The role of uniconazole in improving physiological and biochemical attributes of bean (*Phaseolus vulgaris* L.) subjected to drought stress. *Journal of Crop Science and Biotechnology*, *22*(2), 161–168. https://doi.org/10.1007/s12892-019-0050-0

Keshavarz Mirzamohammadi, H., Modarres-Sanavy, S. A. M., Sefidkon, F., Mokhtassi-Bidgoli, A., & Mirjalili, M. H. (2021). Irrigation and fertilizer treatments affecting rosmarinic acid accumulation, total phenolic content, antioxidant potential and correlation between them in peppermint (*Mentha piperita* L.). *Irrigation Science*, *39*, 671–683. https://doi.org/10.1007/s00271-021-00729-z

Lerotholi, L., Chaudhary, S. K., Combrinck, S., & Viljoen, A. (2017). Bush tea (*Athrixia phylicoides*): A review of the traditional uses, bioactivity and phytochemistry. *South African Journal of Botany*, *110*, 4–17. https://doi.org/10.1016/j.sajb.2016.06.005

Lobo, V., Patil, A., Phatak, A., & Chandra, N. (2010). Free radicals, antioxidants and functional foods: Impact on human health. *Pharmacognosy Reviews*, *4*(8), 118–126. https://doi.org/10.4103/0973-7847.70902

Mabhaudhi, T., Chibarabada, T. P., & Modi, A. T. (2019). Nutritional water productivity of selected sweet potato cultivars (*Ipomoea batatas* L.). *Acta Horticulturae*, *1253*, 295–302. https://doi.org/10.17660/ActaHortic.2019.1253.39

Maedza, K. V. (2015). *Effects of micronutrients on growth and quality of bush tea (Athrixia phylicoides* DC.) [Master's dissertation, University of South Africa].

Mandizvo, T., Odindo, A. O., & Mashilo, J. (2021). Citron watermelon potential to improve crop diversification and reduce negative impacts of climate change. *Sustainability*, *13*, 2269. https://doi.org/10.3390/su13042269

Mandizvo, T., Odindo, A. O., & Mashilo, J. (2022). Nutrient composition and physical properties of citron watermelon (*Citrullus lanatus* var. *citroides* (LH Bailey) *Mansf*. ex *Greb*.) seeds are related to seed coat visual appearance. *South African Journal of Botany*, *145*, 405–419. https://doi.org/10.1016/j.sajb.2022.02.015

Mohale, K. C., Hintsa, A. T., Emanuel, M. A., & Mudau, F. N. (2018). Metabolic profiling of cultivated bush tea (*Athrixia phylicoides* DC.) in response to different pruning types. *HortScience*, *53*, 993–998. https://doi.org/10.21273/hortsci13023-18

Motsa, N. M., Modi, A. T., & Mabhaudhi, T. (2015). Sweet potato *(Ipomoea batatas* L.) as a drought tolerant and food security crop. *South African Journal of Science*, *111*, 8. https://doi.org/10.17159/sajs.2015/20140252

Mudau, F. N., Ngele, A., Mashela, P. W., & Soundy, P. (2007). Seasonal variation of tannin content in wild bush tea. *Medicinal and Aromatic Plant Science and Biotechnology*, *1*(1), 74–76.

Ponmurugan, P., Manjukarunambika, K., & Gnanamangai, B. M. (2016). Impact of various foliar diseases on the biochemical, volatile and quality constituents of green and black teas. *Australasian Plant Pathology*, *45*, 175–185. https://doi.org/10.1007/s13313-016-0402-y

Rahil, M. (2022). Estimation of water productivity of cucumber and potato crops for water management in Palestine. *International Journal of Plant & Soil Science*, *34*(23), 891–904. https://doi.org/10.9734/ijpss/2022/v34i232500

Rakuambo, Z. J., Du Toit, E. S., Soundy, P., & Olivier, J. (2009). Indigenous knowledge system of bush tea from the local people in Venda. *Indilinga African Journal of Indigenous Knowledge Systems*, *8*(2), 158–162.

Ramphinwa, M. L., Madala, N. E., McHau, G. R., Ramabulana, A. T., & Mudau, F. N. (2022). Effect of UV-induced geometrical isomerization of hydroxyl-cinnamic acid-containing molecules of bush tea (*Athrixia phylicoides* DC.) using UHPLC-QTOF-MS. *Scientia Horticulturae*, *301*, 111124. https://doi.org/10.1016/j.scienta.2022.111124

Ramphinwa, M. L., McHau, G. R. A., Madala, N. E., Nengovhela, N., Ogola, J. B. O., & Mudau, F. N. (2022). Response of plant growth and development, and accumulation of Hydroxyl-Cinnamoyl acid derivatives to selected shade nets and seasonality of field-grown bush tea (*Athrixia phylicoides* DC). *HortScience*, *57*, 87–96. https://doi.org/10.21273/HORTSCI16171-21

Reichelt, K. V., Hoffmann-Lücke, P., Hartmann, B., Weber, B., Ley, J. P., Krammer, G. E., Swanepoel, K. M., & Engel, K. H. (2012). Phytochemical characterization of South African bush tea (*Athrixia phylicoides* DC.). *South African Journal of Botany*, *83*, 1–8. https://doi.org/10.1016/j.sajb.2012.07.006

Rostamza, M., Chaichi, M. R., Jahansooz, M. R., Mashhadi, H. R., & Sharifi, H. R. (2011). Effects of water stress and nitrogen fertilizer on multi-cut forage pearl millet yield, nitrogen, and water use efficiency. *Communications in Soil Science and Plant Analysis*, *42*(20), 2427–2440. https://doi.org/10.1080/00103624.2011.609252

Shao, H. B., Chu, L. Y., Jaleel, C. A., & Zhao, C. X. (2008). Water-deficit stress-induced anatomical changes in higher plants. *Comptes Rendus Biologies*, *331*(3), 215–225. https://doi.org/10.1016/j.crvi.2008.01.002

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Tshikhudo, P. P., Ntushelo, K., Kanu, S. A., & Mudau, F. N. (2019). Growth response of bush tea (*Athrixia phylicoides* DC.) to climatic conditions in Limpopo Province, South Africa. *South African Journal of Botany*, *121*, 500–504. https://doi.org/10.1016/j.sajb.2018.12.012

Tshivhandekano, I., Ngezimana, W., Tshikalange, T. E., Makunga, N. P., & Mudau, F. N. (2018). Nitrogen application influences quality, pharmacological activities and metabolite profiles of *Athrixia phylicoides* DC. (Bush tea) cultivated under greenhouse and field conditions. *Acta Agriculture Scandinavica, Section B—Soil & Plant Science*, *68*(5), 388–400. https://doi.org/10.1080/09064710.2017.1412496

Yang, J., Tian, H., Pan, S., Chen, G., Zhang, B., & Dangal, S. (2018). Amazon drought and forest response: Largely reduced forest photosynthesis but slightly increased canopy greenness during the extreme drought of 2015/2016. *Global Change Biology*, *24*(5), 1919–1934. https://doi.org/10.1111/gcb.14056

How to cite this article: Rumani, M., Mabhaudhi, T., Mandizvo, T., Ramabulana, A.-T., Madala, N. E., Ramphinwa, M. L., Magwaza, L. S., & Mudau, F. N. (2024). Investigating the influence of varying water regimes on the growth and development and nutritional water productivity of bush tea (*Athrixia phylicoides* DC.). *Urban Agriculture & Regional Food Systems*, *9*, e20073. https://doi.org/10.1002/uar2.20073

25751220, 2024, 1, Downloaded from https://acsess.onlinelibrary.wiley.com/doi/10.1002/uar2.20073 by Test, Wiley Online Library on [14/08/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

https://dspace.org/

Investigating the influence of varying water regimes on the growth and development and nutritional water productivity of bush tea (Athrixia phylicoides DC.)

Rumani, Muneiwa; Mabhaudhi, Tafadzwanashe; Mandizvo, Takudzwa; Ramabulana, AnzaTshilidzi; Madala, Ntakadzeni Edwin ...

2024-07-29
Wiley
https://doi.org/10.1002/uar2.20073
Rumani M, Mabhaudhi T, Mandizvo T, et al., (2024) Investigating the influence of varying water regimes on the growth and development and nutritional water productivity of bush tea (Athrixia phylicoides DC.). Urban Agriculture & Regional Food Systems, Volume 9, Issue 1, 2024, Article number e20073

Downloaded from a DSpace repository. https://dspace.org/