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Comparing the nutritional, phytochemical, and anti-microbial potential of wild and cultivated *Tetragonia decumbens* mill.: A promising leafy vegetable for bio-saline agriculture in South Africa

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ABSTRACT

Tetragonia decumbens is a neglected edible halophyte that grows naturally in coastal areas of South Africa. Its underutilisation is due to the limited literature on its nutraceutical potential. So, this research was designed to assess the nutritional value, secondary metabolites, and anti-microbial potential of wild and greenhouse cultivated *T. decumbens* to further support its consumption and potential medicinal use. Samples of *T. decumbens* were collected from three coastal areas (Strand beach, Muizenberg beach and Blouberg beach) during the dry and wet seasons in Cape Town, and the greenhouse cultivated were subjected to varying salinity doses (0, 50, 100, 150, 200 and 250 mM). Results revealed a considerable increase in minerals (N, P and Mg) and proximate composition (Ash, moisture, and carbohydrates) in greenhouse cultivated plants subjected to 50 mM of salinity while the highest crude fat and neutral detergent fibre were recorded in wild samples. Moreover, heavy metal accumulation (Zn and Fe), phytochemicals, anti-nutrients and anti-microbial activities were more pronounced in wild plants than in cultivated samples. Wild plants collected at Blouberg beach had more heavy metals, anti-nutrients, phytochemicals, and anti-microbial activity. These findings validate for the first time, the relevance of nutritional quality of *T. decumbens* in assessing its suitability as a source of nutrients and antioxidants with possible medicinal value as shown by the inhibition of harmful bacteria and fungal strains.

1. Introduction

Climate change and increasing soil salinity are already having a significant effect on crop production losses around the globe [1,2]. Thus, the alternative use of resilient crops like halophytes is crucial to fulfil the increasing food demand escalated by the increasing human population [3]. Edible halophytes are crops that can tolerate high temperatures, drought, and salinity, making them the ideal choice for cultivation in regions impacted by both salinity and drought [4]. These species are known to provide needed calories, proteins, fats, and nutrients as per human daily needs [5]. Moreover, they have recently attracted attention due to their nutritional and medicinal value. The aforementioned characteristics often arise from secondary metabolites that these species synthesise in response to oxidative damage caused by salt stress. Phenolic chemicals and some vitamins are examples of metabolites that possess well-established biological attributes such as antioxidant, anti-microbial and anti-inflammatory activity [6].

Halophytes serve as a food source with functional qualities due to their nutritionally balanced composition and the presence of secondary metabolites [7]. Recently, upscale restaurants in Europe and Asia have started including these plants into their menus as a novel ingredient that also promotes a nutritious diet [8,9]. This led to the inclusion of these plants on supermarket shelves which resulted into the emergence of commercial cultivation due to the increasing demand of sustainable supply [10].

In most African countries including South Africa, edible halophytes are still underutilized and understudied even though these species could provide an alternative source of nutrients to the growing human

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population [11]. Recently, *Tetragonia decumbens* a neglected South African edible halophyte has been cultivated under saline conditions and showed promising production returns for bio-saline agriculture [12]. The salty leaves of this vegetable can be eaten raw in green salads or cooked like spinach and added to soups and stews [13,14]. However, its nutritional value remains undocumented, contributing to its under-utilisation among coastal households. Therefore, it became imperative to study the nutritional value, phytochemical composition, and anti-microbial potential of wild and greenhouse cultivated *T. decumbens* to encourage its domestication, consumption, and utilisation by coastal inhabitants. Results from this study are anticipated to aid as a paradigm for prospective commercial growers, researchers and coastal inhabitants who may have an interest in using this plant for enhancing food variety, food security and developing medicinal precursors.

2. Materials and methods

2.1. Wild collection and sample preparation

Fresh green leaves of *T. decumbens* were randomly harvested on three plant populations growing along the coastal areas of Strand beach (34°06′10.7″S 18°48′55.7″E), Muizenberg beach (34°06′11.0″S 18°29′05.8″E) and Blouberg beach front (33°49′31.9″S 18°28′41.5″E) during the wet (June 2023) and dry (December 2023) seasons (Mediterranean climate) in Cape Town, South Africa. The climatic conditions of the selected areas are shown in Table 1. The harvested arial plant parts were cleaned with distilled water, oven-dried at 35 °C to complete dryness and pulverised. The pulverised material was then kept at 4 °C for further analysis.

2.2. Greenhouse cultivation and sample preparation

2.2.1. Growth conditions and experimental location

Greenhouse cultivation of *T. decumbens* was completed in the research centre affiliated with the Department of Horticultural Sciences at the Cape Peninsula University of Technology. The design and technology of the greenhouse allowed for precise regulation of the environment within the greenhouse. The ambient temperature ranged from 20 to 27 °C throughout the day and 11–17 °C at night. The relative humidity remained at a constant level of 60 %, while the photosynthetic photon flux density was kept at 4020 μmol m^{-2} s^{-1} during the experimental period.

2.2.2. Preparation of plant material and saline conditions

Tetragonia decumbens plants were generated from cuttings following the propagation method described by Sogoni et al. [14]. Homogeneously established plants (180) were transplanted in black plastic pots (12.5 cm) filled with a combination of peat and sand (1:1) and stationed in the hardening off area to acclimatize. The plants were then watered with a full Nutrifeed ™ solution produced by STARKE AYRES Pty. Ltd., South Africa. After sixteen days of plant development, plants were irrigated with reverse osmosis water for six days to eliminate any salt residue before being subjected to saline treatments, each containing ten replicates and the study was repeated three times. Saline conditions were established on treatments by elevating the concentration of NaCl in the nutritive solution (0, 50, 100, 150, 200, and 250 mM) as described by Sogoni et al. [15]. Each plant received 300 mL of nutrient solution with graded NaCl and were irrigated every two days. The control plants were only irrigated with nutritive solution without salinity. To verify that the right concentration of salinity in each pot was sustained, drain water from each pot was collected and the electrical conductivity was measured. After four months of salt treatment, plant leaves were harvested, washed with distilled water, oven-dried at 35 °C to complete dryness and milled. The pulverised material was then kept at 4 °C for further analysis.

Table 1
Climatic conditions of selected coastal areas (adapted from weathersa.co.za).

Wild	Temperature (°C)		Precipitation (mm)	Humidity %
Place	Min	Max	Average	Average
SS	13	32	27	64.5
SW	4	20	33.8	60.6
BS	12	35	25.7	67.6
BW	4	23	35.4	63.5
MS	13	32	19.5	64.7
MW	8	20	33.9	60.8

Note: SS= Strand summer, SW= Strand winter, BS= Blouberg summer, BW= Blouberg winter, MS = Muizenberg summer and MW = Muizenberg winter.

2.3. Mineral composition

The Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES; Varian 710–ES series, SMM Instruments, Cape Town, South Africa) was utilised to determine the mineral constituents of the samples as previously explained by Bulawa et al. [16].

2.4. Proximate analysis

Proximate analyses were performed in a commercial laboratory of the Department of Agriculture and Rural Development, Kwazulu Natal Province, South Africa. The accredited in-house standard Association of Official Analytical Chemists procedures were utilised to determine moisture, ash, crude fat, crude protein, non-fibre carbohydrate and neutral detergent fibre of the samples as reported by Tshayingwe et al. [17].

2.5. Anti-nutrients composition

Alkaloid and Saponin constituents of the samples were determined using the methods explained by Jimoh et al. [18], and oxalate was evaluated using a modified titration approach previously described by Adetunji et al. [19].

2.6. Phytochemicals and antioxidant assays

2.6.1. Preparation of the crude extract

About, 100 mg of the pulverised samples was mixed with 70 % ethanol (10 mL) for 24 h and centrifuged at 400 rpm for 5 min. The supernatants were subsequently used for phytochemical and antioxidant activity analyses.

2.6.2. Determination of phytochemicals and antioxidant activity

The Folin-Ciocalteu technique described by Ingarfield et al. [20] was utilised to determine the total phenolic content of the samples. The results were expressed as mg gallic acid equivalent per g dry weight (mg GAE. g^{-1} DW). The flavonoid content was determined using the aluminium chloride spectrophotometric test reported by Cebani et al. [11] and expressed as mg quercetin equivalent per g dry weight (mg QE. g^{-1} DW). The radical scavenging activity was determined using the DPPH free radical scavenging assay and Ferric Reducing Antioxidant Power (FRAP) assay following the methods described by Ngxabi et al. [21]. The results were expressed as μM Trolox equivalent per g dry weight (μM TE. g^{-1} DW) for DPPH and μM ascorbic acid equivalents (AAE) per g dry weight (μM AAE. g^{-1} DW) for FRAP.

2.7. Antimicrobial activity

2.7.1. Test strains/micro-organisms

The antimicrobial efficacy of the crude extracts was assess using the following strains: Gram negative bacteria (*Acinetobacter baumannii* ATCC 19606T, *Burkholderia cepaciae* ATCC 25416T and *Klebsiella* *pneumoniae* subsp. *pneumoniae* ATCC 700603), Gram positive bacteria (*Enterococcus faecalis* ATCC 29212, *Bacillus cereus* ATCC 10876 and *Staphylococcus aureus* subsp. *aureus* ATCC 33591) and Fungi (*Candida albicans* ATCC 90028D-5, *Candida krusei* ATCC 14243 and *Candida tropicalis* ATCC 750).

2.7.2. Disc diffusion assay

About 2 g of the dried leaf powder was harmonized with 20 mL of 70 % ethanol for 24 h and centrifuged at 400 rpm for 5 min. The supernatants of the samples were evaporated to dryness and later reconstituted in the same solvent to obtain a concentration of 50 mg mL^{-1}. A disc diffusion assay was utilised to evaluate the antimicrobial activity of the samples as described by Akter et al. [22]. For each test strain, a commercial antibiotic was used as a positive control. Gentamicin (20 mg mL^{-1} stock) and ampicillin (100 mg mL^{-1} stock) were used for the bacterial test strains, while fluconazole (50 mg mL^{-1} stock) was used for the yeast/fungi test strains. The solvent without the extract was included as the negative control. The inoculated plates were incubated at 37 °C overnight (30 °C for the *C. krusei* and *C. tropicalis* strains). The zones of inhibition were assessed using a 150 mm Digital Calliper after incubation. The antimicrobial activity was categorised as follows: strong (>13 mm), moderate (6–12 mm), weak (≥5 mm), and no activity (<5 mm).

2.8. Statistical analysis

The results of this study were analysed using STATISTICA, version 13.5.0.17. A multivariate ANOVA was conducted to determine substantial differences among treatments, followed by Tukey's (LSD) test at $p \leq 0.05$. The Shapiro-Wilk test was conducted before the analysis of variance to verify the validity of normality, while Levene's test was employed to evaluate the homogeneity of variance. The data was shown as mean values ± standard error.

3. Results

3.1. The mineral composition of wild and greenhouse cultivated T. decumbens

The study revealed significant differences in mineral constituents of both the wild and greenhouse cultivated *T. decumbens* as shown in Tables 2 and 3. Plants cultivated in the greenhouse had a substantial increase in macro-nutrients such as N (3300 mg.100 g^{-1}), P (700 mg.100 g^{-1}), K (7800 mg.100 g^{-1}), Mg (1100 mg.100 g^{-1}) and Na (24100 mg.100 g^{-1}) compared to values obtained from the wild samples. Most of these minerals were more pronounced in plants subjected to 50 mM salinity except K and Na, where the highest yields were recorded in the control plants for K, and in 250 mM for Na. Conversely, Ca was more pronounced in plants collected from the wild than in greenhouse cultivated plants. The highest Ca (2100 mg.100 g^{-1}) was noted in plants collected at Strand beach during the summer period.

Accumulation of micro-nutrients such as Zn, Mn, Cu and Fe varied among the wild and greenhouse cultivated plants (Table 3) consderably. These heavy metals were more pronounced in wild samples than those cultivated in the greenhouse. As a result, the highest yields of Zn (8.2 mg.100 g^{-1}), Cu (1.5 mg.100 g^{-1}) and Fe (71.5 mg.100 g^{-1}) were all recorded from plant samples collected at Blouberg beach during the summer period.

Table 3
Micronutrient composition of wild and greenhouse cultivated *T. decumbens* expressed in mg.100 g^{-1} DW.

		Zn	Mn	Cu	Fe
Cultivated	Control	4.75 ± 0.5e	4.85 ± 0.05d	0.1 ± 0.02g	19.2 ± 0.03f
	50 mM	6.05 ± 0.1c	5 ± 0.02cd	0.2 ± 0.01f	24.6 ± 0.04d
	100 mM	2.75 ± 0.5h	5.6 ± 0.03bc	0.2 ± 0.01f	16.1 ± 0.01h
	150 mM	4.7 ± 0.02ef	7.5 ± 0.2a	0.05 ± 0.01h	24 ± 0.03d
	200 mM	6.05 ± 0.1c	7.3 ± 0.03a	Nd	18.3 ± 0.8g
	250 mM	4.5 ± 0.05f	6 ± 0.4b	Nd	21.4 ± 0.1e
Wild	SS	6.65 ± 0.06b	2.5 ± 0.02e	0.5 ± 0.1b	26.5 ± 0.05c
	SW	4.6 ± 0.02ef	0.85 ± 0.03g	0.4 ± 0.01c	12.7 ± 0.9i
	BS	8.2 ± 0.04a	2.25 ± 0.05e	1.45 ± 0.5a	71.5 ± 0.2a
	BW	6.75 ± 0.07b	1.6 ± 0.06f	0.5 ± 0.01b	28.2 ± 0.6b
	MS	5.75 ± 0.01d	0.7 ± 0.07g	0.35 ± 0.05d	16.2 ± 0.01h
	MW	3.1 ± 0.01g	0.65 ± 0.09g	0.3 ± 0.01e	11.1 ± 0.034j

Means with the different letters along the columns are significantly different at (P ≤ 0.05), (n = 3). Note: nd = not detected, SS= Strand summer, SW= Strand winter, BS= Blouberg summer, BW= Blouberg winter, MS = Muizenberg summer and MW = Muizenberg winter.

3.2. The proximate composition of wild and greenhouse cultivated T. decumbens

The proximate composition of tested samples varied significantly as depicted in Table 4. The ash content was at its highest (50.7 %) in greenhouse cultivated plants subjected to 50 mM of salinity. On the contrary, crude fat content was more pronounced in plants collected at strand beach (4.4 %) during the summer season. However, this was comparable to greenhouse cultivated plants subjected to 50 mM of salinity. Similarly, the highest protein content (20.8 %) was obtained in

Table 2
Macronutrient composition of wild and greenhouse cultivated *T. decumbens* expressed in mg.100 g^{-1} DW.

		N	P	K	Mg	Na	Ca
Cultivated	Control	2400 ± 1.5e	600 ± 0.2b	7800 ± 1.1a	900 ± 0.23b	1500 ± 0.4j	900 ± 0.8f
	50 mM	3300 ± 0.6a	700 ± 0.1a	5200 ± 0.86b	1100 ± 0.5a	5600 ± 0.9h	600 ± 1.3g
	100 mM	2400 ± 0.1e	500 ± 0.6c	3100 ± 1.5c	400 ± 1.8e	15700 ± 1.3d	200 ± 0.01i
	150 mM	2400 ± 1.1e	500 ± 0.9c	2400 ± 0.5e	400 ± 0.42e	19400 ± 0.4c	300 ± 0.05h
	200 mM	2600 ± 0.4d	600 ± 0.2b	2400 ± 0.9e	300 ± 0.98f	20500 ± 1.2b	200 ± 0.11i
	250 mM	2600 ± 1.3d	400 ± 0.8d	1800 ± 1.1g	300 ± 0.5f	24100 ± 1.5a	300 ± 0.8h
Wild	SS	1800 ± 0.07g	100 ± 0.02h	2200 ± 00.5f	900 ± 0.02b	6100 ± 0.9g	2100 ± 0.2a
	SW	3100 ± 0.4b	260 ± 0.06e	2500 ± 0.1d	600 ± 0.01c	5000 ± 0.4i	1600 ± 0.5c
	BS	2800 ± 0.7c	170 ± 0.01g	1300 ± 0.1k	600 ± 0.04c	7300 ± 0.5e	1700 ± 0.2b
	BW	2000 ± 0.1f	200 ± 0.01f	1400 ± 0.2j	500 ± 0.06d	6600 ± 0.1f	1500 ± 0.1d
	MS	1600 ± 0.1h	100 ± 0.8h	1600 ± 0.5h	600 ± 0.07c	7400 ± 0.5e	1000 ± 0.2e
	MW	2600 ± 0.2d	190 ± 0.03f	1500 ± 0.9i	700 ± 0.0b	4900 ± 0.2i	1000 ± 0.2e

Means with the different letters along the columns are significantly different at (P ≤ 0.05), (n = 3). Note: SS= Strand summer, SW= Strand winter, BS= Blouberg summer, BW= Blouberg winter, MS = Muizenberg summer and MW = Muizenberg winter.

Table 4
Proximate composition of wild and cultivated *T. decumbens*.

		Ash%	Crude fat%	Protein%	Moisture%	NFC%	NDF%
Cultivated	Control	25.8 ± 0.6g	3.6 ± 0.6bc	15.4 ± 0.4d	9.8 ± 0.3a	28.4 ± 0.1 ab	39.8 ± 0.7cd
	50 mM	50.7 ± 0.2a	4.3 ± 0.5 ab	19.4 ± 0.2 ab	9 ± 0.3 ab	30.6 ± 0.9a	29.8 ± 0.9d
	100 mM	40.6 ± 0.3c	3.7 ± 0.1b	15.1 ± 0.3d	8.7 ± 0.1b	26.2 ± 0.6bc	26.6 ± 0.2e
	150 mM	45.8 ± 0.1b	3.8 ± 0.5bc	15.1 ± 0.1d	8.3 ± 0.2b	22.2 ± 0.7e	28.2 ± 1.2de
	200 mM	45.1 ± 0.6b	3.4 ± 0.3cd	16.5 ± 0.9c	8.3 ± 0.7b	26.5 ± 0.7bc	24.9 ± 0.3f
	250 mM	40.2±1c	3.1 ± 0.2d	16.4 ± 0.4c	8.1 ± 0.9b	23.7 ± 0.5de	22.4 ± 0.4g
Wild	SS	30.5±1f	4.4 ± 0.4a	11.5 ± 0.05f	4.2 ± 0.1cd	27.1 ± 0.5b	40.3 ± 0.07c
	SW	28.3 ± 0.04f	2.4 ± 0.2f	20.8 ± 0.9a	4.9 ± 0.1c	28.6 ± 0.04 ab	40.5 ± 0.03c
	BS	36.7 ± 0.02d	2.6 ± 0.2e	17.8 ± 0.4b	4.5 ± 0.2cd	22.7 ± 0.5e	40.5 ± 0.3c
	BW	45.3 ± 0.8b	3 ± 0.7de	13 ± 0.2e	3.6 ± 0.2d	7.7 ± 0.9g	43.7 ± 0.1b
	MS	36.1 ± 0.7de	3 ± 0.6de	10 ± 0.9g	4.7 ± 0.7c	18.6 ± 1.3f	42.1 ± 0.2bc
	MW	25.2 ± 0.3g	2.2 ± 0.2f	16 ± 0.01c	4.9 ± 0.2c	24.1 ± 1.5d	48.2 ± 0.9a

Means with the different letters along the columns are significantly different at ($P \leq 0.05$), ($n = 3$). Note: NFC = non fibre carbohydrate, NDF = neutral detergent fibre, SS= Strand summer, SW= Strand winter, BS= Blouberg summer, BW= Blouberg winter, MS = Muizenberg summer, MW = Muizenberg winter.

wild samples collected at Strand beach during the winter season, which was comparable to greenhouse cultivated plants subjected to 50 mM of salinity. Conversely, the moisture contents of all tested samples were more noticeable in greenhouse cultivated plants. The highest moisture value (9.8 %) was obtained in control plants, which was equivalent to plants treated with 50 mM (9 %). The non-fibre carbohydrate was at its highest in plants subjected to 50 mM of salinity (30.6 %) in cultivated samples which was comparable to control plants (28.4 %) and wild plants collected at Strand beach during winter season (28.6 %). The wild samples had higher neutral detergent fibre substantially than the cultivated plants. The highest neutral detergent fibre content (48.2 %) was recorded in plants harvested at Muizenberg beach during the winter season.

3.3. Anti-nutrient composition of wild and greenhouse cultivated T. decumbens

Table 5 shows the variability in anti-nutrient contents of wild and greenhouse cultivated plant samples. Plants cultivated under greenhouse conditions had far less alkaloids compared to those harvested in the wild except samples collected at Muizenberg during winter. The highest alkaloid content (1.4 %) was recorded in plant samples harvested at Blouberg beach during the summer compared to cultivated and other wild collections. As for saponin content, greenhouse cultivated plants subjected to 250 mM had substantially more saponin (8.7 %) than other saline treatment including the wild harvested samples. The same trend was also observed for oxalate, where plants subjected to higher saline treatments (200 and 250 mM) had more oxalate content at 3.3 % for both treatments.

Table 5
Anti-nutrient composition of wild and greenhouse cultivated *T. decumbens*.

		Alkaloids%	Saponin%	Oxalate%
Cultivated	Control	0.2 ± 0.01h	6.4 ± 0.02g	2.4 ± 0.01h
	50 mM	0.2 ± 0.02h	7 ± 0.01e	2.4 ± 0.01g
	100 mM	0.49 ± 0.03g	7.2 ± 0.04d	2.7 ± 0.02e
	150 mM	0.55 ± 0.01f	7.2 ± 0.02d	2.8 ± 0.05d
	200 mM	0.62 ± 0.01e	7.6 ± 0.04c	3.3 ± 0.01a
	250 mM	0.62 ± 0.03e	8.7 ± 0.05a	3.3 ± 0.02a
Wild	SS	1.2 ± 0.02b	7.7 ± 0.3b	2.9 ± 0.03c
	SW	0.7 ± 0.06d	6.6 ± 0.1f	2.7 ±0.05f
	BS	1.4 ± 0.02a	6.1 ± 0.1h	3.1 ± 0.04b
	BW	0.89 ± 0.05c	5.6 ± 0.1i	2.7 ± 0.01f
	MS	0.89 ± 0.03c	7.7 ± 0.1b	2.7 ± 0.03f
	MW	0.2 ± 0.02h	6.1 ± 0.2h	3.1 ± 0.05b

Means with the different letters along the columns are significantly different at ($P \leq 0.05$), ($n = 3$). Note: SS= Strand summer, SW= Strand winter, BS= Blouberg summer, BW= Blouberg winter, MS = Muizenberg summer and MW = Muizenberg winter.

3.4. Phytochemical composition and antioxidant activity of wild and cultivated T. decumbens

The wild environment had a substantial impact on the build-up of phytochemical and antioxidant contents in *T. decumbens* (Table 6). Polyphenols were more pronounced in quantity in plants harvested from the wild, with Blouberg samples collected during summer (9.6 mg GAE. g^{-1}) followed by samples collected at Strand during summer (7.8 mg GAE. g^{-1}). A similar trend was also noted for flavonols where the highest content (1.9 mg QAE. g^{-1}) was recorded in winter Blouberg samples. Moreover, the highest antioxidant activity was again noted in wild samples compared to the cultivated ones. Similarly, the highest FRAP (101.9 µmol AAE. g^{-1}) and DPPH (56.6 µmol TE. g^{-1}) contents were recorded in Blouberg samples during summer.

Table 6
Phytochemical and antioxidant activity of wild and greenhouse cultivated *T. decumbens*.

		Polyphenols (mg GAE. g^{-1})	Flavonols (mg QE. g^{-1})	FRAP (µmol AAE. g^{-1})	DPPH (µmol TE. g^{-1})
Cultivated	Control	5.2 ± 0.02g	0.9 ± 0.07e	27.9 ± 1.4g	4.2 ± 0.1h
	50 mM	5.3 ± 0.01g	1.1 ± 0.05d	32.1 ± 0.7f	18.2 ± 0.2e
	100 mM	6.9 ± 0.06d	1.5 ± 0.02b	47.2 ± 1.2cd	17.4 ± 0.2ef
	150 mM	7.0 ± 0.01d	1.3 ± 0.01c	39.5 ± 0.2e	21.4 ± 0.5cd
	200 mM	7.0 ± 0.07d	1.3 ± 0.05c	39.1 ± 0.1e	22.5 ± 0.5cd
	250 mM	7.5 ± 0.05c	1.4 ± 0.2bc	51.3 ± 1.1b	28.3 ± 0.4b
Wild	SS	7.8 ± 0.05b	1.0 ± 0.05de	48.8 ± 1.4bcd	28.5 ± 0.3b
	SW	5.7 ± 0.02f	1.1 ± 0.02d	31.8 ± 1.3f	16 ± 0.2f
	BS	9.6 ± 0.1a	1.5 ± 0.05b	101.9 ± 2.7a	56.6±1a
	BW	7.7 ± 0.1b	1.9 ± 0.07a	49.1 ± 1.1bc	23.4 ± 1.1c
	MS	6.3 ± 0.5e	1.5 ± 0.05b	45.2 ± 0.3d	20.9 ± 1.2d
	MW	4.7 ± 0.1h	0.8 ± 0.01f	17.6 ± 0.9h	8 ± 0.7g

Means with the different letters along the columns are significantly different at ($P \leq 0.05$), ($n = 3$). Note: SS= Strand summer, SW= Strand winter, BS= Blouberg summer, BW= Blouberg winter, MS = Muizenberg summer and MW = Muizenberg winter.

3.5. Anti-microbial activity of wild collected and greenhouse cultivated *T. decumbens*

Crude extracts of wild and greenhouse cultivated *T. decumbens* had a significant effect on some bacterial and fungal strains as seen in Table 7. Strains where the crude extract did not show zone of inhibition were excluded from the table. Crude extract of samples harvested at Blouberg beach during summer had more anti-microbial activity which was shown by the highest zone of inhibition (13.1 mm) against *A. baumannii* and this was higher than all tested treatments. The same trend was also observed for *S. aureus* and *C. Krusei*, where the highest zones of inhibition (11 mm for *S. aureus* and 15.2 mm for *C. Krusei*) were recorded in crude extract of plant samples collected at Blouberg beach during the summer period. Surprisingly, the highest zone of inhibition (16.2 mm) against *C. tropicalis* was again noted in crude extract of samples collected at Blouberg beach during summer but this was comparable to the zone of inhibition (16 mm) recorded in greenhouse cultivated plants subjected to 250 mM of salinity.

4. Discussion

Climate change and increasing soil salinity are already having a significant effect on crop production losses around the globe [23,1,24,2]. Thus, the alternative use of resilient crops like halophytes is crucial to fulfil the increasing food demand escalated by the increasing human population. Recently, a neglected edible halophyte (*Tetragonia decumbens*) has been cultivated under saline conditions and showed promising production returns for bio-saline agriculture [12]. However, its nutritional value remains undocumented, contributing to its underutilisation among coastal households. Therefore, it became imperative to study the nutritional value, phytochemical composition, and anti-microbial potential of wild and greenhouse cultivated *T. decumbens* to support its domestication, consumption, and utilisation among coastal households.

Plant based mineral nutrients are known to be important components of human diet since they play a substantial role in the maintenance of certain physicochemical processes required to life [25]. Hence scouting for new resilient crops with high mineral composition is crucial in the mist of global changes in climate and food insecurity. In this study, high mineral content obtained in wild and cultivated samples of this leafy vegetable attest to earlier reports that neglected wild leafy vegetables are a good source of minerals. Furthermore, the variability in mineral composition of wild and cultivated *T. decumbens* showed that increasing salinity and place of collection modulated the accumulation of minerals in plant samples. In greenhouse saline cultivation, this could be attributed to excessive Na^{+} absorption by the plant roots which inhibits the absorption, transport, and buildup of other nutrients. While the variability in plant samples collected from the wild could be linked to abiotic factors such as microclimate (temperature and rainfall), soil texture and availability of nutrients in each site of collection [26]. Nevertheless, almost all the minerals assessed in both the wild and in cultivation were above the recommended daily allowance (RDA). Magnesium (Mg) for instance has a 55 mg RDA and this is far below the values obtained in both the wild and cultivated samples. The Mg yield ranged from 300 to 1100 mg/100g with the highest value attained in greenhouse cultivated plants subjected to 50 mM of salinity. The recorded Mg values in this study are substantially greater than those reported in commercially cultivated leafy vegetables such spinach [27,28] and lettuce [29]. This suggests that this neglected leafy vegetable can be an alternative source of nutritional Mg. Moreover, magnesium performs essential roles in several biological processes in humans, including structural support in proteins, nucleic acids, polyribosomes, and facilitating neurotransmitter release, promoting cell adhesion, maintaining calcium-potassium balance, and serving as a cofactor for enzyme activities [30]. Hence, consistently consuming this plant will ensure the serum maintains an ideal level of magnesium content.

When assessing the accumulation of potassium in leaf samples, most greenhouse cultivated plants meet the RDA of 2000 mg except plants subjected to 250 mM of salinity. Increasing salinity has been reported to reduce the potassium levels due to the antagonistic effect of sodium in plant roots [31]. These findings substantiate those of Atzori et al. [32] where *Tetragonia tetragonioides* cultivated under saline conditions had reduced potassium with increasing salinity. On the contrary, most wild samples did not meet the RDA except plant samples collected at Strand beach during summer and winter seasons. This could be due to the physiochemical composition of the soil of which potassium was sufficiently available. *Tetragonia decumbens* has shown to be a valuable source of potassium when cultivated, which is a crucial element for a holistic diet. Potassium is physiologically important as intracellular and extracellular cations that are necessary for regulating blood pressure, muscle contraction, and transmission of nerve signals [33].

When examining the phosphorus composition of the tested samples, only the greenhouse cultivated plants subjected to 50 mM of salinity meet the RDA of 700 mg. These findings are contrary to those obtained by Castañeda-Loaiza et al. [34] on commercially cultivated halophytes suchs as *Suaeda maritima, Mesembryanthemum nodiflorum,* and *Sarcocornia fruticosa*, where leaf phosphorus was below the daily recommended allowance. Thus, suggest that this neglected vegetable can be a source of dietary phosphorus. Calcium and phosphorus are important component of bone and teeth minerals in human skeleton [35]. The calcium content of the tested samples was more pronounced in wild samples than those in greenhouse cultivation. As a result, all samples collected from the wild met the RDA of 1000 mg, while all cultivated treatments fell short. This is due to the alteration of ion transport and accumulation of nutrients caused by Na+and Cl-ions competitors, which limits the uptake of calcium [36]. These findings substantiate those of Šamec et al. [37] on *Brassica* leafy vegetables where increasing salinity reduced the calcium content in leaves and roots.

High accumulation of sodium in edible parts of halophytes under bio-saline agriculture has been reported by Accogli et al. [38]. This was the scenario in this study where both the wild and cultivated *T. decumbens* had sodium that is well above the RDA of 200–500 mg. Sodium is the predominant cation in extracellular fluid and is crucial for the regulation

Table 7
Antimicrobial activity of wild and greenhouse cultivated *T. decumbens*.

Zone of inhibition (mm)					
		A. baumannii	*S. aureus*	*C. krusei*	*C. tropicalis*
Cultivated	Control	4.2 ± 0.04g	3.0 ± 0.07i	2.7 ± 0.4h	5.7 ± 0.1e
	50 mM	4.2 ± 0.03g	3.8 ± 0.08gh	3.4 ± 0.3g	6.1 ± 0.04e
	100 mM	5.4 ± 0.1f	4.0 ± 0.1g	6.5 ± 0.2d	6.2 ± 0.06e
	150 mM	7.2 ± 0.01d	4.2 ± 0.03f	6.9 ± 0.01d	9.1 ± 0.1d
	200 mM	7.8 ± 0.02c	5.0 ± 0.04e	8.8 ± 0.1c	10.8 ± 0.2c
	250 mM	8.0 ± 0.01c	5.2 ± 0.03d	9.0 ± 0.01c	16.0 ± 0.4a
Wild	SS	10.1 ± 0.05b	8.2 ± 0.04b	12.3 ± 0.01b	14 ± 0.2b
	SW	4.2 ± 0.05g	2.1 ± 0.01j	5.0 ± 0.02f	5.8 ± 0.2e
	BS	13.1 ± 0.01a	11.0 ± 0.01a	15.2 ± 0.01a	16.2 ± 0.02a
	BW	6.8 ± 0.02e	3.7 ± 0.1h	6.0 ± 0.03e	9.1 ± 0.2
	MS	6.9 ± 0.03e	7.1 ± 0.05c	8.6 ± 0.05c	11.5 ± 0.3c
	MW	2.2 ± 0.01h	1.9 ± 0.04k	3.1 ± 0.03gh	4.2 ± 0.04f

Means with the different letters along the columns are significantly different at ($P \leq 0.05$), ($n = 3$). Note: SS= Strand summer, SW= Strand winter, BS= Blouberg summer, BW= Blouberg winter, MS = Muizenberg summer and MW = Muizenberg winter.

of acid-base equilibrium and serves as a precursor for the transmission of nerve signals [39]. However, high consumption of Na mineral may cause some health complications such as cardiovascular disease, hypertension, and stroke [40]. It is therefore crucial to boil the leaves for 5 min to reduce the sodium composition before consumption as stated by Caparrotta et al. [41].

Micronutrients, particularly iron, zinc, copper, and manganese, are essential for the well-being of human diets since they contribute to the prevention of malnutrition [42]. It is estimated that over 3.7 million children worldwide suffer from malnutrition due to deficits in certain micronutrients each year [43]. Even though these trace elements are needed in small quantities, their daily intake of no less than 20 mg is necessary. In this study, the macronutrients of the tested samples fell below the RDA except iron. The reduction in micro-nutrients under increasing saline conditions have been reported on numerous edible halophytes such as *Salicornia bigelovii, Salicornia ramosissima* and *Tetragonia tetragonioides* respectively [32,9]. Nevertheless, the iron content of some samples in both the wild and in cultivation meet the RDA of 20 mg. Iron is often found to be lacking in school children, making it the most commonly deficient micronutrient [44]. This deficiency has been linked to anaemia, weariness, and blood-related disorders [45]. Most individuals get iron by consuming vegetables, specifically spinach [7]. Compared with spinach, it is evident that the leaves of *T. decumbens* contain much higher quantities of iron, with values that are 5–10 times greater than those found in spinach. Moreover, the lower values in heavy metals within the tested samples suggest that this neglected vegetable is safe for consumption.

Proximate analysis is used to determine the nutritional relevance of a particular food source [46,47]. In the study, moisture content, ash, crude protein, crude fat, non-fibre carbohydrate and neutral detergent fibre of the wild and cultivated samples were determined. The ash content within samples ranged from 25.2 to 50.7 %, which was higher than the values obtained in other wild edible halophytes such as *Arthrocnemum indicum* (12 %), *Halocnemum strobilaceum* (15 %) and *Suaeda fruticose* (6 %) [4]. The elevated ash content in the leaves of this vegetable suggests that it has a significant quantity of nutritional fibres, which serve as a habitat for digesting microorganisms in the gastrointestinal system. Generally, wild leafy vegetables have been reported to have low fat content that usually range from 1 to 3% [48]. This was this case in this study, where the fat content of the examined samples ranged from 2.2 to 4.4 %. High levels of dietary fat may result in elevated cholesterol levels, which are a significant contributing factor to cardiovascular problems. Thus, the intake of this vegetable would be effective in controlling weight loss and problems induced by excessive fat content.

The protein composition of wild and cultivated *T. decumbens* leaves ranged from 10 to 20.8 %. These values were comparable to the results obtained by Jimoh et al. [18] on *Amaranthus caudatus (20.2 %),* but higher than most commercially cultivated edible halophytes such as *Salicornia ramosissima* (12.6 %), *Sarcocornia fruticose* (14.4 %), *Crithmum maritimum* (13.9 %) and *Mesembryanthemum crystallinum* (12.7 %) [49]. The non-fibre carbohydrates within the samples ranged from 7.7 to 30.6 %. This was higher than most consumed wild vegetables in southern Africa as reported by Bvenura et al. [50]. Moreover, the moisture content of the tested samples was substantially higher in cultivated plants than those collected in the wild. Nevertheless, all samples had lower moisture content which ranged from 3.6 to 9.8 %. Thus, connoting that this vegetable could possess lesser microbial contamination and chemical deterioration, which are generally linked with high moisture content [51].

Halophytes have been reported to possess high amounts of anti-nutrients in edible parts which impair the uptake of nutrients or diminish their bioavailability [10]. In most edible halophytes, oxalate, alkaloids and saponins have been reported as major anti-nutrients [52]. In this study the alkaloid content of tested samples were very low in both the wild and cultivated plants, while oxalate and saponin were substantially higher ranging from 2 to 8.7 %. In addition, saponin and oxalate levels were optimized at higher salinity in the cultivated plants, suggesting that cultivating *T. decumbens* with little to no salt dosages could minimize its antinutrional factors. Various strategies to reduce anti-nutrients in halophytes have been documented, these include soaking, blanching, and cooking [10,41]. In *Tetragonia expansa,* blanching the leaves lowered the total oxalate and saponin content by 25 % when immersed into hot water for 2 min [10,53]. This method has proven to be the best anti-nutrient reduction in most vegetables [54]. However, blanching causes leaf wilting and about 35 % reduction in vitamin C and is not suitable when crips leaves are needed for salad dressing. This method can be utilised for *T. decumbens* to reduce the composition of anti-nutrients on its edible leaves.

Halophytes are also recognised for their production of various secondary metabolites such as phenolics under extreme saline conditions for defence against free radicals [55]. These phenolics compounds provide added-value products in food due to their health benefits [56]. In the present study, secondary metabolites such as polyphenols were more pronounced in quantity in plants harvested from the wild, with Blouberg samples collected during the summer season having the highest content. A similar trend was also noted for flavonols where the highest content was again recorded in wild samples. The variability in metabolites between the wild and cultivated samples may be linked to the differences in climatic conditions, salinity concentration within the soil and anthropogenic disturbances. These results, substantiate the findings of Mangoale and Afolayan [57] on *Alepidea amatymbica* and Xie et al. [58] on *Corydalis Saxicola*, where wild collected samples had more phytochemicals than the cultivated plants.

Phytochemicals in halophytes such as phenolics are well known to have numerous biological activities such as antioxidant, anti-microbial and anti-inflammatory activities [6]. Thus, in this study, the crude extracts of both the wild and cultivated samples of this edible halophyte were tested for their anti-microbial activities against gram-negative and gram-positive bacterial strains as well as fungal strains. Plant samples harvested from the wild had more anti-microbial activity than the cultivated ones. Crude extract of plants collected at Blouberg beach during the summer period had the highest zone of inhibition against the gram-positive *Acinetobacter baumannii* ATCC 19606T (13.1 mm) and gram-negative *Staphylococcus aureus* subsp. *aureus* ATCC 33591 (11 mm). These results correlate to the findings of Pandey and Gupta [59] on *Chenopodium album* and Mouderus et al. [60] on *Traganum nudatum*, where the methanolic extract inhibited the growth of *A. baumannii and S. aureus* respectively. Thus, suggesting that the crude extract of *T. decumbens* is susceptible to bacterial strains and might be suitable for anti-bacterial applications. The same trend was also observed on fungal strains such as *Candida Krusei and Candida tropicalis,* where the highest zones of inhibition (15.2 mm for *C. Krusei* and 16.2 for *C. tropicalis*) were recorded in crude extract of plant samples collected at Blouberg beach during the summer period. These results are in agreement with those reported by Chekroun-Bechlaghem et al. [61] on *Arthrocnemum macrostachyum* and *Salicornia europaea* where the extracts inhibited the growth of *Candida Krusei and Candida tropicalis* respectively. The inhibition activity of *T. decumbens* leaf extracts against bacterial and fungal strains can be linked to the high level of phenolics and flavonols quantified in this halophyte, which are known for their anti-microbial properties [56].

5. Conclusion

The current study revealed that greenhouse cultivated plants subjected to low saline treatment had enhanced minerals and proximate properties as compared to wild collected samples. Given the significant amount of minerals, proximate composition and low anti-nutrients found in this study, it is evident that consuming *T. decumbens* may meet the daily needs for minerals and proximate nutrients. Moreover, the efficacy of antimicrobial metabolites of the crude extract of wild collection of *T. decumbens*, suggest that this halophyte might be suitable for both anti-bacterial and anti-fungal applications. Therefore, for optimal yield of minerals and proximate constituents, it is recommended to cultivate this species under 50 mM of salinity while for medicinal purposes, wild collected samples are recommended.

CRediT authorship contribution statement

Avela Sogoni: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Muhali Olaide Jimoh:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Pamella Mngqawa:** Investigation. **Sihle Ngxabi:** Methodology. **Marilize Le Roes-Hill:** Supervision. **Learnmore Kambizi:** Writing – review & editing, Supervision, Resources, Conceptualization. **Charles Petrus Laubscher:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no competing interest to declare.

Data availability

Data will be made available on request.

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