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Impact of postharvest osmodehydration treatments and drying processes on the nutritional quality, bioactive compounds and preservation of leaf amaranth (*Amaranthus cruentus*)

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Summary

Amaranth leaves are rich in micronutrients and health-promoting secondary metabolites, but highly perishable. The effect of osmodehydration and drying on nutritional quality, health- promoting compounds and their postharvest preservation in *Amaranthus cruentus* leaves was investigated. The experimental set up consisted of four treatment variants with different levels of osmotic solution (NaCl) concentration, temperature and immersion time, i.e.; variant 1 (2.5%, 20 °C, 60 min), variant 2 (10%, 20 °C, 60 min), variant 3 (10%, 40 °C, 60 min), and variant 4 (10%, 40 °C, 180 min). Osmodehydrated leaves were oven-dried at 30 °C or 60 °C, freeze-dried or stored at ambient temperature for 3 days, with non-osmodehydrated leaves as control. Results showed that proteins, minerals (Ca, Mg, Fe, Zn), carotenoids, flavonoids, and phenolic acids were preserved in osmodehydrated leaves with no significant changes, except proteins in freeze-dried and a significantly decreased chlorophyll content in both freeze- and oven-dried leaves of variant 4, corresponding to higher osmotic solution concentration, temperature and longer immersion time. During shelf-life, most nutrients and secondary metabolites were maintained with no significant changes, except protein that significantly increased while ascorbic acid and chlorophylls in both osmodehydrated and control leaves significantly decreased. Lower-temperature and shorter-time immersion resulted in better quality preservation.

Key words: Amaranth, postharvest treatment, nutritional quality, health-promoting compounds, preservation

Introduction

The demand for leafy vegetables, particularly in sub-Saharan Africa is increasing due to their nutritional and health benefits, notably providing micronutrients, vitamins, and antioxidants (VON BRAUN et al., 2023; SARKER et al., 2022). In sub-Saharan Africa, indigenous vegetables have the potential to play a significant role in food security, nutrition and household income due to their high adaptability and resilience to climate variations (BOKELMANN et al., 2022). However, their supply chain faces challenges due to high perishability, leading to high quantitative and qualitative postharvest losses (YESHIWAS and TADELE, 2021). Therefore, postharvest treatment and processing are crucial for preserving the nutritional value of these vegetables as well as diversifying their utilization range. Appropriate postharvest treatment can ensure that healthy, nutritious, and tasty fresh and processed food products are available for use as functional foods and ingredients that can be included in complex foods such as dried vegetables, fortified vegetable-based foods, and bakery products (CHANDRA and KUMARI, 2015). However, these treatments are not well developed for indigenous underutilized vegetables such as amaranth (ELOLU et al., 2023). Amaranth is an African indigenous vegetable that is rich in nutrients and health-promoting compounds, is widely consumed, and can adapt to marginal growing conditions, but it is prone to huge postharvest losses (JOSHI and VERMA, 2020; NEUGART et al., 2017). Specifically, due to high postharvest losses, up to 50% of African indigenous vegetables can be lost along the supply chain from farm to market (GOGO et al., 2018). One strategy to minimize losses incurred in the vegetable supply chain is through processing fresh leaves into low moisture products. Therefore, production of dehydrated or dried products (e.g., from amaranth) could contribute to reducing postharvest losses. However, production of dried products could also lead to loss of important quality parameters such as vitamins, macro- and micronutrients, and bioactive compounds (YUSUF et al., 2023) and needs further investigations.

Drying processes reduce water activity and prevent spoilage in food products, impacting nutritional and bioactive properties, depending on the method used (YUSUF et al., 2023). It can therefore diversify utilization of vegetables by reducing postharvest losses and increasing the potential product range. Common methods for drying fresh vegetables include oven- and freeze-drying. However, long drying times, high energy costs, and nutritional changes have led to the need for pre-treatments that can improve efficiency and effectiveness of drying processes (PROSAPIO and NORTON, 2017). Pre-treatments such as blanching, hot water treatment and osmodehydration have been applied to obtain superior quality dried products from leafy vegetables (KORUS, 2021).

Osmodehydration (OD) is a postharvest treatment recommended to improve the quality of fruits and vegetables by partially dehydrating them, and modifying the raw materials' structural, nutritional, sensory, and functional properties (PANDISELVAM et al., 2022). However, the food industry uptake of OD has been slow partly due to limited information on its application on a wide range of products (RASTOGI, 2023; CHANDRA and KUMARI, 2015). Specifically, OD involves placing the solid/semi solid food material, whole or in pieces, in a hypertonic solution (e.g. sugar and/or salt), causing simultaneous counter diffusion between the osmotic solution and vegetable tissues (RAMYA and JAIN, 2017). This process however produces a product that is not shelf stable and therefore additional drying is recommended (YUSUF et al., 2023). In general, OD is suitable for perishable foods like fresh leafy vegetables, which have heat-sensitive nutrients. For instance, OD was used to enhance nutrient retention of dried kale leaves showing higher contents of bioactive compounds (PASŁAWSKA et al., 2018). However, its application on leafy vegetables has generally received little attention in literature. Specifically, despite its emergence as an important vegetable in many African countries (IMATHIU, 2021), the application of OD for producing dried amaranth products has not been explored before.

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The application of OD as a pre-treatment before drying could provide additional benefits to fast and efficient drying. PROSAPIO and NORTON (2017) showed that OD significantly improves oven-drying and freeze-drying performance in terms of moisture content, water activity, rehydration ability, textural properties and microstructure. It can trigger internal changes in food properties, preserving natural compounds and minimizing injury during drying processes (SHAMSHER, 2020; CHANDRA and KUMARI, 2015). For instance, direct oven-drying is recommended for preserving agricultural produce, but some cases of nutritional damage have been observed at high drying temperatures (JOSHI and MEHTA, 2010). Although temperatures between 30 to 60 °C are considered appropriate for oven-drying of leafy vegetables (ABIONA et al., 2021), its effect in combination with osmotic pre-treatment has to be explored. Additionally, freeze-drying of vegetables such as spinach, kale and broccoli had positive influence on phytochemical content and physical properties (VARGAS et al., 2022), but its influence in combination with OD has to be further investigated. Although OD has been a subject of numerous studies over the years, most of the works evaluate the process kinetics in terms of water loss and solid gain and only a few studies report the process effect on nutritional and bioactive compounds of further dried products (LANDIM et al., 2016). Moreover, it has been reported that OD conditions such as osmotic solution, temperature and immersion time may influence the outcome of the process differently (RAMYA and JAIN, 2017; AHMED et al., 2016). Therefore, the purpose of this study was to evaluate the effect of different postharvest OD treatment conditions and drying processes (oven and freeze-drying) on the nutritional and bioactive compounds of leaf amaranth (*A. cruentus*).

Material and methods

Plant material and growing conditions

Seeds of green leaf amaranth (*A. cruentus*, accession P1636182) were obtained from Bio Innovation Zimbabwe Institute (BIZ) in Harare, Zimbabwe and grown in a greenhouse at the experimental station in Berlin-Dahlem at Humboldt-Universität zu Berlin between March and June 2022. Seedlings were raised in mini-pots and transplanted to 10 L pods after 30 days. During the experimental period, the maximum temperature was 34.2 °C, with a mean of 19.8 °C, while the maximum relative humidity was 93.4%, with a mean of 64.2% using climate system PTF30 (Steinbeis GmbH & Co.KG). Fresh amaranth leaves were harvested 45 days after transplanting and immediately transported in cool boxes to the Department of Food Biotechnology and Food Process Engineering at the Technische Universität Berlin where OD experiments were conducted.

Osmodehydration experiment and conditions

The OD conditions i.e., the osmotic agent, concentration of the osmotic solution, temperature, and immersion time, were predetermined based on previous experiments (SHETE et al., 2018; RAMYA and JAIN, 2017; AHMED et al., 2016). Essentially, NaCl (obtained from Merck, Darmstadt, Germany) was selected as the osmotic agent. NaCl has been previously recommended for application in osmodehydration of vegetables due to its expected positive impact on the nutritional and sensory properties of the final product (NIĆETIN et al., 2021). Fresh leaves were subjected to two osmotic solution concentrations (2.5% & 10% NaCl, in deionized water), temperatures (20 °C, 40 °C) and immersion times (60, 180 min). The treatment combinations were derived based on preliminary experiments, typically representing low temperature-low concentration condition (20 °C, 2.5% NaCl, 60 min) and high temperature-high concentration conditions (40 °C, 10% NaCl, 60 min) and then, high temperature-high concentration-long immersion time conditions (40 °C, 10%, 180 min). Samples of fresh amaranth leaves were placed in each of the solutions and maintained at the corresponding temperatures in a water bath, for the corresponding time durations defined in the design protocol (Tab. 1). Osmodehydrated samples were then taken out from respective solutions, washed with 100 ml deionized water and prepared for drying and further analysis. A portion of the freshly harvested leaves (approximately 50 g) were left with no OD as the control. Both, osmodehydrated leaves and the control, were either further dried (by oven- and freeze-drying) or stored at ambient temperature before further analysis. The experiment was repeated twice, with three replications in each treatment.

Tab. 1: Experimental conditions for OD treatment of fresh amaranth leaves

Treatment label	Osmotic solution concentration	Temperature	Immersion time (min)
Variant 1 (Var 1)	2.5%	20 °C	60
Variant 2 (Var 2)	10%	20 °C	60
Variant 3 (Var 3)	10%	40 °C	60
Variant 4 (Var 4)	10%	40 °C	180

Drying of amaranth leaves

Both osmodehydrated and control leaves were subjected to drying using a drying oven (Heraeus Instruments, Hanau, Germany) at two different temperatures (30 °C, 60 °C), denoted as T-30 and T-60) and freeze-drying, denoted as FD (0.009 mbar and temperatures from -20 °C to 10 °C for 3 days, Gamma 1-16 LSC, Software version 2274, Martin Christ Gefriertrocknungsanlagen GmbH, Osterode, Germany). Oven-drying was conducted at a constant airflow velocity. Inside the oven dryers, amaranth leaves were uniformly placed in trays and kept in the dryers for 48 h until weight constancy.

Storage conditions

Fresh and osmodehydrated amaranth leaves (Variants 1 and 3) were placed on clean trays and kept at constant ambient temperatures of 20 ± 2 °C for 3 days. From the range where good nutrient retention results were observed, the higher and lower-level treatment combinations were selected for the storage trial. Therefore, variants 1 and 3 were selected as they also fall within the temperature range of 20-40 °C which is recommended to minimize heat induced quality deterioration during osmodehydration (SHETE and CHAVAN, 2018). The period of 3 days was considered as this was established to be within the maximum possible shelf life of amaranth leaves under ambient temperature conditions (GOGO et al., 2017). The leaves were then lyophilized, and the nutritional and bioactive compound quality changes determined.

Determination of dry matter content

Dry matter was determined by weighing the leaf material before and after drying in an oven (Heraeus Instruments, Hanau, Germany) at 105 °C for 24 h (constant weight). Percentage [%] of dry matter was calculated by computing the ratio of the dry weight to the fresh weight of the leaves.

Determination of total soluble solids (TSS)

The TSS content, measured as percentage (%) was determined using a hand-held refractometer (PR-101, ATAGO). TSS was measured in the osmotic solutions before and after leaf incubation.

Determination of ascorbic acid

A modified method described by GU et al. (2018) and TIWARI et al. (2009) was used. Briefly, 10 mg of dried, pulverized material (2 min, frequency 30 Hrz; MM400, Retsch GmbH, Germany) was extracted

with 1 mL 2.5% phosphoric acid for 1 h at 4 °C on a thermomixer (500 rpm). After centrifugation (10,000 rpm, 6,800 × g, 5 min, 4 °C) the supernatant was collected in a new tube and filled up to 1 mL with extraction solution. The extract was filtered (0.22 µm, Costar® SpinX tubes) and transferred to HPLC vials. Extracts were analyzed by HPLC (Ultimate 3000 equipped with an autosampler WPS-3000TR, pump LPG-3400RS, column compartment TCC-3000RS, diode array detector DAD-3000RS, Thermo Scientific, Germany). For peak evaluation, the software Chromeleon version 7.2 was used. A volume of 10 µL extract was injected and separated using an AcclaimTM RP18 column (3 µm, 120 Å, 2.1 × 250 mm, Thermo Scientific). Isocratic separation was performed at a flow rate of 0.6 ml/min by using the following eluent: 25 mM KH_2PO_4: acetonitril, 95:5 (v/v). The column oven temperature was 30 °C. Detection was carried out at 254 nm on a photodiode array detector. Ascorbic acid was quantified by using a calibration curve from a chemical reference (Fluka™ Analytical Standards, Seelze GmbH-Germany).

Determination of protein content

Elemental analysis was performed using the Vario Max Cube GmbH, Germany, according to the laboratory specification DIN-ISO-10694 (1995) and DIN-ISO-13878 (1998). Briefly, 500 mg of finely ground leaf material was weighed into clean dry crucibles and catalytically combusted with pure oxygen gas at 900 °C. Nitrogen and carbon were then separated by passing the products of the combustion process through specific adsorption columns. The results of nitrogen analysis were calculated using glutamic acid as the standard reference and subsequently the protein content was determined using nitrogen to protein conversion factor of 6.25 (Sosulski and Imafidon, 1990).

Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) determination of mineral content

For determination of calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), and zinc (Zn), the ICP-OES analytical method was used (VDLUFA, 1976). Specifically, dry finely ground leaf material was weighed (0.5 g) and exact mass of the sample recorded and transferred into microwave digestion tubes. A volume of 5 mL of nitric acid (65%) followed by 3 mL of hydrogen peroxide (30%) was then added to the material in the digestion tubes. The microwave tubes were then sealed and left under a fume cupboard overnight. Thereafter, the microwave tubes were placed in the microwave (MARS Xpress, CEM, USA) for digestion. After digestion, each tube was rinsed twice with 20 mL of ultrapure water into a 50 mL volumetric flask which was then filled up with ultrapure water. Then, the solution was filtered (grade 125 mm) and the elemental compositions of the samples were determined with reference to the multielement standard.

Determination of chlorophyll and carotenoid contents

The sample extraction for chlorophylls and carotenoids followed the method described by Mageney et al. (2016) with slight modifications. Generated extracts were dried in a nitrogen stream, and thereafter diluted with 100 µL dichloromethane and 300 µL isopropyl alcohol, and filtered. Then 200 µL of the filtrate was transferred into HPLC vials (dark with inserts). Extracts were analyzed by HPLC (Ultimate 3000 equipped with an autosampler WPS-3000TR, pump LPG-3400RS, column compartment TCC-3000RS, diode array detector DAD-3000RS, Thermo Scientific, Germany). For peak evaluation the software Chromeleon version 7.2 was used. A volume of 10 µL extract was injected and separated using a YMC-carotenoid column (YMC Co. Ltd. Japan, YMC C30, 100 × 2.1 mm, 3 µm) with measurement at 330 nm. Separation was performed at a flow rate of 0.2 mL/min by using the two eluents consisting of methanol, methyl tert-butyl ether, ultrapure water (Eluent A: 18/15/4), Eluent B: 6/90/4) and the following gradient run: 0-10 min 0% B, 10-40 min 0-100% B, 40-42 min 100% B, 42-45 min 100-0% B, 45-55 min 0% B. The oven temperature was 25 °C. The chlorophyll and carotenoid contents were quantified by using a calibration curve from a chemical reference (DHI, Denmark).

Determination of phenolic acids and flavonoid contents

Extracts were generated according to the method described by Mewis et al. (2011) and modified by Förster et al. (2015). Phenolic acids and flavonoids in the extracts were quantitatively analyzed by HPLC (Ultimate 3000 equipped with an autosampler WPS-3000TR, pump LPG-3400RS, column compartment TCC-3000RS, diode array detector DAD-3000RS, Thermo Scientific, Germany). A volume of 10 µL extract was injected and separated using a C16 column (AcclaimPA, 3 µm, 150 × 2.1 mm, Thermo Scientific, Germany) with the following gradient program: 0-1 min: 0.5% B, 1-10 min: 0.5-40% B, 10-12 min: 40% B, 12-18 min: 40-80% B, 18-20 min: 80% B, 20-24 min: 80-100% B, 24-30 min: 100% B, 30-34 min: 100-0.5% B, and 34-39 min 0.5% B at a flow rate of 0.4 m/min. Two solvents were used for analysis: solvent A: H_2O (0.5% formic acid), B: 40% acetonitrile. The oven temperature was 35 °C. Detection of phenolic acids and flavonoids was carried out at 290 nm on a photodiode array detector against the internal standard 4-methoxycinnamic acid (1 mM, Sigma Aldrich, Germany).

Statistical analysis

Data were analyzed using IBM SPSS Statistics software Version 21. A two-way ANOVA was performed to examine the differences between the quality parameters as a function of the osmotic treatment and drying method used. While one-way ANOVA was used to analyze quality preservation during storage. The means were tested for statistical differences using Tukey's HSD test, at $p \leq 0.05$ level of significance.

Results and discussion

Dry matter

Leaf dry matter was significantly higher in leaves osmodehydrated at higher temperature, higher solution concentration and longer immersion time (variant 4) compared to both the control and other OD conditions (Fig.1). However, it was significantly lower in leaves of variant 1, compared to the control as well as variant 4. OD disrupts vegetable tissues, accelerates water loss, facilitates mass transfer, and capillary flow of osmotic solution into intercellular spaces, leading to dry matter retention (Azuara et al., 2009). The mass transfer facilitated by counter diffusion during OD leads to modification of the cell wall and other internal tissue components of food products (Nowicka et al., 2015). Concentration of osmotic solution, immersion time and temperature are key drivers of mass transfer during OD (Ahmed et al., 2016). A maximum dry matter increase of 14.7% after OD was found in variant 4 where OD temperature and immersion time were 40 °C and 180 min, respectively. Therefore, at 2.5% concentration (variant 1), the low dry matter could be attributed to the slow mass transfer expected at this lower concentration compared to the other variants, i.e., 2, 3 and 4 which were at 10% NaCl concentration, higher immersion time and higher temperatures.

Total soluble solids (%) in the osmotic solution

TSS (%) significantly increased after all OD treatments (Fig. 2). It is expected that softening of leaf tissues during OD allows faster penetration of salt that in turn causes increase in TSS (Azuara et al.,

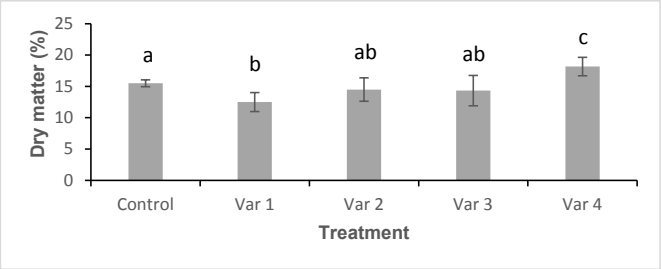

Fig. 1: Dry matter (%) of amaranth leaves subjected to different osmodehydration treatments. Mean ± standard deviation (Different letters indicate significant differences between treatments at P≤0.05, Tukey's HSD test). Var 1=variant 1 (2.5%, 20 °C and 60 min), Var 2=variant 2 (10%, 20 °C and 60 min), Var 3=variant 3 (10%, 40 °C and 60 min), and Var 4=variant 4 (10%, 40 °C and 180 min).

2009). A combination of longer immersion time, higher osmotic solution concentration and higher temperatures facilitates higher rates of mass transfer, leading to higher gains in total solids. Temperature drives mass transfer due to increased cell membrane permeability, while the osmotic solution creates a concentration gradient against which mass transfer and water loss takes place during OD (YUSUF et al., 2023). Although TSS changes can indicate the quality of fresh vegetables in terms of metabolic rate, maturity stage, organic matter degradation, shelf-life and nutrients preservation (HUANG et al., 2023; JIN et al., 2021), in this study, the TSS was determined in the osmotic solution before and after osmotic treatment. Therefore, the results only indicate diffusion from leaf tissues towards the osmotic solution, exemplifying the typical OD process, but the TSS in the osmodehydrated leaves would have to be measured to indicate any potential relation to shelf-life or quality retention in osmodehydrated amaranth leaves.

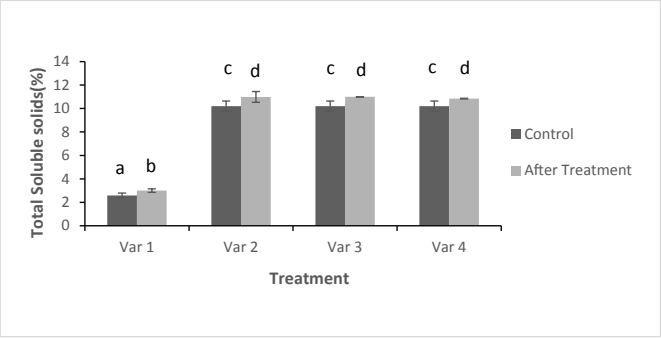

Fig. 2: Total soluble solids (%) in the osmotic solution after different osmodehydration treatments. Mean ± standard deviation (Different letters indicate significant differences between treatments at P≤0.05, Tukey's HSD test). Var 1=variant 1 (2.5%, 20 °C and 60 min), Var 2=variant 2 (10%, 20 °C and 60 min), Var 3=variant 3 (10%, 40 °C and 60 min), and Var 4=variant 4 (10%, 40 °C and 180 min).

Nutritional quality of amaranth leaves

Leaf protein content was significantly influenced by the osmotic treatments, but not by drying method and their interactions (Two-way ANOVA, Appendix A). Pairwise comparisons showed that osmodehydrated leaves of variants 1 and 2 had higher protein content compared to the control and variants 3 and 4 (Tab. 2). However, variant 4 freeze-dried leaves had significantly lower protein content compared to all variant 1 and variant 2 oven-dried leaves (Tab. 2). In comparison to the control, the increase in protein content was between 7.9 to 9.1% and 8.3 to 9.9% in osmodehydrated leaves of variant 1 and variant 2, respectively. In general, the results indicate that OD could improve the content of protein in dehydrated leaves under conditions in variant 1 and 2. Although protein contents in variants 1 and 2 were slightly higher, while that of variants 3 and 4 were slightly lower, they were generally within the range of 23.24 to 24.10% previously reported by TRAORÉ et al. (2017) for shade- and oven-dried *A. cruentus*. Drying could lead to significant increase in protein content of leafy amaranth (ABIONA et al., 2021), similar to what we observed with osmodehydrated amaranth leaves of variants 1 and 2. This further exemplifies the relative importance of OD with regard to improving protein retention in dried amaranth.

Whereas osmotic treatment significantly influenced the contents of Ca, Mg, Fe, Zn, Na and the drying method significantly influenced the Ca, and Mg content, the interaction effects of both factors were only found for the Ca content (Two-way ANOVA, Appendix A). Amaranth is known to be a good source of micronutrients, i.e. Ca, Mg, Fe, and Zn (SURUKITE et al., 2020; KACHIGUMA et al., 2015)**.** Therefore, their preservation during postharvest is important given their essential role in human health (WANG et al., 2021). Iron, an essential element for haemoglobin formation, oxidation of fat, carbohydrate and proteins was well maintained in the osmodehydrated leaves, as its content did not significantly change in osmodehydrated leaves, except for variant 4 corresponding to higher osmotic solution concentration, longer immersion time and higher oven drying temperature (T-60) and freeze-dried leaves, which were only significantly lower than the control leaves oven dried at lower temperature (T-30) (Tab. 2). Although Fe ranged between 58.25 to 104.64 mg kg^{-1} DM, the highest values were obtained in osmodehydrated leaves of variant 1 corresponding to lower temperature, lower concentration and lower immersion time. A similar trend was observed for Mg with variant 1 having the highest contents ranging between 4.9 to 8.1 g kg^{-1} DM. Further, the content of Zn, which is essential for the immune system and thyroid function ranged from 13.90 to 28.47 mg kg^{-1} DM in osmodehydrated leaves while in the control it was between 26.83 and 46.84 mg kg^{-1} DM. However, only the content in the oven-dried control at 60 °C was significantly higher than most of the osmodehydrated variants, except for variant 1 oven-dried at 60 °C and freeze-dried, as well as variant 3 oven-dried at 60 °C. This suggests that a higher level of retention of Zn could be favored by oven-drying of pre-osmodehydrated and control leaves at a higher temperature (T-60) compared to both freeze-drying and oven-drying at a lower temperature of (T-30). In terms of Ca, an essential mineral in regulating normal heart rhythms and nerve functions (WIMALAWANSA et al., 2017), no significant differences were found between the control and all oven-dried osmodehydrated leaves, and freeze-dried leaves of variants 1, 2 and 3. However, pairwise comparison showed that oven-dried osmodehydrated leaves of variants 2, 3 and 4 were significantly lower than freeze-dried control leaves. There was generally an increase in Na content in osmodehydrated leaves, with subsequently higher concentration, higher temperature and longer immersion time OD treatments (variants 2, 3 and 4) showing significantly higher Na content compared to the control (Tab. 2). The increase in Na content is a consequence of the diffusion from the osmotic solution into the leaf tissues, a process driven by concentration, temperature and leaf immersion time (RAMYA and JAIN, 2017).

In general, changes in mineral contents can arise due to breakdown of complex compounds in amaranth leaf tissues into more simple forms because of OD pre-treatment and drying. This was found in previous work of SAMTIYA et al. (2020) who reported that mineral elements can be made available in considerable amounts by destroying anti-nutritional factors by drying and soaking which might inhibit the mineral elements in foods. In fact, the OD process involves soaking the plant tissues in a hypertonic solution and this could trigger such changes that can enhance mineral availability in the osmodehydrated leaves. Similarly, additional drying by oven- or freeze-drying could also elicit the advantages of destroying antinutritional factors and

hence freeing minerals in the amaranth leaves (BABU et al., 2018). It should be noted however that, with exception of variant 4, in the case of Fe, Mg and Ca, lower temperature oven-drying and freeze-drying tended to favor higher retention in osmodehydrated leaves, but the reverse is observed with regards to Zn (Tab. 2). By inference, these results indicate that with OD, it could be possible to produce micronutrient-rich dehydrated amaranth leaves. Despite the observed positive influence of OD on nutritional quality of amaranth, the influence of NaCl on the organoleptic properties of the dried amaranth was not explored in this study. However, the influence of NaCl OD solution concentration on organoleptic properties of vegetables is reported in literature. For instance, SANGEETA and HATHAN, (2016) found no significant influence of salt (NaCl) concentrations between 5 and 10% but an organoleptic change with a solution higher than 15% salt concentration in osmo-air dried *A. campanulatus*. Although this example is not for a leafy vegetable, it shows the organoleptic influence of NaCl used in OD-which needs to be further explored for amaranth.

Chlorophyll and carotenoid contents

Leaf chlorophylls and carotenoids contents are presented in Tab. 3. Both the osmotic treatments and drying methods significantly influenced chlorophyll b, chlorophyll a, and total chlorophyll contents, with a significant interaction between the two factors (Two-way ANOVA, Appendix B). As a key indicator of plant vitality, changes in chlorophylls can predict postharvest quality changes in leafy vegetables. Degradation of leaf chlorophylls can occur due to high temperature and long-term storage (INDRASTI and ANDARWULAN, 2018; MANOLOPOULOU and VARZAKAS, 2016). Overall, low temperature (T-30) oven-dried leaves had the highest total chlorophyll content in both the control and osmodehydrated leaves (variants 1, 2 and 3), with the content in T-30 oven-dried control leaves significantly higher than the rest of the treatments (Tab. 3). However, variant 4 leaves corresponding to longer immersion time, higher osmotic concentration and temperature had significantly lower contents, irrespective of the drying method. Oven-dying and freeze-drying could both lead to reduction in chlorophyll content in plant leaves (NGUYEN et al., 2022). However, pairwise comparisons showed that there were no significant impacts of OD treatment on total chlorophyll content at 2.5-10% NaCl, 20 °C and 60 min (variants 1 and 2), while at 10% NaCl, 40 °C, 60 min and 180 min (variants 3 and 4 respectively) there were significant reductions (Tab. 3). Although changes attributed to OD treatment could also be a result of the alkalizing effect of NaCl solutions that has potential to slow down chlorophyll degradation (GUPTA et al., 2013), our results suggest that incubation temperature seems to have higher impact as observed in variant 4.

Osmotic treatment significantly influenced the ß-carotene content but not lutein and total carotenoids content, whereas the drying method significantly influenced the lutein content and total carotenoids content (Two-way ANOVA, Appendix B). However, interaction between the factors only significantly influenced the ß-carotene content. There were generally no significant changes in total carotenoids and lutein (Table 3). However, there were significant reductions in β-carotene at higher osmotic concentration (10% NaCl) and temperature (40 °C) (variant 3), as well as higher immersion time (180 min, variant 4) (Tab. 3). In general, lutein was more abundant in the amaranth leaves compared to β-carotene in this study, similar to HAN and XU (2014) who found lutein as more abundant in raw, simmered and blanched *Amaranthus mangostanus* leaves. Lutein is particularly important for its anti-inflammatory properties and associated health benefits (BUSCEMI et al., 2018). Despite a lack of comparable literature on effects of OD treatment on the lutein content in amaranth leaves, we found no negative influence on the content of lutein in osmodehydrated amaranth leaves, suggesting good preservation effect. On the other hand, drying temperature can induce loss in carotenoid content. Drying at moderate temperature

Tab. 2: Protein and mineral contents of amaranth leaves subjected to different osmodehydration treatments and drying processes

Treatment	Protein content (%)	Calcium (g kg^{-1} DM)	Magnesium (g kg^{-1} DM)	Iron (mg kg^{-1} DM)	Zinc (mg kg^{-1} DM)	Sodium (g kg^{-1} DM)
Control						
T-30	23.53±1.10^{abc}	31.13±2.22^{abcd}	7.74±0.95^{ab}	126.30±17.84^{a}	30.20±4.42^{ab}	0.48±0.12^{a}
T-60	23.99±2.19^{abc}	28.31±1.64^{abcd}	6.54±0.23^{abc}	93.40±16.28^{ab}	46.84±18.14^{a}	0.83±0.54^{a}
FD	24.11±1.32^{abc}	37.53±3.41^{a}	8.06±1.38^{a}	93.61±10.53^{ab}	26.83±0.51^{ab}	0.49±0.13^{a}
Variant 1						
T-30	26.50±1.03^{ab}	34.03±4.84^{ab}	7.95±1.68^{ab}	104.64±34.84^{ab}	24.33±6.49^{b}	6.61±1.70^{a}
T-60	26.30±2.13^{ab}	34.30±1.69^{ab}	8.31±0.81^{a}	100.75±29.94^{ab}	28.24±0.24^{ab}	6.29±0.72^{a}
FD	25.89±1.67^{ab}	29.25±0.66^{abcd}	6.92±0.2^{abc}	83.40±14.93^{ab}	33.12±4.10^{ab}	8.30±1.10^{a}
Variant 2						
T-30	26.75±0.90^{a}	23.42±3.77^{d}	6.57±0.39^{abc}	68.17±30.41^{ab}	23.52±2.93^{b}	28.13±5.17^{b}
T-60	26.02±0.47^{ab}	24.89±4.68^{bcd}	5.79±0.31^{abc}	77.92±17.32^{ab}	22.81±6.02^{b}	28.97±4.21^{b}
FD	25.67±2.43^{abc}	28.84±0.79^{abcd}	7.13±0.55^{abc}	80.10±16.33^{ab}	22.44±2.83^{b}	25.83±2.40^{b}
Variant 3						
T-30	23.70±1.49^{abc}	24.69±3.19^{bcd}	6.10±0.95^{abc}	71.48±6.96^{ab}	23.00±10.43^{b}	44.79±1.48^{c}
T-60	21.62±1.99^{abc}	24.66±5.68^{bcd}	5.39±0.92^{abc}	89.29±42.3^{ab}	28.46±10.75^{ab}	45.41±1.61^{c}
FD	21.73±0.53^{abc}	27.88±4.43^{abcd}	6.17±1.53^{abc}	64.74±7.04^{ab}	21.07±6.80^{b}	43.11±12.38^{c}
Variant 4						
T-30	21.87±3.24^{abc}	24.15±3.25^{bcd}	6.51±0.28^{abc}	67.07±4.91^{ab},	23.32±4.59^{b}	44.64±0.79^{c}
T-60	21.26±2.00^{abc}	25.56±1.16^{bcd}	4.92±0.20^{c}	58.25±11.33^{b}	13.90±1.44^{b}	53.40±0.15^{c}
FD	20.38±2.59^{c}	23.84±4.18^{cd}	5.77±0.33^{abc}	61.20±14.52^{b}	17.73±4.87^{b}	49.40±4.68^{c}

Mean ± standard deviation; different letters indicate significant differences between treatments (P≤0.05, Tukey's HSD test).
Variant 1 (2.5%, 20 °C and 60 min), Variant 2 (10%, 20 °C and 60min), Variant 3 (10%, 40 °C and 60 min), and Variant 4 (10%, 40 °C and 180 min). T30-Oven-drying at 30 °C, T60-Oven-drying at 60 °C and FD-Freeze-drying.

Tab. 3: Chlorophyll and carotenoid contents of amaranth leaves subjected to different osmodehydration treatments and drying processes

Treatment	Chorophylls			Carotenoids		
	Chlorophyll a (mg g^{-1} DM)	Chlorophyll b (mg g^{-1} DM)	Total Chlorophyll (mg g^{-1} DM)	Lutein (mg g^{-1} DM)	ß-carotene (mg g^{-1} DM)	Total carotenoids (mg g^{-1} DM)
Control						
T-30	5.62±0.40^{a}	2.35±0.13^{a}	7.97±0.51^{a}	0.60±0.24^{a}	0.14±0.03^{abc}	0.74±0.25^{a}
T-60	3.20±1.54^{bc}	1.49±0.55^{bc}	4.69±2.07^{bc}	0.69±0.16^{a}	0.13±0.08^{abc}	0.82±0.24^{a}
FD	2.54±0.22^{bcd}	0.99±0.24^{de}	3.53±0.45^{bc}	0.30±0.15^{a}	0.25±0.10^{a}	0.55±0.24^{a}
Variant 1						
T-30	3.62±0.55^{b}	1.44±0.27^{bc}	5.06±0.82^{b}	0.75±0.06^{a}	0.10±0.01^{bcd}	0.86±0.07^{a}
T-60	2.84±0.17^{bc}	1.39±0.09^{bc}	4.23±0.16^{bc}	0.85±0.17^{a}	0.14±0.03^{abc}	0.99±0.19^{a}
FD	2.48±0.32^{bcd}	1.09±0.30^{bcd}	3.57±0.62^{bc}	0.39±0.15^{a}	0.15±0.01^{ab}	0.54±0.15^{a}
Variant 2						
T-30	3.46±0.27^{b}	1.56±0.13^{b}	5.02±0.36^{b}	0.62±0.14^{a}	0.12±0.00^{bcd}	0.74±0.14^{a}
T-60	1.77±0.06^{cde}	1.10±0.23^{bcd}	2.87±0.19^{cd}	0.60±0.03^{a}	0.15±0.04^{abc}	0.75±0.05^{a}
FD	2.18±0.39^{bcd}	0.81±0.19^{cdef}	2.99±0.58^{cd}	0.36±0.08^{a}	0.15±0.03^{ab}	0.51±0.01^{a}
Variant 3						
T-30	2.90±0.28^{bc}	1.45±0.10^{bc}	4.35±0.34^{bc}	0.47±0.07^{a}	0.14±0.03^{bcd}	0.61±0.10^{a}
T-60	0.30±0.19^{ef}	0.25±0.07^{f}	0.55±0.23^{e}	0.62±0.44^{a}	0.03±0.03^{cd}	0.65±0.41^{a}
FD	1.77±0.50^{cde}	1.17±0.25^{bc}	2.94±0.25^{cd}	0.46±0.21^{a}	0.05±0.03^{cd}	0.52±0.18^{a}
Variant 4						
T-30	0.05±0.01^{f}	0.27±0.16^{ef}	0.32±0.16^{e}	0.59±0.18^{a}	0.00±0.00^{d}	0.59±0.18^{a}
T-60	0.14±0.14^{f}	0.16±0.01^{f}	0.30±0.13^{e}	0.57±0.10^{a}	0.00±0.00^{d}	0.57±0.10^{a}
FD	1.09±0.10^{def}	0.37±0.33^{def}	1.46±0.23^{e}	0.55±0.25^{a}	0.01±0.01^{d}	0.56±0.25^{a}

Mean ± standard deviation; different letters indicate significant differences between treatments (P≤0.05, Tukey's HSD test).
Variant 1 (2.5%, 20 °C and 60 min), Variant 2 (10%, 20 °C and 60 min), Variant 3 (10%, 40 °C and 60 min), and Variant 4 (10%, 40 °C and 180 min). T30-Oven-drying at 30 °C, T60-Oven-drying at 60 °C and FD-Freeze-drying.

(30 ± 2 °C) is recommended for better retention of β-carotene (Negi and Roy, 2000) although in the present study, no drying temperature effect was found for ß-carotene. However, with OD, there was better retention under oven-drying at 60 °C compared to 30 °C, and even higher content in freeze-dried leaves. According to Addis et al. (2009), direct drying of leafy vegetables significantly affects the level of individual carotenoids compared to when pre-treatment such as water blanching was applied. Increased leaf tissue permeability can induce greater extraction of bound phenolic compounds, and greater contact of phenolic compounds with enzyme responsible for the oxidation reactions, a trend previously observed in vegetables that were pre-treated by blanching prior to drying (Dhiman et al., 2022; Djendoubi et al., 2013) Therefore, our results could be attributed to a better extraction and reduced degradation of some carotenoids by pro-oxidant enzymatic activities in osmodehydrated leaves. However, further research needs to be conducted to investigate this in detail.

Phenolic acids and flavonoids composition

Phenolic acids and flavonoids contents are presented in Tab. 4. Osmotic treatment significantly influenced the contents of ferulic acid derivatives and total phenolic acids. The drying method significantly influenced the caffeoyl quinic acid and total phenolic acids content, while the interaction only significantly influenced the ferulic acid derivatives (Two-way ANOVA, Appendix B). Pairwise comparison of the means indicated that ferulic acid derivatives and caffeoyl quinic acid contents did not significantly vary within and across the treatments, except for variant 4 oven-dried at T-60 whose caffeoyl quinic acid content was significantly lower than all freeze-dried leaves as well as variants 1, 2 and 3, T-30 oven-dried leaves (Tab. 4). Similarly, the total phenolic content did not significantly change, except for the variant 4 leaves that were oven-dried at T-60 whose content was significantly reduced. However, the total phenolic acids content tended to increase in leaves of variants 1 and 2 corresponding to lower temperature and shorter time OD, while there was decreasing tendency for variants 3 and 4 corresponding to higher temperature and longer time OD. This could be attributed to alteration of leaf tissue permeability induced by OD, leading to greater extraction yield of bound phenolic compounds or contact with enzymes responsible for oxidation reactions (Boudhrioua and Courtois, 2013). Conversely, the significant reduction in phenolic acid content in variant 4 could be associated with the temperature and immersion time. Korus (2021) reported that time and temperature play a critical role in the retention of phytochemicals in pre-treated leafy vegetables. Particularly, these could cause changes in chemical structure and chemical reaction of phenols with other compounds (Ghafoor et al., 2022). Further, osmotic solution concentration can contribute to the retention of phenolics via mechanisms such as lowering water activity, inhibition of chemical reactions and chelation of metal ions which catalyze the oxidation of phenols (Lončarić et al., 2016). Moreover, the phenolic acids content of variant 3 which had the same concentration of osmotic solution as variant 4 was not significantly different from the control, yet, the content in variant 4 oven-dried at T-60 was significantly lower, implying that the observed loss was probably due to temperature or incubation time rather than the osmotic solution concentration.

Both the osmotic treatment and drying method significantly influenced quercetin-3-rutinoside, but not kaempferol-glucoside content, while the total flavonoids content was only significantly influenced by the drying method (Two-way ANOVA, Appendix B). In general, total flavonoids content was maintained with no significant changes in all osmodehydrated leaves compared to the control. However, pairwise comparisons showed that the content in variant 1 freeze-dried leaves were significantly higher than the content of oven-dried variant 3 leaves at T-30 and all variant 4 leaves, except for the freeze-dried leaves (Tab. 4). Apparently, the temperature and drying method play

Tab. 4: Phenolic acids and flavonoids contents of amaranth leaves subjected to different osmodehydration treatments and drying processes

Treatment	Phenolic acids			Flavonoids		
	Caffeoyl quinic acid (µmol g^{-1} DM)	Ferulic acid derivatives (µmol g^{-1} DM)	Total Phenolic acids (µmol g^{-1} DM)	Quercetin-3-rutinoside (µmol g^{-1} DM)	Kaempferol-glucoside (µmol g^{-1} DM)	Total Flavonoids (µmol g^{-1} DM)
Control						
T-30	4.39±1.71^{ab}	9.93±1.62^{a}	14.31±1.41^{ab}	0.84±0.25^{ab}	0.11±0.04^{a}	0.95±0.28^{ab}
T-60	2.91±2.14^{ab}	11.17±1.52^{a}	14.08±1.35^{ab}	1.61±0.43^{ab}	0.20±0.05^{a}	1.81±0.43^{ab}
FD	9.48±1.81^{a}	7.39±2.27^{a}	16.87±3.84^{a}	0.95±0.46^{ab}	0.11±0.05^{a}	1.07±0.51^{ab}
Variant 1						
T-30	6.33±1.63^{a}	8.76±1.97^{a}	15.09±1.56^{ab}	0.85±0.02^{ab}	0.08±0.07^{a}	0.92±0.06^{ab}
T-60	2.38±1.64^{ab}	12.23±1.38^{a}	14.61±3.87^{ab}	1.37±0.61^{ab}	0.10±0.09^{a}	1.47±0.68^{ab}
FD	3.50±0.45^{ab}	13.51±0.69^{a}	17.02±0.59^{a}	2.23±1.18^{a}	0.17±0.05^{a}	2.41±1.22^{a}
Variant 2						
T-30	6.32±2.32^{a}	9.72±2.47^{a}	16.04±3.17^{a}	0.99±0.32^{ab}	0.14±0.08^{a}	1.13±0.38^{ab}
T-60	4.32±3.54^{ab}	11.57±2.36^{a}	15.90±1.20^{a}	0.94±0.46^{ab}	0.12±0.04^{a}	1.06±0.49^{ab}
FD	8.19±4.17^{a}	11.21±1.23^{a}	19.40±3.70^{a}	0.94±0.30^{ab}	0.10±0.01^{a}	1.04±0.31^{ab}
Variant 3						
T-30	6.42±0.55^{a}	7.55±1.89^{a}	13.96±2.21^{ab}	0.76±0.41^{b}	0.08±0.03^{a}	0.84±0.39^{b}
T-60	1.96±1.77^{ab}	10.15±2.83^{a}	12.11±4.34^{ab}	1.29±0.36^{ab}	0.15±0.05^{a}	1.43±0.41^{ab}
FD	9.83±5.71^{a}	9.47±1.42^{a}	19.30±4.28^{a}	1.16±0.64^{ab}	0.12±0.10^{a}	1.28±0.68^{ab}
Variant 4						
T-30	4.08±0.99^{ab}	9.17±2.14^{a}	13.25±2.34^{ab}	0.67±0.32^{b}	0.08±0.02^{a}	0.76±0.34^{b}
T-60	0.84±0.25^{b}	5.92±0.21^{a}	6.76±0.45^{b}	0.78±0.00^{b}	0.09±0.00^{a}	0.87±0.00^{b}
FD	6.22±3.11^{a}	6.77±0.20^{a}	12.99±3.28^{ab}	0.86±0.12^{ab}	0.07±0.06^{a}	0.93±0.18^{ab}

Mean ± standard deviation; different letters indicate significant differences between treatments (P≤0.05, Tukey's HSD test).
Variant 1 (2.5%, 20 °C and 60 min), Variant 2 (10%, 20 °C and 60 min), Variant 3 (10%, 40 °C and 60 min), and Variant 4 (10%, 40 °C and 180 min). T30-Oven-drying at 30 °C, T60-Oven-drying at 60 °C and FD-Freeze drying.

an important role in the biosynthesis of flavonoids (NGUYEN et al., 2022; NANA et al., 2012). Relatedly, according to MASEKO et al. (2019), sun-, oven-, and shade-drying resulted in higher or similar flavonoids content of *A. cruentus*. However, we found that quercetin-3-rutinoside and kaempferol-glucoside contents were significantly reduced in variant 4, corresponding to higher osmotic concentration, higher immersion time and higher temperature. These results signify that appropriate postharvest OD and drying processes could play a positive role in enhancing flavonoids retention in leaf amaranth.

Changes of nutritional compounds during shelf-life

Osmodehydrated leaves from two treatments (variants 1 and 3) were subjected to ambient shelf-life conditions for 3 days and analyzed for characteristic nutritional and health promoting compounds, i.e., proteins, ascorbic acid, minerals (Tab. 5), total carotenoids and chlorophylls, as well as total phenolic acids and flavonoids (Tab. 6). Ascorbic acid content significantly declined, while protein content significantly increased after 3 days of storage. Ascorbic acid in vegetables is prone to losses during storage, depending on the kind of postharvest treatment (LEE and KADER, 2000). Essentially, temperature and soaking of the vegetable during OD expose ascorbic acid to leaching from leaf tissues, hence its reduction. Further, conditions that favor water loss such as tissue bruising and physical damage during postharvest handling can result in loss of ascorbic acid in leafy vegetables (LEE and KADER, 2000). Therefore, additional osmotic pressure due to the concentration gradient created by the osmotic solution could facilitate loss of ascorbic acid. The content

Tab. 5: Changes in nutritional compounds in osmodehydrated leaf amaranth during ambient storage conditions

Treatment	Storage time	Proteins (%)	Vitamin C (mg g^{-1} DM)	Ca (g kg^{-1} DM)	Mg (g kg^{-1} DM)	Fe (mg kg^{-1} DM)	Zn (mg kg^{-1} DM)
Control							
	Day 0	24.61±0.97^{a}	17.08±0.75^{a}	28.57±1.41^{a}	7.39±0.25^{a}	94.44±10.54^{a}	50.98±26.93^{a}
	Day 3	26.61±2.65^{b}	10.09±2.99^{b}	30.96±4.49^{a}	8.02±0.91^{a}	88.55±12.43^{a}	44.21±11.29^{a}
Variant 1							
	Day 0	25.05±1.83^{a}	14.35±0.04^{a}	27.95±1.64^{a}	7.64±0.20^{a}	78.71±11.26^{a}	42.10±11.49^{a}
	Day 3	27.54±2.59^{b}	6.06±0.042^{b}	28.23±1.44^{a}	7.78±0.35^{a}	85.32±9.66^{a}	41.77±10.28^{a}
Variant 3							
	Day 0	23.69±0.66^{a}	9.38±0.49^{a}	26.97±0.99^{a}	6.88±0.36^{a}	67.08±7.57^{a}	29.82±1.87^{a}
	Day 3	24.29±1.71^{b}	1.98±0.16^{b}	28.63±11.2^{a}	7.77±3.16^{a}	81.52±37.90^{a}	29.79±4.19^{a}

Mean ± standard deviation; different letters indicate significant differences between each treatment after storage (P≤0.05, Tukey's HSD test). Variant 1 (2.5%, 20 °C and 60 min), Variant 3 (10%, 40 °C and 60min).

Tab. 6: Change in secondary plant metabolites in osmodehydrated leaf amaranth during ambient storage conditions

Treatment	Storage	Total Chlorophyll (mg g^{-1} DM)	Total Carotenoids (mg g^{-1} DM)	Total Phenolic acids (µmol g^{-1} DM)	Total Flavonoids (µmol g^{-1} DM)
Control					
	Day 0	3.56±0.74[a]	0.35±0.14[a]	17.42±0.54[a]	1.44±0.49[a]
	Day 3	2.29±0.27[b]	0.42±0.09[a]	16.03±1.38[a]	1.65±0.12[a]
Variant 1					
	Day 0	4.03±0.81[a]	0.39±0.04[a]	14.55±1.63[a]	1.76±0.13[a]
	Day 3	2.79±0.46[b]	0.49±0.07[a]	15.40±1.02[a]	2.23±1.01[a]
Variant 3					
	Day o	3.73±0.36[a]	0.83±0.36[a]	13.30±0.72[a]	0.90±0.01[a]
	Day 3	2.64±0.75[b]	0.85±0.21[a]	8.88±1.56[b]	0.73±0.07[a]

Mean ± standard deviation; different letters indicate significant differences between each treatment after storage (P≤0.05, Tukey's HSD test). Variant 1 (2.5%, 20 °C and 60 min), Variant 3 (10%, 40 °C and 60 min).

of Ca, Mg, Fe, and Zn could be preserved for 3 days of storage irrespective of the treatments. Although Gogo et al. (2017) reported significant losses of Zn and Fe after 2 days of storage of fresh amaranth leaves at 20 °C, in our study, the contents of these minerals were not significantly affected by any of the OD treatments applied.

The total phenolic acids, flavonoids and carotenoids contents were maintained after ambient storage for 3 days, except for total phenolic acids content of variant 3 which significantly declined after 3 days of storage. Although chlorophyll content was significantly reduced in both the control and osmodehydrated leaves, the reduction was lower in osmodehydrated leaves (29.22%) for variant 3, followed by 30.77% for variant 1, and higher (35.67%) in control leaves. Related results on OD treated leaves under ambient storage could not be found in previous studies, but Gogo et al. (2018) reported an increase in total phenolic acids and flavonoids content, while total chlorophylls in fresh amaranth leaves were reduced under ambient storage conditions. Further, Negi and Roy (2003) reported a decline in carotenoids content after 2 days of ambient storage of fresh amaranth. However, our results showed higher total carotenoids contents in both osmodehydrated and control leaves after 3 days, although the increase was not significant (Tab. 6). This suggests a contribution of OD towards enhanced preservation of carotenoids which needs to be further studied.

Conclusion

OD pre-treatment contributes to improved retention of important nutritional properties and health promoting compounds in amaranth leaves during postharvest. Specifically, protein, total phenolic acids, total flavonoids and total carotenoids contents were even higher in osmodehydrated leaves (variants 1 and 2), while the mineral contents (Ca, Mg, Fe, Zn) could be in general maintained. On the other hand, the uptake of sodium significantly increased at higher osmotic solution concentration. This, however, could present a challenge due to health concerns related to high salt consumption as well as the potential impact on product sensory properties. Therefore, the concentrations used in the present osmotic treatment need to be optimised accordingly. The variation in the level of retention of compounds studied between the different osmotic treatments showed that more benefits are obtained at osmotic solution concentration between 2.5 - 10%, temperature of 20 - 40 °C and immersion time of 60 min. Overall, lower temperature oven-drying (T-30°C) and freeze-drying resulted in a better nutrient and bioactive compound retention following OD. In light of these findings, the contributions of this study are two-fold: first, improving knowledge and evidence on preservation of nutritional and health properties that can be realised by applying OD as a pre-treatment for green leafy amaranth, and secondly, from a technological point of view, it contributes empirical pointers on how process conditions such as osmotic solution concentration, temperature and immersion time can influence food nutritional quality and bioactive compounds in osmodehydrated leafy vegetables. However, despite the promising results, two major limitations have to be addressed through further research namely: evaluating the influence of the treatments on organoleptic properties which are important for consumer uptake of dehydrated products and further optimisation of the process for small- or large-scale industrial application by dehydrated leaf amaranth processors.

Authorship contribution statement

Samuel Elolu: Conceptualization, Methodology, Investigation, Writing – original draft. Nadja Förster: Investigation, Review and Editing. Anne Kathrin Baier: Methodology, Investigation, Review and Editing. Susanne Huyskens-Keil: Supervision, Conceptualisation, Review and Editing. Arnold M. Opiyo: Supervision, Review and Editing.

Conflict of interest

No potential conflict of interest was reported by the authors.

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Appendices

Appendix A. Main effects and interactions of osmotic treatment and drying method (two-way ANOVA) on nutritional quality of Amaranth leaves

Source of variation	Statistic	Protein (%)	Ca (g kg^{-1}DM)	Mg (g kg^{-1}DM)	Fe (mg kg^{-1}DM)	Zn (mg kg^{-1}DM)	Na (g kg^{-1}DM)
Osmotic treatment	F	14.14	11.92	9.74	6.20	6.61	269.6
	P	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***
	Partial η2	0.65	0.61	0.57	0.45	0.47	0.97
Drying method	F	1.01	1.65	3.44	0.75	1.21	1.10
	P	0.38	0.21	**0.05***	0.48	0.31	0.35
	Partial η2	0.06	0.10	0.19	0.05	0.07	0.07
Treatment*dying method	F	0.30	2.34	1.58	1.16	2.18	0.90
	P	0.96	**0.04***	0.17	0.35	0.06	0.53
	Partial η2	0.08	0.38	0.29	0.24	0.37	0.19

Values in bold with* are statistically significant at P≤0.05

Appendix B. Main effects and interactions of osmotic treatment and drying method (two-way ANOVA) on secondary plant metabolites in Amaranth leaves

Source of Variation		Chlorophylls (mg g^{-1} DM)			Carotenoids (mg g^{-1} DM)		
	Statistic	Chlorophyll a	Chlorophyll b	Total Chlorophyll	Lutein	ß-carotene	Total carotenoids
Osmotic treatment	F	61.13	39.47	64.44	0.84	21.49	1.58
	P	**0.00***	**0.00***	**0.00***	0.51	**0.00***	0.21
	Partial η2	0.89	0.84	0.90	0.10	0.74	0.17
Drying method	F	36.67	24.52	38.87	6.75	2.42	4.36
	P	**0.00***	**0.00***	**0.00***	**0.00***	0.11	**0.02***
	Partial η2	0.71	0.62	0.72	0.31	0.14	0.23
Treatment*drying	F	8.64	7.66	9.63	0.82	2.78	0.47
	P	**0.00***	**0.00***	**0.00***	0.59	**0.02***	0.87
	Partial η2	0.70	0.67	0.72	0.18	0.43	0.11
		Phenolic acids (μmol g^{-1}DM)			Flavonoids (μmol g^{-1}DM)		
		Caffeoyl quinic acid	Ferulic acid Derivatives	Total Phenolic acids	Quercetin-3-rutinoside	Kaempferol-glucoside	Total Flavonoids
Osmotic treatment	F	1.80	7.64	5.78	2.71	1.23	2.61
	P	0.16	**0.00***	**0.00***	**0.05***	0.32	**0.06**
	Partial η2	0.19	0.50	0.44	0.27	0.14	0.26
Drying method	F	13.55	1.66	9.26	3.33	1.35	3.33
	P	**0.00***	0.21	**0.00***	**0.05***	0.27	**0.05***
	Partial η2	0.48	0.10	0.38	0.18	0.08	0.18
Treatment*drying	F	1.24	3.20	1.00	1.61	1.30	1.72
	P	0.31	**0.00***	0.46	0.16	0.28	0.14
	Partial η2	0.25	0.46	0.21	0.30	0.26	0.32

Values in bold with* are statistically significant at P≤0.05