

Article

Nutrient Status and Antioxidant Activity of the Invasive *Amaranthus retroflexus* L.

Mihaela Lacatus ¹, Patricia Tarkanyi ¹, Luminita Pirvulescu ^{2,*}, Tiberiu Iancu ², Ioan Ladislau Caba ^{3,*}, Nicolae-Valentin Vlăduț ³, Aurica Breica Boroșan ⁴, Simion Alda ⁴ and Despina-Maria Bordean ¹

¹ Faculty of Food Engineering, University of Life Sciences “King Mihai I” from Timisoara, 300645 Timisoara, Romania; mihaela.lacatus.fia@usvt.ro (M.L.); patricia-cristina.tarkanyi.fia@usvt.ro (P.T.); despinabordean@usvt.ro (D.-M.B.)

² Faculty of Management and Rural Tourism, University of Life Sciences “King Mihai I” from Timisoara, 300645 Timisoara, Romania; tiberiuiancu@usvt.ro

³ National Institute of Research-Development for Machines and Installations Designed to Agriculture and Food Industry-INMA, 013813 Bucharest, Romania; valentin_vladut@yahoo.com

⁴ Faculty of Engineering and Applied Technologies, University of Life Sciences “King Mihai I” from Timisoara, 300645 Timisoara, Romania; auricaborozan@usvt.ro (A.B.B.); simion_alda@usvt.ro (S.A.)

* Correspondence: luminita_pirvulescu@usvt.ro (L.P.); cabaioan@yahoo.com (I.L.C.); Tel.: +40-0742139774 (L.P.); +40-0744515964 (I.L.C.)

Abstract: *Amaranthus retroflexus* L. is widely regarded as one of the world’s most invasive weeds, often linked to significant agricultural losses due to its resilience and herbicide resistance. However, unlike other amaranth species already recognized for their health benefits, *A. retroflexus* remains largely overlooked as a potential nutritional and pharmacological resource. This study investigates whether this abundantly growing plant could be repurposed as sustainable food. We focused on three main questions: Can weed be transformed into a food source? Does *A. retroflexus* offer comparable nutritional value as its relatives? And how can it be harvested safely for human use? Mineral content, total antioxidant capacity, and polyphenol content were analyzed across different plant parts. Results revealed high levels of essential minerals, antioxidants, and other bioactive compounds, suggesting strong potential as a nutrient-dense food. However, traces of heavy metals—such as lead, cadmium, and arsenic—were detected in some samples, emphasizing the need for controlled cultivation. Overall, the findings support the safe and sustainable valorization of *A. retroflexus* in food and pharmaceutical applications.

Keywords: common weed; food crisis; minerals; total antioxidant capacity; fingerprint



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1. Introduction

Global food security remains a pressing challenge, especially in the context of climate change, resource scarcity, and population growth. One promising solution is multiple cropping, which increases land use efficiency by cultivating multiple species in the same space. In this context, an often-overlooked opportunity lies in the spontaneous growth of weeds alongside major crops. Instead of solely viewing them as threats, certain weeds may be reimagined as valuable resources—both nutritionally and environmentally.

Among such candidates, species of the genus *Amaranthus* stand out. These plants not only grow abundantly across a wide range of agroecological conditions, but also contribute to carbon sequestration, potentially playing a role in climate change mitigation [1]. However, repurposing such species for food and health applications requires rigorous evaluation of their nutritional profiles and proper post-harvest processing systems.

Genus *Amaranthus*, a member of the family *Amaranthaceae*, includes approximately 60 to 70 species [2], many of which are classified as invasive weeds due to their aggressive growth and adaptability to poor soil, drought, and shade conditions [3,4]. One of the most widespread is *Amaranthus retroflexus* L. (redroot pigweed), known for its prolific seed production and capacity to dominate cultivated fields. A single plant can yield thousands of seeds with dormancy lasting up to 15 years, making eradication difficult once established [5,6].

Many of the plants considered today as weeds used to be consumed thousands of years back. Despite their weedy reputation in North America and Europe, amaranths have a long history as a nutritious food plant. Native American communities used both the seeds and aerial parts for culinary and medicinal purposes [7]. Based on the Encyclopedia of Food Grains, “Amaranth is one of the oldest food crops with evidence of its cultivation reaching back as far as 6700 BCE in the Americas”, and it is considered a traditional food in India, Mexico, Peru, and some other countries. Hindus consider amaranth grains as “Ramdana”, meaning “God’s grain”, used as a high-protein grain or as a leafy vegetable in many Indian dishes [8,9]. According to Kwapata & Maliro (1997) [8], in certain rural and urban areas of Africa, the increasing ignorance among people regarding the existence of indigenous vegetables that are rich in nutrients was causing a decline in their consumption, leading to inadequate nutrition. In Africa, some of the amaranth species contribute to the nutritional well-being of rural populations by providing necessary nutrients and also for the prevention of diseases associated with nutritional disorders, for example, blindness due to vitamin A deficiency. In regions such as the Caribbean and India, amaranth leaves are widely consumed in traditional diets, e.g., in dishes like callaloo or cooked greens [1]. The seeds are increasingly appreciated as pseudocereals in gluten-free products due to their rich nutritional profile and absence of gluten. Even knowing all that, many reluctant people still consider the value of *Amaranthus* spp. to be low and delay recognizing it as a beneficial source of food [8,10].

Several studies have highlighted the mineral richness of amaranths, with high levels of calcium, iron, magnesium, zinc, and potassium—minerals essential for metabolic function, bone health, and disease prevention [11,12]. Given these benefits, amaranth has gained attention as a functional food ingredient, particularly suitable for plant-based or gluten-free diets.

Moreover, *Amaranthus* spp. are recognized for their antioxidant content, especially polyphenols, which have been linked to chronic disease prevention, including type 2 diabetes and cardiovascular conditions [13,14]. These bioactive compounds also influence food processing strategies and can enhance the functional and therapeutic value of derived food products.

In light of the global demand for sustainable, health-promoting foods, it is timely to re-evaluate underutilized plants like *Amaranthus retroflexus*. As early as the 1980s, the U.S. National Academy of Sciences identified amaranths as “underexploited tropical plants with promising economic value” [15]. Yet, compared to more commonly cultivated species, *A. retroflexus* remains understudied—particularly in terms of its nutritional potential and safe integration into food systems.

This study aims to bridge this knowledge gap by exploring the nutritional composition, mineral content, antioxidant potential, and polyphenol content of *Amaranthus retroflexus*. We assess whether its characteristics align with those of better-known edible amaranth species and examine its suitability as a food ingredient. Through this, we advocate for the inclusion of neglected plant species in future strategies for food security, environmental sustainability, and public health.

2. Materials and Methods

To highlight the potential of *Amaranthus retroflexus* in both the food and pharmaceutical industries, we investigated its nutritional profile by analyzing the mineral content of various plant parts and evaluating its total antioxidant capacity and total polyphenol content. The study was carried out in six key stages:

1. Collection and sample preparation;
2. Mineral content analysis;
3. Antioxidant capacity evaluation;
4. Total Polyphenol Content (TPC) determination;
5. Statistical data analysis;
6. Investigation of harvesting and cultivation techniques.

2.1. Collection and Sample Preparation

The plant samples were collected in the autumn of 2024 from six locations in Timiș County, Romania (Figure 1).

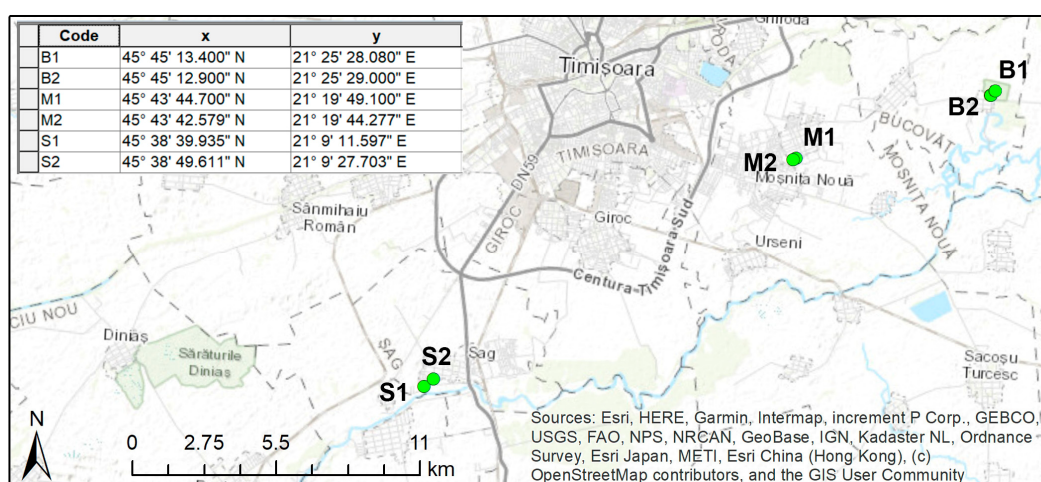


Figure 1. Map of the sample's locations [16]. Legend: sample collection points: S1, S2, M1, M2, B1, B2.

Randomly selected specimens were combined to form representative composite samples for laboratory testing. The plants were thoroughly washed with tap water to remove surface dust and soil, and excess soil was gently shaken off the roots. The plant material was then separated into roots, stems, leaves, and flowers. All parts were air-dried and ground using a laboratory mill designed for food-grade samples to ensure uniformity. Approximately 5 g of each sample were pressed into pellets using a manual hydraulic press at 10 tons for 30 s. These pellets were analyzed directly using the XRF device without additional chemical processing, following established protocols for plant material analysis [17,18].

2.2. Mineral Content Analysis

To determine the mineral composition of the plant, we used a Hitachi XMET8000 portable X-ray fluorescence (XRF) spectrometer (Hitachi High-Tech Analytical Science, Oxford, UK). This non-destructive technique enables rapid, multi-elemental analysis with minimal sample preparation, and has been increasingly applied for evaluating soil and plant mineral profiles, environmental risks, and nutrient availability in agricultural systems [17,19]. Each sample was scanned in triplicate with an acquisition time of 90 s per replicate, to ensure analytical precision [17,20]. The following elements were quantified: macronutrients (K and Ca) and micronutrients and trace elements (Fe, Ba, Cu, Mn, Mo,

Zn, Ni, Ti, Zr, Sr, Rb, Cr, Ta, Pb, Sb, Cd, As, Sc). These elements were selected based on their nutritional relevance and detectability using XRF in plant tissues [17,21]. Instrument calibration was verified using certified reference materials (CRMs) suitable for plant and soil matrices. All results were expressed in mg/kg dry weight (D.W.).

2.3. Total Antioxidant Capacity Analysis

To evaluate antioxidant potential, 5.00 g of dried, ground plant material was extracted with 50.0 mL of a 50% ethanol solution under magnetic stirring. The resulting mixture was filtered, and the antioxidant activity of the extract was assessed using the CUPRAC (Cupric Ion Reducing Antioxidant Capacity) method, following the protocol described by Bordean (2016) [22]. Absorbance was measured at 450 nm using a Spekol 205 spectrophotometer (Analytik Jena GmbH, Jena, Germany) after a 30 min reaction time. Results were expressed as micromoles of Trolox equivalents per gram of dry plant weight ($\mu\text{mol TE/g DW}$), in accordance with Apak et al. (2008) [23]. All measurements were conducted in triplicate to ensure reliability.

2.4. Total Polyphenol Content (TPC) Determination

The total polyphenol content (TPC) was determined using the Folin–Ciocalteu colorimetric method. Absorbance was measured spectrophotometrically at 750 nm, following a 2 h reaction period. A calibration curve was constructed using gallic acid as the reference standard, and TPC values were expressed as milligrams of gallic acid equivalents (GAE) per gram of dry plant weight. Plant extracts were obtained using a 50% ethanol solution, following the protocol of Bordean et al. (2019) [24]. All reagents used in the analysis were ultra-pure analytical grade.

2.5. Statistical Analysis

The data collected were subjected to statistical analysis and modeling using PAST (version 2.17c) and MVSP software (version 3.22) packages to identify correlations and patterns within the mineral and antioxidant profiles. Two visual elements, the graphical representation of the correlation between total polyphenol content and total antioxidant capacity and the heatmap, were generated with the assistance of ChatGPT (version GPT-4o, part of OpenAI's GPT-4 family, developer OpenAI, San Francisco, CA, USA) under human supervision. All figures were verified, refined, and finalized by the authors to ensure scientific accuracy.

2.6. Investigation of Harvesting and Cultivation Techniques

As part of this study, we explored a range of potential harvesting methods that could be suitable for *Amaranthus* species, especially in the context of mixed-cropping systems. Our focus was on identifying existing technologies and farming practices that might be adapted to selectively harvest amaranth without disrupting the main crop. We looked at different approaches based on farm size and resources from manual tools used on small plots to more advanced, automated systems suitable for large-scale operations. Post-harvest techniques, such as mechanical cleaning and optical sorting, were also considered, along with smart farming tools like drones and AI-based plant detection, which could help improve efficiency in future applications. While these methods were not tested in our research, they were reviewed as part of a broader discussion on how *A. retroflexus* could be integrated into sustainable agricultural systems. Although often classified as a weed, its widespread occurrence in fields cultivated with cereals and legumes makes it a practical candidate for selective harvesting using existing infrastructure. Its natural coexistence with major crops allows for the possibility of leveraging its presence rather than eliminating it, particularly in systems focused on biodiversity, resource efficiency, and low-input farming.

By acknowledging its dual role—as both a spontaneously occurring species and a potential alternative food source—this investigation explores feasible pathways for its integration without necessitating major changes in land use or crop management.

3. Results and Discussions

3.1. *Amaranth spp. as a Food of the Future*

The results obtained demonstrate that *A. retroflexus*, commonly regarded as a weed, shows a notable mineral profile, along with a high content of polyphenols and a strong antioxidant capacity. Our study confirms the high mineral content across different plant parts, as well as their significant total polyphenol content and antioxidant capacity (Table 1, Figures 2 and 3). These findings highlight the plant's considerable nutritional and pharmacological potential and also recommend a structured harvesting protocol to facilitate its use in both the food and pharmaceutical industries.

Table 1. Analyzed parameters from *Amaranthus retroflexus* plant parts.

Analyzed Parameters	M.U.	Root	Stem	Leaves	Flower with Seeds
K	g/kg	84.19 ± 2.24	83.45 ± 3.76	74.92 ± 5.26	63.33 ± 2.63
Ca	g/kg	42.46 ± 1.02	47.82 ± 0.49	71.80 ± 3.30	35.53 ± 2.14
Fe	g/kg	1.49 ± 0.11	1.01 ± 0.03	2.44 ± 0.07	3.85 ± 0.17
Cu	ppm	20.91 ± 1.28	13.80 ± 0.53	12.23 ± 0.83	25.20 ± 0.54
Mn	ppm	ND	114.21 ± 1.97	296.46 ± 8.82	170.94 ± 4.75
Mo	ppm	7.74 ± 0.13	5.83 ± 0.16	6.96 ± 0.32	7.74 ± 0.13
Zn	ppm	72.93 ± 2.78	70.70 ± 4.34	76.54 ± 3.50	111.90 ± 2.84
Ni	ppm	ND	ND	ND	ND
Ti	ppm	125.97 ± 3.75	123.88 ± 2.14	238.93 ± 6.65	478.96 ± 29.41
Ba	ppm	126.29 ± 3.35	110.53 ± 6.79	160.32 ± 9.85	160.32 ± 9.85
Zr	ppm	5.04 ± 0.11	2.84 ± 0.08	5.83 ± 0.16	10.52 ± 0.28
Sr	ppm	123.88 ± 2.14	93.09 ± 2.36	151.51 ± 4.21	26.84 ± 1.23
Rb	ppm	6.96 ± 0.32	6.96 ± 0.32	7.74 ± 0.13	6.96 ± 0.32
Cr	ppm	ND	8.46 ± 0.21	8.46 ± 0.21	10.52 ± 0.28
Ta	ppm	ND	21.05 ± 0.56	21.05 ± 0.56	ND
Pb	ppm	5.83 ± 0.16	5.83 ± 0.16	ND	2.04 ± 0.14
Sb	ppm	21.05 ± 0.56	15.12 ± 0.32	15.12 ± 0.32	17.87 ± 0.45
Cd	ppm	ND	ND	13.80 ± 0.53	13.80 ± 0.53
As	ppm	ND	ND	2.84 ± 0.08	2.84 ± 0.08
Sc	ppm	124.38 ± 8.49	229.21 ± 6.38	375.52 ± 6.48	84.19 ± 2.24
H ₂ O	%	51.73 ± 1.76	69.72 ± 3.30	50.40 ± 1.18	74.92 ± 5.26
TAC	μmol TE/g D.W.	10.28 ± 0.46	22.96 ± 1.53	193.75 ± 1.35	70.40 ± 0.35
TPC	mg GAE/g D.W.	54.3 ± 0.28	57.7 ± 0.91	202.35 ± 1.17	70.7 ± 0.46

Legend: TAC = Total Antioxidant Capacity; TE = Trolox Equivalent; ND = not detected; FS—flower with seeds; LE—leaves; ST—stem; RO—root; TPC = Total Polyphenol Content; GAE = Gallic Acid Equivalent; K—Potassium; Ca—Calcium; Fe—Iron; Cu—Copper; Mn—Manganese; Mo—Molybdenum; Zn—Zinc; Ni—Nickel; Ti—Titanium; Ba—Barium; Zr—Zirconium; Sr—Strontium; Rb—Rubidium; Cr—Chromium; Ta—Tantalum; Pb—Lead; Sb—Antimony; Cd—Cadmium; As—Arsenic; Sc—Scandium; H₂O—Water content.

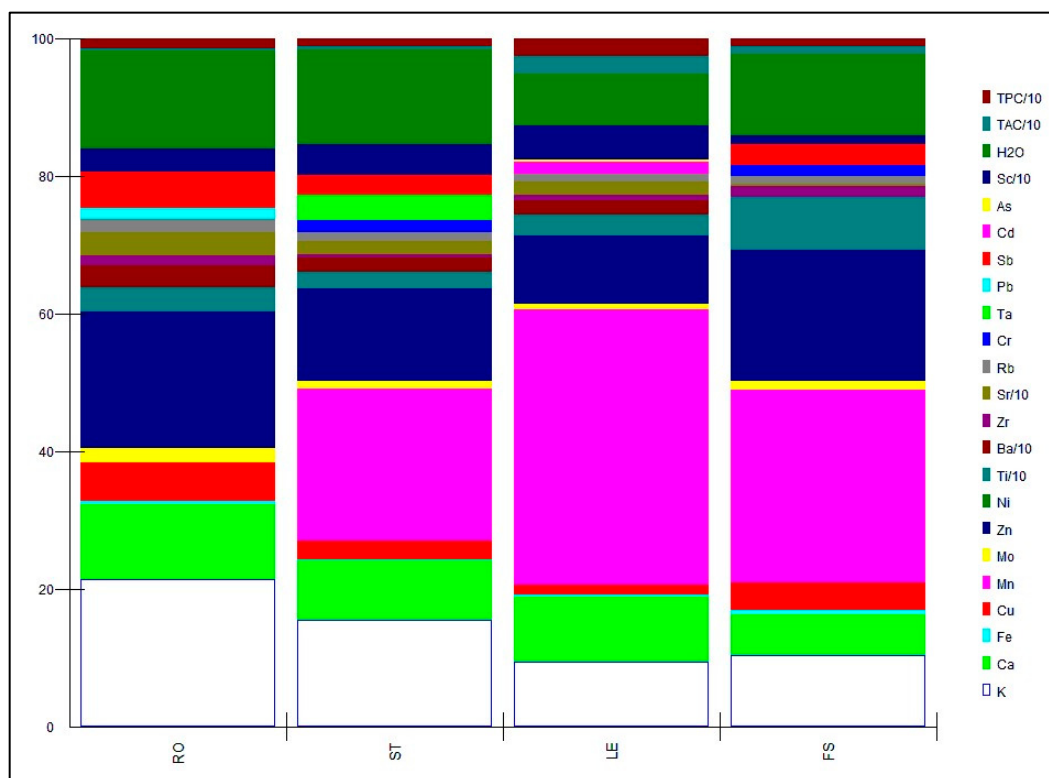


Figure 2. Fingerprint of *A. retroflexus* plant parts. Legend: FS—flower with seeds; LE—leaves; ST—stem; RO—root; TAC—Total Antioxidant Capacity; TPC = Total Polyphenol Content; GAE = Gallic Acid Equivalent; K—Potassium; Ca—Calcium; Fe—Iron; Cu—Copper; Mn—Manganese; Mo—Molybdenum; Zn—Zinc; Ni—Nickel; Ti—Titanium; Ba—Barium; Zr—Zirconium; Sr—Strontium; Rb—Rubidium; Cr—Chromium; Ta—Tantalum; Pb—Lead; Sb—Antimony; Cd—Cadmium; As—Arsenic; Sc—Scandium; H₂O—Water content.

All samples show relatively similar levels of potassium (K) with small variations in standard deviation, the highest being present in root and stem samples while the lowest describes the flower and seed samples. K is highest in roots and stems, making them the best sources of this mineral. Calcium (Ca) concentration shows large variations across samples, with leaves being the richest in calcium content, while flowers and seeds show the lowest content. Iron (Fe) increases noticeably from roots to flowers. Regarding Fe, a mineral necessary for red blood cell production and oxygen transport, it shows the highest concentration in flowers with seeds (3.85 g/kg), making it a great source for supporting iron levels. Leaves (2.44 g/kg) also have a considerable amount of iron. Copper (Cu) also seems to be concentrated in the roots and flowers, while leaf and stem concentrations are lower. Manganese (Mn) presents high variability between samples, while molybdenum (Mo) is consistent across all samples, indicating it is less sensitive to environmental variations. Manganese important for bone health, wound healing, and metabolism is present in big amounts (296.46 ppm) in LE, followed by FS (170.94 ppm) and ST (114.21 ppm). Flowers with seeds (111.90 ppm) contain the most zinc (Zn), indicating strong immune-boosting properties, while leaves (76.54 ppm) also have a good Zn content. Mo (Molybdenum), which is recommended for interfering in protein synthesis, is present in all plant parts, ranging from 5.83 ppm (stem) to 7.74 ppm (root, flowers with seeds).

The potentially harmful elements seem to be concentrated in the roots and stems (Pb—5.83 ppm), while Cd (cadmium) and As (arsenic) are in leaves. Chromium (Cr), which is beneficial in trace amounts but toxic at higher concentrations, is present in stems and

leaves (8.46 ppm) as well as in the flowers with seeds (10.52 ppm). The moderate chromium content can be beneficial in low amounts for insulin regulation.

Based on the analysis of the results, the most nutritious plant parts are the leaves due to their high content of calcium, iron, manganese, zinc, and total antioxidant capacity, making them one of the most nutritious parts. However, the presence of cadmium and arsenic makes them potentially risky, and recommended to consume them when they are very fresh, before accumulating harmful elements from the atmosphere. Since the *Amaranthus* species are known to accumulate nitrates, and *Amaranthus retroflexus* has been linked to cases of livestock poisoning—particularly in pigs and cattle—due to an unidentified toxic compound [25], it is advisable to consume the plant only after proper thermal treatment. Alternatively, harvesting and consuming the plant while still young may help reduce the risk, as nitrate levels tend to be lower in the earlier stages of growth. The flowers with seeds are rich in iron, zinc, and total antioxidant capacity, making it another highly nutritious option with relatively low levels of toxic metals. The least nutritious is the root.

The fingerprint provides a sort of map that typically refers to the unique chemical composition of plant parts, including the presence of minerals, bioactive compounds, and potentially harmful substances like heavy metals. Knowing the fingerprint of *A. retroflexus* plant parts is of great importance when considering its potential usage in nutrition, pharmacology, and agriculture. The fingerprints of the plant's different parts are presented in Figure 2.

TAC (total antioxidant capacity) indicates the presence of bioactive compounds and proves the plant's ability to fight against oxidative stress, which is crucial for preventing chronic diseases. The total antioxidant capacity (TAC) of the leaf samples, determined by CUPRAC assay, reached 193.75 $\mu\text{mol TE/g D.W.}$, placing them at the upper limit of values typically reported for antioxidant-rich plant species. This level of activity is consistent with that found in aromatic and medicinal plants, such as *Origanum vulgare* and *Rosmarinus officinalis*, which are well-documented for their elevated polyphenol content and strong antioxidant responses [26]. The high TAC values observed in this study correlate closely with the total polyphenol content (TPC), reinforcing the role of phenolic compounds as key contributors to antioxidant function. Given that the CUPRAC method is sensitive to both hydrophilic and lipophilic antioxidants [27], the results likely reflect the presence of a broad spectrum of active metabolites in the leaf tissue. Collectively, these findings underscore the antioxidant potential of the leaves and suggest their suitability for use in formulations aimed at mitigating oxidative stress in functional food or phytopharmaceutical contexts [27].

A strong and statistically significant correlation was observed between total polyphenol content (TPC) and antioxidant capacity (TAC) across the analyzed plant parts ($R^2 = 0.955$, $p = 0.023$; Figure 3). Both parameters reached their highest values in the leaves, supporting the widely accepted view that polyphenolic compounds play a central role in antioxidant defense. The ascending trend from root to stem, flower, and ultimately leaves was consistent for both TPC and TAC, with a slight deviation between stem and flower values. This inversion is likely attributed to the presence of other antioxidant molecules in flowers, such as carotenoids or vitamins, which contribute to TAC independently of TPC.

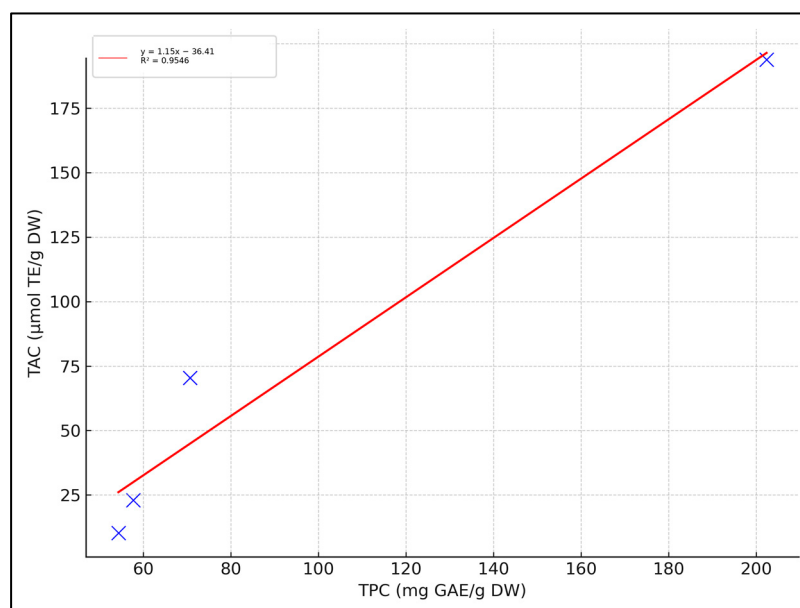


Figure 3. Correlation between TPC and TAC. Created with the assistance of ChatGPT (OpenAI, 2025), under the guidance of the authors [28]. Legend: TAC—Total Antioxidant Capacity; TPC = Total Polyphenol Content; GAE = Gallic Acid Equivalent; TE = Trolox equivalent.

Leaves exhibited the greatest accumulation of polyphenols, a feature commonly associated with their exposure to environmental stressors like ultraviolet radiation and herbivory, which stimulate the biosynthesis of phenolic compounds [29]. In contrast, the root system, being underground and less exposed to such stress, demonstrated markedly lower levels of both TPC and TAC [30]. Flowers also showed appreciable polyphenol content, possibly linked to their role in attracting pollinators and ensuring reproductive success [31]. The robust correlation between TPC and TAC underscores the potential of TPC as a predictive marker for antioxidant capacity in phytochemical screenings. These findings highlight leaf extracts as particularly promising for applications in functional foods, nutraceuticals, and phytotherapeutic formulations aimed at mitigating oxidative stress.

The heatmap (Figure 4) shows the distribution of mean concentrations for all measured elements across the four sample types (RO, ST, LE, FS). Darker shades indicate higher concentrations, while lighter shades reflect lower values or missing data (ND).

To illustrate the relationship between different plant parts and mineral compounds, we have applied Principal Component Analysis (PCA). Based on fingerprint (Figure 2) and Joint Plot PCA representation (Figure 5), we prove the relationships between different plant parts and the elements/compounds they contain. Each plant part shows distinct associations with certain elements, reflecting their chemical composition and possible roles in nutrient storage or uptake.

Figure 5 helps to interpret how different plant parts (RO = root, FS = flower with seeds, ST = stem, LE = leaves) relate to various elements or compounds based on their loadings in two dimensions (Principal Component 1 and Principal Component 2).

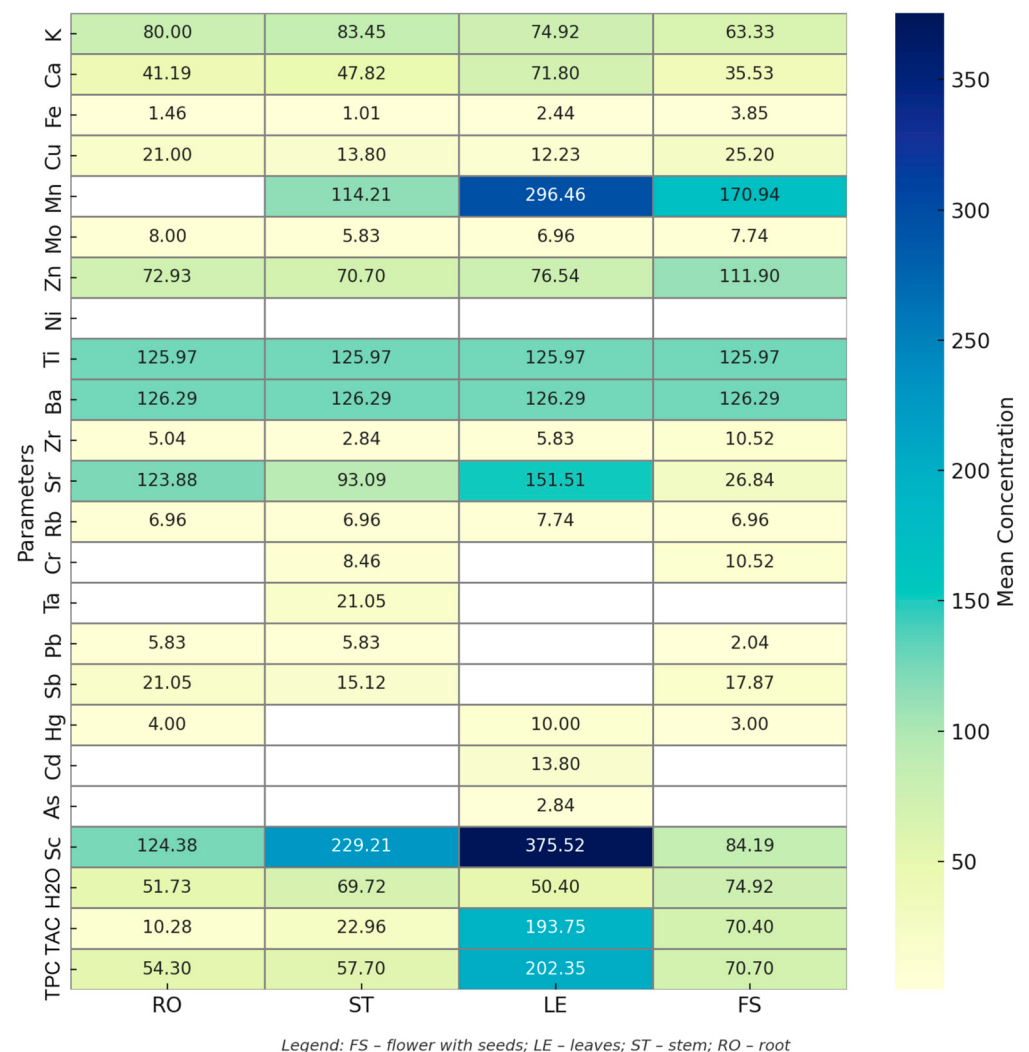


Figure 4. Heatmap of mineral and biochemical parameters in *Amaranthus retroflexus* organs. Created with the assistance of ChatGPT (OpenAI, 2025) [28], under the guidance of the authors. Legend: FS—flower with seeds; LE—leaves; ST—stem; RO—root; TAC—Total Antioxidant Capacity; TPC = Total Polyphenol Content; GAE = Gallic Acid Equivalent; K—Potassium; Ca—Calcium; Fe—Iron; Cu—Copper; Mn—Manganese; Mo—Molybdenum; Zn—Zinc; Ni—Nickel; Ti—Titanium; Ba—Barium; Zr—Zirconium; Sr—Strontium; Rb—Rubidium; Cr—Chromium; Ta—Tantalum; Pb—Lead; Sb—Antimony; Cd—Cadmium; As—Arsenic; Sc—Scandium; H₂O—Water content.

Because strong positive correlations are visible between elements whose arrows point in the same direction, while negative correlations are obvious between elements pointing in opposite directions, we discover the following: TAC is correlated with Mn, As, Ca, and Sc concentration; moisture content is positively correlated with Fe, Zr, Zn, and Mo, while Sb with Pb; and Ta is positively correlated with Sr, Ba, and K. The plant parts (FS, RO, ST, LE) represented by blue triangles suggest which minerals are most present. The flowers with seeds (FS) indicate a high content of Cu, Cr, and Zn. The leaves (LE) are strongly associated with Ca, As, Sc, Sr, and Ba. The root (RO) shows a direct association with Pb and Sb, while the ST (stem) is positioned near Pb and Ta, suggesting these elements are more prevalent in the stem.

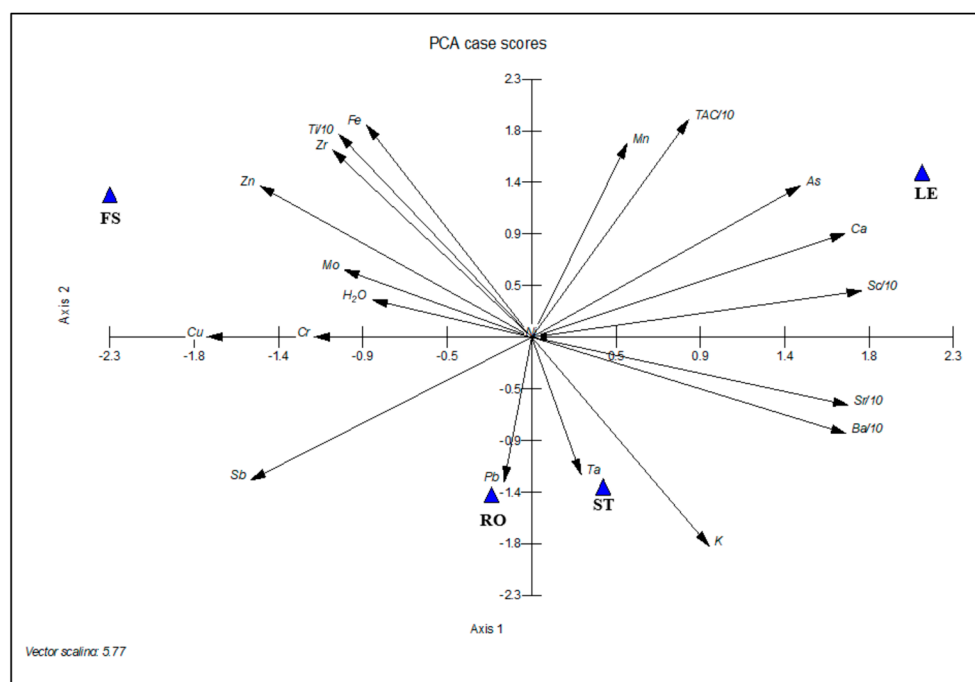


Figure 5. PCA graphical representation of data. FS—flower with seeds; LE—leaves; ST—stem; RO—root; TAC—Total Antioxidant Capacity; Mn—manganese; As—arsenic; Ca—calcium; Sc—scandium; Sr—strontium; Ba—barium; K—potassium; Ta—tantalum; Pb—lead; Sb—antimony; Cu—copper; Cr—chromium; H₂O—water; Mo—molybdenum; Zn—zinc; Zr—zirconium; Ti—titanium; Fe—iron.

3.2. Harvesting and Cultivation of *Amaranth* spp.

Although this study did not include experimental planting trials, we recognize that cultivation parameters—such as sowing density, planting depth, and intercropping compatibility—are essential for the successful integration of *Amaranthus retroflexus* in mixed-cropping systems. Our intention was to highlight the potential of amaranth as a dual-purpose species that grows spontaneously alongside crops, particularly in low-input systems. However, to fully assess its agronomic value, future research should focus on field-based evaluations of optimal seeding practices, crop competition dynamics, and yield performance under different cultivation scenarios. These aspects will be crucial in determining whether *A. retroflexus* can transition from a tolerated weed to a purposefully managed functional crop.

As interest grows in finding alternative, sustainable food sources, *Amaranthus* species are gaining attention not just as weeds, but as potential dual-purpose crops. Although our study did not involve the physical testing of harvesting methods, we explored a range of technologies that could be applied in practice, especially in systems where amaranth is grown alongside traditional crops. In mixed-cropping systems [32], amaranth could be successfully integrated with cereals like wheat, corn, or barley, as well as legumes such as soybeans and lentils. Techniques like intercropping, sowing in designated strips, and using crop rotation not only help manage the land more efficiently but also support long-term soil health. These practices are already familiar to many farmers, which makes the idea of introducing amaranth into existing systems more realistic.

While we did not test specific machinery in field conditions, we reviewed the types of equipment and technologies currently available that could be adapted for amaranth harvesting at various farm scales. For small farms, hand-harvesting remains the most accessible option—affordable but time-consuming. For mid-sized operations, tools like walk-behind harvesters or modified machines designed for multiple crops offer more

efficiency. On larger farms, advanced technologies such as robotic harvesters or AI-assisted systems may be more viable. These approaches could help selectively target amaranth without damaging the main crop, saving both time and resources.

Post-harvest processing is equally important in maintaining the quality of the final product. Traditional mechanical cleaning systems like air screens or gravity separators are still widely used, but modern technologies such as optical sorters can significantly improve seed purity by identifying differences in color or shape. These improvements are particularly beneficial if amaranth is to be marketed for human consumption or medicinal use.

Newer smart farming tools like drones and AI-based plant recognition systems also show promise. These technologies can help monitor plant health, predict yields, and even guide targeted harvesting [33,34]. While such tools may not be accessible to every farmer, they represent a direction worth considering—especially for larger farms or specialized cultivation. Remote sensing imagery offers valuable historical data for monitoring crop dynamics, and its spatial resolution enables precision-level interventions suitable for amaranth cultivation [35]. In more controlled environments, such as greenhouses or vertical farms, amaranth could be grown year-round with consistent quality. Techniques like hydroponics and aeroponics are already proving effective for leafy varieties, offering high yields with minimal water and nutrient waste. These methods also reduce the risk of contamination from heavy metals or pathogens, which is particularly relevant if amaranth is used for food or pharmaceutical purposes.

Depending on the size and type of farm, different harvesting equipment may be more appropriate. For smaller plots, simpler machines like hand-held vacuum harvesters may suffice, while larger farms might benefit from automated, high-capacity systems. These recommendations (see Table 2) are meant to provide a flexible framework that can be adapted to different growing conditions and resource levels.

Table 2. Recommendations based on farm size, crop type, and harvesting equipment.

Farm Size	Primary Crop	Harvesting Equipment
Small farm (<10 ha)	wheat, barley, maize	Hand-held vacuum harvesters, walk-behind brush strippers
Medium farm (10–100 ha)	soybeans, sunflowers, legumes	Robotic weed pullers, high-clearance weed strippers
Large farm (>100 ha)	corn, cereal grains	AI-driven robotic harvesters, optical sorting, drones

For medicinal uses, harvesting must be performed with care to preserve the bioactive compounds in the plant. One solution already in use for other medicinal plants involves a towed harvesting machine operated by a tractor. This machine cuts the plants, separates the seeds using a vibrating grate, and collects both seeds and biomass in different compartments. It is a relatively straightforward system but has proven effective in protecting the quality of the harvested material while maintaining efficiency.

3.3. Harvesting Medicinal Amaranth for Therapeutic Use

Medicinal plants, including certain *Amaranth* spp. varieties, must be harvested at full maturity to preserve their therapeutic properties. Based on studies analyzing mineral composition and bioactive compounds, the most efficient and straightforward harvesting method is presented below (Figure 6), ensuring the optimal retention of bioactive compounds while maintaining cost efficiency.

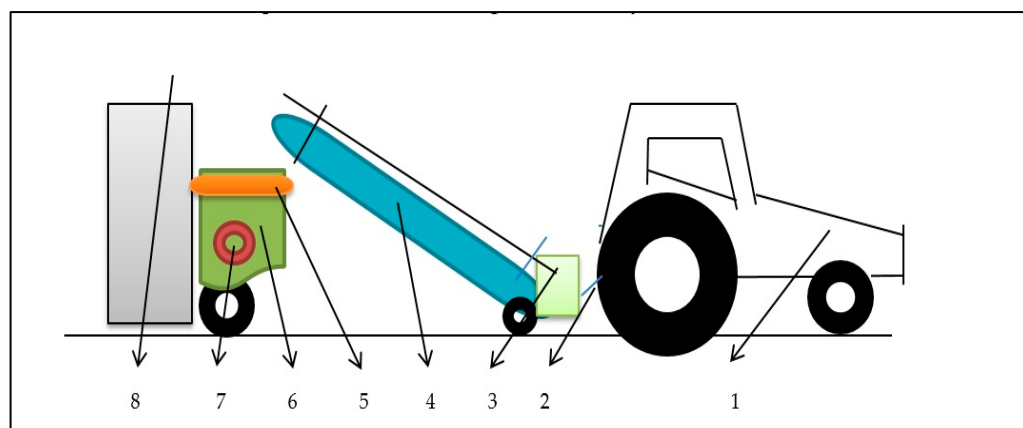


Figure 6. Towed machine for complete harvesting of medicinal plants (operation scheme). Legend: 1—tractor; 2—harvesting machine; 3—cutting device; 4—rubber conveyor belt; 5—shaker grate with holes; 6—collecting basin; 7—conveyor screw; 8—conveyor belt with scrapers.

The harvesting process involves a specialized machine (2) pulled by a tractor (1) with at least 100 hp (horsepower). The machine runs on hydraulic motors powered by the tractor and is operated manually for better control during fieldwork. The tractor follows a designated path left open during sowing and moves forward at a very slow pace to prevent damage or crop loss. Once in motion, the plants are gently cut by the machine's blade system (3) and placed onto a rubber conveyor belt (4). At the end of the belt, the seeds are funneled into a collection basin (6), while a shaker grate (5) mounted above helps separate the seeds from the stalks. Meanwhile, the remaining plant material—stems and leaves—is carried by a secondary belt with scrapers (8) to a transport area, where it is stored in large containers or bags weighing between 500 and 600 kg. The seed collection basin is emptied into transport containers either by activating a conveyor screw (7) or using a suction system, depending on the setup.

4. Conclusions, Observations, and Recommendations

The PCA plot highlights the clear relationships between various plant parts and their associated elements, offering insight into how different tissues contribute to nutrient storage and uptake. Each part of the plant exhibits a distinct chemical profile, suggesting functional differentiation that may influence both nutritional value and safety. Among the findings, the roots and leaves showed traces of toxic metals—lead in the roots, and cadmium and arsenic in the leaves—raising concerns about potential health risks. These parts should be consumed with caution, particularly if the plant is grown in areas prone to heavy metal contamination. This reinforces the need for proper monitoring of soil quality and environmental conditions before the plant is recommended for consumption. On the other hand, the leaves and the flower-seed structures emerged as the most nutrient-dense parts, rich in essential minerals, antioxidants, and polyphenols. These findings underline the plant's promising potential as a functional food, particularly if cultivated in controlled or low-contamination environments.

Overall, *Amaranthus retroflexus* demonstrates a compelling nutritional profile, with many characteristics aligning it with the growing category of so-called “superfoods”. However, this potential can only be fully realized if toxic element levels are reduced through selective cultivation, site control, and careful post-harvest handling. With further research and appropriate safeguards in place, this underutilized plant could play a valuable role in future food systems, offering both health benefits and agricultural versatility.

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