



Leaves, stems, and seeds of black nightshade (*Solanum nigrescens*): Potential for functional food applications

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Abstract:

This article describes the physicochemical, techno-functional, and antioxidant properties of leaves, stems, green seeds, and mature seeds of black nightshade (*Solanum nigrescens* M. Martens & Galeotti), evaluating its potential for functional food formulations.

The plant materials were dehydrated at 60°C, ground, and analyzed using standardized methods for chemical composition, techno-functional properties, and antioxidant activity.

The results indicated significant variations ($p < 0.05$) in moisture, ash, lipid, protein, fiber, and carbohydrate contents across the plant parts, reflecting their potential nutritional uses. *S. nigrescens* leaves demonstrated the highest protein content (22.58 g/100 g) while mature seeds exhibited the highest lipid content (6.32 g/100 g), suggesting suitability as functional lipid sources. In terms of techno-functional properties, stems presented superior water absorption capacity (9.76 g/g), which could be valuable in food formulations requiring high hydration. Additionally, the leaf extract showed the highest total phenolic content (12,038.33 mg GAE/g) and total flavonoids (13,192.15 mg EC/g), which correlated with significant antioxidant activity (90.55% DPPH⁺ inhibition). These results highlighted the high potential of *S. nigrescens* leaves as a bioactive ingredient in functional foods.

S. nigrescens proved to be a rich source of nutrients and bioactive compounds that can be used in food products, including protein-rich supplements, lipid-based functional ingredients, hydrating agents in bakery products, and natural antioxidant additives in beverages, nutraceuticals, and health-promoting formulations.

Keywords: Black nightshade, *Solanum nigrescens*, antioxidant capacity, functional foods, physicochemical attributes, techno-functional properties

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INTRODUCTION

Recent years have seen a dramatic surge in chronic degenerative diseases, e.g., diabetes mellitus, cardiovascular disorders, neurodegenerative diseases, and various types of cancer. These conditions are strongly associated with oxidative stress, which makes it one of the most critical public health challenges worldwide. Oxidative stress arises from an imbalance between the generation of reactive oxygen species and the capacity of endogenous antioxidant defense systems, leading to cellular damage of lipids, proteins, and nucleic acids. This phenomenon is strongly linked to the initiation and progression of chronic non-communicable diseases, thereby stimulating intense scientific interest in dietary

strategies aimed at enhancing antioxidant intake through natural sources [1]. In this context, functional foods fortified with bioactive compounds have gained significant attention as cost-effective, accessible, and preventive tools that mitigate oxidative damage and promote long-term health.

Natural antioxidants derived from plant-based foods exert multiple biological effects, including free radical scavenging, metal chelation, modulation of inflammatory pathways, and regulation of cellular redox homeostasis. Phenolic compounds, flavonoids, carotenoids, vitamins, and other secondary metabolites play a pivotal role in these mechanisms and are increasingly valued not only for their health-promoting properties but also

for their technological functionality in food systems [2]. Consequently, the search for novel, sustainable, and culturally relevant plant sources of antioxidants has intensified, particularly in regions rich in biodiversity but underrepresented in scientific research.

Among these sources, native and underutilized vegetables emerge as promising candidates due to their high nutritional density, adaptability to local agroecological conditions, and traditional consumption by rural communities. These plant resources often exhibit superior contents of micronutrients, dietary fiber, and phytochemicals compared to widely commercialized crops, while simultaneously contributing to food security, dietary diversification, and the preservation of traditional knowledge [3]. However, despite their high potential, many of these plants remain poorly characterized from a physicochemical, techno-functional, and bioactive standpoint, limiting their incorporation into modern food formulations and value-added products.

Black nightshade (*Solanum nigrescens* M. Martens & Galeotti) is one of such underexplored plants. This species belongs to the *Solanaceae* family, which is widely distributed throughout tropical and subtropical regions of the Americas. In the southern states of Mexico, particularly in Oaxaca, *S. nigrescens* is traditionally harvested from wild or semi-cultivated environments and consumed as part of regional gastronomy. It is highly appreciated for its distinctive flavor and reputed medicinal properties. Ethnobotanical records indicate its use in the treatment of gastrointestinal disorders, inflammation, and other ailments, suggesting the presence of biologically active compounds with therapeutic potential [4–6].

Several studies conducted on related species within the *Solanum* genus, such as *Solanum nigrum* f. *brevipetiolare* (Chodat) Chodat, *Solanum scabrum* Mill., and *Solanum retroflexum* Dunal., reported significant antioxidant, antimicrobial, anti-inflammatory, and hypoglycemic activities. These effects have been largely attributed to their rich profiles of phenolic acids, flavonoids, alkaloids, saponins, and steroidal glycosides [7–9]. In addition, leaves of African nightshade species are recognized as a valuable source of protein, minerals, and carotenoids (provitamin A), which reinforces their importance in combating micronutrient deficiencies in vulnerable populations.

Despite the growing body of literature on African and Asian *Solanum* species, scientific information regarding *S. nigrescens* remains scarce, particularly regarding its individual vegetative structures. Leaves, stems, and seeds represent metabolically distinct tissues that may differ substantially in their chemical composition, functional behavior, and antioxidant capacity. Such structural differentiation can significantly affect water and oil absorption capacities, emulsifying properties, color attributes, and the concentration of bioactive compounds, all of which are critical parameters for food for-

mulation and processing¹ [10]. Nevertheless, comprehensive studies addressing these aspects in *S. nigrescens* are limited or absent.

Furthermore, from a technological perspective, the incorporation of novel plant ingredients into food matrices requires a thorough understanding of their techno-functional properties, including water absorption capacity, solubility, oil binding ability, emulsifying activity, and bulk density. These properties directly affect texture, stability, mouthfeel, and overall product quality, determining the feasibility of their application in functional foods, nutraceuticals, and reformulated traditional products. Without such information, the industrial utilization of underutilized plants remains constrained.

In Mexico, the valorization of native plant resources aligns with the current trends toward sustainable food systems, clean-label ingredients, and the use of local biodiversity to develop health-oriented products with cultural identity. However, the lack of systematic scientific characterization of *S. nigrescens* limits its recognition beyond traditional consumption and hinders its potential integration into functional food development strategies aimed at reducing the burden of oxidative stress-related diseases.

Therefore, the objective of the present study was to comprehensively characterize the physicochemical composition, color attributes, techno-functional properties, and antioxidant capacity of *S. nigrescens* leaves, stems, and seeds at different maturity stages. By generating robust scientific evidence on the nutritional and functional potential of this underutilized plant, this research seeks to support its valorization as a functional ingredient to be incorporated into innovative food products that target health-conscious consumers and populations at risk of chronic degenerative diseases.

STUDY OBJECTS AND METHODS

Raw materials. Bundles of black nightshade (*Solanum nigrescens* M. Martens & Galeotti) were acquired from the Central Market in the municipality of San Juan Bautista Tuxtepec, Oaxaca, Mexico. The leaves, stems, and seeds were washed and disinfected; excess water was removed. Subsequently, they were dehydrated at 60°C for 3 h in a tray dryer (POLI-REP, Mexico). Afterwards, we ground the dried materials using a coffee grinder (Krups® Mod. GX4100, USA) and sieved them through an 80-mesh sieve (0.177 mm).

Chemical composition, total energy, and pH. The chemical tests relied on standard methods outlined by the Association of Official Analytical Chemists: Method 934.01 for moisture², Method 942.05 for ash³, Method 948.22 for lipids⁴, Method 960.52 for proteins ($N \times 6.25$)⁵,

¹ AOAC. Official methods of analysis of the Association of Official Analytical Chemists: Official methods of analysis of AOAC International. 21st ed. Washington: AOAC, 2019.

² The same.

³ The same.

⁴ The same.

⁵ The same.

Method 962.09 for crude fiber⁶, and Method 981.12 for pH⁷. Total carbohydrates were calculated by difference. Total energy was calculated in line with the methodology reported by Hernández-Santos *et al.* [11].

Color parameters. The color parameters were determined using a USVIS1347 Hunter-Lab colorimeter (Hunter Associates Laboratory, USA). The included luminosity (L^*), chromatic coordinates a^* (redness–greenness), and b^* (yellowness–blueness). These values made it possible to calculate chroma $C^* = (a^2 + b^2)^{1/2}$ and hue angle $h^\circ = \arctan(b^*/a^*)$.

Techno-functional properties. The water absorption capacity, water solubility capacity, oil absorption capacity, emulsifying capacity, and apparent density were determined in line with the methodology reported by Hernández-Santos *et al.* [11]. The swelling power was determined following the method described by Rodríguez-Miranda *et al.* [12].

Extracts. We mixed 10 g of each sample with 100 mL of 80% ethanol and placed the mix in an Elmasonic P 60 H ultrasonic bath (Elma Schmidbauer GmbH, Germany) for 11 min at 90% amplitude and 80 kHz. Subsequently, it was centrifuged for 15 min at 3,000 rpm in a Z 200A compact centrifuge (HERMLE Labortechnik GmbH, Germany). The supernatant was then separated and evaporated using an Eyela N-1 rotary evaporator (Tokyo Rikakikal Co., Japan) at 40°C.

Total phenolic content. To define total phenolics, we mixed an aliquot of 125 μ L of each extract with 125 μ L of Folin-Ciocalteu's reagent and 500 μ L of distilled water. The mix was vortexed for 30 s and allowed it to stand for 6 min. Subsequently, we added 1,250 μ L of 7% sodium carbonate (NaCO_3) and 1,000 μ L of distilled water before incubating the resulting mix in the dark for 90 min. The absorbance was measured at 760 nm using a Cary 60 UV-Vis spectrophotometer (Agilent Technologies, USA) [13, 14]. Gallic acid served as standard curve. The results were expressed as milligrams of gallic acid equivalents (mg GAE/100 g of sample).

Total flavonoid content. To define total flavonoids, we mixed a total of 250 μ L of each extract with 75 μ L of 5% sodium nitrite (NaNO_2), 150 μ L of 10% aluminum chloride (AlCl_3), and 500 μ L of 1 M sodium hydroxide (NaOH). Subsequently, the volume was adjusted to 2,500 μ L with deionized water. The mix was vortexed for 30 s and allowed to react for 5 min for absorbance to be measured at 510 nm. A calibration curve using catechin served for quantification [14]. The results were expressed as mg of catechin equivalents (mg CE/100 g of sample).

Antioxidant capacity (DPPH[•]). A 50 μ L aliquot of extract or calibration solution was mixed with 1,050 μ L of DPPH[•] solution. The reaction was incubated for 30 min in the dark, after which absorbance was measured at 515 nm. The results were expressed as the percentage inhibition of the DPPH[•] radical [15, 16].

Statistical analysis. The results represented the mean of three replicates $\pm$ standard deviation. The data were analyzed using a one-way ANOVA followed by a comparison of means. The procedure involved the least significant difference test with a confidence level of 95% and Statistica 10.0 (StatSoft, USA).

RESULTS AND DISCUSSION

Chemical composition, total energy, and pH. We found significant differences ($p < 0.05$) between the parts of black nightshade (*Solanum nigrescens* M. Martens & Galeotti) (Table 1), which can be attributed to specific physiological characteristics of each plant structure. These results provide valuable insights into the potential technological and nutritional applications of each plant part.

The moisture content differed significantly ($p < 0.05$) across the plant parts, with green seeds exhibiting the highest moisture level (20.61 g/100 g), followed by mature seeds (12.68 g/100 g), stems (7.53 g/100 g), and leaves (5.78 g/100 g). When compared to other nightshade species, *S. nigrescens* shows both similarities and differences in various aspects of its chemical composition. For example, studies conducted on *Solanum scabrum* Mill. and *Solanum villosum* Mill. reported comparable moisture contents, which were higher in unripe fruits and decreased as the fruit matured [2]. This trend is consistent with our findings for *S. nigrescens* green and mature seeds.

The highest ash content ($p < 0.05$) belonged to the stem (19.70 g/100 g), highlighting it as a potential mineral-rich resource. *S. scabrum* was reported to have higher values in its leaves (10.57 g/100 g) [2], which contrasts with our results for *S. nigrescens*, where the stem exhibited the highest value. Sivakumar *et al.* [9] reported a lower value of 3.4 g/100 g in *Solanum retroflexum* Dunal. This data suggests a high mineral concentration, consistent with previous findings of essential minerals (Ca, Mg, K) in *S. nigrescens* leaves [17]. These differences may indicate species-specific variations in mineral accumulation influenced by genetic or agronomic factors.

The lipid content exhibited significant variability ($p < 0.05$), with the highest values observed in mature seeds (6.32 g/100 g), followed by leaves (3.88 g/100 g), suggesting a potential source of functional lipids. Our results were consistent with the findings reported for other *Solanum* species, where lipid accumulation tended to be higher in mature seeds [2]. However, the lipid levels reported in this study fall within the range observed for other varieties: *Solanum nigrum* f. *brevipetiolare* (Chodat) Chodat at 7.11 g/100 g [2] and *S. retroflexum* at 5.1 g/100 g [9]. According to Mohamed Saleem *et al.* [18], *S. nigrum* seeds are rich in essential fatty acids, suggesting that, as a member of the same botanical family, *S. nigrescens* may offer comparable health benefits.

The protein content was significantly higher ($p < 0.05$) in the leaves (22.58 g/100 g), highlighting their potential as an alternative plant-based protein source to be used in functional foods or nutritional supplements [19]. Mature and green seeds exhibited similar, significantly lower values (10.45 g/100 g), with no significant differences

⁶ AOAC. Official methods of analysis, Association of Official Analytical Chemists International, 18th ed. Washington: AOAC, 2012.

⁷ AOAC. Official Methods of Analysis. Association of Official Analytical Chemists, 15th ed. Washington: AOAC, 1990.

Table 1 Chemical composition, total energy, and pH of black nightshade (*Solanum nigrescens* M. Martens & Galeotti)

Component	Leaves	Stems	Green seeds	Mature seeds
Moisture, g/100 g	5.78 ± 0.18 ^a	7.53 ± 0.06 ^b	20.61 ± 0.34 ^d	12.68 ± 0.10 ^c
Ash, g/100 g	12.81 ± 0.05 ^c	19.70 ± 0.00 ^d	2.94 ± 0.02 ^a	3.48 ± 0.02 ^b
Lipid, g/100 g	3.88 ± 0.14 ^c	1.48 ± 0.00 ^b	1.24 ± 0.02 ^a	6.32 ± 0.03 ^d
Protein, g/100 g	22.58 ± 0.07 ^c	12.92 ± 0.20 ^b	10.45 ± 0.04 ^a	10.45 ± 0.06 ^a
Fiber, g/100 g	9.34 ± 0.04 ^a	18.53 ± 0.52 ^c	7.08 ± 0.04 ^b	9.65 ± 0.17 ^a
Carbohydrates, g/100 g	51.38 ± 0.21 ^b	47.34 ± 0.42 ^a	78.26 ± 0.03 ^d	70.07 ± 0.17 ^c
Total energy, kJ/100 g	1,383.98 ± 9.95 ^b	1,064.40 ± 10.42 ^a	1,531.63 ± 1.92 ^c	1,585.54 ± 4.98 ^d
pH	6.35 ± 0.00 ^a	6.35 ± 0.00 ^a	6.51 ± 0.01 ^c	5.75 ± 0.02 ^b

The values are represented as the mean of three determinations ± standard deviation. Different superscript letters in the same row indicate a statistically significant difference ($p < 0.05$)

Table 2 Color parameters of black nightshade (*Solanum nigrescens* M. Martens & Galeotti)

Parameter	Leaves	Stems	Green seeds	Mature seeds
Lightness (L^*)	18.06 ± 0.02 ^a	24.17 ± 0.02 ^c	33.59 ± 0.00 ^d	22.24 ± 0.01 ^b
Redness–greenness coordinate (a^*)	1.49 ± 0.01 ^a	2.04 ± 0.01 ^b	6.19 ± 0.01 ^c	6.65 ± 0.01 ^d
Yellowness–blueness coordinate (b^*)	34.34 ± 0.05 ^d	28.02 ± 0.02 ^c	19.34 ± 0.01 ^b	14.94 ± 0.02 ^a
Hue angle (h°)	87.51 ± 0.01 ^d	85.85 ± 0.00 ^c	72.27 ± 0.02 ^b	66.01 ± 0.02 ^a
Chroma (C^*)	34.37 ± 0.05 ^d	28.09 ± 0.02 ^c	20.31 ± 0.01 ^b	16.36 ± 0.02 ^a

The values are represented as the mean of three determinations ± standard deviation. Different superscript letters in the same row indicate statistically significant differences ($p < 0.05$)

between them ($p > 0.05$), suggesting a less prominent role in protein contribution compared to the leaves.

On the other hand, the protein concentration in *S. nigrescens* leaves (22.58 g/100 g) was lower than that reported for other species: *S. retroflexum* (32.8 g/100 g) [9], *Solanum aethiopicum* L. (37.53 g/100 g), *S. nigrum* (39.53 g/100 g) [1], and *S. scabrum* (39.74 g/100 g) [2]. These findings align with previous studies reporting high protein levels in the vegetative parts of *Solanaceae*, commonly used in vegetarian diets [4].

The highest fiber content belonged to the stem (18.53 g/100 g), followed by mature seeds (9.65 g/100 g), leaves (9.34 g/100 g), and green seeds (7.08 g/100 g), with significant differences among them ($p < 0.05$). Dietary fiber plays an essential role in gastrointestinal health, suggesting that black nightshade stems may have potential applications for fiber fortification in processed foods for either animal or human consumption [2, 20]. These values fall within the fiber content range reported for *Solanum* species (14.07 to 35.78 g/100 g) [1, 2].

The carbohydrate content was significantly higher ($p < 0.05$) in green seeds (78.26 g/100 g), followed by mature seeds (70.07 g/100 g), leaves (51.38 g/100 g), and stems (47.34 g/100 g). This trend is consistent with other reports on seeds of various species, where carbohydrates serve as the primary energy reserve [19]. These values exceed those reported for *S. scabrum*, which showed 60.69 g/100 g [2].

The total energy content, kcal, also showed significant differences ($p < 0.05$), with mature seeds containing the highest amount of energy (1585.54 kcal), followed by green seeds (1,531.63 kcal), leaves (1,383.98 kcal), and stems (1,064.40 kcal). These results clearly highlight the potential of seeds particularly mature ones as important

energy sources in the diet. The energy content recorded in mature seeds was consistent with findings reported for other species, e.g., *S. nigrum* and *S. scabrum*, which also showed higher energy levels in mature seeds due to their lipid and carbohydrate reserves [2].

The pH levels also varied significantly ($p < 0.05$), with green seeds exhibiting slightly alkaline values (6.51) while mature seeds showed a more acidic profile (5.75). This behavior may be attributed to the shifts in acid-base metabolism during ripening [21]. Such differences could benefit certain sensory or technological properties in food systems and may also affect the antioxidant activity, which is often more stable at pH ≤ 6 [22].

In summary, the variability in chemical composition, pH, and energy content across the vegetative parts of Mexican *S. nigrescens* underscores its potential for diversified applications in the food and nutrition industry (Table 1). Notably, the leaves stand out as a protein source, the stem as a source of fiber and minerals, and the mature seeds as providers of lipids and energy.

Color parameters. The values obtained for color parameters showed statistically significant differences ($p < 0.05$) between leaves, stems, green seeds, and mature seeds. The clear variability in their chromatic characteristics (Table 2) may be associated with differential pigment composition and secondary metabolite content.

Lightness (L^*) values were highest in green seeds (33.59), followed by stems (24.17), mature seeds (22.24), and leaves (18.06). The higher L^* value in green seeds may be related to a lower concentration of dark pigments: chlorophylls or phenolic compounds generally reduce brightness in plant tissues [1]. In comparison, *S. scabrum* was reported to exhibit higher L^* values in leaves (35–

40), indicating a lower concentration of dark pigments, i.e., chlorophylls and polyphenols [2]. Similarly, *S. villosum* showed intermediate values (L^* 28–32), suggesting a lighter color profile than that of *S. nigrescens* [6].

Regarding the a^* color parameter, we observed a clear difference ($p < 0.05$), with the highest value recorded in mature seeds (6.65), followed by green seeds (6.19), stems (2.04), and leaves (1.49). All the values were positive, placing them within the red color quadrant with varying shades. These results suggest a higher concentration of red or brown pigments in mature seeds, possibly linked to the presence of carotenoids or other phenolic compounds [23]. Traoré *et al.* [2] reported lower a^* values in fresh *S. scabrum* leaves (0.8–2.5). In mature *S. nigrum* seeds, a^* values were also reported to increase, reaching levels similar to those we observed in *S. nigrescens*, which may indicate anthocyanin or oxidized carotenoid accumulation during ripening [1].

In contrast, the b^* color parameter exhibited an inverse trend, with the highest values in leaves (34.34) and the lowest in mature seeds (14.94) ($p < 0.05$). All the values were located in the yellow color quadrant. This result suggests a higher concentration of yellow pigments, likely flavonoids, in leaves compared to other plant parts [2]. Yellow coloration is commonly associated with such pigments as lutein and β -carotene [23], which are functionally relevant due to their antioxidant capacity and provitamin A activity [1].

The hue angle (h°) was significantly higher ($p < 0.05$) in leaves (87.51°), corresponding to a more yellow-green tone, and progressively decreased toward mature seeds (66.01°), which exhibited a more reddish hue. This variation in hue angle reflects substantial changes in pigment composition during the development and maturation of plant structures [11]. This pattern is similar to that reported for *S. villosum* and *S. scabrum*, although with less pronounced variation, suggesting differences in pigment transitions during maturation [6].

The chroma (C^*) followed a pattern similar to that of the b^* parameter, with the highest values observed in leaves (34.37) and the lowest in mature seeds (16.36). This parameter represents color intensity, or saturation. The greater chromatic richness in leaves was likely due to higher concentrations of color-contributing pigments, e.g., chlorophylls and flavonoids [1]. Similar values were reported for *S. scabrum*, which may be related to pigment oxidation or tissue lignification [1, 6, 23].

These results (Table 2) confirm considerable chromatic variability across vegetative structures of *S. nigrescens*, which stands out for its lower lightness and higher chromatic saturation in leaves compared to other *Solanaceae* species, such as *S. scabrum* and *S. villosum*. This distinction is closely related to the differential presence and concentration of specific pigments, e.g., carotenoids, chlorophylls, flavonoids, and phenolic compounds [4, 23, 24]. These pigments are crucial for color expression and contribute significantly to the antioxidant and functional properties of plant tissues [9].

Techno-functional properties. Table 3 presents the techno-functional properties of leaves, stems, green seeds, and mature seeds of *S. nigrescens*. These properties are essential for determining the suitability of these plant tissues as functional food ingredients, particularly in the formulation of food products, functional flours, or fortified foods.

Water absorption capacity. Stems exhibited the highest water absorption capacity at 9.76 g/g, followed by leaves (6.63 g/g) while both green and mature seeds showed significantly lower values (2.67 and 2.40 g/g, respectively; $p < 0.05$). The high water absorption capacity observed in vegetative tissues can be attributed to their higher content of soluble and insoluble dietary fiber, which contains hydroxyl groups capable of forming bonds with water molecules [11]. This behavior depends on the presence of structural polysaccharides and hydrophilic protein interactions.

Our values were higher than the water absorption capacity of 4.02 g/g reported for *S. scabrum* in [2]. However, the water absorption capacity values we found in seeds aligned with those reported by Rodríguez-Miranda *et al.* [12] for pumpkin seed flours, in which protein and fiber-rich fractions showed enhanced water retention, favoring their use in bakery, as texturizing agents in soups, and for improving viscosity and sensory acceptability [24].

The highest water solubility capacity belonged to *S. nigrescens* leaves, followed by green seeds, stems, and, finally, mature seeds, with significant differences among them ($p < 0.05$). The value found in leaves (68.42%) indicated a high availability of water-soluble components, such as sugars, peptides, or phenolic compounds. This behavior suggests that leaves can serve as sources of soluble bioactive compounds for functional applications. In contrast, mature seeds showed the lowest water solu-

Table 3 Techno-functional properties of black nightshade (*Solanum nigrescens* M. Martens & Galeotti)

Property	Leaf	Stem	Green seed	Mature seed
Water absorption capacity, g/g	6.63 $\pm$ 0.10 ^c	9.76 $\pm$ 0.02 ^d	2.67 $\pm$ 0.00 ^b	2.40 $\pm$ 0.01 ^a
Water solubility capacity, %	68.42 $\pm$ 1.07 ^c	57.24 $\pm$ 0.72 ^a	59.08 $\pm$ 0.61 ^a	51.76 $\pm$ 0.39 ^b
Oil absorption capacity, g/g	3.23 $\pm$ 0.02 ^c	3.28 $\pm$ 0.00 ^d	2.53 $\pm$ 0.01 ^b	2.37 $\pm$ 0.00 ^a
Emulsifying capacity, %	46.15 $\pm$ 0.00 ^b	38.67 $\pm$ 0.26 ^a	38.57 $\pm$ 0.34 ^a	37.87 $\pm$ 0.88 ^a
Apparent density, g/cm ³	0.54 $\pm$ 0.00 ^a	0.53 $\pm$ 0.00 ^a	0.70 $\pm$ 0.00 ^c	0.69 $\pm$ 0.00 ^b

The values are represented as the mean of three determinations $\pm$ standard deviation. Different superscript letters in the same row indicate statistical differences ($p < 0.05$)

bility capacity (51.76%), which may be related to a higher proportion of low solubility structural macromolecules (starch or proteins) bound to fiber matrices. This value was higher than that reported for defatted ebony seed flours (26.06%) by Hernández-Santos *et al.* [25], indicating a potential use as a source of soluble bioactive compounds. Therefore, *S. nigrescens* leaves could be incorporated into water-soluble formulations, e.g., soups, purées, or emulsions.

Oil absorption capacity. The highest ($p < 0.05$) oil absorption capacity was observed in stems and leaves (3.28 and 3.23 g/g, respectively). This behavior is associated with the presence of proteins and structural components containing hydrophobic regions capable of binding lipids. These values were higher than those reported for *S. scabrum*, which showed an oil absorption capacity of 2.91 g/g [9]. Such quality is desirable, especially in restructured meat products, where lipid retention is important for flavor and texture enhancement [11, 12].

Emulsifying capacity. Leaves also exhibited the highest emulsifying capacity at 46.15%, which was significantly higher ($p < 0.05$) than the other plant parts. This property indicates a strong potential to stabilize oil-in-water emulsions, which is crucial for dressings, sauces, and meat analogues. According to Téllez-Morales *et al.* [26], this capacity is closely related to protein content and the three-dimensional conformation of proteins, which act as natural surfactants [11]. Although emulsifying capacity has never been directly assessed in *S. nigrescens*, studies on *S. nigrum* seeds demonstrated the ability to form stable emulsions due to their lipid and protein content [3].

The **apparent density** was significantly higher ($p < 0.05$) in green and mature seeds, with values of 0.70 and 0.69 g/cm³, respectively. These results suggest that seeds possess a more compact and dense structure. This property is relevant for packaging, handling, and solid food products [11].

Swelling power (Fig. 1) is closely related to water retention capacity and starch gelatinization. It is essential for evaluating the functional behavior of ingredients in food matrices. Leaves and stems exhibited significantly higher swelling power values ($p < 0.05$) at all temperatures, ranging from 8.56–8.87% for leaves and 8.19–8.62% for stems. This behavior may be attributed to their lower starch content and a higher presence of non-starch polysaccharides and dietary fiber with strong water-binding affinity. Similar trends were reported for *S. scabrum* leaves, which contained elevated levels of hemicellulose and cellulose compounds known to enhance water retention and swelling [9].

In contrast, mature and green seeds showed significantly lower swelling power values ($p < 0.05$), particularly at 60°C (1.67 and 3.83%, respectively). This outcome suggests reduced availability of swellable starch or a more compact matrix that restricts water penetration. This effect may be associated with the higher lipid (6.32 g/100 g) and protein (10.45 g/100 g) content in mature seeds, which can form complexes with starch that inhibit its gelatinization, as reported for other legumes and seeds [27].

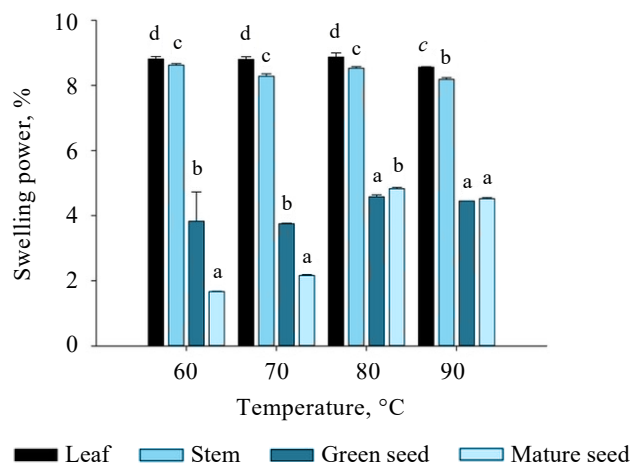


Figure 1 Swelling power of black nightshade (*Solanum nigrescens* M. Martens & Galeotti). The values are represented as the mean of three determinations $\pm$ standard deviation. Different letters on the columns at the same temperature indicate statistically significant differences ($p < 0.05$)

At 80 and 90°C, the swelling power increased in the seeds, reaching 4.83% in mature seeds at 80°C. Higher temperatures promoted greater starch gelatinization and disruption of the cellular structure, which facilitated water absorption. This observation was consistent with the findings by Shand *et al.* [28], who reported that temperatures above 70°C enhanced protein aggregate dissociation and starch gelatinization in protein-rich seeds.

Similar swelling power values were documented in plant matrices with high concentrations of insoluble fibers. For instance, Focho *et al.* [29] reported a swelling power of 8.1% in dried *S. scabrum* leaves while *S. villosum* seeds reached only 2.5% under similar conditions, supporting the trends observed in the present study. Furthermore, swelling power values highly correlated with water absorption capacity (Table 3), which was highest in stems (9.76 g/g) and leaves (6.63 g/g) and lowest in seeds (2.67 and 2.40 g/g for green and mature seeds, respectively). Therefore, leaves and stems stand out for their high swelling power, positioning them as promising ingredients for functional foods that require high hydration or gelation capacity.

Total phenolic content, total flavonoids, and antioxidant activity (DPPH). Figure 2 shows significant differences ($p < 0.05$) in total phenolic content across the plant parts. Leaves exhibited the highest phenolic content (12,038.33 mg GAE/g), followed by stems (9,205.00 mg GAE/g). Green and mature seeds showed lower values (620.50 and 1,062.17 mg GAE/g, respectively). These findings were consistent with previous studies in other *Solanaceae* species [5]. For example, in *S. villosum*, the leaf phenolic content reached up to 38.8 g GAE/kg (equivalent to 3,880 mg GAE/100 g) under moderate water stress, with even higher levels recorded in *S. scabrum* shoots (46.41 g GAE/kg) [6]. Nevertheless, the phenolic content observed in *S. ni-*

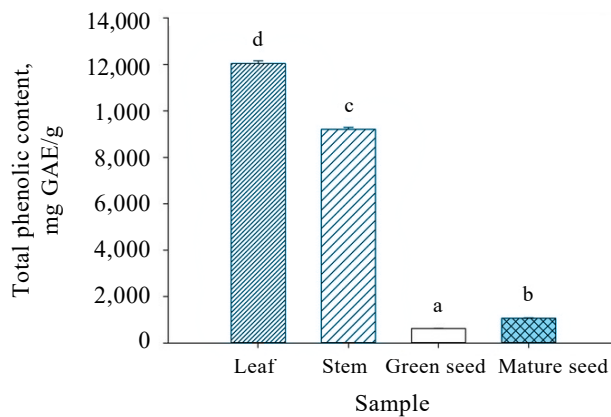


Figure 2 Total phenolic content in black nightshade (*Solanum nigrescens* M. Martens & Galeotti). The values are represented as the mean of three determinations $\pm$ standard deviation. Different letters on the columns indicate statistically significant differences ($p < 0.05$)

gescens leaves far exceeds these values, indicating superior antioxidant potential, likely associated with genotypic variation, agroecological conditions, and vegetative maturity [9]. Chlorogenic acid is the predominant phenolic acid in *Solanum* species, known for its high radical-scavenging capacity and greater abundance in leaves compared to other vegetative structures [5, 9]. Therefore, the leaves of *S. nigrescens* represent the richest source of phenolic compounds, supporting their potential use as a functional ingredient in the formulation of foods with bioactive properties.

The total flavonoid content showed a highly differential distribution across the plant organs analyzed (Fig. 3), with significantly higher values ($p < 0.05$) in leaves (13,192.15 mg QE/g) and stems (3,584.32 mg QE/g), compared to green seeds (197.65 mg QE/g) and mature seeds (191.76 mg QE/g), where were observed no significant differences ($p > 0.05$). The difference suggests a preferential localization of these secondary metabolites in photosynthetically active structures, where they participate in antioxidant defense, signaling, and photoprotection. This pattern is consistent with some observations reported for other species of the *Solanum* genus. For instance, Okello *et al.* [6] reported a greater accumulation of phenolic compounds, including flavonoids, in the shoots of *S. villosum* grown under moderate water stress, reaching up to 46.41 g GAE/kg of total phenolics. This quality is attributed to the upregulation of biosynthetic pathways for bioactive compounds in response to environmental stress [5, 6].

S. nigrescens possesses such flavonoids as quercetin, kaempferol, rutin, and their glycosides [30]. From a functional perspective, these flavonoids exhibit strong free radical scavenging activity, metal chelation capacity, and modulation of cellular signaling pathways, conferring antioxidant, anti-inflammatory, and vasodilatory properties.

The high flavonoid concentration in leaves may be related to their high exposure to UV radiation, which stimulates flavonoid biosynthesis as a photoprotective

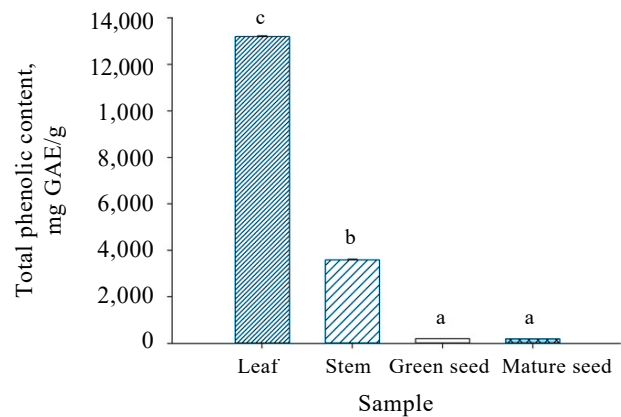


Figure 3 Total flavonoid content in black nightshade (*Solanum nigrescens* M. Martens & Galeotti). The values are represented as the mean of three determinations $\pm$ standard deviation. Different letters on the columns indicate statistically significant differences ($p < 0.05$)

response. Furthermore, the flavonoid content in *S. nigrescens* leaves exceeds that reported for other African solanaceous species, such as *S. scabrum* or *S. villosum*, suggesting an especially strong phytochemical profile in this species [5].

In contrast, both green and mature seeds exhibited very low flavonoid levels (200 mg QE/g), which was consistent with their reproductive function, where the storage of carbohydrates, proteins, and lipids is prioritized over the synthesis of secondary metabolites. These findings confirm that *S. nigrescens* leaves are the main source of flavonoids and, therefore, may be considered functional ingredients with potential applications in the prevention of oxidative stress and non-communicable chronic diseases [5].

The percentage of DPPH⁺ radical scavenging in *S. nigrescens* reveals a clear correlation with the total phenolic and flavonoid content (Fig. 4). Leaves exhibited the highest DPPH⁺ neutralization capacity (90.55%), followed by stems (89.49%). In contrast, green seeds (9.76%) and mature seeds (12.78%) displayed much lower antioxidant activity. These differences were statistically significant ($p < 0.05$). This pattern supports the evidence that antioxidant capacity in this species largely depends on the concentration and diversity of secondary metabolites present in the vegetative organs. The inhibition values above 90% observed in leaves were comparable to, and even surpassed, those reported in similar studies on other *Solanaceae* species. For example, Okello *et al.* [6] reported an antioxidant activity of 52.68% in *S. scabrum* leaves grown under controlled irrigation, which was substantially lower than the value we observed for *S. nigrescens*.

The high antioxidant efficiency of *S. nigrescens* leaves and stems indicated a high concentration of compounds capable of neutralizing free radicals, likely including flavonoids (quercetin and rutin), phenolic acids (chlorogenic acid), and antioxidant alkaloids, as previously documented in phytochemical studies [5, 30].

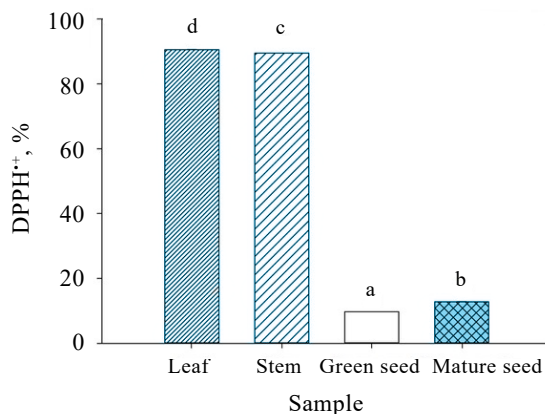


Figure 4 Percentage of inhibition by the DPPH⁺ method in leaves, stems, green seeds, and mature seeds of black nightshade (*Solanum nigrescens* M. Martens & Galeotti). The values are represented as the mean of three determinations $\pm$ standard deviation. Different letters on the columns indicate statistically significant differences ($p < 0.05$)

In contrast, the low DPPH⁺ activity observed in the seeds may be attributed to their lower phenolic content and a phytochemical profile more oriented toward nutrient storage than antioxidant defense. This distribution is also consistent with the reduced exposure of seeds to oxidative stress factors compared to more exposed leaves and stems. The high DPPH⁺ inhibition percentage in the leaves and stems positions *S. nigrescens* as a prominent plant source of natural antioxidants, with potential applications in functional and nutraceutical foods.

CONCLUSION

Black nightshade (*Solanum nigrescens* M. Martens & Galeotti) possesses significant physicochemical, techno-functional, and antioxidant properties, which vary depending on the plant part. In this study, *S. nigrescens* leaves exhibited outstanding protein content and high concentrations of phenolic and flavonoid compounds, along with notable antioxidant capacity. Mature seeds stood out for their high lipid content, indicating potential use as functional lipid-rich ingredients. Stems displayed remarkable water absorption capacity, suggesting its usefulness in products that require enhanced hydration retention. *S. nigrescens* has high potential as an ingredient in protein supplements, lipid-fortified foods, and bakery products requiring high moisture retention, as well as in beverages, nutraceuticals, and functional foods aimed at promoting health by leveraging the antioxidant and nutritional properties of green plants.

CONTRIBUTION

J. Rodríguez-Miranda, R.G. Tejeda, J.G. Torruco-Uco, and B. Hernández-Santos conducted the experiments, analyzed the data, and wrote the manuscript. B. Hernández-Santos designed the experiments, wrote the review, and edited the manuscript. J.M. Rivadeneyra-Rodríguez, J.M. Juárez-Barrientos, and M.A. Hermenegildo-Sebastián performed the experiments.

CONFLICT OF INTEREST

The authors declared no conflict of interest regarding the publication of this article.

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