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VALORIZATION OF YOUNG PRICKLY PEAR (*Opuntia ficus-indica*) CLADODES AS A SUSTAINABLE LIVESTOCK FEED SUPPLEMENT: PHYSICOCHEMICAL, NUTRITIONAL VALUE AND ANTIOXIDANT ACTIVITY

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ABSTRACT: The prickly pear cactus (*Opuntia ficus-indica*) is prevalent in arid and semi-arid environments, known for its drought tolerance and ability to thrive in poor soils. The cladodes, or pads, are particularly relevant as a nutritional supplement for animals due to their high nutrient content and water-retention capacity. This study aims to analyze the nutritional qualities of young *Opuntia ficus-indica* cladodes growing in the Chorfa region of Mascara Province, Algeria for prospective integration into feedstuff. The physicochemical study was based on the determination of moisture, dry matter, sugar, protein, fat, ash, minerals, starch, and fiber content. The phytochemical analysis was performed by total phenolic content determination. It was followed by antioxidant potential evaluation using DPPH free radical scavenging assay and energetic value assessment. The physicochemical study revealed that the cladodes had a high-water content (93.86 ± 0.15%) and very low dry matter (6.32 ± 0.2%). The total ash content was 21.9 ± 0.03%, with calcium as the most abundant mineral, followed by potassium and sodium. The cladode had a good amount of dietary fiber (18.8 ± 1.1%) and presented values of 11.46 ± 0.2%, 11.02 ± 1.1%, and 8.84 ± 0.3% for carbohydrate, protein, and fat content, respectively. Based on the phytochemical characterization, cladodes were a noteworthy source of antioxidant compounds. The estimated energy values are 1.32 MFU/kg and 1.31 MEFU/kg. The methanolic extract was effective in inhibiting the free radical DPPH• in a concentration-dependent manner with an IC50 value of 524.6 µg/mL. *Opuntia ficus-indica* cladodes were found to be a good source of sugars, proteins, and dietary fiber, making them potentially valuable ruminant feed.

Keywords: Cladodes, Fiber content, Opuntia *ficus-indica*, Physicochemical analysis, Livestock nutrition.

INTRODUCTION

In Algeria, a vast territory rich in largely unexplored flora offers a precious reservoir of active ingredients for various sectors. The prickly pear (*Opuntia ficus-indica* (L.)) is a perfect example of this plant wealth, which is underestimated locally, mainly due to a lack of recognition by the expert community. *Opuntia ficus-indica*, a perennial arborescent cactus native to Mexico, is extensively cultivated in arid and semi-arid regions worldwide. The species is characterized by its flattened, photosynthetic stem segments (cladodes) that function as water-storing organs rich in mucilage, and by its fleshy, edible fruits known as prickly pears. Due to its remarkable drought tolerance and nutritional value, *O. ficus-indica* has become an important species for food, forage, and industrial applications (Martins et al., 2023). In Algeria's arid and semi-arid zones, the availability of forage resources is a major constraint on the development of livestock farming. Faced with climatic variability and the degradation of natural pastures, it is essential to identify and develop local resources adapted to difficult ecological conditions. The prickly pear, a xerophilous plant widely distributed in these regions, offers great potential as alternative forage (Kalli et al., 2023).

One creative and sustainable way to address the lack of forage supplies in these regions is to incorporate prickly pear cladodes into cattle feed (Medjekal et al., 2023). Indeed, this plant is nutrient-dense and extremely heat- and drought-resistant. It can be a significant source of water, fiber, minerals, and some vitamins, which makes it a perfect animal feed supplement, especially during periods when conventional fodder is in short supply (Pastorelli et al., 2022). To assess possible application in animal feed, this study investigates the nutritional qualities of *Opuntia ficus-indica* cladodes grown in Mascara, northwest Algeria.

MATERIALS AND METHODS

Plant material preparation

The plant material consisted of young cladodes of the *Opuntia ficus-indica*. Samples measuring 30–40 cm in length and 15–18 cm in width were collected from the Chorfa region, Sig, Mascara province, Algeria (35° 25′ 55″ North, 0° 14′ 43″ West) in January 2024. After harvesting, the cladodes were thoroughly rinsed with running tap water to remove any

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adhering impurities, and then blotted dry with absorbent paper to remove residual moisture. The cleaned cladodes were then cut into small sections and either used fresh or homogenized and centrifuged to obtain the fresh supernatant. For the preparation of the dried material, the cladodes were sliced and oven-dried at 40°C until a constant weight was achieved. The dried samples were ground in an electric grinder, and the resulting powder was passed through a 250 µm sieve to ensure a fine, homogeneous particle size (Figure 1).

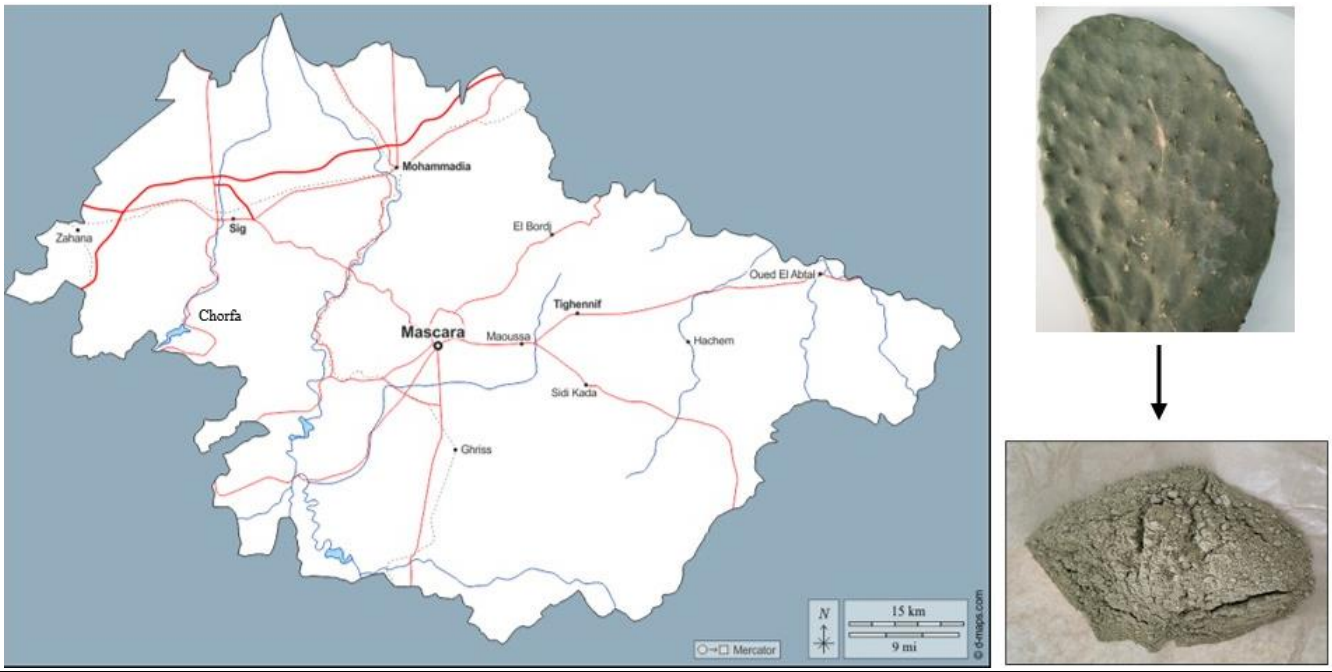

Figure 1 - Location of the study area.

Physicochemical analysis

Several measurements were used to evaluate the physicochemical composition of the cladodes. The following techniques were used to assess moisture, dry matter, ash content, pH, sugar, protein, and lipid content (AOAC, 1995; AOAC, 2002). This was followed by the measurement of fibre, pectin, and chlorophyll content (Yuan et al., 2022). The minerals were quantified by atomic absorption spectrophotometry, and the starch was determined by polarimetry. Every calculation was carried out in triplicate.

Phytochemical screening

Extraction of phenolic substances

The extraction of polyphenols was carried out according to the protocol described by Song et al. (2010), which consists of macerating 10 g of cladode powder in a methanol-water mixture (1.3/8.7: V/V) in a ratio of 1/10 (W/V) for 72 hours, with solvent changes every 24 hours and occasional stirring. The macerates were combined, filtered through filter paper, and the solvent in the filtrate was evaporated under reduced pressure at 40 °C using a rotary evaporator. The resulting dry extract was then weighed and kept in the dark at 4 °C until further analysis.

Determination of total phenolic content

1 ml of the methanolic extract was mixed with 1 ml of Folin-Ciocalteu reagent. After stirring and allowing the mixture to stand for 6 minutes, 8 mL of a 7.5% aqueous Na_2CO_3 solution was added. The mixture was then left to stand for 120 minutes at room temperature and in the dark. Finally, absorbance was measured at 765 nm (Shui and Leong, 2002). A standard curve was prepared with gallic acid, and the total polyphenol content was expressed as mg of gallic acid equivalents (GAE) per gram of extract.

DPPH free radical scavenging assay

Antioxidant activity was determined by the 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging assay (Amzad and Dawood, 2015). 750 µL of the methanolic extract at various concentrations was added to 1.75 mL of DPPH (2 mg DPPH/100 mL methanol). The mixture was incubated in the dark for 30 min. Absorbance was measured at 517 nm against a negative control using a spectrophotometer. Ascorbic acid was used as a positive control in the same concentration range as the extracts. Every calculation was carried out in triplicate. The DPPH free radical scavenging activity was calculated using the formula 1: DPPH-Inhibition (%) = (Abs C – Abs E) /Abs C × 100 (1)

Where: Abs C: absorbance of the control (without the sample); Abs E: absorbance of the solution containing the methanolic extract or ascorbic acid.

Estimating energy value

To estimate the energy value of cactus cladodes, we can use Atwater's coefficients, which allow us to determine the energy provided by the following macronutrients: protein, fat, carbohydrates (starch and sugar), and fibre. The Atwater coefficients are as follows: Protein: 4 kcal/g, Fat: 9 kcal/g, Carbohydrates (starch and sugar): 4 kcal/g, Fibre: 2 kcal/g (this coefficient is an approximation because dietary fibre provides little usable energy). The energy provided by each component is calculated based on its percentage. However, we must first convert these percentages to grams for a quantity of 100 grams of dry matter of the cladodes; then, we multiply each value by its respective Atwater coefficient, calculate the energy provided by each component, add all the energy contributions, and calculate the sum to obtain the total energy value. MFU (Milk Feed Units) and MEFU (Meat Feed Units) are units used in animal nutrition to estimate the nutritional value of forages and concentrates for ruminants. They take into account not only the energy value, but also the specific use of this energy for milk (MFU) or meat (MEFU) production (Chibani et al., 2010). To apply the nutritional value prediction equations to a feed, in this case young prickly pear cladodes, we proceeded using the following formulas:

Calculation of the digestibility of organic matter (dOM): $dOM(\%) = -1.14 \times CC + 99.18$

Calculation of the milk feed unit (MFU): $MFU = -0.0018 \times CC + 1.3585$

Calculation of the meat feed unit (MEFU): $MEFU = -0.0021 \times CB + 1.350$

Calculation of metabolizable energy (ME): $ME\ (kcal/kg) = 38.474 \times dOM - 149.4676$

Calculation of the digestible nitrogen (DN) using the total nitrogen content (TN), $DN\ (g/kg) = 8.824 \times TN - 22.43$.

All analyses of energy value were performed in triplicate, and results are expressed as mean ± standard deviation.

RESULTS AND DISCUSSION

Extraction yield

Drying yield is measured as the percentage of water evaporated relative to the initial weight of the cladodes. The extraction yield of 6.31±0.2 % for *Opuntia ficus-indica* cladodes appears to be higher than those reported by Msaddak (2015) and Ait Maamar and Has (2019), which were 5.20% and 5.7%, respectively. This result is lower than those presented by Khefif and Sedjerari (2023; 7.39%) and by Nair et al. (2024; 6.7%), who worked in the area of Mascara. This percentage may vary, depending on several factors, including the drying method used, environmental conditions, and the variety of the *Opuntia ficus-indica*. In general, the drying process of the cladodes can significantly reduce their water content, making them easier to store and transport while preserving some of their nutritional components. Ayadi et al. (2009) showed that cacti's cladodes are very rich in water; therefore, their drying performance is much lower.

Physicochemical characteristics

Table 1 presents the physicochemical characteristics of *Opuntia ficus-indica* cladodes. The moisture content of the young cladodes of Opuntia has been estimated at 93.86 ± 0.15% of fresh weight, which is very similar to the results reported by Nair et al. (2024; 93.25%). It is superior to that reported by Abdessemed et al. (2014; 91.9%), Khefif and Sedjerari (2023; 91.1%), and to the results reported by Msaddak (2015). The moisture content of the cladodes usually ranges between 88% and 97% (Martins et al., 2023); a large proportion of this can be explained by their role in storing water (Benattia and Arrar, 2018). The results for dry matter content showed a low rate of 6.32 ± 0.2%, indicating that almost the entire weight of cladodes is water (93.86% of fresh weight). From these results, it is observed that the rackets are rich in water. For this reason, this plant is well adapted to hot, dry climates, including desert environments, in arid and semi-arid regions. It is for this reason that the *Opuntia* may be useful in resolving the problem of livestock in these areas. The high-water content in the *Opuntia*'s tissues represents a valuable source of liquid for animals (Lee et al., 2003).

Ash content is a measure of the total mineral content of the cladodes studied. The analyses reveal that the cladodes are mineralized (21.9 ± 0.03%). These results are superior to those reported by Khefif and Sedjerari (2023) (17.1%) and lower than those reported by Hernández-Urbiola (2011), Toure et al. (2015), Msaddak (2015), and Nair et al. (2024). The variability in these results can be attributed to geographical location, climate, and the physical properties of soils in different matrices (Teklu et al., 2023).

The pH of the young cladodes is 4.46 ± 0.1, which is slightly lower than Boutakiout (2015) value of 4.7. Khefif and Sedjerari (2023), who worked in the Mascara area, reported that the cladodes in this region have a pH of 5.1. The pH variations are mainly due to differences in climatic conditions and the maturation process (Silva et al., 2023). In addition, acidity increases at night and decreases during the day, varying considerably with time of day (Inglese, 2018). In general, organic acids are mediators of metabolic processes, and the rackets tend to acidify during growth, whereas the fruit acidifies during ripening. Variations in acidity are due to differences in estimation procedures, climatic conditions, and maturation processes (Maiuolo et al., 2024).

Dietary fibres are essential compounds for a balanced diet and contribute to animal digestive health by promoting intestinal transit and regulating digestion. The results also show that the powder of cladodes is a good source of dietary fibre (18.8 ± 1.1%), a rate in line with 5-20% reported by Inglese et al. (2018). This content is close to that quoted by Moussaoui (2020; 18%) and higher than that reported by Khefif and Sedjerari (2023; 8.5%).

The total content of substances, pectic cladodes of the study area (1.16%), considered as a soluble fibre, is lower than that found by Moussaoui (2020; 1.69 ± 0.06%) and is included in the interval described by Boutakiout (2015) for the Moroccan cladodes (0.1 to 2.25%). The pectin content of the plant under study is higher than that reported by Khefif and Sedjerari (2023; 0.41%). This difference may be due to growth conditions and harvest timing, but it is also related to the assay method.

Table 1 - Physicochemical composition (g/100 g) of young *Opuntia ficus-indica* cladodes.

Parameters	Value
Moisture	93.86 ± 0.15
Total solids	6.32 ± 0.2
Ash	21.9 ± 0.03
Reducing carbohydrate	11.46 ± 0.2
Starch	7.55 ± 0.2
Fats	8.84 ± 0.3
pH	4.46 ± 0.1
Fibers	18.8 ± 1.1
Proteins	11.02 ± 1.1
Chlorophyll a	0.164
Chlorophyll b	0.130
Potassium (K)	2.83
Sodium (Na)	1.29
Calcium (ca)	4.56

Table 2 - Predicted nutritional and energy values of *Opuntia ficus-indica* cladodes.

Nutrient parameter	Value
dOM (%)	77.748 ± 1.5
Crude cellulose (CC)	18.8 ± 1.1
Total Nitrogen	11.02 ± 1.2
MFU	1.32
MEFU	1.31
ME (kcal/kg)	2842.51
DN (g/kg)	948.91

dOM= digestibility of organic matter; MFU= Milk Feed Units; MEFU= Meat Feed Units; ME= metabolizable energy; DN= digestible nitrogen.

Table 2 showed that the content of chlorophyll a (0.164 mg/100 g) is lower than that achieved by Moussaoui (2020; 0.322 ± 0.034 mg/100 g), and by Khefif and Sedjerari (2023; 0.321 mg/100 g). Chlorophyll (b) reached a value of 0,130 mg/100g, which is similar to that obtained by Moussaoui (2020) (0.131±0.069 mg /100 g) and higher compared to those cited by Khefif and Sedjerari (2023; 0.110 mg/100 g). The predominance of chlorophyll a over chlorophyll b in the cladodes of the study area observed in this work has also been reported by Guevara-Figueroa et al. (2010).

The results for the mineral elements of the cladodes in the study area are listed in Table 1. We note the predominance of calcium (4.56%), followed by potassium (2.83%) and sodium (1.29%). Our results are in concordance with those of Moussaoui (2020) who has found the dominance of calcium, with a percentage of (9.04 ± 1.21%), followed by potassium (1.10 ± 0.43%) and with those of Khefif and Sedjerari (2023), which showed the predominance of calcium (8.58%), followed by potassium (3.21%) and sodium (2.43%). The exact amount of these mineral elements in the cladodes *of Opuntia ficus-indica* can vary depending on many factors. Still, the cladodes of the young prickly pear are generally regarded as a good source of some of these minerals, especially calcium, potassium and magnesium.

Starch is an important energy source for animals and is widely used in animal feed to provide the calories needed for growth, milk production, and other metabolic functions. The cladodes of the study area had a starch content of 7.55 ± 0.2% (Table 1). Carbohydrates are a total of 36% to 37% of the total dry weight of cladodes, with an average grade of 85 to 171 mg/ g of dry weight of starch (Ginestra et al., 2009). The starch may contribute to the total energy intake of the

feed, but it must be included in the diet in appropriate amounts and combined with other nutrients to provide a well-balanced diet (Nozière et al., 2026).

According to Table 1, the carbohydrate content in the rackets is 11.46 ± 0.2%. This value is lower than those reported by Nair et al. (2024; 23.33%) and by Bouzoubaa et al. (2016), which ranged from 13.5 to 15.87% across different varieties of *Opuntia ficus indica* in Morocco. The carbohydrate content can vary considerably depending on the specific cactus variety, growing conditions, the age of the rackets, and other environmental factors (Boutakiout, 2017).

The fat content of the plant studied was 8.84 ± 0.3 % (Table 1). This value is much higher than those reported in the literature by Msaddak (2015; 3.02%), Nair et al. (2024; 0.3%), and Khefif and Sedjerari (2023; 1.3%). However, the thorny rackets and the 2-year study by Ayadi (2009) showed higher concentrations in fat, respectively, 3.95% and 4.69%. The highest levels of the cactus in lipids are recorded at the beginning of fruiting. In general, forages have low fat content, and *Opuntia* is no exception. Its content, which is 1.96% for snowshoes aged 1 year, decreases with age; this level also varies across periods (Rodrigues et al., 2023).

Protein is essential for growth, muscle development, reproduction, and general health of the animals (Nozière et al., 2026). The results of the protein are represented in Table 1. We note that the rate of protein cladodes studied, 11.02 ± 1.1%, is higher than that reported by Msaddak (2015;7.43%) and higher than that reported by Khefif and Sedjerari (2023; 3.15%). This value is in agreement with the results published by El Kharrassi (2015), which range from 4.65% to 14.22% for mature cladodes. A protein level of 11.02% in the rackets of cacti can significantly contribute to the overall nutritional intake of animals, especially when combined with other protein sources in their diet.

Phytochemical screening

Total phenolic content

The results showed that the total phenolic content in the cladodes of the fig tree (44.78 mg GAE/g) is much higher than that described by Msaddak (2015; 24.85 mg GAE /g). However, Nair et al. (2024) reported that the total phenolic content of the cladodes of the region of Mascara was 44.17 mg GAE /g.

DPPH free radical scavenging activity

Figure 2 shows that the methanolic extract of *Opuntia ficus-indica* cladodes exhibited a concentration-dependent DPPH• radical-scavenging activity, although it was less potent than ascorbic acid, with IC_{50} values of 524.6 and 295.5 µg/mL, respectively. Compared with Nair et al. (2024), who reported a much lower DPPH IC_{50} of 4.816 µg/mL for a methanolic cladode extract from the Mascara region, the present extract showed considerably lower antioxidant potency. Nevertheless, both studies confirm the antioxidant potential of *O. ficus-indica*, while the marked difference in IC_{50} values indicates substantial variability between independent experiments. Other parameters also differed slightly, including ash content (21.9% vs. 22.5%) and total phenolic content (44.78 vs. 44.17 mg GAE/g). The value of the concentration of the inhibitory IC50 reported by Messadek (2018) is of the order of 1.45 mg/ml. Previous work reports a positive linear correlation between scavenging activity and total phenol content (Bahloul et al., 2016).

The differences in antioxidant activity may be related to variations in extraction procedures, plant maturity, harvesting and storage conditions, genotype, and analytical methods. Moreover, the similar total phenolic contents but markedly different DPPH responses suggest that total phenolics alone do not determine antioxidant activity; the qualitative composition and interactions of phenolic compounds, flavonoids, betalains, and other antioxidant constituents may also play important roles (Perucini-Avendaño et al., 2021).

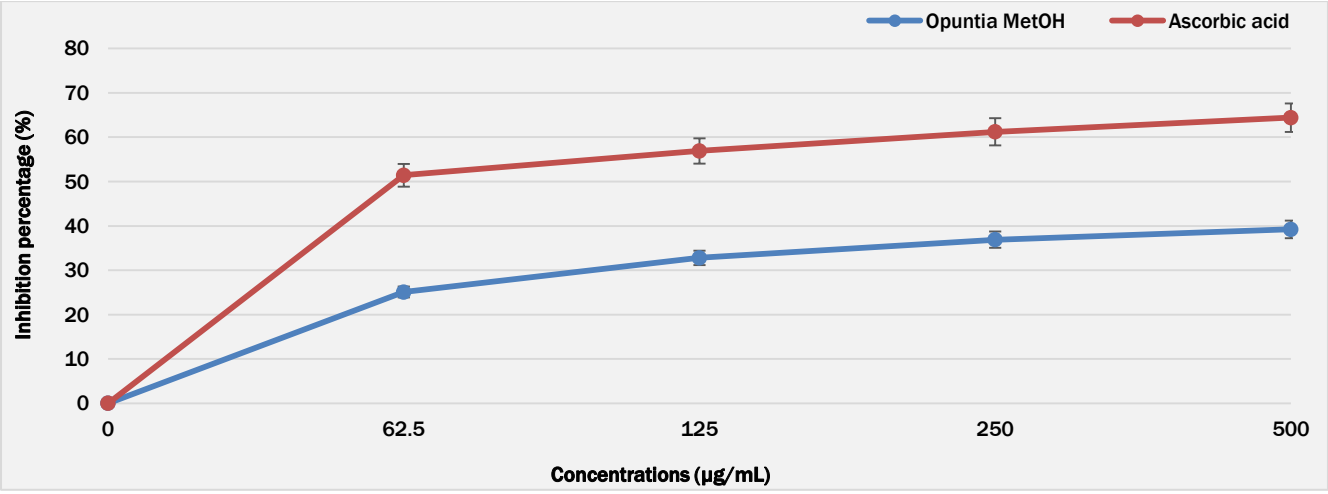

Figure 2 - DPPH free radical scavenging activity (%) of the methanolic extract of *Opuntia ficus-indica* cladodes in comparison with ascorbic acid.

Energy value

The prediction models offer a cost-effective method for estimating the nutritive value of *O. ficus-indica* cladodes. They can play an important role in integrating these food resources into farming systems. The selection of the model of prediction of the nutritive value for the *O. ficus-indica* cladodes was based on extensive work on the chemical composition and digestibility of the organic matter (dOM) of 71 forages, conducted over a period of forty years. This research has enabled the development of mathematical models that are reliable for estimating the energy and nitrogen content of forage, thus facilitating their use in routine processes (Chibani et al., 2010). The models were developed with explanatory variables including crude cellulose (CC), neutral detergent fibre (NDF), acid detergent fibre (ADF), mineral matter (MM), and total nitrogen (TN). The nutritional values were given in Table 2, in which the content of crude cellulose (CC) was 18.8 ± 1.1 g/100 g and the concentration of total nitrogen was 11.02 ± 1.2g/100 g.

According to Table 2, the prediction models provide a useful estimate of the nutritional value of *O. ficus-indica* cladodes. The digestibility of organic matter is relatively high (77.74 ± 1.5%). The energy values forage of the *O. ficus indica* was of the order of 1.32 MFU and 1.31 MEFU. These values are higher than the spontaneous early head announced by Bencherchali and Houmani (2017), which are 0.72 in MFU and 0.66 in MEFU, and are superior to the values of the rebus pitted (1.18 in MFU and 1.15 in MEFU). The metabolizable energy (ME) of the plant studied was 2842.51 kcal/kg, and the nitrogen matter digestibility was 948.91 g/kg.

The dOM (%) value of 77.748 ± 1.5 indicated the proportion of the organic (non-mineral) fraction that rumen microbes and the animal can break down and utilize. A value close to 78% is considered good for a succulent forage, showing relatively high digestibility compared to many dry grasses or crop residues common in North Africa. The moderate variability (±1.5) can arise from factors such as cladode age, variety, soil conditions, or season. Higher dOM generally translates into better energy supply for the animal (Teklu et al., 2023).

Crude cellulose (CC) at 18.8 ± 1.1 represents the cellulose content, a key structural component of plant cell walls (often linked to the acid detergent fibre, ADF, fractions in forage analysis). At approximately 19%, this level provides necessary "bulk" for proper rumen function, supporting microbial activity and preventing digestive disorders. However, excessive fibre can reduce voluntary intake and energy density. Young prickly pear cladodes typically show moderate fibre levels with relatively good digestibility because they contain lower lignin (the indigestible woody component) than mature grasses. Recent studies confirm cellulose values in Opuntia cladodes commonly range between 11–20%, aligning well with the table (Pessoa et al., 2022). The total nitrogen content of 11.02 ± 1.2 (most likely in g/kg) is used to estimate crude protein (CP) by multiplying by the factor 6.25. This is a low-to-moderate protein level for forage. Younger cladodes generally contain higher nitrogen/protein than older ones. While sufficient for basic rumen microbial needs (the optimal range is often cited as 6–8%), it is usually too low to fully support high-production animals without supplementation from protein-rich sources such as legume hay, urea, or concentrates. Multiple recent analyses report average CP in Opuntia cladodes between 3–10%, with many values clustering around 5–8%, consistent with this table (Rodrigues et al., 2016).

MFU (1.32) and MEFU (1.31) are energy units commonly used in French and North African feeding systems. One MFU approximates the energy provided by 1 kg of standard barley. These values indicate solid energy density for a succulent forage, supporting both lactation and growth/maintenance. The closeness of the two figures suggests balanced utility across production types. The metabolizable energy (ME) of 2842.51 kcal/kg (approximately 11.9 MJ/kg) reflects the energy actually available to the animal after digestive losses (faeces, urine, and methane). This is a moderate-to-good level for cactus forage — comparable to many hays but enhanced by the plant's natural juiciness when fed fresh. It can contribute effectively to maintenance and moderate production when combined with other feeds. Finally, DN at 948.91 g/kg most likely refers to digestible nitrogenous matter or a related measure of the highly utilizable dry matter/nitrogen fraction. The very high value (~95%) reinforces the excellent overall digestibility shown by the dOM figure and indicates that the cladodes are efficiently broken down by rumen microbes (Todaro et al., 2020; Erol et al., 2022).

Overall, the cladodes of prickly pear demonstrate clear strengths in digestibility and energy provision, as well as high moisture content. Their limitations lie mainly in moderate protein and fibre levels. In practice, especially in Algerian livestock systems, they are often fed fresh as a drought-resistant supplement or base feed, combined with higher-protein forages or concentrates to create balanced rations.

CONCLUSION

This study focuses on the valorization of young prickly pear (*O. ficus-indica*) cladodes, often regarded as a by-product, which can be processed into flour rich in bioactive compounds and exhibiting high antioxidant activity. Physicochemical analysis revealed that the cladodes are very rich in water and have a relatively low dry matter. The ash content was high, with calcium being the most abundant mineral, followed by potassium and sodium. Overall, the flour was also found to be a good source of sugars, proteins, and dietary fiber, making it potentially valuable for both ruminant feed. This work contributes to a better understanding of the young prickly pear's characteristics and supports its recovery and sustainable utilization.

DECLARATIONS

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Data availability
The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Authors' contribution
S. Nair: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft.
H. Belkhodja: Formal analysis, Writing - Review & Editing
S. M. Belhadj: Validation, Formal analysis, Writing - Review & Editing

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Competing interests
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