Nutritional characterization of leaf powder of introduced *Moringa oleifera* genotypes in the lower Shiwalik hills of the western Himalays, India

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ABSTRACT: *Moringa oleifera Lam., commonly known as the drumstick or miracle tree, is recognized for its exceptional nutritional and medicinal potential. In this study, six genotypes viz.,PKM1, PKM2, Jodhpur Local, Odisse Local, Mandya Local, and PM1 (Punjab Local) were evaluated under a completely randomized block design with three replications. Leaves were harvested green, shade dried, milled into powder, and analyzed for proximate composition, vitamin content, and macro and micronutrients. Dry matter content ranged from 18.20 ± 0.92 % (PKM 2) to 21.00 ± 1.61 % (Jodhpur Local), and ash content varied between 11.47 ± 0.31 % (Jodhpur Local) and 14.47 ± 0.31 % (PKM 2). Crude protein content was highest in PKM 1 (27.71 ± 2.01 %) and lowest in PM 1 (18.75 ± 2.72 %), while crude fiber ranged from 13.57 ± 1.47 % (PKM 1) to 16.20 ± 0.71 % (Jodhpur Local). The vitamin profile showed considerable variation, with PKM 1 exhibiting the highest values for Vitamin A (16.00 ± 0.50 mg100 g^{-1}), Vitamin B1 (2.62 ± 0.02 mg100 g^{-1}), Vitamin B2 (21.33 ± 0.76 mg100 g^{-1}), Vitamin B3 (8.47 ± 0.31 mg 100 g^{-1}), Vitamin C (17.63 ± 0.67 mg 100 g^{-1}), and Vitamin E (115.33 ± 2.52 mg 100 g^{-1}). Macronutrient content varied notably across genotypes: calcium was highest in PKM 1 (26.33 ± 1.53 mg100 g^{-1}), phosphorus in PM 1 (3.06 ± 0.053 mg 100 g^{-1}), potassium in PM 1 (19.71 ± 0.63 mg100 g^{-1}), magnesium in PM 1 (4.44 ± 0.082 mg100 g^{-1}, sodium in Odisse Local (0.75 ± 0.029 mg 100 g^{-1}), and sulphur in PKM 2 (16.33 ± 0.10 mg 100 g^{-1}). Micronutrient analysis revealed maximum manganese in PKM 1 (51.81 ± 1.89 mg kg-1), zinc in PM 1 (32.11 ± 1.15 mg kg^{-1}), copper in PM 1 (15.15 ± 0.76 mg kg^{-1}), iron in Jodhpur Local (395.67 ± 11.68 mg kg^{-1}), and boron in PKM 1 (52.25 ± 0.87 mg kg^{-1}). These findings demonstrate significant genotypic variation in the nutritional composition of Moringa oleifera Lam., with PKM 1, PKM 2, PM 1 (Pumjab local), and Jodhpur Local identified as promising candidates for nutritional enhancement and health-based applications.*

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1. INTRODUCTION

Moringa oleifera Lam. (Saijan) is native to the Indian subcontinent, but with time due to its remarkable adaptability, it has spread to parts of the world. It is also known as the drumstick tree or miracle tree, this fast-growing tree is valued for variety of uses both as nutritional supplement and medicine (Fahey, 2005). It is now a global enterprise as it is grown in the Caribbean, Southeast Asia, parts of South America and almost every African countries. (Anwar *et al.*, 2007). Drumstick grows well under varied climatic conditions as well as soil types and this has contributed greatly to its wider distribution. Its proliferation into varied climatic conditions globally underscores its importance as a sustainable and versatile crop having potential for supporting food security and health benefits (Babbar *et al.*, 2011; Gupta *et al.*, 2012).

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Moringa oleifera Lam (Saijan) has been used in traditional medicine over the years, and scientific research has confirmed most of its uses. Among the various health benefits, its nutritional profile is the major one. The leaves are known as a powerhouse of essential vitamins and minerals. They are rich in vitamins A, C, and E, all of which are important for immune function and skin health (Babbar *et al.*, 2011).

Drumstick leaves are also rich source of minerals such as calcium, iron, and potassium (Anwar *et al.*, 2007). The high concentration of nutrients makes this species a very good dietary supplement, especially in areas where malnutrition is prevalent in the masses. The health benefits of drumstick go beyond its nutritional content as it contains a large amount of antioxidants, comprising flavonoids, phenolic acids, and ascorbic acid and these compounds have a important function in the reduction of oxidative stress and neutralization of free radicals (Moyo *et al.*, 2012). The oxidative stress is considered as one of the major causes of chronic diseases such as cancer and cardiovascular conditions. These antioxidants help to reduce this risk by protecting cells against this damage and promoting their overall health.

Another important health benefit of drumstick is that it might help in controlling blood sugar levels. Numerous studies have indicated that the extracts from its leaves lower the blood glucose level both in human and animals. Gupta *et al*., 2012 reported that the hypoglycemic effect may be a result of enhanced insulin sensitivity and reduced absorption of glucose in the intestines. The blood sugar regulation property of *Moringa oleifera* Lam. thus presents a promising supplementary treatment against diabetes. Drumstick Anti-inflammatory properties might help in the management of chronic inflammatory diseases such as arthritis and asthma. It contain quercetin and chlorogenic acid, which are known to inhibit inflammatory pathways and reduce markers of inflammation (Alia *et al*., 2022). This anti-inflammatory action decreases pain and improves the quality of life of patients suffering from inflammatory diseases. Saijan has been reported to have antimicrobial activities, in addition to anti-inflammatory and antioxidant properties. Few studies have shown that extracts of Saijan are effective against a wide variety of pathogenic microorganisms, including bacteria, fungi, and viruses. (Pareek *et al*., 2023). It is thus a potential reservoir of compounds that can enhance immune function and provide protection against infections. Another major benefit is its support for cardiovascular well being. The polyphenols and antioxidants within drumstick decrease blood pressure and cholesterol levels, which reduces the risk of heart diseases. It has been found that regular consumption improves lipid profiles and reduces arterial stiffness, hence contributing to cardiovascular health.

Keeping in view the health benefits of the *Moringa olefera* Lam., genotypes from different locations were evaluated in the submontaneous region of lower shiwaliks hills of Punjab for their suitability and nutritional profile. This will help in identification of nutritionally superior genotype that can be recommended for the benefit of the people of the region.

2. MATERIALS AND METHODS

The experiment was conducted at Punjab Agricultural University. Regional research Station, Ballowal Saunkhri situated in the lower Shiwalik hills of North-Western Himalayas. The site is located at 31°05′32″ N, 76°23′07″ E with an altitude of 369.71 m amsl. The average annual rainfall in the area is about 1067 mm out of which 80% rainfall is received during the monsoons. The annual maximum and minimum temperature ranges from 28.5 to 31.0°C and 15.2 to 17.4°C, respectively (Sharma *et al*., 2017). The soils of the experimental field was sandy loam having pH 7.4, low in organic carbon (0.26%) and available nitrogen (142.4 kg/ha); medium in available phosphorus (20.25 kg ha^{-1}) and high in potassium (245 kg ha^{-1}).

Six genotypes of Moringa *viz.,* PKM1, PKM2, Jodhpur Local, Odisse Local, Mandya Local and Pm1 (Punjab Local) were evaluated in a completely randomized block design (CRBD) having three replication and there were 5 plants of each genotype per replication. The leaves were harvested green, air dried under shade and milled into powder through 1 mm sieve and were stored at room temperature.

Dried powdered Moringa leaves were assessed for dry matter, crude protein, Ash content, crude fibre, calcium (Ca), phosphorus (P), potassium (K), magnesium (Mg),sodium (Na), sulphur (S), manganese (Mn), , zinc (Zn), copper (Cu), iron (Fe) and Boron (B) using the Association of Official Agricultural Chemists[9](AOAC, 2005). Vitamin C, vitamin B1, vitamin B2, vitamin B3, vitamin A and vitamin E content was estimated as per the method given by Xiao, 2012. The statistical analysis of the data generated was done using online software package OP STAT (Sheoran *et al*.,1998)

3. RESULTS

Proximate composition

The proximate compositions of Saijan leaves varied among the different genotypes. The dry matter contents varied significantly among the cultivars, ranging from 18.20±0.92 % to 21.00±1.61 %. The highest dry matter content was found in Jodhpur local, whereas the lowest was found in PKM 2. PKM 2 contained the highest ash content (14.47±0.31%) which was statistically at par with PKM 1(14.10±0.26%), whereas Jodhpur local contained the lowest content (11.47±0.31%). The crude protein contents (27.71±2.01%) was found to be highest in PKM 1 and PKM 2 (24.17±0.72%) and lowest (18.75±2.72%) in PM 1 Punjab local. The crude fiber content (16.20±1.47%) was highest in Jodhpur local, whereas the lowest (13.57±0.71%) was found in PKM 1 (Table 1).

Dry matter content found in this study were slightly different in six genotypes but overall content reported was in agreement with Offor *et al*. (2014) and Zheng *et al*. (2019) who have reported dry matter between 80 – 85%. The ash content for the genotypes reveals moderate variation, reflecting the differences in their mineral content but overall contents were similar as reported by Afzal *et al*. (2020) and Qadir *et al*. (2022) who reported between 10.36% - 15.90%. The crude protein contents found in this study were slightly different among genotypes overall contents were less as reported by Anwar *et al*. (2007) and Oluduro *et al.* (2008), who reported the crude protein contents about 31.65% and 27.51%, respectively. However, findings of this study for crude protein are in agreement with Jongrungruangchok *et al*. (2010) and Asaolu *et al*. (2011), who found these values 19.15%, 28.80% and 17%, respectively. Similarly Sultana 2020 also reported protein content, ranging from (22.99-29.36%). The data for crude protein was in accordance with reported earlier by Sánchez Machado *et al*. (2010), Zheng *et al*. (2019) and Afzal *et al*. (2020). Higher levels of crude protein contents are desired as it helps in improving the health and prevention of diseases in humans and livestock (Jongrungruangchok *et al*., 2010; Offor *et al*., 2014). The differences in crude protein among the genotypes imply that the Moringa genotypes can have different applications based on protein needs. Higher crude fiber contents reported in present study is in line with higher crude fibre (about 16.30-23.89%) reported in earlier studies by Jongrungruangchok *et al*. (2010) and Afzal *et al*. (2020).

Vitamin profile

The vitamin profile of Saijan *(Moringa oleifera*) leaves varied significantly among the different genotypes. Vitamin A content ranged from 11.53 ± 0.70 to 16.00 ± 0.50 mg 100 g^{-1}, with PKM 1 exhibiting the highest concentration (16.00 ± 0.50 mg 100 g^{-1}), which was statistically at par with Mandya Local (15.70 ± 1.30 mg 100 g^{-1}), followed by PKM 2 (14.07 ± 0.75 mg 100 g^{-1}) (Table 2). The lowest vitamin A content was recorded in Jodhpur Local (11.53 ± 0.70 mg 100 g^{-1}). Vitamin B1 (thiamine) content showed a wide range from 1.20 ± 0.20 mg 100 g^{-1} to 2.62 ± 0.02 mg 100 g^{-1}. The maximum was found in PKM 2 (2.62 ± 0.02 mg 100 g^{-1}), which was statistically at par with Mandya Local (2.27 ± 0.42 mg 100 g^{-1}), whereas Jodhpur Local contained the minimum amount (1.20 ± 0.20 mg 100 g^{-1}) (Table 2). For vitamin B2 (riboflavin), PKM 1 recorded the highest value (21.33 ± 0.76 mg 100 g^{-1}), followed by PKM 2 (19.83 ± 1.23 mg 100 g^{-1}) and Odisse Local (18.73 ± 0.50 mg 100 g^{-1}), while Jodhpur Local had the lowest riboflavin content (17.17 ± 0.35 mg 100 g^{-1}) (Table 2). The vitamin B3 (niacin) content varied between 6.73 ± 0.50 mg 100 g^{-1} and 8.47 ± 0.31 mg 100 g^{-1}. PKM 1 showed the highest value (8.47 ± 0.31 mg 100 g^{-1}), which was statistically at par with Mandya Local (8.23 ± 0.25 mg 100 g^{-1}) and PKM 2 (8.17 ± 0.21 mg 100 g^{-1}) (Table 2). The minimum B3 content was found in Jodhpur Local (6.73 ± 0.50 mg 100 g^{-1}). Vitamin C content ranged from 14.07 ± 0.70 to 17.63 ± 0.67 mg 100 g^{-1}, with PKM 1 containing the highest amount (17.63 ± 0.67 mg 100 g^{-1}), followed by PKM 2 (16.07 ± 0.81 mg 100 g^{-1}). Jodhpur Local

Table 1: Proximate analysis of different genotypes of *Moringa oleifera* Lam.

Genotype	Dry matter (%)	Ash Content (%)	Crude protein (%)	Crude fibre (%)
PKM 1	18.50±1.00^{b}	14.10±0.26^{a}	27.71±2.01^{a}	13.57±0.71^{bc}
PKM 2	18.20±0.92^{b}	14.47±0.31^{a}	24.17±0.72^{ab}	13.87±0.35^{c}
Jodhpur local	21.00±1.61^{a}	11.47±0.31^{d}	22.29±1.30^{bc}	16.20±1.47^{a}
Odisse Local	19.40±0.85^{ab}	12.43±0.40^{c}	19.38±1.65^{c}	14.33±0.57^{abc}
Mandya Local	18.73±0.40^{b}	13.50±0.30^{b}	23.75±2.50^{ab}	14.43±0.68^{bc}
PM 1	20.37±1.70^{ab}	11.80±0.40^{d}	18.75±2.72^{c}	15.40±1.06^{ab}
C.D.	NA	0.601	3.915	1.857

Note: Mean±Standard deviation values with the same letter in the same column (a, b, c, d, e, f, g, h) for a specific concentration and extract type do not differ significantly at $p < 0.05$.

Table 2: Vitamin profile (mg 100 gm^{-1}) of powdered leaves of different genotypes of *Moringa oleifera*

Genotype	Vitamin A	Vitamin B1	Vitamin B2	Vitamin B3	Vitamin C	Vitamin E
PKM 1	16.00±0.50^{a}	2.62±0.02^{a}	21.33±0.76^{a}	8.47±0.31^{a}	17.63±0.67^{a}	115.33±2.52^{a}
PKM 2	14.07±0.75^{b}	2.45±0.05^{a}	19.83±1.23^{b}	8.17±0.21^{a}	16.07±0.81^{b}	113.00±1.00^{ab}
Jodhpur local	11.53±0.70^{c}	1.20±0.20^{c}	17.17±0.35^{de}	6.73±0.50^{c}	14.07±0.70^{c}	111.33±0.58^{bc}
Odisse Local	12.80±0.40^{bc}	1.80±0.20^{b}	18.73±0.50^{bc}	7.50±0.26^{b}	15.83±0.35^{b}	113.00±1.00^{ab}
Mandya Local	15.70±1.30^{a}	2.27±0.42^{a}	18.00±0.20^{cd}	8.23±0.25^{a}	16.07±0.81^{b}	112.67±1.15^{ab}
PM 1 (Punjab Local)	11.80±0.60^{c}	1.53±0.31^{bc}	16.43±0.40^{e}	6.07±0.23^{d}	14.40±0.85^{c}	109.33±1.53^{c}
CD(0.05)	1.38	0.43	1.20	0.56	1.29	2.58

Note: Mean ±Standard deviation values with the same letter in the same column (a, b, c, d, e, f, g, h) for a specific concentration and extract type do not differ significantly at $p < 0.05$.

recorded the lowest value (14.07 ± 0.70 mg 100 g^{-1}). The highest vitamin E content was observed in PKM 1 (115.33 ± 2.52 mg 100 g^{-1}), whereas the lowest was found in PM 1 (Punjab Local) (109.33 ± 1.53 mg 100 g^{-1}) (Table 2).

The vitamin profile of *Moringa oleifera* Lam. leaves exhibited significant variability across the studied genotypes, particularly in the concentration of essential vitamins. Among all, the genotype PKM 1 demonstrated the highest levels of several key vitamins, including Vitamin A, B1, B2, B3, C, and E. This suggests its superior nutritional value, particularly in relation to antioxidant activity (Vitamin E), immune function enhancement (Vitamin C), and energy metabolism (B-complex vitamins). Although other genotypes also contained appreciable levels of these vitamins, the observed differences can largely be attributed to genetic diversity, environmental influences, and cultivation conditions. Previous studies have documented that *M. oleifera* is a rich source of both fat soluble vitamins such as Vitamin A (in the form of β-carotene), D, and E and water-soluble B-complex vitamins, including folic acid, pyridoxine, and nicotinic acid, along with Vitamin C (Mbikay, 2012). Similarly, Moringa leaf powder has been reported to contain substantial quantities of β-carotene, thiamine, riboflavin, niacin, pyridoxine, biotin, ascorbic acid, cholecalciferol, tocopherol, and Vitamin K (Broin, 2006). The vitamin concentrations obtained in the present study align with findings reported by Fuglie (2005), Olagbemide and Alikwe (2014), Gopalakrishnan *et al*. (2016), and Islam *et al*. (2021). In line with these results, Fuglie (2001) reported Vitamin C levels of 113 mg 100 g^{-1}in dried Moringa leaves. Additionally, Phullakhandam and Failla (2007) documented lutein and β-carotene contents of 418 and 272 mg kg^{-1} in fresh leaves, and 472 and 166 mg kg^{-1}, respectively, in dried leaf powder. These findings reinforce the high vitamin content and nutritional potential of *M. oleifera* leaves.

Macronutrient composition

Significant variation was observed among the genotypes for all measured macronutrient contents. The highest calcium content was recorded in PKM 1 (26.33 ±1.53 mg 100 g^{-1}), whereas the minimum was found in Jodhpur local (16.00 ±1.73 mg 100 g^{-1}). For phosphorus, PM 1 exhibited the maximum value (3.06±0.053 mg 100 g^{-1}), which was statistically at par with Jodhpur local (2.99 mg 100 g^{-1}); the lowest phosphorus content was observed in PKM 1 (2.19 ±0.031 mg 100 g^{-1}) and Mandya Local (2.22 ±0.009 mg 100 g^{-1}), both being statistically similar. Potassium content was highest in PM 1 (19.71 ±0.63 mg 100 g^{-1}), while the minimum value was recorded in PKM 1 (13.33±0.14 mg 100 g^{-1}). In the case of magnesium, PM 1 recorded the highest concentration (4.44 ±0.082

Table 3: Macronutrients (gm kg^{-1}) composition of different genotypes of *Moringa oleifera* Lam.

Genotype	Calcium (Ca)	Phosporous (P)	Potassium (K)	Magnesium (Mg)	Sodium (Na)	Sulphur (S)
PKM 1	26.33±1.53[a]	2.19±0.021[e]	13.33±0.14[e]	2.31±0.022[f]	0.18±0.009[c]	13.62±0.18[c]
PKM 2	21.33±3.06[b]	2.72±0.003[c]	15.76±0.18[c]	2.52±0.001[e]	0.17±0.003[c]	16.33±0.10[a]
Jodhpur local	16.00±1.73[d]	2.99±0.031[b]	14.70±0.10[d]	3.90±0.017[b]	0.70±0.014[a]	10.96±0.12[d]
Odisse Local	18.67±0.58[bcd]	2.53±0.013[d]	16.03±0.49[c]	3.31±0.022[d]	0.75±0.029[a]	10.15±0.11[e]
Mandya Local	20.67±3.06[bc]	2.22±0.009[e]	16.90±0.30[b]	3.40±0.009[c]	0.20±0.006[c]	15.52±0.24[b]
PM 1	16.67±2.31[cd]	3.06±0.053[a]	19.71±0.63[a]	4.44±0.082[a]	0.32±0.025[b]	11.15±0.03[d]
CD (0.05)	4.00	0.058	0.653	0.065	0.030	0.262

Note: Mean±Standard deviation values with the same letter in the same column (a, b, c, d, e, f, g, h) for a specific concentration and extract type do not differ significantly at $p < 0.05$.

Table 4: Micronutrients (mg kg^{-1}) composition of powdered leaves of different genotypes of *Moringa oleifera* Lam.

Genotype	Manganese (Mn)	Zinc (Zn)	Copper (Cu)	Iron (Fe)	Boron (B)
PKM 1	51.81±1.89[a]	31.45±0.29[a]	9.81±0.58[c]	313.33±6.43[b]	52.25±0.87[a]
PKM 2	51.31±1.26[a]	29.45±2.08[b]	10.65±0.29[bc]	256.67±8.08[d]	43.25±0.50[c]
Jodhpur local	39.98±1.32[d]	29.95±0.29[ab]	14.31±0.29[a]	395.67±11.68[a]	38.75±0.50[d]
Odisse Local	48.31±1.53[b]	31.78±1.32[a]	11.15±0.29[b]	295.00±9.17[c]	35.25±0.87[e]
Mandya Local	49.65±0.29[ab]	22.45±0.58[c]	7.48±1.00[d]	198.67±9.02[e]	43.58±0.29[c]
PM 1	43.65±2.02[c]	32.11±1.15[a]	15.15±0.76[a]	309.67±9.02[bc]	48.58±1.04[b]
CD (0.05)	2.69	2.07	0.79	16.25	1.31

Note: Mean±Standard deviation values with the same letter in the same column (a, b, c, d, e, f, g, h) for a specific concentration and extract type do not differ significantly at $p < 0.05$.

(3.90±0.017 mg 100 g^{-1}); the lowest was observed in PKM 1 (2.31 ±0.022 mg 100 g^{-1}). Sodium was found to be highest in Odisse Local (0.75±0.029 mg 100 g^{-1}), statistically similar to Jodhpur local (0.70 ±0.014 mg 100 g^{-1}), whereas the lowest sodium content was noted in PKM 2 (0.17±0.003 mg 100 g^{-1}). Sulphur content reached its peak in PKM 2 (16.33 ±0.10 mg 100 g^{-1}), which was statistically at par with Mandya Local (15.52 ±0.24 mg 100 g^{-1}); the minimum sulphur content was found in Odisse Local (10.15 ±0.11 mg 100 g^{-1}).

The mineral profiling of different genotypes in the present study confirms the plant's considerable nutritional significance. Minerals such as calcium, potassium, copper, and magnesium were abundantly present in *M. oleifera* leaves (Selahvarzi *et al*. 2021). The macronutrient composition findings are consistent with earlier observations by Mikore and Mulugeta (2017), who reported significant nutrient levels in M. oleifera leaves. Similarly, Aslam *et al*. (2005) noted that leaves and pods collected from different regions of Punjab Province (Pakistan) contained high levels of Fe, Cu, Na, Zn, P, Mn, K, Mg, and Ca, underscoring the plant's diverse mineral content. These findings align with previously reported calcium content in moringa leaf powder, which ranged from 2.47 mg to 2003 mg (Offor *et al*., 2014; Thapa *et al*., 2019; Afzal *et al*., 2020). Several studies have reported Ca content in *M. oleifera* leaves ranging between 1.91–3.65% and 2.47–2003 mg (Anjorin *et al.*, 2010; Olugbemi *et al*., 2010; Ogbe and Affiku 2011; Asante *et al*., 2014; Offor *et al*., 2014). In the current study, phosphorus levels ranged from 2.20 g kg^{-1} to 3.06 g kg^{-1}. These values are in agreement with reports by Sultana (2020) and Afzal *et al*., (2020), which confirm similar phosphorus levels in Drumstick leaves. Phosphorus is vital for cellular energy transfer and structural integrity of nucleic acids and cell membranes. Potassium is another crucial element, responsible for fluid balance, nerve signal transmission, and muscle contractions. PM 1 (Punjab Local) exhibited the highest potassium content, positioning it as a strong candidate for addressing potassium-related nutritional needs. These findings are consistent with potassium levels reported by Sultana (2020), which ranged from 1.317 to 2.025 g 100 g^{-1} in dry moringa leaf samples. Magnesium (Mg), essential for skeletal structure, muscle function, and ATP synthesis, was found to range between 2.31 g kg^{-1} (PKM 1) and 4.44 g kg^{-1} (PM 1). These values are similar to those reported by Asante *et al*., (2014), Offor *et al*., (2014), and Afzal *et al*., (2020). Mg plays an integral role in energy metabolism and structural development (Oluduro 2012; Offor *et al*. 2014), and the values observed in this study align with previous reports (Anjorin *et al*., 2010; Olugbemi *et al*., 2010; Ogbe and Affiku 2011; Asante *et al*., 2014; Offor *et al*., 2014), confirming *M. oleifera* as a potent dietary source of magnesium. Sodium (Na) content was low across all genotypes, ranging from 0.17 g kg^{-1} in PKM 2 to 0.75 g kg^{-1} in Odisse Local. This aligns with findings by Afzal *et al*., (2020) and Ogbe and Affiku (2011)[35], which also reported lower sodium levels in Moringa leaf extracts. Earlier studies have also reported lower sulphur concentrations than those observed in the current study (Moyo *et al*., 2011; Thapa *et al*., 2019). Sulphur, though less frequently studied in moringa, remains essential for amino acid synthesis and enzyme function. Overall, the mineral composition observed in this study confirms that *M. oleifera* genotypes such as PKM 1, PM 1, and PKM 2 are nutritionally superior and well-suited for addressing mineral deficiencies. These findings are consistent with previous reports emphasizing the richness of Moringa leaves in key minerals including potassium, zinc, magnesium, iron, and copper (Kasolo *et al*., 2010). The variation in nutrient accumulation among genotypes also highlights the potential for targeted cultivar selection for specific nutritional and therapeutic applications.

Micronutrient composition

The genotypes showed significant differences in the micronutrient content of moringa leaves. The maximum manganese content was recorded in PKM 1 (51.81 ± 1.89 mg kg^{-1}), which was statistically at par with PKM 2 (51.31 ± 1.26 mg kg^{-1}), while the minimum was observed in Jodhpur local (39.98 ± 1.32 mg kg^{-1}). Zinc concentration was highest in PM 1 (32.11 ± 1.15 mg kg^{-1}), statistically at par with Odisse Local (31.78 ± 1.32 mg kg^{-1}) and PKM 1 (31.45 ± 0.29 mg kg^{-1}); the minimum zinc content was found in Mandya Local (22.45 ± 0.58 mg kg^{-1}). The highest copper content was noted in PM 1 (15.15 ± 0.76 mg kg^{-1}), which was statistically similar to Jodhpur local (14.31 ± 0.29 mg kg^{-1}); the lowest copper value was observed in Mandya Local (7.48 ± 1.00 mg kg^{-1}). Iron concentration was significantly highest in Jodhpur local (395.67 ± 11.68 mg kg^{-1}), with no genotype at par, while the minimum iron content was reported in Mandya Local (198.67 ± 9.02 mg kg^{-1}). Boron content was found to be maximum in PKM 1 (52.25 ± 0.87 mg kg^{-1}), followed by PM 1 (Punjab Local) (48.58 ± 1.04 mg kg^{-1}); the lowest boron concentration occurred in Odisse Local (35.25 ± 0.87 mg kg^{-1}).

The present study revealed considerable genotypic variation in the micronutrient composition of *Moringa oleifera* Lam. leaves. Among the genotypes, PKM 1 exhibited the highest concentrations of manganese, boron and iron, highlighting its potential as a superior source of essential micronutrients with wide ranging health benefits. Similarly, PM 1 (Punjab Local) recorded the highest levels of copper and underscoring its likely role in supporting immune function, enzymatic activity, and erythropoiesis. In contrast, genotypes such as Odisse Local and Mandya Local showed comparatively lower boron and iron content, which may limit their effectiveness as dietary sources of these key elements. The micronutrient values observed in this study corroborate earlier reports by Moyo *et al*., (2011), Castillo-López *et al*., (2017), Thapa *et al*., (2019), and Qadir *et al*., (2022), affirming the nutritional richness of M. oleifera foliage. Zinc concentrations in this study (up to 32.113 mg kg^{-1}) were notably higher than those reported by Barminas *et al*., (1998), who recorded 25.5 mg kg^{-1}in dried Moringa leaves. As an essential trace element, zinc plays a pivotal role in nucleic acid synthesis, insulin function, and the structural integrity of numerous enzymes (Brisibe *et al*., 2009). Furthermore, zinc is vital for cellular replication and growth, particularly in reproductive cells, and is recognized for its anti-viral, anti-bacterial, anti-fungal, and anti-carcinogenic properties. Copper, also present in substantial quantities, is associated with enhanced immune response (Anwar *et al*., 2007).

4. CONCLUSION

This study underscores the considerable genotypic variation in the nutritional composition of *Moringa oleifera* Lam., affirming its status as a highly valuable multipurpose tree with wide-ranging applications in human and animal nutrition. The findings reveal that nutrient content in leaves particularly proteins, vitamins, and essential macro and micronutrients varies not only across genotypes but also in response to ecological and geographical conditions. PKM 1 emerged as a superior genotype for protein and vitamin content, while Jodhpur Local demonstrated potential for iron enrichment and high fiber applications. PM 1 (Pumjab Local) and PKM 2 showed specific strengths in mineral profiles such as potassium, magnesium, calcium, sulphur, and trace elements. These variations highlight the importance of genotype selection tailored to specific nutritional objectives or environmental conditions. Further research is warranted to explore nutrient dynamics at different phenological stages and under controlled agronomic inputs, which may open new avenues for optimizing drumstick nutritional potential through genotype environment management interactions.

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