Analysis of Nutritional Components in Different Parts of Malania oleifera Postprint

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Abstract

To clarify the nutritional value characteristics and development directions of different parts of Malania oleifera, this study utilized its kernel, pericarp, leaf, branch bark, and trunk bark as materials. Conventional food nutrient analysis methods were employed to determine the types and contents of basic nutrients, amino acids, and minerals in various parts, and the nutritional value of amino acids in each part was evaluated. The results showed: (1) Regarding basic nutritional components, the ash content of pericarp was higher than other parts, at 5.7 g/100 g. The crude fat and protein contents in kernel were higher than other parts, at 36.0 and 14.0 g/100 g, respectively; the vitamin C content in leaf was higher than other parts, at 33.9 mg/100 g; the crude fiber content in branch bark was higher than other parts, at 40.5 g/100 g; the carbohydrate content in trunk bark was higher than other parts, at 78.6 g/100 g; volatile oils were detected only in kernel and leaf, at 0.26 and 0.15 mL/100 g, respectively. (2) A total of 16 amino acids were detected in Malania oleifera, including 7 essential amino acids. The total amino acid content and total essential amino acid content in kernel were significantly higher than other parts, at 12.71 and 4.8 g/100 g, respectively. In terms of amino acid nutritional value, kernel and pericarp had the highest nutritional value, followed by leaf, branch bark, and trunk bark, with essential amino acid ratio coefficient scores (SRC) of 62.98, 59.40, 57.31, 52.25, and 48.17, respectively. (3) Regarding macroelements, the highest macroelement in kernel, pericarp, and leaf was K, while in branch bark and trunk bark it was Ca; Na content was the lowest in all five parts of Malania oleifera. Regarding microelements, the Mn and Fe contents in the five parts of Malania oleifera were higher than other microelements, with the highest Mn content in kernel and the highest Fe content in branch bark. The comprehensive results indicate that the kernel of Malania oleifera has the highest nutritional value, while other parts also possess unique development and utilization potential, enabling effective and precise development and utilization according to the different value characteristics of each part.

Full Text

Preamble

Analysis of Nutritional Components in Different Parts of Malania oleifera

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Abstract: To clarify the nutritional value characteristics and development potential of different parts of Malania oleifera, this study analyzed the kernel, peel, leaf, branch bark, and bark to determine the types and contents of basic nutrients, amino acids, and minerals using conventional food nutrient analysis methods, and evaluated the nutritional value of amino acids in each part. The results showed: (1) Regarding basic nutrients, the peel had the highest ash content at 5.7 g/100 g. The kernel contained the highest crude fat and protein at 36.0 g/100 g and 14.0 g/100 g, respectively. Leaves showed the highest vitamin C content at 33.9 mg/100 g. Branch bark had the highest crude fiber content at 40.5 g/100 g. Bark contained the highest carbohydrate content at 78.6 g/100 g. Volatile oils were detected only in the kernel and leaves at 0.26 mL/100 g and 0.15 mL/100 g, respectively. (2) A total of 16 amino acids were detected across all parts, including 7 essential amino acids. The kernel had significantly higher total amino acids and essential amino acids than other parts at 12.71 g/100 g and 4.8 g/100 g, respectively. In terms of amino acid nutritional value, the kernel and peel ranked highest, followed by leaves, branch bark, and bark, with essential amino acid ratio coefficient scores (SRC) of 62.98, 59.40, 57.31, 52.25, and 48.17, respectively. (3) Among macroelements, K was highest in kernel, peel, and leaves, while Ca was highest in branch bark and bark. Na was the lowest in all five parts. For trace elements, Mn and Fe were higher than other elements across all parts, with the highest Mn in kernel and highest Fe in branch bark. Overall, the kernel showed the highest nutritional value, while other parts also demonstrated unique development potential, enabling targeted exploitation based on their distinct value characteristics.

Keywords: Malania oleifera; different parts; nutritional components; amino acids; mineral elements

Introduction

Malania oleifera, a rare evergreen tree species belonging to the family Olacaceae and genus Malania, is a nationally protected second-class single-species plant endemic to China. Commonly known as "Malanhua" (Zhuang language in Guangxi), "Shantongguo" (Guangnan dialect), "Houziguo," or "Mimin," it grows only in low mountain areas of western Guangxi and in Guangnan and Funing counties of Yunnan Province (Huang et al., 2008). As an important mountain woody oil crop, M. oleifera offers comprehensive utility, with its branches, leaves, and fruits all harboring significant research and application value. The kernel represents the most studied and utilized part, containing up to 65% healthy oil with nervonic acid (tetracosenoic acid) as the dominant component at 50.71% of total lipids, followed by oleic acid and linolenic acid (Zhang et al., 2016). Nervonic acid, a long-chain polyunsaturated fatty acid, plays crucial roles in neural cell development and repair, memory improvement (Yuan et al., 2013), and serves as a key ingredient in drugs such as Yunnan Baiyao and Shexiang Baoxin pills (Zhou, 2017). Kernel proteins also exhibit high medicinal value, showing strong cytotoxicity against Hela and Vero cells (Yang, 2020) and inhibitory effects on human leukemia K562 cell growth in vitro (Yuan et al., 2014). Beyond the kernel, fruit shells and peels contain small amounts of crude fat at 6.47% and 6.60%, respectively (Yang et al., 2022), while fruit shells and branch wood are rich in lignin, opening new avenues for comprehensive utilization (Tang et al., 2013). Studies have identified volatile oils in fresh branches, leaves, and peel pulp, with benzyl alcohol, benzaldehyde, and mandelonitrile as main components (Tang et al., 2013). Huang et al. (2008) analyzed leaf volatile oils, identifying five compounds comprising 98.75% of total content, with mandelonitrile showing the highest relative content followed by benzaldehyde. These findings demonstrate that different parts of M. oleifera contain varying volatile oil compositions and abundant natural fragrance components applicable in cosmetics and food industries. Additionally, M. oleifera timber is valued for its straight trunk, fine grain, high density, and corrosion resistance, making it premium material for furniture and shipbuilding with market prices around 4,000 yuan/m^3 (Chen et al., 2021).

In recent years, as the economic value of M. oleifera resources has become increasingly apparent and afforestation technology has advanced, industrial production and processing have become inevitable. However, after harvesting fruits and timber, branches, leaves, peels, and bark remain underutilized, causing resource waste and environmental pollution. Moreover, M. oleifera has a long cultivation cycle, typically requiring 10 years to reach full production, necessitating comprehensive development research to enhance economic benefits and stimulate cultivation. Current research has focused primarily on oil, polysaccharide (Yuan et al., 2009), protein, lignan, and nervonic acid extraction from kernels, while nutritional studies on kernels and the whole plant remain nascent. Zhang et al. (2012) first determined seven metal elements (Al, Ca, Fe, K, Mg, Mn, Zn) in kernels using wet nitric-perchloric acid digestion, providing a theoretical basis for mineral element research. Subsequently, Su et al. (2021) analyzed protein, crude fat, fatty acid composition, and mineral elements in kernels, evaluating amino acid nutritional value and concluding that kernels possess high nutritional value, rich nutrients, and no heavy metal contamination, showing great potential for deep food processing. Beyond these two studies, nutritional research remains scarce, with many questions unanswered: Which part has the highest nutritional value? What are the characteristics of different parts? What is the material basis for nutritional value formation? Do mineral elements and nutritional components vary among M. oleifera from different regions?

Therefore, to comprehensively develop M. oleifera resources, clarify nutritional value characteristics of different parts, and enhance cultivation economic benefits, this study builds on previous research by analyzing five parts of the whole plant—kernel, peel, leaf, branch bark, and bark—using conventional food nutrient analysis methods. We determined basic nutrients, amino acids, and minerals, evaluated nutritional value, identified differences and characteristics among parts, explored underlying mechanisms, and 挖掘 development potential to provide precise theoretical support for product development and utilization, achieving both economic and ecological benefits.

1.1 Materials and Instruments

Plant Materials: Mature fruits, leaves, branch bark, and bark of M. oleifera were collected in mid-October 2021 from five healthy adult plants of the same age in Jiaole Tiankeng, Bama County, Hechi City, Guangxi Zhuang Autonomous Region. The specimens were identified as M. oleifera by researcher Wei Xiao from Guangxi Institute of Botany. The collection site features a subtropical monsoon climate with distinct wet and dry seasons; June-August constitute the rainy season with abundant precipitation, which essentially ends by early October. The tiankeng interior has lower temperatures, minimal water evaporation, and rivers/underground streams, creating a humid climate with fertile, neutral-to-alkaline calcareous soil.

Instruments: QE-100 high-speed pulverizer (Zhejiang Yili Industry & Trade Co., Ltd.); L-8900 amino acid analyzer, automatic Kjeldahl nitrogen analyzer (Jinan Haineng), electronic balance (Mettler), high-speed refrigerated centrifuge (Hitachi, Japan), high-performance liquid chromatography system (Waters, USA), double-beam scanning UV-Vis spectrophotometer (Thermo Fisher, USA), ZEEEnit 700 atomic absorption spectrometer (Analytik Jena, Germany), IRIS Intrepid inductively coupled plasma optical emission spectrometer (Thermo Fisher, USA), X7 Series inductively coupled plasma mass spectrometer (Thermo Fisher, USA), SA-10 atomic fluorescence speciation analyzer (Beijing Jitian), TU-1810 UV-Vis spectrophotometer (Beijing Puxi), among others.

1.2.1 Raw Material Pretreatment

Kernels and peels from mature fruits were manually separated, washed, and then oven-dried at 60°C to constant weight along with washed leaves, branch bark, and bark. The dried materials were pulverized, passed through a 60-mesh sieve, and stored as sample powder for analysis.

1.2.2 Determination of Basic Nutrients, Amino Acids, and Mineral Elements

This study employed Chinese national standard methods for food nutrient analysis to detect ash, crude fat, protein, amino acids, and mineral elements in different parts of M. oleifera. Specific methods included: ash (gravimetric method, GB 5009.4—2016), crude fat (Soxhlet extraction, GB 5009.6—2016) (Zhang et al., 2011), crude protein (Kjeldahl method, GB 5009.5—2016) (Yang, 2017), crude fiber (gravimetric method, GB/T 8310—2013), carbohydrates (phenol-sulfuric acid method, GB 28050—2011) (Zhu et al., 2005), vitamin C (HPLC, GB 5009.86—2016), volatile oils (toluene method, GB/T 30385—2013), and amino acids (automatic amino acid analyzer).

1.2.3 Determination of Mineral Elements

Approximately 1.00 g of powdered kernel, peel, leaf, branch bark, and bark samples were placed in digestion tubes with 5.0 mL HNO_3 and 2.0 mL H_2O_2, then digested in a microwave digestion system. After digestion, tubes were placed in an acid evaporation unit, and the residue was diluted to volume with 2% HNO_3 for analysis. K, Ca, Mg, Na, Fe, and Cu were determined by inductively coupled plasma optical emission spectrometry, while P, Mn, Zn, and Se were analyzed by inductively coupled plasma mass spectrometry (Wang et al., 2021). Each sample was analyzed in triplicate, and mean values were calculated.

1.3 Amino Acid Nutritional Value Evaluation

The amino acid ratio coefficient method (Hou et al., 2019) was used to evaluate amino acid nutritional value in kernel, peel, leaf, branch bark, and bark. Using the essential amino acid pattern recommended by WHO/FAO as standard, we calculated: ratio of amino acids (RAA), mean value of RAA (R̄AA), amino acid ratio coefficient (RC), mean value of RC (R̄C), coefficient of variation of RC (CV), standard deviation of RC (SD), and score of ratio coefficient of amino acid (SRC). Calculations were as follows:

$$\mathrm{RAA} = \frac{\text{Content of a certain essential amino acid in sample}}{\text{Content of that essential amino acid in pattern}}$$

$$\mathrm{RAA} = \frac{\sum \mathrm{RAA}}{n}$$

$$\mathrm{RC} = \frac{\mathrm{RAA}}{\mathrm{RAA}}$$

$$\mathrm{SRC} = 100 - 100 \times \mathrm{CV}$$

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{RC}}$$

1.4 Data Processing

Data were processed using Excel 2016 and statistically analyzed using SPSS 18.0.

2.1 Composition and Content of Basic Nutrients in Kernel, Peel, Leaf, Branch Bark, and Bark

The composition and content of basic nutrients in different parts of M. oleifera are shown in Table 1 . Except for carbohydrates, the remaining seven basic nutrients showed extremely significant differences among the five parts ($P<0.01$). Ash content was highest in peel at 5.7 g/100 g, while kernel had the lowest. The ranking was: peel > bark > branch bark > leaf > kernel. Crude fat content was highest in kernel at 36.0 g/100 g and lowest in branch bark, following the order: kernel > peel > leaf > bark > branch bark. Protein content was highest in kernel at 14.0 g/100 g and lowest in branch bark, with the pattern: kernel > leaf > bark > peel > branch bark. Crude fiber content peaked in branch bark at 40.5 g/100 g and was lowest in peel, showing: branch bark > kernel > bark > leaf > peel. Carbohydrate content was highest in bark at 78.6 g/100 g and lowest in kernel, with the sequence: bark > branch bark > leaf > peel > kernel.

Vitamin C content was highest in leaves and lowest in kernel, following: leaf > bark > branch bark > peel > kernel. Volatile oils were detected only in kernel and leaves, with significant differences between them ($P<0.05$). The predominant basic nutrients varied by part: kernel was rich in crude fat and carbohydrates; peel primarily contained carbohydrates; leaves were characterized by carbohydrates and vitamin C; branch bark and bark were dominated by crude fiber and carbohydrates. These results demonstrate that each part of M. oleifera has distinct nutrient profiles with varying degrees of difference, enabling targeted development based on these characteristics.

2.2.1 Total Amino Acid Analysis in Kernel, Peel, Leaf, Branch Bark, and Bark

Amino acid composition and content in the five parts are presented in Table 2 . Sixteen amino acids were detected in kernel, peel, and leaves, including 7 essential amino acids. Branch bark and bark contained 15 amino acids with 6 essential amino acids; methionine (Met) was not detected. Total amino acid contents were 12.71, 3.35, 7.32, 2.21, and 4.46 g/100 g for kernel, peel, leaf, branch bark, and bark, respectively. Kernel showed significantly higher total and individual amino acid contents than other parts ($P<0.05$), while branch bark had the lowest contents ($P<0.05$). Glutamic acid (Glu) and aspartic acid (Asp) were the most abundant amino acids across all parts. Except for methionine, significant differences existed for the same amino acid among different parts ($P<0.01$), with methionine showing significant variation ($P<0.05$).

Essential amino acid content varied considerably among parts, with kernel highest at 4.8 g/100 g and branch bark lowest, following: kernel > leaf > bark > peel > branch bark. The highest essential amino acid in kernel and leaves was leucine (Leu), while lysine (Lys) was predominant in peel, branch bark, and bark. Leaves showed the highest ratios of essential amino acids to total amino acids (EAA/TAA) and essential to non-essential amino acids (EAA/NEAA) at 40.02% and 66.74%, respectively.

2.2.2 Essential Amino Acid Nutritional Evaluation

Based on the FAO/WHO recommended pattern, RAA, RC, and SRC values were calculated for kernel, peel, leaf, branch bark, and bark (Tables 3 and 4). An RC value <1 indicates relative deficiency, while RC >1 indicates relative excess. Table 4 shows that methionine + cysteine (Met+Cys) had the lowest RC values across all five parts, making it the first limiting amino acid in each.

Modern nutrition research suggests that both amino acid deficiency and excess limit food nutritional value. SRC is commonly used for comprehensive evaluation of food protein amino acids, comparing amino acid composition with the recommended pattern. SRC=100 indicates perfect alignment and higher nutritional value, while lower SRC values indicate poorer quality. Table 5 shows SRC values in ascending order: bark (48.17) < branch bark (52.25) < leaf (57.31) < peel (59.40) < kernel (62.98). These results confirm that kernel has the highest nutritional value, followed by peel and leaf.

2.3.1 Macroelements in Kernel, Peel, Leaf, Branch Bark, and Bark

Macroelement composition and content are shown in Table 6 . Potassium (K) was the most abundant macroelement in kernel (1.08$×10^{3}$ mg/100 g), peel

(2.73×10^{3} mg/100 g), and leaves (704 mg/100 g). Calcium (Ca) was highest in branch bark (1.28×10^{3} mg/100 g) and bark (1.32×10^{3} mg/100 g). Sodium (Na) was the lowest in all parts. All five macroelements showed extremely significant differences among parts ($P<0.01$). Kernel had significantly higher P and Mg than other parts ($P<0.05$). Peel showed significantly higher K and Na ($P<0.05$), while bark had significantly higher Ca ($P<0.05$).

2.3.2 Trace Elements in Kernel, Peel, Leaf, Branch Bark, and Bark

Trace element composition and content are presented in Table 7 . In kernel and bark, the descending order was Mn>Fe>Zn>Cu>Se, with Mn highest. Peel and leaves showed Fe>Mn>Zn>Cu>Se, with Fe highest. Branch bark exhibited Fe>Zn>Mn>Cu>Se, with Fe highest. All trace elements differed significantly among parts, with Mn, Fe, Zn, and Cu showing extremely significant differences ($P<0.01$) and Se showing significant differences ($P<0.05$). Kernel contained the highest Mn, which was not significantly different from leaves and bark ($P>0.05$) but was significantly higher than peel and branch bark ($P<0.05$). Selenium was detected in small amounts, highest in kernel (not significantly different from leaves, $P>0.05$) and significantly higher than other parts. Branch bark had the highest Fe and Zn contents ($P<0.05$), while bark showed the highest Cu content ($P<0.05$).

3 Discussion and Conclusion

The five parts of M. oleifera showed substantial variation in basic nutrient content. As the primary application and research focus, the kernel contained significantly higher crude fat and protein than other parts. Oil content serves as a key indicator for oil crops, reflecting quality and providing basis for germplasm selection. Studies report crude fat content exceeding 60% in Yunnan kernels (Zhao and Ou, 2010; Su et al., 2021), whereas kernels from Jiaole Tiankeng in Bama, Guangxi contained only 36% crude fat—significantly lower. While adequate soil moisture generally favors oil accumulation, especially during reproductive periods (Li et al., 2006), the calcareous soils in Jiaole Tiankeng have poor water retention. However, the region receives abundant rainfall, and the tiankeng’ s interior maintains low temperatures, minimal evaporation, and humid conditions with rivers and underground streams. Therefore, factors beyond soil moisture likely contribute to lower oil content, such as long-term karst environmental stress and soil element availability. Lai et al. (1999) found that soil mineral elements caused significant differences in chlorophyll content between M. oleifera leaves from rocky vs. soil mountain habitats. Thus, soil and environmental factors should be considered during introduction and cultivation to select suitable varieties.

Unlike traditional development focused solely on kernels, this study 首次 analyzed nutrients in leaves and branches, revealing significant development potential beyond kernels. Leaves contained 33.9 mg/100 g vitamin C—significantly higher than other parts and exceeding common vegetables such as lettuce (12.54 mg/100 g), water spinach (11.92 mg/100 g), pumpkin shoots (16.29 mg/100 g), and sweet potato leaves (11.83 mg/100 g) (Zhu et al., 2020). Vitamin C (ascorbic acid) plays vital roles in human growth and development and has demonstrated anti-tumor efficacy. Research shows vitamin C can directly kill tumor cells without toxicity to normal cells (Chen et al., 2005) and induce tumor cell apoptosis by interfering with cell cycles (Kang et al., 1999). Thus, M. oleifera leaves could serve as a natural vitamin C source for processing. Vitamin C content varies widely among plants and tissues, determined genetically and exhibiting tissue specificity. External factors like light also influence content in specific tissues. As the primary photosynthetic organ, leaf vitamin C correlates with light intensity—high light improves carbohydrate pools and activates galactonolactone dehydrogenase (GalLDH), a key enzyme in vitamin C synthesis, increasing production (An et al., 2004). This may explain the higher vitamin C content in leaves.

Glutamic acid (Glu) and aspartic acid (Asp) were the most abundant amino acids across all parts. Both are characteristic umami amino acids used in monosodium glutamate and sodium aspartate production, and both possess high medicinal value. These findings provide theoretical basis for developing M. oleifera-based foods and health products. In humans, Glu and Asp are excitatory amino acids (EAAs) and major excitatory neurotransmitters in the central nervous system. Glu participates in learning and memory processes (Lutgen et al., 2016), but excessive levels cause excitotoxicity, damaging neurons and triggering neurological diseases (Morizane et al., 1997). Asp promotes nucleic acid formation and energy synthesis in liver cells, aiding damaged cell repair (Cheng, 2015). Therefore, Glu and Asp content should be monitored during food and drug development from kernels.

According to FAO/WHO protein patterns, high-quality protein should have EAA/TAA $ $40% and EAA/NEAA $ $60% (Feng et al., 2019). Only leaves met these criteria among the five parts. Su et al. (2021) reported EAA/TAA of 37% in kernels, consistent with our findings. Our study found kernel (SRC=62.98) had the highest nutritional value, followed by peel (SRC=59.40) and leaves (SRC=57.31), demonstrating that besides kernels, peel and leaves also possess high nutritional value. The first limiting amino acid in all parts was Met+Cys, partly because methionine is abundant in animal proteins but scarce in plant proteins (Wang and Zhou, 1999), and cysteine may be destroyed during hydrolysis. Therefore, sulfur-containing amino acids should be supplemented during development to improve nutritional value.

All five parts contained rich mineral elements. Potassium, concentrated in the most physiologically active plant tissues, was highest in peel, indicating active physiological processes during fruit maturation. Although K does not directly participate in organic synthesis, it promotes photosynthate conversion and transport to roots and seeds (Zhang et al., 2001). Studies on pecan found positive correlation between kernel oil content and hull K content (Pe' er and Kessler, 1984; Duan, 2005). During M. oleifera fruit maturation, K may transport from leaves and kernels to peel while nutrients like crude fat accumulate in kernels. Potassium also promotes nitrate nitrogen absorption and protein synthesis (Duan, 2005), potentially increasing peel protein content and facilitating protein transport to kernels. In human health, K regulates intracellular osmotic pressure and pH. Studies show that increasing blood K levels enhances vascular elasticity, dilates blood vessels, and prevents lipid deposition, reducing hypertension risk (Tobian et al., 1985; Kieneker et al., 2014). Notably, all parts showed high K/Na ratios, especially kernels (3223:1) and peel (3353:1), characteristic of "high potassium, low sodium" foods. Research indicates that high-K, low-Na diets reduce cardiovascular disease mortality by 41% in elderly populations (Chang et al., 2006), making M. oleifera fruit ideal for developing such products.

Branch bark and bark were rich in calcium. Calcium serves as both essential nutrient and signaling molecule, participating in neurotransmitter transmission, muscle contraction in humans, and photosynthesis, nutrient absorption, and enzyme regulation in plants (Cashman, 2002; Barr et al., 1982; White and Broadley, 2003). Calcium is immobile and unevenly distributed in plants, transported primarily through transpiration pull (Jing et al., 2012). Stems (bark) and leaves (especially older ones) typically have higher Ca content, while fruits and seeds have lower content that stabilizes after transport (Zhou and Lin, 2000). Therefore, tissues with more vigorous transpiration and longer growth periods accumulate more Ca, possibly explaining higher Ca in branch bark and bark. Yu (2013) found M. oleifera grows better in high-calcium habitats, showing calciphilic characteristics. The sampling site in Bama Jiaole Tiankeng features typical karst topography with high soil Ca content. M. oleifera' s Ca absorption and utilization not only supports its growth but also enriches soil Ca, facilitating development of calcium-enriched products such as fertilizers or animal feed from bark and branch bark.

Phosphorus, a mobile mineral element, shifts among tissue pools during plant growth. During early vegetative growth, P mainly distributes in leaves. At late vegetative and reproductive stages, P stored in senescent leaves is remobilized to actively growing organs like fruits and new leaves (Sun et al., 2021). Studies show that in oil flax, 35.14-55.24% of grain P originates from leaf remobilization during flowering to maturity (Wu et al., 2016), and wheat grain P increases fourfold from anthesis to maturity while leaf and straw P decrease (Masoni et al., 2006). Our study found kernel P significantly higher than other parts, with leaf P second only to kernel. Whether kernel P accumulates through leaf remobilization and the dynamics among tissues warrant further investigation.

Phosphorus is closely related to lipid metabolism. Plant lipids derive from carbohydrates, and P participates in carbohydrate synthesis and conversion to glycerol and fatty acids (Duan, 2005). Kernel P enrichment likely facilitates oil accumulation, suggesting P fertilizer application before oil accumulation could increase kernel fat content. Studies on algae show P significantly affects polyunsaturated fatty acid (PUFA) content (Liang et al., 2016), and high P treatment increases oleic acid while decreasing PUFAs in olive oil (Qu, 2021). Our study also found higher Mg in kernels. Jernejc and Legisa (2002) reported Mg addition increased PUFA content in Aspergillus niger, while Fan et al. (2018) found no significant correlation between P and oil content but negative correlation between Mg and PUFA in apricot kernels. Differences in fatty acid synthesis pathways among plants may explain these discrepancies. Understanding relationships between oil accumulation and mineral elements is crucial for M. oleifera cultivation.

Among trace elements, Mn and Fe were predominant across all parts. Most crops are considered Mn-deficient at $<20\ \mathrm{mg \cdot kg^{-1}}$ (An and Fang, 2002). Kernel Mn content was highest at $18.3\ \mathrm{mg \cdot kg^{-1}}$, suggesting possible Mn deficiency in Jiaole Tiankeng M. oleifera. Manganese deficiency is a major nutritional disorder in calcareous soils after Fe deficiency (An and Fang, 2002). Mn serves as a cofactor for many enzymes in protein and fatty acid synthesis pathways, activating peptidases to promote protein synthesis (Liu, 1995). Studies show Mn affects lipid content and unsaturated fatty acid composition in Euglena gracilis (Constantopoulos, 1970). Su et al. (2021) reported Yunnan kernels contained $24.26\ \mathrm{mg \cdot kg^{-1}}$ Mn with 61.05% crude fat and 21.02% crude protein—higher than our values. Whether Mn deficiency affects oil and protein accumulation requires further investigation.

Mn transport varies by tissue, moving relatively easily to seeds but difficulty to roots (Liu, 1991). Under Mn deficiency, stored Mn in roots and stems transports to seeds via phloem (An and Fang, 2002). The relatively high kernel Mn may partly result from deficiency-induced remobilization. In humans, Mn plays important roles in central nervous system neurohormone transmission; deficiency may reduce dopamine levels and cause epilepsy or dwarfism (Ma et al., 2009). Mn also stimulates hematopoiesis for anemia treatment (Yang et al., 2006). Adults contain about 10-20 mg Mn and require 2.5-5 mg daily intake (Xiang et al., 2010). With Mn content of $16.1\text{-}18.3\ \mathrm{mg \cdot kg^{-1}}$ in kernels, leaves, and bark, these parts could serve as Mn supplements.

Iron is essential for plant growth and development, with most plants containing $100\text{-}300\ \mathrm{mg \cdot kg^{-1}}$ Fe, though content varies by species and tissue (Dong and Guo, 2014). Approximately 90% of Fe in aboveground parts distributes in chloroplasts (Gyana and Sunita, 2015). However, most Fe in corn resides in stem nodes rather than leaves (Yun and Zhao, 2012), apple trees have highest Fe in branches (Xue et al., 2003), and tea plants accumulate most Fe in roots and stems (Shan et al., 2017). Our results similarly showed highest Fe in branch bark, followed by leaves. Iron transport depends on transpiration pull from roots through stems to leaves; stems as transport intermediates may accumulate more Fe. Alternatively, leaf Fe may translocate to fruits during maturation, reducing leaf content.

Iron ranks first among essential human trace elements, participating in hemoglobin and enzyme synthesis and closely related to hematopoiesis (Sun and Guo, 2011). Iron deficiency causes anemia. With branch bark Fe content of 21.4 $\mathrm{mg \cdot kg^{-1}}$—far exceeding other parts—it could be developed for Fe supplementation products. Both Mn and Fe treat anemia, suggesting kernels and leaves with high combined Mn+Fe could be used for related products.

In summary, all parts of M. oleifera have development value with distinct characteristics. Kernels offer high fat, amino acids, P, and Mg with the highest nutritional value, showing broad potential in food and health products. Peel has the highest K content and second-highest amino acid nutritional value. Leaves exceed common vegetables in vitamin C and perform well in amino acid evaluation, indicating value for food or feed development. Although bark and branch bark have lower nutritional value, their high crude fiber, carbohydrate, and Ca content suit them for animal feed additives. The high K/Na ratios across all parts, especially in peel and kernel, demonstrate significant development potential. However, this study represents a single-timepoint comparison; dynamic changes in nutrient composition require further research to determine optimal harvest times. Overall, this comparative nutritional analysis clarifies value characteristics of each part, enhancing economic benefits while maintaining ecological benefits and promoting industry development and wild resource protection.

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