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RESEARCH ARTICLE

Cultivation to commercialization: A holistic view of the moringa oil supply chain

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Abstract

Moringa oleifera, commonly known as the miracle tree, is widely cultivated for its nutritional and industrial benefits. Every part of the tree contributes to nutritional and culinary uses. This study examines the supply chain of moringa oil in Tamil Nadu, a key production region in India. It identifies major stakeholders, supply chain processes and challenges in moringa oil production. Data were collected from farmers, traders, processors, exporters, retailers and consumers through structured interviews, using a snowball sampling method. The study highlights key moringa varieties such as PKM1, ODC3 and Jaffna, commonly used for oil extraction. The research outlines different oil extraction techniques, including hydraulic and wood cold press methods and assesses their efficiency. The supply chain is mapped across six major channels, illustrating product flow from farms to consumers, both domestically and internationally. The findings indicate that moringa oil is in high demand across the cosmetics, pharmaceutical and food industries, with a growing global market. Quality standards vary at different stages of the supply chain, affecting pricing and product acceptance. The study emphasizes the need for better supply chain coordination and quality awareness to enhance efficiency and profitability. These insights contribute to optimizing the moringa oil industry and supporting its sustainable development.

Keywords: cold press extraction; mapping; moringa; moringa oil; *Moringa oleifera*; quality standards; stakeholders; supply chain; value chain mapping

Introduction

Moringa oleifera, commonly referred to as the miracle tree, is a tropical plant native to northwest India and belongs to the family Moringaceae. It is cultivated for its nutrient-dense leafy greens, flower buds and green fruit pods, which are rich in minerals such as iron and calcium (1). *M. oleifera* is an important food commodity which has gained significant attention as the 'natural nutrition of the tropics'. Almost all the parts of this plant: root, bark, gum, leaf, fruit (pods), flowers, seed and seed oil have been used for various ailments in the indigenous medicine of South Asia (2).

In India, moringa is grown across a total area of 43600 hectares. Among the leading states, Andhra Pradesh has the most extensive cultivation, covering 15665 hectares. Tamil Nadu follows closely with 13042 hectares, while Karnataka grows moringa on 10280 hectares. The remaining 4,613 hectares are spread across various other states for the year (2022) (3).

The moringa products market is anticipated to achieve a compound annual growth rate (CAGR) of 9.20 % and touch USD 9.4 billion by 2027. The worldwide market for moringa products is projected to develop rapidly due to the health benefits of the tree's products. Moringa is used in countries such as India and those in Africa in feeding programs, as the dried leaves retain high levels of vitamins and minerals. As an antioxidant, it appears to help protect cells from damage leading to its use in capsules and pills as a supplement. Moringa oil is also regarded as the new coconut oil as many products using into cosmetic products such as shampoos, lip oils, blushes, hair oils and moisturisers (2).

The global moringa oil market is driven by its demand in the cosmetics and pharmaceutical industries. The market size in 2022 was valued at US$ 11164.0 million, with an expected revenue of US$ 15895.6 million by 2031, growing at a CAGR of 4.2 %. Moringa oil usage in pharmaceutical industry had a market size of US$ 859.5 billion in 2022, projected to reach US$ 2301.6 billion by 2032 with a higher CAGR of 11.56 %. The increasing preference for natural ingredients such as moringa oil in the cosmetic industry is a key growth factor, particularly in formulations that incorporate natural pigments. Moringa oil plays a major role in pharmaceuticals industry which includes applications, distribution channels, drug types, formulations and regional markets (4, 5).

Moringa seeds are used to extract oil called the Ben oil, which is rich in oleic acid, tocopherols and sterols. It withstands oxidative rancidity (6). Seeds from *M. oleifera* considered as primary commercially available natural flocculant for water

treatment and wastewater treatment (7). Moringa oil is a good substitute for olive oil in the diet and has non-food applications such as biodiesel production, cosmetics and lubrication of fine machinery. The seed cake used in wastewater treatment as a natural coagulant or as an organic fertilizer to improve agricultural productivity (8). Absence of odor and high concentration of oleic acid permits the oil to be used as a natural cosmetic ingredient (9).

Studies have shown that oleic acid in moringa oil promotes wound healing in diabetic patients (10). Chemical compositions of *M. oleifera* seed oil, have been found suitable for use in pharmaceutical preparations, particularly for skin hydration (11). Moringa seed oil can be considered as a sustainable and efficient fuel option. With yield of 6-10 seeds for a fruit and 38-40 % of oil. It is rich in oleic acid which makes the oil as a perfect candidate for biodiesel production (12). There are many possibilities for moringa oil can be used as feedstock of biodiesel production (13). Content of phytosterol compounds and fatty acids in moringa seed oil has potential as an anti-alopecia. Tocopherols can act as antioxidants to protect the scalp and help effective circulation in the scalp to provide nutrients for the hair (14). *M. oleifera* is a highly nutritious and medicinal plant. Because of these health benefits, a value-added product instant moringa idly mix is now being developed to make its nutrients more accessible in daily diets (15).

Moringa oil in the cosmetic industry is valued for its anti-aging properties; it rejuvenates skin tissues and reduces wrinkles. It is used in the manufactures of creams, lotion, body oils, balms, scrubs and hair oils (3). Moringa seed oil has some significant ultraviolet (UV) protective characteristics, so it has been recommended that it be utilized to keep the natural pigmentation of the epidermis intact (16). Moringa seed oil contains antioxidant, maintains skin hydration level and no report of skin irritation so the moringa seed oil can be used in skin cream and other cosmetic purposes (11).

Through sensitivity analysis, average value addition of moringa can fluctuated from Rs. 45.16 to 232.82 in a range of Rs. 4.75 to 242.94. Average gross profit margin changes from 41.32 % to 89.5 % at a range of 9.82 % - 90.64 % (17).

Miracle tree life science is focusing on international markets by exporting some of its key products. Among them, moringa wonder mix has gained a good reputation in Germany. This product is sold at ₹ 700 per 100 g (approximately $10.77) due to its premium ingredients and is used to support general health and vitality. Other products like moringa oil and moringa leaf tablets are priced at ₹ 370 and ₹ 360 per unit, respectively (18).

Moringa is a highly useful plant with many applications, including water purification, medicine, fuel wood, animal feed and green manure. Among all the countries that grow moringa, India especially the state of Tamil Nadu leads in both production and productivity. Different parts of the moringa plant can serve as valuable raw materials for small businesses and agro-based entrepreneurs, offering good profits with relatively low investment. With the growing global demand for natural food products, organic cosmetics and value-added items made from moringa, there are strong opportunities for marketing and exporting these products. This growth in moringa-based businesses could help boost India's position in agricultural exports worldwide (19).

The supply chain of *M. oleifera* classified as both a vegetable and a traditional herbal medicine (V-THM) was studied within the local and wider domestic markets of Bosso and Chanchaga local government areas in Niger State, Nigeria. The study examined how different actors currently operate within the supply chain. This localized supply chain includes growers, pickers, wholesalers and retailers who are involved in cultivating, harvesting and marketing moringa. The distribution route follows a typical pattern, starting from the Beji growing fields and moving through Maikunkele market, Bosso market, Kasuwan Gwadabe vegetable market in Minna, Kure market and finally reaching Kasuwan Tunga (20).

Despite its high nutritional and economic value, moringa oil production in Tamil Nadu faces major hurdles like low seed yield, limited market awareness and costly certifications. These challenges make it difficult for farmers and traders to scale up and access global markets. Addressing these issues is crucial to unlock the full potential of the moringa oil supply chain. Limited studies have focused on moringa seed oil. No comprehensive research has been conducted on the supply chain for moringa oil. This study aims to address the gap and provide a supply chain of moringa oil.

The objective of this study is to understand the supply chain and value chain models of moringa oil, along with their market dynamics. By doing so, it highlights the areas that require attention to enhance efficiency and strengthen the overall supply network. It also focuses on six major supply chain channels operating in the study area and further discussed about the key constraints in supply chain of moringa oil.

Materials and Methods

Selection of study area

Tamil Nadu is a leading state in moringa cultivation, boasting a wide range of genotypes that come from diverse geographical regions. Additionally, the state has also incorporated moringa varieties introduced from Sri Lanka, further enriching its genetic diversity (1). Tamil Nadu has a total of 21501 hectares dedicated to moringa cultivation for the year (2023-2024). Among the districts, Dindigul leads with the largest cultivated area of 5623 hectares. Karur comes next with 3080 hectares, followed by Theni, which has 2936 hectares under moringa farming. Tiruppur contributes 2090 hectares (21). Since moringa production is high in this region, farmers choose to let the pods mature for seed extraction when the market demand for fresh pods is low. The extracted seeds are then used for oil production. Therefore, these districts were selected as the primary study sites due to their significant role in moringa seed oil production.

Selection of sample

The study focuses on key stakeholders involved in the moringa value chain, includes farmers, traders and wholesalers, processing firms (such as Miracle Tree, Moringa Promise Wellness, Mornutree, MNS Agronomics, Nature Dew Drops and Naga Exports), exporters, retailers and consumers. The

selected study areas include Dindigul, Theni, Aravakurichi, Erode and Madurai, where moringa cultivation and processing are prominent. A snowball sampling approach was adopted and primary data were collected through structured personal interviews to gain qualitative insights into the supply chain

Source of data

The primary data were gathered from the selected respondents through comprehensive structured questionnaires. Secondary data relevant to the study area, including information on cultivation area, production and productivity, was obtained from farmers welfare department policy note. Additionally, details on the industrial uses of moringa oil and its demand across various industries were sourced from the global moringa oil report by Astute Analytica, 2023.

Results and Discussion

Varieties

The most used varieties of moringa for oil extraction include ODC3, PKM1 and Jaffna, which are native to South India and MOMAX, which originates from North India. Their purposes and characteristics are briefly described in Table 1 and the corresponding figures are presented in Fig. 1.

Pod characters

PKM 1 has a pod length of 75 cm, a girth of 7 cm and weighs 154 g when fresh. It produces 175 pods per tree, with 14 seeds per pod as shown in Table 2. PKM 2 has the longest pod at 126 cm and a girth of 8.3 cm. It yields 220 pods per tree. Aravakurichi Local has a pod length of 52 cm, a girth of 7.5 cm and the highest dry weight of 37 g. It yields 377 pods per tree with 20 seeds per pod. Nattu Ragam has a short pod at 40 cm and 7.5 cm girth, with a fresh weight of 70 g. It produces 313 pods per tree, with 10 seeds each. ODC 3 has a pod length of 55 cm, a girth of 6.6 cm and a fresh weight of 139 g. It yields 362 pods per tree with 19 seeds per pod. Jaffna has 600 pods per tree.

Seed characters

In Table 3, the largest seed comes from PKM 1, measuring 0.92 cm in length and 1.24 cm in diameter. On the other hand, ODC 3 has the smallest seed, with a length of 0.72 cm and a diameter of 0.96 cm. When it comes to seed yield per tree, Aravakurichi Local produces the highest yield at 2.827 kg, while PKM 1 has the lowest yield, producing only 0.894 kg per tree.

Harvesting maturity for moringa seeds

The harvesting of pods takes place approximately 20 d after anthesis, ensuring they reach the right stage for collection. The pods are harvested once they turn brown and dry, indicating maturity. After harvesting, the seeds are carefully stored in a cool, dry and shaded area to maintain their quality and viability. The availability of seeds typically spans from June to October, making this the ideal period for collection and processing.

Extraction of oil (process)

Hydraulic cold press machine

The process of extracting moringa oil using a hydraulic cold press machine begins with the collection of mature and ripened pods. The seeds are carefully removed from the pods and then graded into two categories: 'A' grade for plantation purposes and 'B' grade for oil extraction. The seeds designated for oil extraction undergo further processing, including the removal of wings and deshelling. To reduce moisture content, the kernels are sun-dried before being fed into the hydraulic cold press machine, which extracts oil from approximately 30 to 60 kg of kernels at a time. The extracted oil is then subjected

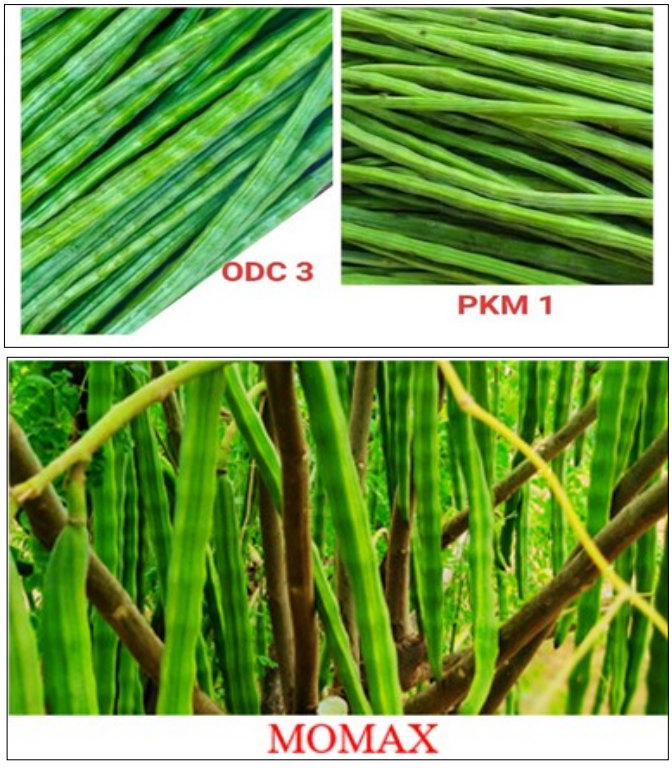

Fig. 1. Best varieties of moringa for extracting ben oil (moringa oil).

Table 1. Purpose and characteristics of three different varieties

Variety name	Purpose	Characteristics	References
PKM1	Leaf production Pods (200-225 pods/ tree / year) Weight of each pod about 150 g Oil	This is an annual cultivar, grown from seeds, has a productive life of 3 to 4 years. It's a bushy, dwarf plant reaching about 4 meters in height with dark green and broad leaves. It matures early, flowering in 3 to 4 months and producing pods in 6 to 7 months. The pods are flexible, uniform and have a long shelf life. The plant also regrows quickly, ensuring steady yields.	(2)
ODC 3	Pods (65-75 tonnes / ha) Oil (seeds) Leaves	This perennial cultivar grows from seeds and remains productive for about 10 years. It needs less water than PKM1 and handles drought better. It can grow in various soils and withstand changing weather conditions. The pods are thicker, tastier and last longer than PKM1, with harvest starting in 6 months. Its seeds have nearly double the oil content of PKM1 and its leaves are darker and tougher.	(2)
Jaffna	For pods - soft flesh and good taste	A Yazphanam type moringa introduced from Sri Lanka. Its fruits are 60-90 cm long with soft flesh and good taste. This type yields around 40 pods from the second year of planting which increases up to 600 pods per tree from the third year onwards. It is cultivated commercially in Tirunelveli and Tuticorin districts of Tamil Nadu (AICRP - vegetable crops).	(22)

Table 2. Pod characters of different moringa types (23)

Varieties	Pod length (cm)	Pod girth (cm)	Fresh pod weight (g)	Dry pod weight (g)	No. of pods / tree	No. of seeds / pod
PKM 1	75	7.0	154	24	175	14
PKM 2	126	8.3	280	-	220	-
Aravakurichi Local	52	7.5	118	37	377	20
Nattu Ragam	40	7.5	70	26	313	10
ODC 3	55	6.6	139	23	362	19
Jaffna	60	-	-	-	600	-

Table 3. Seed characters of different moringa types (23)

Varieties	Seed length (cm)	Seed width (cm)	Seed diameter (cm)	Seed yield / tree (kg)
PKM 1	0.92	0.79	1.24	0.894
Aravakurichi Local	0.90	0.78	1.20	2.827
Nattu Ragam	0.76	0.65	1.07	1.126
ODC 3	0.72	0.64	0.96	2.372

to vacuum filtration to remove any impurities, ensuring a high-quality final product and is shown in Fig. 2. The resulting moringa oil is widely used in various industries, including cosmetics, pharmaceuticals and food production.

Wood cold press machine

The extraction of moringa oil using a wood cold press machine is detailed as a pictorial representation in Fig. 3. First, the seeds undergo deshelling, where the outer coverings and wings are removed. Once cleaned, the kernels are sun-dried to eliminate excess moisture. After drying, the kernels are pressed using a wood cold press machine, typically processing around 15 to 20 kg at a time. The extracted oil then goes through a curing and sedimentation process, allowing insoluble impurities to settle. Finally, the purified moringa oil is collected and packaged for various uses.

Channels

Six major marketing channels operate in the study area. Moringa farmers purchase seeds from input suppliers. After harvesting, they sell the produce to local traders, wholesalers or processors for further processing. In some cases, local traders or wholesalers also act as processors, converting the seeds into oil. The processed oil is then transferred to exporters and subsequently to retailers. However, in certain instances, the exported oil undergoes additional processing for specific applications in industries such as cosmetics and pharmaceuticals before reaching retailers.

Channel 1

Farmers → Local traders → Wholesalers → Processors → Retailers → Consumers

Channel 2

Farmers → Processors → Exporters → Processors → Retailers → Consumers

Channel 3

Farmers → Local traders → Wholesalers → Processors → Other states

Channel 4

Farmers → Processors → Exporters → Retailers → Consumers

Channel 5

Farmers → Processors → Consumers

Channel 6

Farmers→ Local traders → Wholesalers → Processors → Exporters → Retailers → Consumers

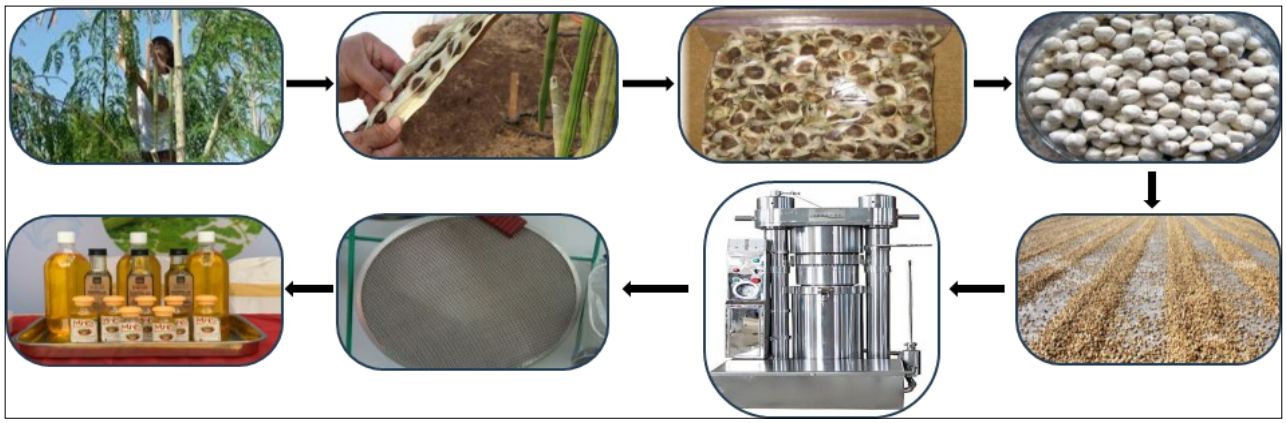

Fig. 2. Extraction process in hydraulic cold press machine.

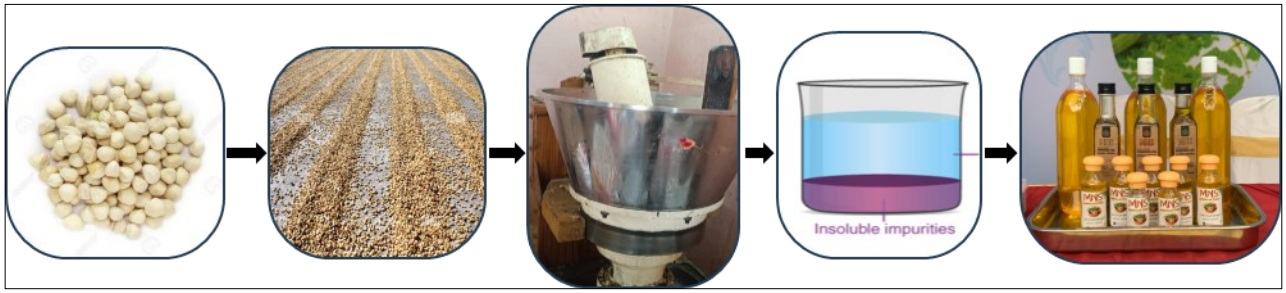

Fig. 3. Extraction process in wood cold press machine.

Moringa oil and their conversion ratio

M. oleifera seeds contain about 36 % oil by weight, which is rich in oleic acid and commonly known as "Ben oil" or "Behen oil." The oil also contains healthy saturated fats like palmitic acid, behenic acid and stearic acid, along with polyunsaturated fats such as linoleic and linolenic acids. Moringa oil can be extracted using either solvent or mechanical methods. No matter the method, the oil naturally contains beneficial plant sterols like β -sitosterol, stigmasterol, campesterol and avenasterol. Because of its composition, moringa oil is considered a good alternative to olive oil for cooking and it also has uses in biodiesel, cosmetics and as a lubricant for delicate machinery. According to Ayurvedic medicine, moringa oil may have many health benefits, including anti-tumour, anti-inflammatory, antioxidant, antibacterial, antifungal and cholesterol-lowering effects, among others (24).

Moringa seeds contain approximately 36.7 % oil by weight, making them a valuable source for oil extraction. When processed using hydraulic methods, the residual oil left in the seed cake is less than 3 %, while the cold press method yields around 7 % oil. The extracted moringa oil has a shelf life of over one year, ensuring its long-term usability. In terms of market pricing, moringa seeds are sold at a rate of Rs. 200 to 250 per kg, whereas kernels, which are a more refined product, cost between Rs. 300 to 350 per kg.

Conversion ratio

As shown in Table 4, 1 kg of seeds yields approximately 600 g of kernels. From 1 kg of kernels, approximately 300 to 350 g of oil can be extracted. In larger processing batches, around 15 to 20 kg of kernels produce between 3.75 to 4.5 kg of oil, with the extraction process taking about 1.5 to 2 hours. On a larger scale, 100 kg of kernels yield roughly 29 % oil. This extracted oil contains approximately 24 % to 28 % fat, making it a valuable source of nutrition and essential fatty acids.

Differences between two extraction machines

Table 5 compares two different oil extraction machines-the hydraulic cold press machine and the wood cold press machine. The hydraulic machine produces a higher oil yield (300-350 mL per kg), uses vacuum filters and has a larger capacity (30-60 kg). However, it is more expensive at ₹ 3.2 lakhs and generates low heat. The wood cold press machine has a lower oil yield (275-300 mL per kg), does not use filters and has a smaller capacity (15-20 kg). It is cheaper at ₹1 lakh and produces high heat.

Mapping product flow in the moringa value chain

Moringa leaves are used to produce various value-added products such as powder, juice, sauce, tablets and plain tea. From moringa seeds, high-quality moringa oil is extracted (Fig. 4). The flowers are processed into moringa flower tablets, while the gum is utilized to make moringa gum powder.

Moringa products and their market value

Moringa-based products are categorized based on their market value and shown in Table 6. Among the high-value products, moringa oil is priced at Rs. 5900 per L and moringa oil capsules are also considered premium items. In the mid-range category, there are several cosmetic and personal care products made from moringa. These include serum, which costs Rs. 590 for a 200 mL bottle, soap priced at Rs. 293 per bar and shampoo available for Rs. 256 per 200 mL. For those looking for more affordable moringa-based options, there are low-value products such as moringa leaf powder, which is sold at Rs. 160 per 100 g and moringa energy bars, which are available for Rs. 40 each.

Table 4. Conversion ratio of seed into kernel and oil

Seed (kg)	Kernel (g)	Kernel (kg)	Oil (mL)
1	600	1	325
1.6	1000 (1 kg)	3 (kernel) = 4.8 (seed)	1000 (1 kg)

Table 5. Evaluation indicators of two different extraction machines

	Hydraulic cold press machine	Wood cold press machine
Oil yield (per kg)	300 to 350 mL	275 to 300 mL
Filters	Vacuum filters	No filters
Machine cost	3.2 lakhs	1 lakh
Capacity of the machine	30 to 60 kg	15 to 20 kg
Heat produced	Low	High

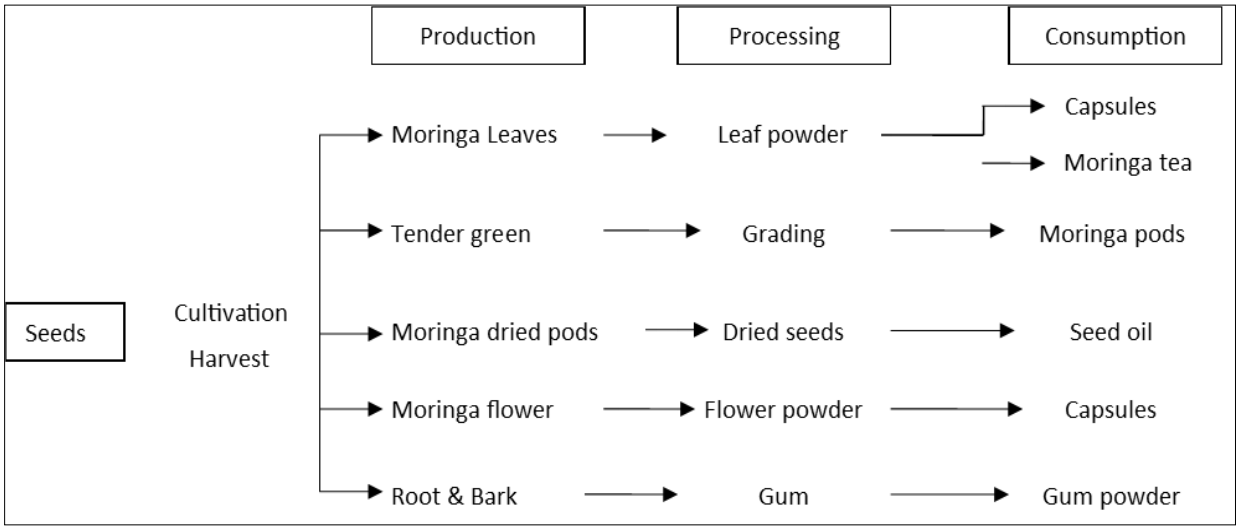

Fig. 4. Mapping product flows in the moringa value chain.

Table 6. Moringa product category and their market value

Product categories	Products	Price
High-value products	Moringa oil and moringa oil capsules	₹ 5900 per litre
Medium-value products	Cosmetic and personal care (serum, soap, shampoo and conditioner)	Serum - ₹ 590 per 200 mL, soap - ₹ 293 per soap and shampoo - ₹ 256 per 200 mL
Low-value products	Moringa leaf powder and moringa energy bar	Energy bar - ₹ 40 and moringa leaf powder - ₹ 160 per 100 g

Export quality for moringa oil

The quality of moringa oil for export is determined by its behenic acid and oleic acid content, along with other essential factors. Behenic acid should be at least 6 %, while the fat content typically ranges between 24 % to 28 %. Oleic acid should exceed 60 %, ensuring the oil's superior quality. Additionally, strict checks are conducted to monitor the presence of heavy metals and pesticide residues, as these factors play a crucial role in meeting international export standards.

Supply chain model for moringa oil

Fig. 5. outlines the supply chain journey of moringa oil from cultivation to final consumption. It starts with farmers and producers, who grow and harvest the crop. The harvested seeds are then transported by wholesalers and traders to local processors and bulk shippers for primary processing and packaging. After refinement and transportation, the oil reaches different industries, including cosmetics, pharmaceuticals and international markets. Finally, it is distributed through supermarkets, pharmacies and international distributors to reach end consumers. This structured process ensures quality and efficiency in delivering moringa oil to customers worldwide.

Challenges for supply chain of moringa oil

Production and marketing challenges

Oil extraction efficiency is impacted by low-yielding moringa varieties and high demand for its pods and fruits, affecting seed availability. Seed quality, especially behenic and oleic acid content, determines oil quality, while prices fluctuate based on market demand. Since moringa isn't primarily grown for seeds, timely harvesting is crucial but adds challenges to large-scale oil production. Moringa oil is one of the most expensive by-products, costing around ₹ 590 for 100 mL, yet many farmers are unaware of its market potential. Obtaining certifications like the USDA-NOP (United States Department of Agriculture - National Organic Program) farming license (₹ 1 lakh) and a processing license (₹ 2-3 lakh) adds to the cost. The USDA-NOP certification ensures that the farming and processing practices meet strict organic standards set by the USA government, which is essential for exporting organic products to international markets, especially the United States. Additionally, the lack of government support in marketing makes it difficult for producers to expand their business.

Conclusion

Mapping moringa oil supply chain helped in trace product and information flows and identify entry for improvement. Moringa oil has wide industrial applications, including in cosmetics, lubricants and pharmaceuticals such as skincare and haircare formulations. It is rich in antioxidants and has anti-inflammatory benefits, making it effective for soothing the skin and promoting overall health. Additionally, its anti-aging and potential anti-tumour properties contribute to its growing demand in the cosmetic industry. Beyond skincare, moringa oil is also used as a lubricant in various applications, including time-series processes. Among all varieties, PKM 1 and ODC 3 yield more oil compared with the other varieties. The efficient extraction type for moringa oil is hydraulic press machine. Moringa oil is primary supplied in a B2B model due its demand across various industries, unlike limited retail consumption. Future research can focus on exploring value-added applications in cosmetics and pharmaceuticals. Studies on supply chain digitization and sustainability practices can further enhance traceability and reduce environmental impact. Market analysis of B2B dynamics and industrial lubricant performance can also guide commercial strategy.

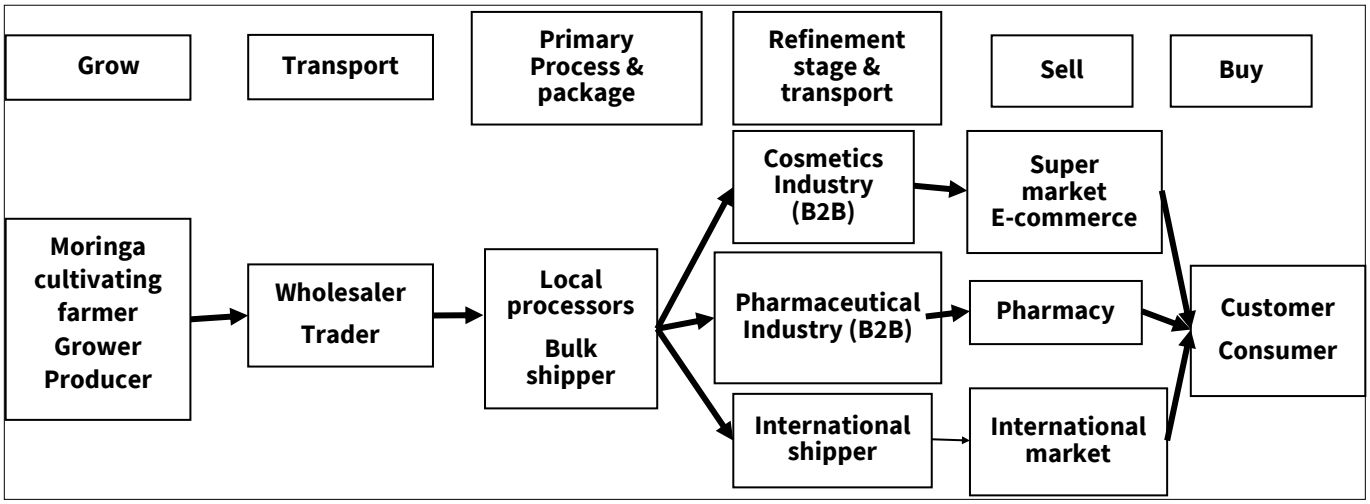

Fig. 5. Supply chain model of moringa oil.

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Authors' contributions

NS carried out the survey for research studies related to moringa and moringa oil and structured a questionnaire and interviewed different stakeholders who are all involved in the supply chain and participated in the sequence alignment and drafted the manuscript. IVM participated in the sequence alignment and drafted the manuscript, as well as for the analysis of content and helped to work supply chain model for moringa oil. MK conceived of the study and participated in its design and coordination. GS participated in the sequence alignment and drafted the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work, the authors used Grammarly to assist in language refinement and grammar correction. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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