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Scaling Up Moringa Leaf Beverage Filtration: A Comparative Evaluation of Traditional, Laboratory-Scale and Pilot-Scale Wire Mesh Prototype System for Clarity and Mineral Retention

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ABSTRACT

Moringa oleifera, commonly called the "miracle tree," is valued in the functional food sector for its high mineral content, which includes calcium, iron, potassium, magnesium and sulphur, but the way a Moringa beverage is processed, in particular its filtration process, is a strong influence on both nutrient retention and visual clarity, a factor that is directly relevant to consumer acceptance. This study therefore compared three filtration pathways of traditional to pilot-scale production, cloth filtration, laboratory-scale filtration with Whatman No. 1 filter paper and a pilot-scale wire mesh system in terms of clarity and mineral retention. Mineral content was quantified using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) at an accredited laboratory. Clarity was visually evaluated as a relevant indicator for consumers. The three products were very different in colour, from dark brown (traditional method) to light yellow (laboratory-scale method), and the pilot scale sample had the highest single measurement values for all five minerals, which were significantly higher than the traditional and laboratory-scale samples by 71 to 200% and 100 to 278% respectively across the mineral panel. Since these values are obtained from a single measurement per sample, without replication or statistical testing, they are preliminary findings. However, the pilot-scale wire-mesh system's combination of greater

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clarity and mineral retention suggests it is a promising, scalable option for SME-level Moringa beverage production.

Keywords: Beverage production, filtration methods, functional food, mineral contents, nutrition support, Moringa leaf, visual clarity

INTRODUCTION

Background

Moringa oleifera is a fast-growing, drought-resistant tree native to the Indian subcontinent and has been widely cultivated in tropical and subtropical areas (Pareek et al., 2023; Su & Chen, 2020). It is often referred to as the 'miracle tree' for its rich phytochemical and nutritional structure. Moringa leaves have high protein, vitamins, antioxidants and minerals such as calcium, potassium, magnesium, sulphur and iron (Hodas et al., 2021; Moyo et al., 2011; Masitlha et al., 2024; Pareek et al., 2023), and a variety of phytochemicals, flavonoids, phenolic compounds, glucosinolates, saponins and carotenoids that contribute to a high antioxidant, anti-inflammatory and other health benefits (Al-Ghanayem et al., 2022; Singh et al., 2020). Moringa leaves are a valuable functional food ingredient, as they are rich in nutrients and are used in health drinks and are generally used as their nutritional value is very high (Islam et al., 2021; Peñalver et al., 2022; Wickramasinghe et al., 2020; Rahmatu et al., 2025). Figure 1 presents a visual representation of *Moringa oleifera* leaves.



Figure 1. Moringa oleifera leaves (Anzano et al., 2021)

In many communities, Moringa leaf extracts are added to beverages and teas to deliver these nutrients: fresh leaves are pulled from stems, mixed with water and strained to get a green infusion (Odey et al., 2012). However, the resulting crude beverage is darkly coloured and viscous due to fine leaf particulates, and this heavy colour and texture can reduce consumer acceptance (Abd El-Rahim et al., 2017). Some dissolved minerals are also associated with these suspended solids, and the filtration step is crucial: it has to remove unwanted particles while preserving the soluble nutrients (Daneluz et al., 2023).

Literature Review

Filtration is a critical procedure in beverage production. It removes fine particulates and suspended solids to provide a clearer, coherent product while preserving soluble nutrients

(Cescon & Jiang, 2020; Sarbatly et al., 2023). Traditional techniques like straining or coarse cloth filtration are conventional for small-scale or household Moringa beverage production, but they generally produce dark, viscous, turbid products that are not shelf-stable. This gap between traditional techniques and product quality that consumers and processors demand has resulted in filtration becoming a leading research and development area in the field of product quality management (Aziz et al., 2024).

Figure 2 shows a typical membrane filtration system in which a feed stream of suspended and dissolved material moves towards the membrane, and the filter is the primary selective barrier controlling which parts pass through it. Particles larger than the membrane pores are kept at the surface and accumulate, forming a layer of accumulated solids that can affect filtration efficiency in the long run, while dissolved substances and the liquid component of the feed pass through as permeate (or filtrate) and a support layer below the membrane provides structural strength to support the feed flow without affecting flow (Daneluz et al., 2023; Loff, 2001).

The same principle of size-selective particle retention is present in all three filtration media that we have studied in this study, but with very different levels of process control.

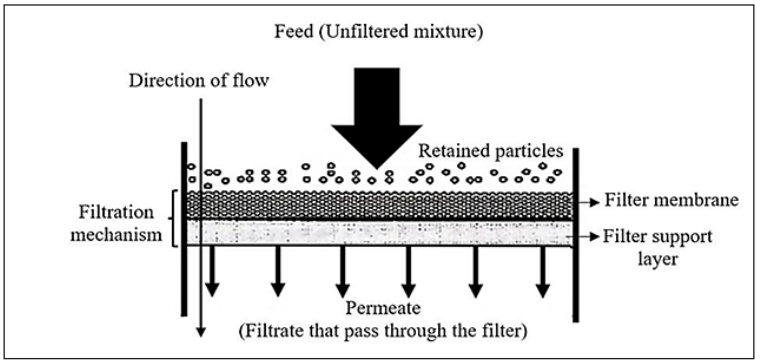

Figure 2. Schematic diagram for filtration
*Source: Nathan et al. (2008)

In *Moringa oleifera* beverage production, there are two important quality parameters to consider for clarity: clarity as measured on visual observation and mineral retention, which is important to use for calcium, potassium, magnesium, sulphur and iron, which are some of the most abundant minerals in Moringa leaves (Pareek et al., 2023). Clarity is the product of suspended fine particles and colloidal matter that are released during the extraction process and is a key factor in terms of visual appearance, mouthfeel and the acceptability of Moringa leaf beverages; poor clarity constrains commercial viability, so effective filtration must reduce turbidity while minimising the loss of soluble bioactive constituents (Columbia, 2020). Yet filtration is a trade-off for this same purpose, as minerals

are either retained in the medium, either through the presence of the suspended particles or adsorption into the filter matrix, and it is important to balance the effective removal of the particles through the filter with the mineral retention in the process (Yerena-Prieto et al., 2022).

In addition to the standard straining media, membrane-based clarification technologies such as microfiltration and ultrafiltration have been widely reported in juice and plant extract clarification, which results in fine, controlled pore sizes and high clarity (Aziz et al., 2024; Sarbatly et al., 2023; Tiwari & Saha, 2022). Tiwari and Saha (2022) applied hollow fibre microfiltration to *Moringa oleifera* leaf juice under optimal transmembrane pressure and pore size and observed significant clarity and turbidity reduction, while Daneluz et al. (2023) also demonstrated the use of microfiltration in kombucha clarification.

Despite the progress in other beverage systems, the transformation of *Moringa oleifera* leaf extracts into commercially viable beverages is significantly hampered by conventional processing methods (Hernández-Fuentes et al., 2025). Traditional preparation, which involves manual straining or coarse cloth filtration analogous to domestic tea infusion, is still prevalent in many communities and small-scale production (Mensah et al., 2025), owing to the largely unstandardised nature of such processes and lack of established operational parameters (Marobhe, 2021). These manual techniques are labour-intensive and time-consuming, and they often require repeated manual agitation, pressing, and multiple stages of cloth filtration to produce even a minimum of clarity.

Though advanced filtration technologies have shown promising capabilities on other beverage systems, systematic multi-scale comparative studies are limited, and few studies have compared traditional manual methods with optimal laboratory-scale and pilot-scale (prototype) filtration systems for Moringa leaf beverages. Recent studies on *Moringa oleifera* leaf-based functional beverages have mostly focused on extraction techniques, sensory acceptability, and basic clarification methods rather than systematic comparisons of filtration methods. Hernández-Fuentes et al. (2025) prepared Moringa leaf infusions using traditional hot water extraction followed by simple gauze filtration and concentration and demonstrated their potential therapeutic benefits for metabolic disorders.

Mensah et al. (2025) optimised a soymilk-Moringa leaf extract beverage through sensory-driven formulation and blending and percale cloth filtration to achieve acceptable sensory properties at specific blending ratios. Tiwari and Saha's (2022) hollow-fibre microfiltration method is still the most methodologically sophisticated filtration method used for Moringa leaf juice.

Combined, these studies reflect growing interest in Moringa-based beverages, but each of them focuses on small-scale extraction and basic straining or on single lab-scale clarification; none provides the systematic, multi-scale comparison across traditional,

laboratory and pilot-scale methods that this study undertakes. This is a crucial gap for efficient, scalable and reproducible production of clear and nutrient-rich Moringa beverages that are in line with consumer expectations of visual appeal, nutritional consistency and functional effectiveness today.

MATERIALS AND METHODS

Materials

All the experiments used dried Moringa leaves as the primary plant substrate and drinking water as the solvent to provide the same process in all filtration settings. To better reflect the production practices of the papers mentioned, we used three experimental setups: traditional, laboratory-scale, and pilot-scale. In the traditional setup, we used basic household utensils such as a boiling vessel and a cotton cloth filter and simulated small and medium enterprise (SME) production. In the laboratory-scale setup, we used controlled scientific equipment (3-neck round-bottom flask and heating mantle, mercury thermometer, Allihn condenser, vacuum pump and Whatman No. 1 filter paper of 11 μm pore size). The pilot-scale method used a custom-designed filtration tank with a wire mesh filter made of food-grade stainless steel to maintain sanitary processing and mechanical stability during large-volume filtration.

These three methods differ in filtration medium, processing scale, and process control, by design. This is because the traditional, laboratory, and pilot-scale Moringa beverage production is done in practice; it is not a controlled, single-variable filtration comparison. The different methods should therefore be considered as a combination of extraction and filtration at each scale, and not as a filtration medium only at each scale. A controlled single-variable follow-up study where the filtration medium is varied independently of the extraction should be considered and is discussed in the following section.

Methods

Optimum Operation for Conducting Experiment Procedures

The optimisation of extraction and filtration parameters was guided by previous studies (Fombang & Saa, 2016; Kamarudin et al., 2020; Pollini et al., 2020). The most important process parameters were temperature, leaf mass (g), water volume (mL), extraction time (min) and solid-to-liquid ratio, all of which affect bioactive compounds, nutrient solubility and clarity of the final filtration. Table 1 summarises the range of optimal operational parameters in this literature.

Table 1
Optimum operating conditions in processing Moringa leaves

Authors	Kamarudin et al. (2020)	Fombang and Saa (2016)	Pollini et al. (2020)
Filter Paper	Whatman No. 1	-	-
Temperature (°C)	82	97	60
Weight of Dried Leaves (g)	1	1	1
Volume of Water (mL)	30	20	60
Extraction Time (min)	48	35	60
Solid-liquid Ratio	1:30	1:20	1:60

Kamarudin et al. (2020) applied Response Surface Methodology (RSM) to optimise heat-assisted extraction of phenolic compounds from *Moringa oleifera* leaves, which was achieved at a temperature of 82°C, 48 minutes of extraction time and a solid-liquid ratio of 1:30 (1 g of dried sample to 30 mL of water), followed by filtration with Whatman No. 1 paper. These parameters reflect a thermally driven extraction process, where high temperatures increase solvent diffusivity and phenolic solubility, while a controlled extraction time reduces degradation of heat-sensitive compounds.

Under this parameter space, Kamarudin et al. (2020) reported that total phenolic content (TPC) and antioxidant capacity were maximised, indicating good liberation of polyphenolics such as flavonoids and phenolic acids. In addition to that, the feedback analysis of the nutrients retained by the plant showed that although some heat-sensitive micronutrients, such as ascorbic acid, may be degraded in part, antioxidant activity remains high and is even strengthened in the presence of phenolic compounds. Fombang and Saa (2016) have optimised phenolic extraction of *Moringa oleifera* leaf powder for functional tea production using RSM and found that brewing at around 97 °C, extracting for 35 minutes, using a solid-to-liquid ratio of 1:20 (1 g sample in 20 mL water), and filtering through Whatman No. 1 paper. At near-boiling temperatures, they can exploit the heat energy to rapidly disrupt and remove phenolics. But this is at the expense of heat-sensitive nutrients in the plant, as vitamin C and other glycosylated flavonoids are hydrolysed and oxidised at temperatures near 100 °C in oxygenated aqueous environments. The authors found that antioxidant activity is high, and some of these compounds are degraded to less stable aglycone forms or into secondary antioxidant species.

In contrast, Pollini et al. (2020) examined ultrasound-assisted extraction (UAE) of antioxidant compounds from *Moringa oleifera* leaves at 60 °C, with a 60-minute extraction time and a high solid-to-liquid ratio of 1:60 (1 g sample in 60 mL water), and then filtered through Whatman No. 1 filter paper. The bulk temperature of the UAE process is low enough to reduce thermal degradation by about half in comparison to conventional heat-assisted extraction, and yield of phenolics, and the high extraction yield at high temperatures

of the oxidant compounds. The method developed by Kamarudin et al. (2020) was chosen for our work as it is able to hold a good balance between high nutrient extraction and nutrient quality preservation: the temperature of 82 °C and the extraction time of 48 minutes should have enough time to release the nutrients without causing significant degradation. Whatman No. 1 filter paper (11 μm) was used for laboratory-scale filtration due to its good retention efficiency and filtration rate.

Experimental Study

The extraction parameters developed by Kamarudin et al. (2020) were tested in the laboratory and on a pilot scale to ensure their ability to be applied to larger production. At laboratory scale, 3 g of dried *Moringa oleifera* leaves were extracted with 90 mL of water and at pilot scale, 1000 g of leaves were extracted with 30,000 mL of water, keeping the same 1:30 solid-liquid ratio. Temperature (82°C) and extraction time (48 minutes) were also kept constant across all scales to ensure a good comparison of filtration efficiency and to see whether the method could be applied on a larger scale without loss of efficiency or quality. The deviation from the traditional method, and the confound it generates, is discussed in detail in the following subsection. Three samples were collected in total, representing the traditional, laboratory-scale and pilot-scale production methods, with subsequent analysis focused on the nutrient content of the resulting beverages. Each sample represents a single production run per method ($n = 1$), with no biological or analytical replicates; therefore, the reported mineral values reflect single certified laboratory measurements rather than replicated trials. This is a stated limitation of the present pilot study: no standard deviation, error bars, or inferential statistical tests (e.g., ANOVA) could be calculated, and the reported percentage differences should be read as descriptive, preliminary observations rather than statistically validated findings.

Traditional Method

Given its widespread household-level practice, owing to its simplicity and minimal operational requirements, this method was replicated in the present study to represent standard traditional practice. The process typically involves boiling herb material in approximately 230 mL of water at a temperature of around 100 °C. This boiling temperature differs from the 82 °C employed for the laboratory- and pilot-scale methods, constituting a further confounding variable, in addition to the differing extraction ratio, that may independently influence extraction yield and filtrate viscosity; this is acknowledged as a limitation in interpreting the comparison between the traditional method and the other scales.

This method closely resembles the common home preparation techniques of tea infusion (e.g., boiling water is poured over the sample and then let to steep before basic filtration, using simple tools such as sieves). This method certainly mimics the real-world consumption process, and it is very practical, but it is not able to control the temperature and extraction time, so for a scientific or industrial scale, it is not so realistic. When applied to large-scale or industrial production, this method is also labour-intensive, and in the case of filtration work, we have to do the entire process manually (often several steps). With much more labour needed, production is at least fast. Thus, the traditional method is suitable for small-scale production and not for mass production. Figure 3 illustrates the traditional method applied to filter Moringa leaves under SME conditions.

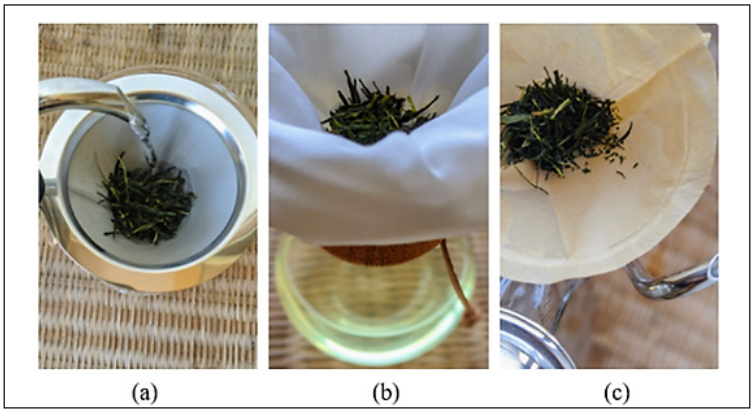

Figure 3. Traditional filtration method: (a) Pouring hot water through a cloth filter; (b) Dried leaves filtered with a cloth filter, and (c) Leaves remain in a cloth filter

Laboratory-Scale Method

The laboratory-scale method was used to test the effectiveness of Kamarudin et al.'s (2020) procedure in a controlled laboratory setting. A systematic scale-up was used to standardise the filtration process: quantities were tripled from Kamarudin et al.'s (2020) original reference value of 3 g *Moringa oleifera* leaves in 90 mL of water, and the original 1:30 solid-liquid ratio was maintained at a temperature of 82 °C for 48 minutes. Table 2 summarises the parameters of the laboratory-scale experiment.

Table 2
Parameters for laboratory-scale experiment

Parameter	Unit	Value
Dried Moringa leaves	g	3
Volume of Water	mL	90
Time	min	48
Temperature	℃	82

Figure 4 shows the laboratory-scale procedure. As shown in (a), 3 g of dried Moringa leaves were placed in 90 mL of water and heated at 82 °C for 48 minutes under carefully controlled, uniform thermal exposure (b). The extract was then filtered by Whatman Filter Paper No. 1 (c), separating the liquid extract from the residue, and the final Moringa extract product is shown in (d).

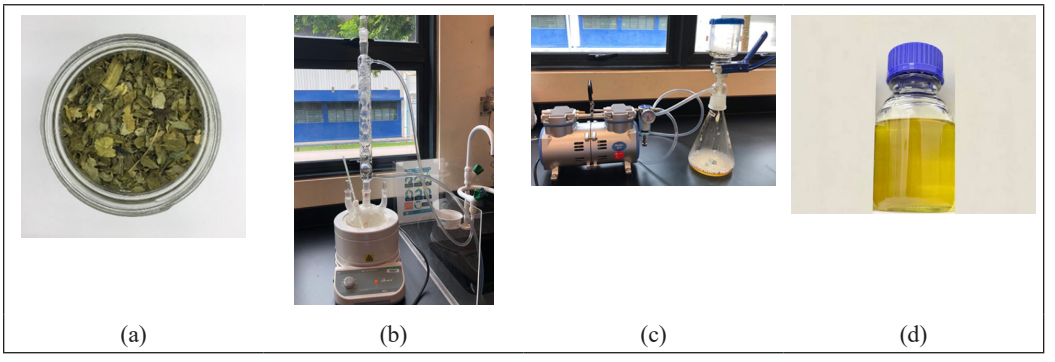

Figure 4. Laboratory-scale method: (a) Dried Moringa leaves; (b) Heating of Moringa leaves; (c) Filtration process, and (d) Moringa extract product (beverage)

Pilot-Scale Method

The pilot-scale filtration system was used under controlled conditions to evaluate the filtration tank with food-grade stainless-steel wire mesh for fluid separation, and the experimental setup was meant to mimic the food and beverage industry. The process was performed about 1000 times the base reference, using 1 kg of dried leaves and 30 L of water at 82 °C for 48 minutes; the parameters are shown in Table 3.

Table 3
Parameters for pilot-scale experiment

Parameter	Unit	Value
Dried Moringa leaves	kg	1
Volume of Water	l	30
Time	min	48
Temperature	℃	82

Figure 5 illustrates the pilot-scale production process for the Moringa beverage. As shown in Figure 5a, 1 kg of dried Moringa leaves was weighed prior to the process, and 30 L of water was added to the wire mesh filter media (Fig. 5b). The mixture was heated at 82 °C for 48 minutes (Fig. 5c) to allow the bioactive compounds to migrate through and minimise thermal degradation before the beverage was collected as the Moringa extract (Fig. 5d) for downstream use.

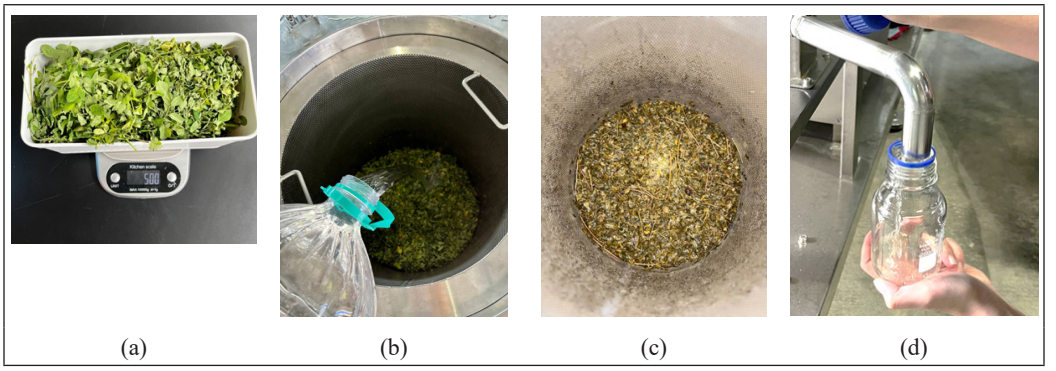

Figure 5. Pilot-scale method: (a) Dried Moringa leaves; (b) Heating process; (c) Filtration process, and (d) Moringa extract product (beverage)

The pilot-scale setup shows the technical feasibility of the wire-mesh filtration system at a larger processing volume. However, processing throughput, filtration rate, energy consumption, labour requirements, cost, and other operational feasibility aspects were not evaluated in this study. These parameters are necessary before the system's scalability for SME production can be realistically demonstrated. A second related but different topic is cleaning behaviour and fouling resistance after repeated cycles. The pilot scale was built from food-grade stainless steel to maintain a clean, corrosion-resistant surface. Cleaning validation data were not collected in this single-run study and are recommended as the next step before use.

Summary of Experimental Study

Experimental Workflow

Figure 6 illustrates the overall experimental workflow. The process commences with raw material preparation, whereby Moringa leaves are conditioned to the desired physical state prior to extraction. This is followed by the brewing stage, during which the leaves are subjected to controlled extraction under defined temperature and time parameters, and subsequently by the filtration stage, which constitutes the core separation process and varies according to methodological scale and operational setup. The resulting filtrate is then collected for further analysis, with care taken to minimise loss and contamination during transfer, before a final assessment of clarity and mineral content, the key indicators of extraction efficiency and filtrate quality. This structured workflow provides a consistent framework that enables direct comparison between the traditional laboratory-scale and pilot-scale methods.

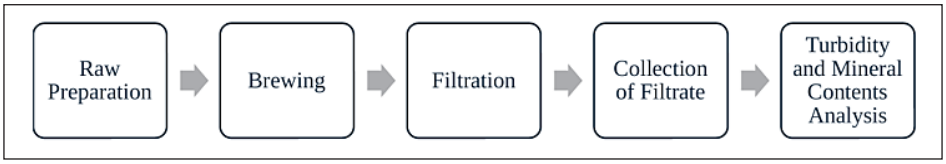

Figure 6. Experimental workflows for all methods

Table 4 compares the key experimental parameters of the three filtration methods. As mentioned above, the traditional method operates under a much less controlled environment than the standard solid-liquid ratio and 82 °C thermal control adopted by the laboratory- and pilot-scale versions.

Table 4
Summary of experimental parameters

Filtration Method	Dried Leaves (g)	Water Volume (mL)	Temperature (°C)
Traditional	1	230	100
Laboratory-scale	3	90	82
Pilot-scale	1000	30 000	82

RESULTS AND DISCUSSION

Each product was then evaluated for clarity, assessed visually based on colour (ranging from dark to light yellow to the lightest colour). Clarity was measured on a visual scale, where a lower value indicates greater transparency and a clearer product. Mineral analyses for calcium (Ca), iron (Fe), potassium (K), magnesium (Mg) and sulphur (S) were done using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) with standard sample digestion procedures.

Product Samples Collected

The experimental study produced three distinct samples, allowing direct comparison among the traditional method (which represents current standard practice, particularly in households and certain SMEs), the laboratory-scale method, and the pilot-scale method. As both the laboratory-scale and pilot-scale experiments followed the same protocol established by Kamarudin et al. (2020), this comparison also allows evaluation of the feasibility and scalability of that methodology for potential mass production. Figure 7 shows the three samples produced:

- Sample 1: Traditional Method
- Sample 2: Laboratory-scale Method
- Sample 3: Pilot-scale Method

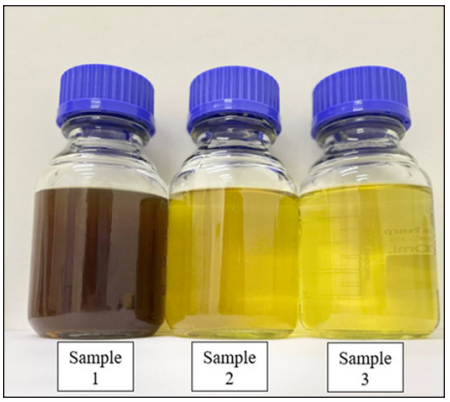

Figure 7. Product samples from three filtration methods

Product Clarity Comparison

Clarity is related to the product's visual appeal and perceived quality. In Moringa-based beverages, turbidity arises from incomplete separation of particulates in filtration; poor clarity (high turbidity) will dilute consumer acceptance and may indicate a lack of production efficiency. Sample 1 (traditional) had the lowest clarity of all three, with the dark brown colour indicating a higher visible particulate load.

That might also be detrimental to shelf stability, since a higher particulate load can accelerate sedimentation and increase the substrate available for microbial growth, though shelf life and microbial stability were not measured here. In contrast, Samples 2 and 3 became a bit lighter in colour and thus showed better particulate removal from the filtration process and a qualitative effect on the appearance of the finished product. Colour was measured only by visual observation, and instrumental turbidity measurement was not performed in this pilot study and is expected to be a focus of future research. A summary of product samples, clarity, and colour comparison is shown in Table 5.

Table 5
Summary of product samples, clarity, and colour comparison

Sample	Key Features	Clarity and Colour
1.	Basic sieves or cloth rely on gravity or minimal pressure and have no controlled parameters.	High clarity: Dark brown hue, indicating residual fine particles.
2.	Uses Whatman No. 1 filter paper, conducted under controlled laboratory conditions.	Moderate clarity: Light-yellow, suggesting effective removal of larger particles, but some fines remain.
3.	Advanced wire mesh with optimised size, conducted in a closed, controlled environment, which ensures uniform filtration.	Low clarity: Near-transparent, lightest colour, demonstrating superior removal of both large and fine particulates.

However, because Moringa extract naturally contains chlorophyll-related pigments and other colour-associated bioactive compounds, the pilot-scale sample's lighter colour cannot, on the basis of visual assessment and the current mineral panel alone, be fully distinguished from a possible partial loss of these coloured phytochemicals during filtration. Dedicated phytochemical pigment assays are recommended in future work to disambiguate desirable clarification from loss of bioactive colour compounds.

Nutrient Contents of Beverage Products

The samples were analysed at ALS Technichem (M) Sdn Bhd, Johor Bahru, Malaysia, which is a STANDARDS MALAYSIA accredited laboratory that uses the methods as well as the Association of Official Analytical Chemists (AOAC) and American Public Health Association (APHA) in terms of the metal analysis techniques. Metals are analysed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) to meet AOAC 999.11 and APHA 3120B standards to detect minerals and measure them in a precise manner. The Limit of Reporting (LOR) was set to 0.05 mg/100 mL for all minerals that were examined, ensuring high analytical sensitivity. The resulting nutrient content data from the certified laboratory test are presented in Figure 8.

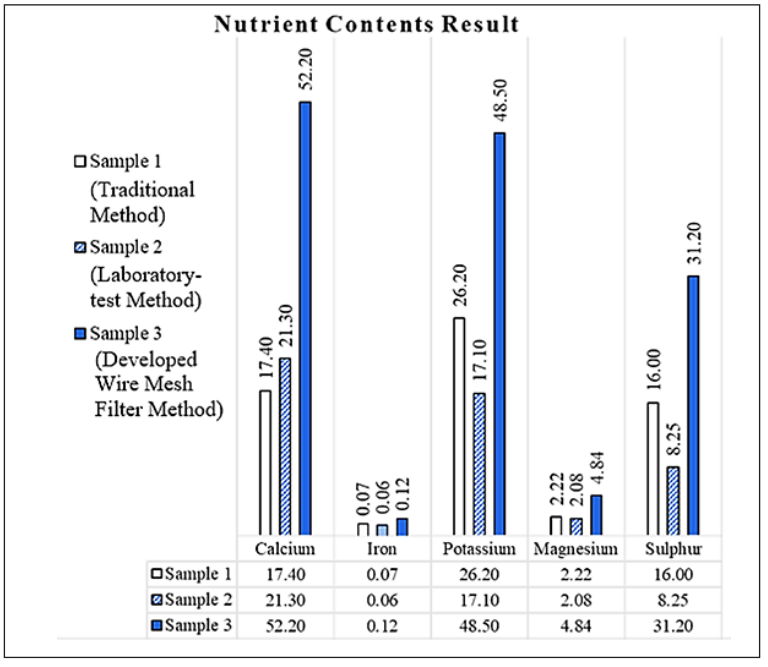

Figure 8. Nutrient contents result (mg/100 mL)

To evaluate the pilot scale method (Sample 3) against the other two methods, percentage difference calculations were performed using the same framework for all five minerals. Table 6 compares the mineral content of Moringa beverage products from the three filtration methods.

Table 6
Comparative nutrients of Moringa beverage products obtained (mg/100 mL)

Sample	Method	Ca	Fe	K	Mg	S
1	Traditional	17.40	0.07	26.20	2.22	16.00
2	Laboratory-scale	21.30	0.06	17.10	2.08	8.25
3	Pilot-scale	52.20	0.12	48.50	4.84	31.20

Sample 3 (pilot-scale) had higher single-measurement mineral values than Samples 1 and 2 for all five minerals analysed. Compared to the traditional and laboratory-scale methods, the pilot-scale sample produced 200% and 145% more calcium, 71% and 100% more iron, 85% and 184% more potassium, 118% and 133% more magnesium, and 95% and 278% more sulphur. Since these figures represent a single measurement per method rather than replicated trials, they are descriptive and not statistically valid; no inferential statistical test has been applied. The same is true for the clarity results reported above. Table 7 shows the summary of nutrient content percentage retention from the pilot-scale.

Table 7
Summary of nutrient contents percentage retention from the pilot-scale

Filtration Method	Ca	Fe	K	Mg	S
Sample 1	200	71	85	118	95
Sample 2	145	100	184	133	278

As previously noted, the traditional method's markedly lower solid-to-liquid ratio (1:230), relative to the laboratory- and pilot-scale methods (1:30), means the traditional-versus-pilot comparison reflects both extraction concentration and filtration medium simultaneously, rather than filtration alone. More notably, although the pilot-scale and laboratory-scale samples were prepared under identical extraction temperature, time and solid-to-liquid ratio, the pilot-scale sample still showed higher mineral concentrations. The same operator, heating protocol, and post-extraction handling were used across all scales to minimise procedural variability, but evaporative concentration and the exact sampling position were not independently measured or controlled, which is acknowledged as a limitation.

As a possible explanation for this laboratory vs. pilot-scale comparison, the larger surface area and lower adsorptive affinity of food-grade stainless steel wire mesh compared to cellulose-based Whatman No. 1 filter paper could reduce mineral loss through matrix adsorption during filtration. This is a plausible mechanism but not a confirmed one, since we have not directly tested it in this study; direct verification, which is a mineral analysis of the filter residue on each medium, is recommended as a specific, tractable next step.

The scope of this study was limited to the five minerals most emphasised in the nutritional literature in Moringa (calcium, iron, potassium, magnesium and sulphur) because there is a scarcity of resources and the minerals available through the accredited ICP-OES service. To separate the effect of the extraction and filtration process at these production scales rather than just taking them together would require a controlled factorial follow-up, in which the filtration method is varied independently of the extraction temperature, time and ratio, which seems to be the most logical next controlled experiment based on this pilot comparison. From a practical perspective, the pilot-scale prototype has qualitative advantages relevant to SME adoption: a reusable, food-grade stainless-steel mesh that is easier to clean than cloth, and a potential for higher single-batch throughput. However, no quantitative data on processing throughput, filtration rate, energy consumption, labour requirement and cost were collected in this study. Considered together, the confounding factors identified above, the traditional method's differing extraction ratio and the unexplained divergence between the laboratory- and pilot-scale samples under otherwise identical conditions, indicate that the clarity and mineral advantages associated with the pilot-scale system, while promising, remain mechanistically unconfirmed at this stage.

CONCLUSION

The findings of this pilot study indicate that the pilot-scale filtration system was associated with improved clarity and enhanced mineral content in Moringa beverage products, relative to both the traditional and laboratory-scale methods, consistent with the wire mesh's superior filtration efficiency and process control. These gains, however, should be interpreted in light of the confounds and open questions identified in the preceding discussion: differing extraction conditions across production scales, an unexplained divergence between laboratory- and pilot-scale results despite otherwise matched conditions, and untested operational parameters, including throughput, energy consumption, and cleaning-cycle validation. Resolving these questions, through a controlled, single-variable factorial follow-up and direct verification of the proposed adsorption-based mechanism, constitutes the necessary next step before the pilot-scale system's advantages can be confirmed and its potential scalability for SME-based functional beverage production can be more broadly generalised.

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REFERENCES

Abd El-Rahim, E. M., Abd El-Gawwad, A. I., Rabie, M. M., & El-Gammal, R. E. (2017). Preparing new beverage from *Moringa oleifera* leaves. *Journal of Food and Dairy Sciences, 8*(7), 303-307.

Anzano, A., Ammar, M., Papaianni, M., Grauso, L., Sabbah, M., Capparelli, R., & Lanzotti, V. (2021). *Moringa oleifera* Lam.: A phytochemical and pharmacological overview. *Horticulturae, 7*(10), Article 409. https://doi.org/10.3390/horticulturae7100409

Aziz, S., Rehman, A., Ali, M., Syed, U., Hamza, M., Yasser, S., & Tariq, R. (2024). A comprehensive review of membrane-based water filtration techniques. *Applied Water Science, 14*(8), Article 169. https://doi.org/10.1007/s13201-024-02226-y

Cescon, A., & Jiang, J.-Q. (2020). Filtration process and alternative filter media material in water treatment. *Water, 12*(12), Article 3377. https://doi.org/10.3390/w12123377

Daneluz, J., da Silva, G. F., Duarte, J., Turossi, T. C., dos Santos, V., Baldasso, C., & Daneluz, A. C. (2023). Membrane separation process of microfiltration applied to the filtration of kombuchas. *Food Chemistry Advances, 3*, Article 100451. https://doi.org/10.1016/j.focha.2023.100451

Fombang, E. N., & Saa, W. R. (2016). Production of a functional tea from *Moringa oleifera* Lam leaf powder: Optimization of phenolic extraction using response surface methodology. *Journal of Nutrition & Food Sciences, 6*(6), Article 1000556. https://doi.org/10.4172/2155-9600.1000556

Hernández-Fuentes, G. A., Sanchez-Ramirez, C. A., Cortes-Alvarez, S. I., Rodriguez-Hernández, A., Cabrera-Medina, A. O., Moy-López, N. A., Guzman-Muñiz, J., Garza-Veloz, I., Rodriguez-Sanchez, I. P., Martinez-Fierro, M. L., Álvarez-Barajas, J. J., Cortes-Alvarez, N. Y., Ceballos-Magaña, S. G., Meza-Robles, C., & Delgado-Enciso, I. (2025). *Moringa oleifera* leaf infusion as a functional beverage: Polyphenol content, antioxidant capacity, and its potential role in the prevention of metabolopathies. *Life, 15*(4), Article 636. https://doi.org/10.3390/life15040636

Hodas, F., Zorzenon, M. R. T., & Milani, P. G. (2021). *Moringa oleifera* potential as a functional food and a natural food additive: A biochemical approach. *Anais da Academia Brasileira de Ciências, 93*(Suppl. 4), Article e20210571. https://doi.org/10.1590/0001-3765202120210571

Islam, Z., Islam, S. M. R., Hossen, F., Mahtab-ul-Islam, K., Hasan, R., & Karim, R. (2021). *Moringa oleifera* is a prominent source of nutrients with potential health benefits. *International Journal of Food Science, 2021*, Article 6627265. https://doi.org/10.1155/2021/6627265

Kamarudin, A. A., Saad, N., Sayuti, N. H., Ab Razak, N. A., & Mohd Esa, N. (2020). Enhancement of phenolics and antioxidant activity via heat assisted extraction from *Moringa oleifera* using response surface methodology and its potential bioactive constituents. *Malaysian Journal of Medicine and Health Sciences, 16*(2), 83-90.

Loff, L. G. (2001). Filter media, filter rating. In L. Svarovsky (Ed.), *Solid-liquid separation* (4th ed., pp. 281-301). Butterworth-Heinemann. https://doi.org/10.1016/B978-075064568-3/50033-X

Marobhe, N. J., & Sabai, S. M. (2021). Treatment of drinking water for rural households using *Moringa* seed and solar disinfection. *Journal of Water, Sanitation and Hygiene for Development, 11*(4), 579-590. https://doi.org/10.2166/washdev.2021.253

Masitlha, E. P., Seifu, E., & Teketay, D. (2024). Nutritional composition and mineral profile of leaves of *Moringa oleifera* provenances grown in Gaborone, Botswana. *Food Production, Processing and Nutrition, 6*(1), Article 3. https://doi.org/10.1186/s43014-023-00183-8

Mensah, R. T., Eklou-Lawson, M., Gambogou, B., Kangni-Dossou, M., & Ameyapoh, Y. (2025). Acceptability of optimized fresh *Moringa oleifera* and soymilk beverage. *CyTA - Journal of Food, 23*(1), Article 2448491. https://doi.org/10.1080/19476337.2024.2448491

Nathan, S. J., Sundran, K. C. S. B., Venkataramana, K. N., & Mani, K. R. (2008). Filtration technique in vaccine manufacturing. *Advanced Biotech*, August, 37-41.

Pareek, A., Pant, M., Gupta, M. M., Kashania, P., Ratan, Y., Jain, V., Pareek, A., & Chuturgoon, A. A. (2023). *Moringa oleifera*: An updated comprehensive review of its pharmacological activities, ethnomedicinal, phytopharmaceutical formulation, clinical, phytochemical, and toxicological aspects. *International Journal of Molecular Sciences, 24*(3), Article 2098. https://doi.org/10.3390/ijms24032098

Peñalver, R., Martínez-Zamora, L., Lorenzo, J. M., Ros, G., & Nieto, G. (2022). Nutritional and antioxidant properties of *Moringa oleifera* leaves in functional foods. *Foods, 11*(8), Article 1107. https://doi.org/10.3390/foods11081107

Pollini, L., Tringaniello, C., Ianni, F., Blasi, F., Manes, J., & Cossignani, L. (2020). Impact of ultrasound extraction parameters on the antioxidant properties of *Moringa oleifera* leaves. *Antioxidants, 9*(4), Article 277. https://doi.org/10.3390/antiox9040277

Sarbatly, R., Sariau, J., & Krishnaiah, D. (2023). Recent developments of membrane technology in the clarification and concentration of fruit juices. *Food Engineering Reviews, 15*(3), 420-437. https://doi.org/10.1007/s12393-023-09346-2

Singh, A. K., Rana, H. K., Tshabalala, T., Kumar, R., Gupta, A., Ndhlala, A. R., & Pandey, A. K. (2020). Phytochemical, nutraceutical and pharmacological attributes of a functional crop *Moringa oleifera* Lam.: An overview. *South African Journal of Botany, 129*, 209-220. https://doi.org/10.1016/j.sajb.2019.06.017

Su, B., & Chen, X. (2020). Current status and potential of *Moringa oleifera* leaf as an alternative protein source for animal feeds. *Frontiers in Veterinary Science, 7*, Article 53. https://doi.org/10.3389/fvets.2020.00053

Tiwari, S., & Saha, S. N. (2022). Micro filtration of *Moringa oleifera* juice using hollow fibre membrane technology for clarification. *International Journal of Health Sciences, 6*(S1), 10743-10757. https://doi.org/10.53730/ijhs.v6nS1.7585

Wickramasinghe, Y. W. H., Wickramasinghe, I., & Wijesekara, I. (2020). Effect of steam blanching, dehydration temperature & time, on the sensory and nutritional properties of a herbal tea developed from *Moringa oleifera* leaves. *International Journal of Food Science, 2020*, Article 5376280. https://doi.org/10.1155/2020/5376280

Yerena-Prieto, B. J., Gonzalez-Gonzalez, M., Vázquez-Espinosa, M., Velasco González-de-Peredo, A., García-Alvarado, M. Á., Palma, M., Rodríguez-Jiménez, G. del C., & Fernández Barbero, G. (2022). Optimization of an ultrasound-assisted extraction method applied to the extraction of flavonoids from *Moringa* leaves (*Moringa oleifera* Lam.). *Agronomy, 12*(2), Article 261. https://doi.org/10.3390/agronomy12020261