Melon Seed Milk (Cucumis melo L.) as a Sustainable, Hypoallergenic, and Competitive Plant-Based Milk Alternative for the Indonesian Market: A Physicochemical Characterization Study

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ABSTRACT

Indonesia ranks among the largest food waste producers in Southeast Asia, generating an estimated 300 kg of food waste per capita annually. Melon (Cucumis melo L.) contributes significantly to this waste stream, primarily through its seeds, which constitute approximately 10% of total fruit weight and are routinely discarded despite their documented nutritional value. This study investigates the feasibility of melon seeds as a raw material for producing a plant-based milk alternative as part of sustainable food innovation. Two melon seed milk variants were prepared—fresh (unsoaked) and dried (pre-soaked in water for 8 hours)—and their physicochemical properties were compared against soy, cow, almond, and oat milks under identical laboratory conditions. Parameters evaluated included pH (over three days), total soluble solids (°Brix), CIELAB colorimetry (L*, a*, b*), protein content (Kjeldahl method, AOAC 979.09), fat content (Soxhlet extraction, AOAC 930.30), and dietary fiber (enzymatic-gravimetric method). Odor acceptability was assessed via sensory evaluation with 11 panelists. Results demonstrated that melon seed milk maintained a stable pH of 6.0 throughout the three-day storage period, outperforming soy and cow milk (pH 6 → 5 by Day 1). °Brix values (~1.0 °Bx) were the lowest among all samples, consistent with minimal fermentable sugar content. Dried melon seed milk contained 1.7% protein, 2.1% fat, and 0.3% fiber (w/v), with fat content comparable to soymilk but lower protein. CIELAB analysis confirmed stable L* values (70–78) over three days, indicating minimal browning and oxidation. Sensory evaluation revealed favorable aroma acceptability for both melon seed milk variants, with no respondents assigning the worst odor score. Overall, melon seed milk demonstrates strong potential as a sustainable, locally sourced, and hypoallergenic milk alternative for the Indonesian market. Future research should address flavor enhancement, shelf-life extension, and large-scale consumer acceptance evaluation.

1. INTRODUCTION

Indonesia ranks among the highest food waste producers in Southeast Asia, generating an estimated 300 kg of food waste per capita annually [13, 32]. A significant portion of this waste originates from households and food service establishments—particularly hotel buffets and restaurants—where large quantities of fruits and vegetables are routinely discarded [9, 30]. Among these, melon (Cucumis melo L.) is a particularly high-waste fruit due to its widespread popularity and high seed content; seeds constitute approximately 10% of total fruit weight yet are almost universally discarded despite their substantial nutritional potential [25].

Cow's milk, while widely consumed in Indonesia, poses challenges for a large segment of the population. Over 90% of Asians are estimated to be lactose intolerant [20], and cow's milk proteins are recognized as a common allergen, particularly among children [28]. These factors have driven growing demand for non-dairy plant-based milk alternatives. However, the most prevalent commercial alternatives—soy, almond, and oat milks—present their own limitations. Soy and almonds are both classified as major allergens [6, 29], many plant-based milks are significantly more expensive than dairy [22], and Indonesia remains heavily import-dependent for soybeans—approximately 78% of soy consumed in 2022 was imported [5]. These compounding challenges underscore the need for a locally sourced, affordable, and hypoallergenic alternative.

Melon seeds are a compelling candidate for such an application. They contain high levels of oil (25–38%), protein (15–45%), and dietary fiber (19–25%) [25], alongside bioactive compounds with anti-inflammatory and antioxidant properties and high levels of polyunsaturated fatty acids [19]. Their relatively soft texture facilitates efficient extraction compared to harder nuts and legumes. Repurposing melon seed waste into a functional food product simultaneously addresses food waste reduction and the demand for diversified, sustainable plant protein sources in Indonesia.

This study therefore characterizes two preparations of melon seed milk—fresh (unsoaked) and dried (pre-soaked for 8 hours)—and compares their physicochemical properties with commercially available soy, cow, almond, and oat milks. The parameters examined were pH stability over three days, total soluble solids (°Brix), CIELAB colorimetry, macronutrient content (protein, fat, and fiber), and aroma acceptability by sensory evaluation. Together, these analyses provide an evidence base for assessing melon seed milk's potential as a viable, sustainable, and locally producible plant-based milk alternative for the Indonesian market.

2. RESEARCH METHOD

2.1 Raw Materials and Sample Design

Melon fruits (Cucumis melo L.) were sourced from household and commercial food waste in Surabaya, Indonesia. Seeds were manually separated from the fruit pulp and cleaned. Two seed preparation variants were produced: (1) Fresh melon seeds — used directly after extraction without further processing; and (2) Dried (pre-soaked) melon seeds — washed, soaked in water at room temperature for 8 hours to partially hydrate cell walls and activate endogenous enzymes [22], then dried on paper towels overnight at room temperature. The soaking treatment was employed to evaluate whether cell wall hydration improved extraction efficiency and product quality, consistent with standard preparation practices in nut and seed milk production.

Six milk samples were prepared for comparison under identical laboratory conditions: (1) Fresh melon seed milk; (2) Dried (pre-soaked) melon seed milk; (3) Commercial soy milk; (4) Commercial cow's milk; (5) Commercial almond milk; and (6) Commercial oat milk. All commercial samples were sourced from local supermarkets in Surabaya and decanted into clean glass bottles under the same conditions as the prepared melon seed milks to minimize handling variability. All samples were analyzed at room temperature without refrigeration during the 3-day experimental period.

2.2 Materials and Equipment

Table 1 lists all materials and equipment used in this study. Melon seed milk was prepared at a seed-to-water ratio of 1:10 (w/v) — 25 g of seeds blended with 250 mL of distilled water — consistent with standard plant milk extraction ratios.

Table 1. Materials and Equipment Used in Melon Seed Milk Preparation and Analysis

Equipment / Material	Quantity	Function
Blender	1 unit	Homogenization of seeds with water to form slurry
Cheesecloth (double-layer)	As needed	Filtration to separate liquid milk from seed pulp
Double boiler pan	1 unit	Pasteurization of filtered milk
Thermometer	1 unit	Temperature monitoring during pasteurization
Stainless steel bowls	Several	Sample collection and processing
Glass bottles (clean, sealed)	6 units	Sample storage for analytical testing
Melon seeds (fresh)	25 g	Raw material — Variant 1 (fresh, unsoaked)
Melon seeds (dried/pre-soaked)	25 g	Raw material — Variant 2 (soaked 8 h, dried overnight)
Distilled water	250 mL per sample	Extraction medium (seed-to-water ratio 1:10 w/v)

Equipment / Material	Quantity	Function
Soy milk, cow milk, almond milk, oat milk	Commercial brands	Comparative reference samples

2.3 Milk Preparation Procedure

The preparation protocol followed four sequential steps, as illustrated in Figure 1. (1) Blending: Seeds and water were blended for 3–5 minutes until a homogeneous slurry was obtained. (2) Filtration: The slurry was strained through a double-layer cheesecloth, with the cloth squeezed manually until all liquid was expressed, yielding the raw melon seed milk extract. (3) Pasteurization: The filtered milk was heated in a double boiler to 63–65°C for 30 minutes with continuous stirring, following low-temperature long-time (LTLT) pasteurization guidelines [11]. (4) Cooling and Storage: The pasteurized milk was cooled to approximately 4.4°C and transferred to sealed glass bottles. For experimental analysis, samples were held at room temperature for 3 days; for consumption purposes, refrigeration below 7°C for up to 7 days is recommended [8].

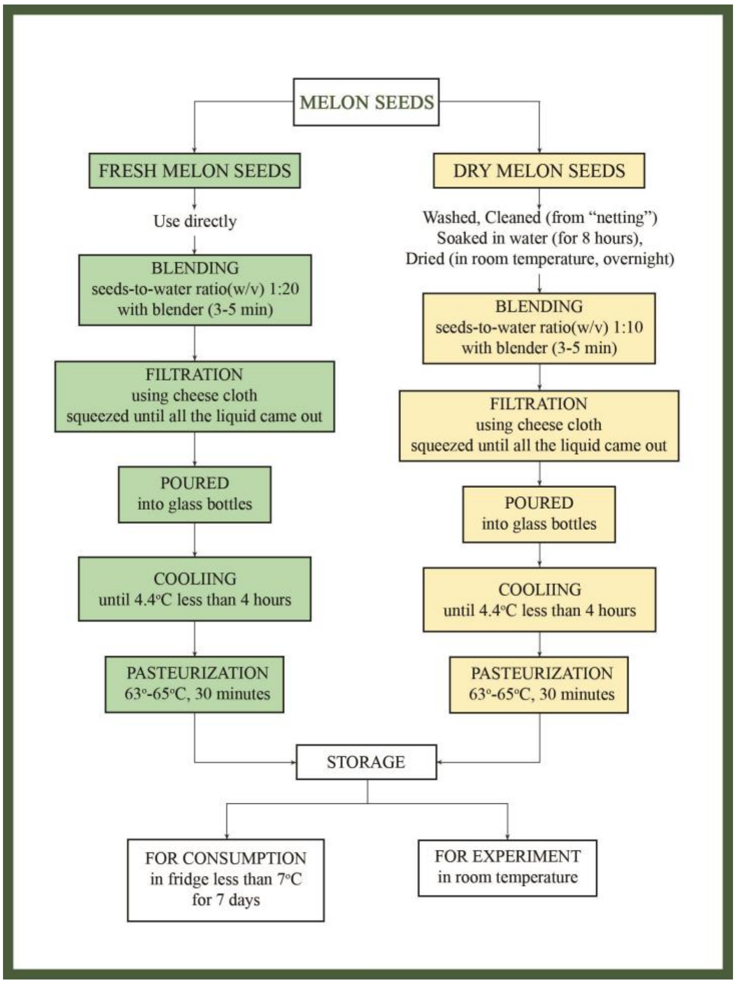

Figure 1. Comparative preparation procedure for fresh melon seed milk (left, green pathway) and dried/pre-soaked melon seed milk (right, yellow pathway), from seed separation through pasteurization to storage.

2.4 Analytical Methods

2.4.1 pH Measurement

Acidity was measured using universal pH strips (range pH 4–9, 0.5-unit increments) on Day 0 (immediately post-production), Day 1, Day 2, and Day 3 to monitor potential fermentation-induced acidification [4]. Strips were immersed in each sample at room temperature and compared against the calibrated color reference chart. Serial pH monitoring provides an indication of microbial stability and short-term shelf life.

2.4.2 Total Soluble Solids (°Brix)

A calibrated handheld refractometer was used to measure the refractive index of each milk sample, expressed as °Brix (% sucrose equivalents) [27]. The instrument was zeroed with distilled water (0 °Bx) prior to each measurement. A few drops of each sample at room temperature were placed on the prism, and readings were taken on Day 0, 1, 2, and 3. °Brix provides an estimate of dissolved soluble solids including sugars, and was used to monitor compositional changes over the storage period.

2.4.3 Colorimetry (CIELAB)

The optical properties of each milk sample were quantified using a portable colorimeter with CIELAB color space output. Three parameters were recorded: L* (lightness, 0 = black, 100 = white), a* (red (+) to green (−) axis), and b* (yellow (+) to blue (−) axis) [10]. Measurements were taken on Days 0–3 by placing each sample in a transparent cuvette and reading the colorimeter sensor against it. Color stability across storage days was used to assess susceptibility to oxidation and Maillard browning reactions.

2.4.4 Protein Content

Protein was determined by micro-Kjeldahl digestion following AOAC Official Method 979.09 [35]. A 10 mL aliquot of each milk sample was digested with concentrated sulfuric acid and a catalyst tablet to convert organic nitrogen to ammonium sulfate. The digest was neutralized with excess base, distilled, and the released ammonia was captured in a boric acid receiver and back-titrated with standardized acid. Total nitrogen was converted to protein using the standard conversion factor N × 6.25. Results are reported as % protein (w/v).

2.4.5 Fat Content

Fat content was determined by Soxhlet extraction following AOAC Method 930.30 [35]. A 50 mL aliquot of each milk was gently evaporated to dryness to obtain total solids. The dried solid was loaded into a Soxhlet thimble and extracted with petroleum ether for several hours. After solvent evaporation, the residual fat was weighed and expressed as % fat (w/v) relative to the original sample volume.

2.4.6 Dietary Fiber

Total dietary fiber was estimated using an enzymatic-gravimetric method adapted from established AOAC procedures. A measured volume of each milk sample was sequentially treated with amylase, protease, and amyloglucosidase to digest starch and protein, thereby isolating the indigestible residue. This residue was filtered, dried, and weighed; the ash fraction (determined by incineration) was subtracted to yield the fiber content, reported as % fiber (w/v).

2.4.7 Organoleptic Evaluation

Aroma acceptability was assessed by 11 non-expert volunteer panelists using a blinded odor evaluation protocol. Commercial reference samples of each milk type were presented without labeling. Panelists rated each sample on a 5-point scale: 1 = good/no smell to 5 = strong/bad smell. Only aroma was evaluated given the non-expert nature of the panelists and the absence of a trained sensory panel; taste and texture evaluations were outside the scope of this study.

3. RESULTS AND DISCUSSION

3.1 pH Stability

Table 2 presents the pH values recorded for all six milk samples over the three-day storage period at room temperature.

Table 2. pH Values of Six Milk Samples over Three Days of Storage at Room Temperature

Day	Melon seed milk (fresh)	Melon seed milk (dried)	Soy milk	Cow milk	Almond milk	Oat milk
0	6	6	6	6	7	7
1	6	6	5	6	6	7
2	6	6	5	5	6	6
3	6	6	5	5	6	6

Scale: pH measured using universal pH strips (range 4–9, ±0.5 unit resolution).

Both fresh and dried melon seed milk samples maintained a stable pH of 6.0 throughout the entire three-day period, demonstrating strong short-term microbial stability. In contrast, soy milk and cow's milk both decreased from pH 6 to pH 5 by Day 1, indicating early-onset fermentation or microbial acidification. Almond and oat milks began at pH 7 and declined to pH 6 by Day 3, showing mild but progressive acidification. The superior pH stability of melon seed milk is consistent with its low fermentable sugar content (as confirmed by low °Brix values) and may also be attributable to the natural antioxidant compounds present in melon seeds, which have been reported to inhibit microbial growth [1, 17]. The generally acceptable pH range for fresh plant-based milks is 6.4–6.8 [34]; while melon seed milk's stable pH of 6.0 is slightly below this range, it remained constant throughout the observation period, suggesting that no active fermentation was occurring.

3.2 Total Soluble Solids (°Brix)

The °Brix values for all samples over the three-day period are presented in Table 3.

Table 3. °Brix (% Total Soluble Solids) of Six Milk Samples over Three Days of Storage

Day	Melon seed milk (fresh)	Melon seed milk (dried)	Soy milk	Cow milk	Almond milk	Oat milk
0	1	1	4	13	2	12
1	1	1	2	11	2	11
2	1	1	2	9	2	10
3	0.9	0.9	1	7	2	9

Melon seed milk (both variants) consistently recorded the lowest °Brix values (~1.0 °Bx on Day 0, declining marginally to 0.9 °Bx by Day 3), while cow's milk showed the highest initial Brix (13 °Bx) and oat milk the second highest (12 °Bx). Soy milk was intermediate at 4 °Bx. The progressive decline in Brix across all samples—particularly pronounced for cow and oat milks—is consistent with microbial consumption of fermentable sugars during ambient-temperature storage [26]. The stability of melon seed milk's Brix values corroborates the pH results, collectively confirming low fermentation activity and inherently low dissolved sugar content. The minimal difference between fresh and dried melon seed milk in °Brix suggests that the 8-hour soaking treatment did not substantially alter the quantity of extractable soluble solids, though it may have improved the physical texture of the resulting milk by facilitating cell wall hydration.

3.3 CIELAB Colorimetry

Color parameters (L*, a*, b*) for all samples on Days 0, 1, 2, and 3 are presented in Table 4. Key values are also summarized in Table 6.

Table 4. CIELAB Color Parameters (L, a*, b*) of Six Milk Samples over Three Days of Storage*

Day	Melon seed milk (fresh)	Melon seed milk (dried)	Soy milk	Cow milk	Almond milk	Oat milk
0	L*:70.7611 a*:-9.49167 b*:2.849318	L*:64.90781 a*:-6.42199 b*:1.269267	L*:74.30255 a*:-6.7375 b*: 0.722657	L*:79.11246 a*:-9.63573 b*:-2.27271	L*:73.35614 a*:-5.6212 b*:-2.35382	L*:71.82068 a*:-4.42992 b*:0.510338
1	L*:78.46994 a*:-9.44459 b*:-0.45097	L*:75.12293 a*:-8.92768 b*:-6.53784	L*:77.7501 a*:-9.39958 b*:-0.40331	L*:81.63763 a*:-9.41404 b*:-4.56201	L*:73.87774 a*:-6.52287 b*:-3.29128	L*:72.50778 a*:-4.82515 b*:1.516732
2	L*:73.70445 a*:-9.50003 b*: 0.914468	L*:71.89095 a*:-8.82628 b*:-2.8928	L*:75.39616 a*:-6.81685 b*:0.645246	L*:80.54271 a*:-9.72439 b*:-2.35711	L*:73.70445 a*:-5.64909 b*:-2.37514	L*:71.45141 a*:-4.39968 b*:0.536404
3	L*:76.39021 a*:10.6974 b*:0.351518	L*:76.71168 a*:-7.06906 b*:-3.57078	L*:74.63816 a*:-6.76728 b*:-0.47465	L*:82.81801 a*:-7.51667 b*: -2.76785	L*:70.67086 a*:4.81695 b*:3.389507	L*:62.33716 a*:-1.1613 b*:7.105853

Both melon seed milk variants maintained moderate L* values in the 70–78 range throughout storage, indicating acceptable and stable brightness. No consistent trend of darkening was observed, suggesting minimal browning reactions (oxidation or Maillard). In comparison, cow's milk had the highest L* values (~79–83), consistent with its white coloration, while oat milk exhibited a notable L* decline from 71.8 to 62.3 by Day 3—indicative of progressive browning, likely driven by oxidation of oat-derived phenolics and enzymatic or Maillard reactions [33]. The a* values for melon seed milk ranged between −6 and −10 (green region), typical for plant-based milks without added colorants [23]. The b* values remained close to neutral (near 0), suggesting neither strong yellowness nor blueness. The color stability of melon seed milk across three storage days is a favorable quality attribute, indicating adequate resistance to oxidative degradation and visual appeal comparable to established commercial plant-based milks.

3.4 Macronutrient Composition

Table 5 presents the protein, fat, and fiber contents of dried melon seed milk, fresh melon seed milk, and soy milk, as the primary comparison group for nutritional evaluation.

Table 5. Protein, Fat, and Fiber Content (% w/v) of Melon Seed Milk Variants and Soy Milk

Sample	Protein (% w/v)	Fat (% w/v)	Fiber (% w/v)
Melon seed milk (dried, pre-soaked)	1.7	2.1	0.3
Melon seed milk (fresh)	1.2	1.8	0.4
Soy milk	3.3	2.0	0.2

Soy milk showed the highest protein content (3.3% w/v), approximately double that of dried melon seed milk (1.7%) and nearly triple that of fresh melon seed milk (1.2%). This differential reflects soybeans' inherently high protein content (~35–40% dry weight) relative to melon seeds (~15–45%) [25], as well as soymilk's standard processing (soaking and blanching to maximize protein solubilization) [7]. The modest increase in protein observed for the pre-soaked versus fresh melon seed milk (1.7% vs. 1.2%) is consistent with literature reports that alkaline or aqueous soaking has a limited but beneficial effect on protein extraction yield [14].

Fat content was broadly comparable across all three samples—dried melon seed milk (2.1%), fresh melon seed milk (1.8%), and soy milk (2.0%)—aligning with reported values for both melon seed beverages [18] and commercial soymilk [12]. The minimal effect of soaking on fat content is expected, as lipids are poorly water-soluble and are extracted primarily through mechanical disruption rather than aqueous soaking. Melon seed fat is predominantly unsaturated (polyunsaturated fatty acids), which is nutritionally favorable and consistent with findings reported by Khalid et al. [19].

Dietary fiber was low across all samples (≤0.4% w/v), which is characteristic of plant milks produced by filtration—the filtration step removes the majority of insoluble fiber with the seed pulp, leaving only trace soluble fiber in the liquid phase [7, 31]. The slightly lower fiber in the dried (pre-soaked) sample compared to fresh (0.3% vs. 0.4%) may reflect partial hydrolysis of seed hull components during the soaking period.

3.5 Organoleptic Evaluation

Figure 2 presents the distribution of aroma acceptability scores assigned by 11 panelists for all six milk types.

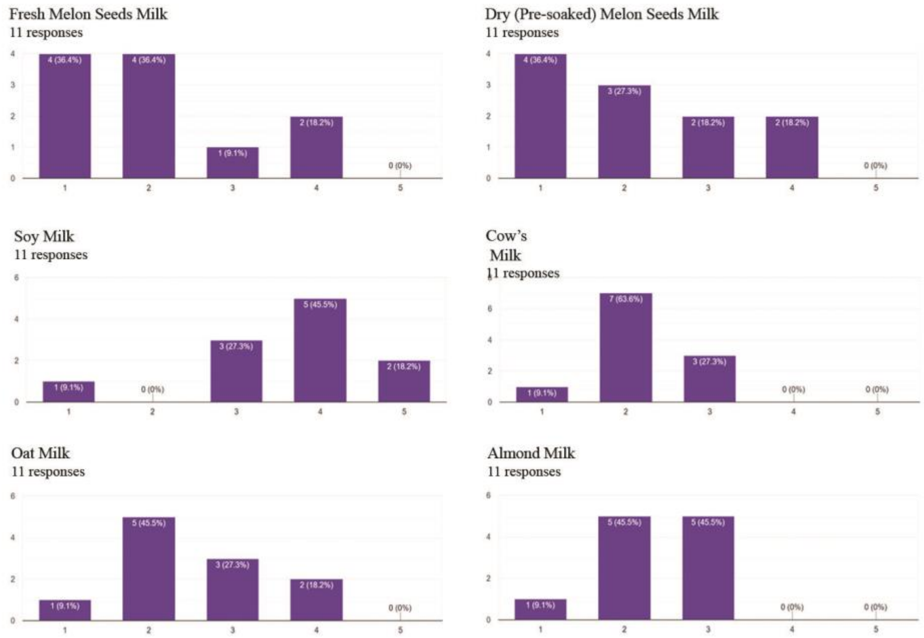

Figure 2. Aroma acceptability scores (1 = good/no smell; 5 = strong/bad smell) for six milk samples, rated by 11 panelists. Charts shown for: fresh melon seed milk (top left), dried melon seed milk (top right), soy milk (center left), cow's milk (center right), oat milk (bottom left), and almond milk (bottom right).

Both fresh and dried melon seed milk received the most favorable aroma ratings, with the majority of responses concentrated in Scores 1–2 (good to mild odor) and no respondent assigning Score 5 (strong/bad smell). In contrast, soy milk received the most unfavorable distribution, with 45.5% of panelists rating it Score 4–5, reflecting its characteristic beany odor. Cow's milk showed the highest concentration at Score 2 (63.6%), consistent with its familiar and generally acceptable dairy aroma. Oat and almond milks were rated similarly, with most responses at Scores 2–3. These results suggest that melon seed milk's aroma is among the most acceptable of all samples tested, representing a favorable sensory attribute for market positioning. However, it should be noted that the panel consisted of non-expert volunteers and only aroma was assessed; comprehensive sensory evaluation including taste, texture, and appearance by a trained panel will be necessary before commercial acceptability conclusions can be drawn.

3.6 Comparative Summary and Market Potential

Table 6 provides a consolidated comparison of all key physicochemical and sensory parameters across all six milk samples.

Table 6. Summary of Physicochemical and Sensory Properties of All Six Milk Samples

Parameter	Melon Fresh	Melon Dried	Soy Milk	Cow Milk	Almond Milk	Oat Milk
pH (Day 0)	6	6	6	6	7	7
pH (Day 3)	6	6	5	5	6	6
°Brix (Day 0)	1.0	1.0	4	13	2	12
°Brix (Day 3)	0.9	0.9	1	7	2	9
Protein (% w/v)	1.2	1.7	3.3	—	—	—
Fat (% w/v)	1.8	2.1	2.0	—	—	—
Fiber (% w/v)	0.4	0.3	0.2	—	—	—
L* Day 0	70.8	64.9	74.3	79.1	73.4	71.8
L* Day 3	76.4	76.7	74.6	82.8	70.7	62.3
Aroma score (modal)	1–2 (good)	1–2 (good)	4–5 (strong)	2 (mild)	2–3 (mild)	2 (mild)

Note: (—) indicates parameter not measured for commercial samples in this study. °Brix and pH values represent Day 0 and Day 3 readings. Aroma score represents modal response from panelist evaluation.

Across all evaluated parameters, melon seed milk demonstrates a distinctive and compelling profile: exceptional pH stability, the lowest sugar content of any tested sample, acceptable visual quality, moderate macronutrient contribution, and superior aroma acceptability. While its protein content is lower than that of soymilk—the dominant plant-based milk in Indonesia—it is nutritionally adequate as a protein-contributing beverage and significantly superior to almond and oat milks in protein provision. Its fat content is comparable to soymilk, and its fatty acid profile (predominantly polyunsaturated) is nutritionally beneficial.

The sustainability dimension is equally compelling. Melon seeds are a widely available waste stream from household and food service consumption, requiring no dedicated cultivation, import infrastructure, or industrial-scale agronomic input. Their conversion into a marketable beverage product directly supports Indonesia's food waste reduction agenda [13], reduces reliance on imported soy [5], and provides an allergen-free alternative to the two most common commercial plant-based milks (soy and almond). The simple, low-technology production process—requiring only a blender, cheesecloth, and a stove—is accessible at small-scale community and cottage-industry level, supporting inclusive economic participation.

4. CONCLUSIONS

This study demonstrated that melon seed milk (Cucumis melo L.), produced through simple blending, filtration, and pasteurization, exhibits strong physicochemical properties as a plant-based milk alternative. Both fresh and pre-soaked (dried) variants showed stable pH (6.0 throughout three days), low °Brix (~1.0 °Bx), stable CIELAB color (L* 70–78), acceptable macronutrient content (1.2–1.7% protein, 1.8–2.1% fat, 0.3–0.4% fiber), and superior aroma acceptability relative to soy milk. Pre-soaking improved protein extraction yield (1.2% → 1.7%) and likely texture without adversely affecting other parameters. The following specific conclusions are drawn:

(1) Melon seed milk exhibited the strongest short-term microbial stability of all tested samples, maintaining pH 6.0 over three days while soy and cow's milk acidified to pH 5 by Day 1. This stability is attributed to its low fermentable sugar content and the natural antioxidant activity of melon seed constituents.

(2) The macronutrient profile of pre-soaked melon seed milk is nutritionally functional: protein content (1.7%) is below soymilk (3.3%) but superior to most nut and grain milks; fat content (2.1%) is comparable to soymilk; and fiber content (0.3%) is within the typical range for filtered plant milks.

(3) Aroma acceptability was the highest among all tested samples, with no panelist assigning the worst odor score to either melon seed milk variant—a critical consumer acceptance advantage in the Indonesian market context.

(4) From a sustainability perspective, melon seed milk uniquely valorizes a high-volume agricultural waste stream, requires no dedicated crop cultivation or imports, and is producible with minimal equipment—making it highly appropriate for small-scale commercial production in Indonesia.

Future research priorities include: flavor optimization through enzymatic treatments or natural additives to address beany or off-notes if present; shelf-life extension studies under refrigerated and ambient conditions; fortification strategies to increase protein content toward soymilk parity; formal sensory evaluation with trained panels; consumer acceptability studies; nutritional bioavailability assessment; and techno-economic feasibility analysis for small-to-medium enterprise production.

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