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PREPARATION OF TODDY FROM COCONUT WATER AND DEVELOPMENT OF FERMENTED TODDY AS AN ENERGY DRINK WITH POTENTIAL HEALTH BENEFITS

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Abstract

Coconut toddy is a mild alcoholic drink which has high nutritive properties. The sap of coco palm undergoes natural fermentation and leads to change in physiochemical, microbiological and nutritive values. The toddy was subjected to various filtration techniques, then the filtered sample was separated into four batches and pasteurized by adding sodium metabisulfite 0.05%, 0.10% and 5% vinegar to each batch. The coconut toddy sample without preservative was used as a control were stored at 4℃ and analyzed for 61 days. The pH of toddy was 5.08 ± 0.02. Toddy containing sodium metabisulfite and vinegar maintained the pH 5.08 ± 0.02 on all days of analysis. The pH of toddy containing no preservatives started to decrease from day 25 and finally reached 4.62 ± 0.02. The viable count test showed that the toddy containing sodium metabisulfite and vinegar showed nil growth till day 61. But the sample without preservative started to show growth from day 25. The alcohol content in toddy containing preservatives maintained the percentage of 2.08 ± 0.02 till the last day of analysis (day 61), whereas the sample stored without addition of preservatives showed increase in alcohol content from day 25 and increased to 3.87 ± 0.02 (%). The reducing sugar concentration was found to be 4.72 ±

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0.02 percentage in samples treated with preservatives, but drastically decreased to 3.75 ± 0.02 percentage in sample stored without preservative from day 25. Further the anti-microbial property of each toddy samples was analyzed. The nutritional values were analyzed by using Indian standard protocols. The energy content was 14.56 Kcal/100g, carbohydrate was 0.7319g/100g, total fibre was 0.0019g/100g, total fat content was 1.097g/100g, total protein content was 0.44/100g and total sugar content was 5.120g/100g.

Keywords: Coconut Toddy; Fermentation; Filtration; Pasteurization; Preservation; Antimicrobial Property; Nutritive Value.

1. INTRODUCTION

Coconut water is a clear liquid, the endosperm of immature coconuts (Cocos nucifera L.), which is a traditional tropical drink that has recently been introduced as a marketed functional beverage in the global market but which is mainly due to its low caloric content, balanced electrolyte status and claimed health-promoting benefits (Tuyekar et al., 2021). According to market investigations, the market value will continue to grow in the future, and the total value of the world market is likely to reach over USD 11 billion in 2030 (Grand View Research, 2025). The physiological relevance of the natural formulation of coconut water, particularly the maintenance of volume and post-exercise rehydration, is due to the natural formulation of coconut water, especially at physiologically relevant levels of potassium, sodium, calcium, magnesium and phosphorus (Halim et al., 2018). According to the recent reviews coconut water might be a natural substitute to unnatural sports drinks, though the hydration advantages would still be based on specific formula, amount of sodium, and exercise level (Leishman, 2015; Rethinam & Krishnakumar, 2022).

The old commercial practice of transforming carbohydrates to alcohol and organic acids by microbes is called fermentation. The most common yeast in the beverage's fermentation is *Saccharomyces cerevisiae* which transforms glucose to ethanol and CO 2 in a process that called glycolysis and alcoholic fermentation (Walker & Stewart, 2016). Controlled fermentations are thoroughly employed in the brewing and wine industries but are inconsistent when applied to natural substrates such as palm sap, which is affected by the natural microbiome, temperature, and pH (Oluwole et al., 2023).

Toddy (palm wine) is a natal spirits beverage that is produced by spontaneous fermentation of the palm trees coconut, palmyra, oil palm and nipa palm to extract sap. Fresh sap is sweet, whitish complement of carbohydrates plus micronutrient mix but it is highly perishable. In few hours after tapping, yeasts begin the process of alcoholic fermentation, lactic acid bacteria add to the acidic ferment and aroma, and acetic acid bacteria then proceed to oxidize ethanol into acetic acid. This fast micro-flora succession lends unique sensory qualities and severely restricts shelf life, resulting in the product tasting sour and unpleasant after 12-24 h. Besides being spoiled, uncontrolled fermentation might end up being unsafe, and adulteration will further go wrong with the quality of a product. The chemical and physicochemical transformations during fermentation are well documented. Fresh sap, initially neutral in pH (7.0–7.5) and dominated by sucrose, undergoes hydrolysis to glucose and fructose by invertase.

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Yeasts rapidly metabolize these monosaccharides to ethanol, while the pH declines to ~3.5 due to organic acid accumulation. Concurrent reductions in total sugars, vitamin C, and amino acids, together with increases in phenolics and volatile acids, significantly alter the nutritional and sensory profile (Kouamé et al., 2020; Titilayo & Temitope, 2019).

Various preservation measures are being explored to eliminate the constraints of traditional approaches. Sodium metabisulfite (SMS) is a widely used preservative in the wine industry and the antimicrobial effect is facilitated by the release of sulfurdioxide (SO_2) and the antimicrobial effect is enhanced in an acidic solution (Smith and Brown, 2025). Recent research on nipa palm sap showed that pre-treatment with SMS especially with potassium sorbate was more effective in increasing the shelf life compared with post-collected treatment (Athirah et al., 2025). However, when SMS is overused or used inappropriately, it can lead to unwanted sensory alterations as well as possible toxicological issues (Yoo et al., 2018). Other chemical preservative agents have been tested including benzoic acid and calcium hydroxide, and natural antimicrobials such as chloro-acetophenone and acetic acid (vinegar) have also been promising (Jara'ee, 2025).

The increasing interest in the application of combined preservation methods such as bio-preservation and hurdle technology to extend the shelf life of palm sap has been seen. It should be noted that a blend of nisin, gentle pasteurization, and refrigeration have been observed to increase the shelf life of palm sap to average of 10 weeks. This combined method also maintains more levels of sucrose and antioxidant than the conventional thermal pasteurization. The easiest and most available method in most areas to the reduction of microbial load is thermal processing and especially pasteurization between 70 and 95°C. Nevertheless, heat methods can readily cause losses of heat-sensitive nutrients, and can also cause undesirable cooked tastes when not done well. As a result, the non-thermal preservation technologies have become a major research interest as promising alternatives. They are high-pressure processing (HPP), ultraviolet (UV) radiation, pulsed light, cold plasma, ultrasound, and membrane filtration. The purpose of these non-thermal procedures is to inactivate microorganisms without causing significant destruction of nutrients or sensory changes to provide a better preservation of the fresh quality of palm sap during a long period of storage (Saengkrajang et al., 2021; Manzano, 2024).

Among them, HPP between 400 and 600 MPa have shown great efficiency with their ability to inactivate microbes and preserve the nutritional and sensorial value of the product (Podolak et al., 2020). Recent studies have also pointed to the possibility of controlled fermentation using specific strains of yeast that would lead to more consistent flavour and food-safety concerns compared to spontaneous processes within the wine industry (Gardner, 2022). With hygienic tapping, clarification/microfiltration, mild heat and selective application of preservatives, toddy can be stabilized without loss of traditional identity (Punzalan et al., 2025). Similar breakthroughs in the area of preserving coconut water, especially by means of forward osmosis combined with HPP, have shown promise

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of long shelf-life (refrigerated) retention of amino acids, phenolics, as well as vitamin C (Liew et al., 2023).

This research came up in a bid to fill the existing gap between the classical toddy fermentation system and the modern mode of beverage preservation techniques.

Particularly, the goals were as follows: (i) to ferment coconut water under repeatable conditions, (ii) to filter and pasteurize coconut water in order to stabilize microorganisms, (iii) to compare the efficacy of the chemical (sodium metabisulfite) compound and the natural (vinegar) preservative on extending the shelf-life, (iv) to track the physicochemical and nutritional changes of the product during storage, and (v) to determine the antimicrobial properties of toddy against some species of bacteria.

The novelty of this work is putting forward toddy as a toddy developed as microbiologically safe, nutritionally rich, and sensorial acceptable functional drink with a mix of controlled fermentation procedure and integrated preservation, thus validating the traditional practices with contemporary clean-label consumerism trends.

2. METHODOLOGY

2.1. Collection and Fermentation of Tender Coconut Sample

Tender coconuts were purchased at suppliers of Mylapore, Chennai (India). Fresh coconut water (500 mL) was taken aseptically and its initial pH noted. The microbial colony counts were done by spreading onto Nutrient Agar (NA), MRS Agar, and Potato Dextrose Agar (PDA) (Peterle et al., 2024). A 500 mL of coconut water was inoculated with *Saccharomyces cerevisiae* (instant dry yeast, commercial source; 2 tsp) and sugar (2 tbsp.) and incubated at 28±2°C for 8 h followed by pH and microbial count analysis (Anyiam & Opara, 2023).

2.2. Filtration and Pasteurization of Tender Coconut Sample

The samples were serially filtered (muslin cloth, Whatman No. 3, centrifuged at 5000 rpm/10 min, nano-charged filter, 0.22 microns syringe filter). The filtrate was uniformly subdivided into four treatments that were; SM-1 (0.05 % sodium metabisulfite), SM-2 (0.10% sodium metabisulfite), V (5% vinegar), and NP (no preservative). Each were pasteurized at 60°C in 10 min and refrigerated under 4^{o}C (Babu et al., 2020).

2.3. Quality Assessment of Fermented Coconut Sample

2.3.1. Microbial Analysis of Fermented Coconut Sample

The microbial quality was monitored at refrigerated conditions (7-61days). To determine total viable counts, samples in sterile saline were serially diluted and 0.1mL aliquots plated on Plate Count Agar (PCA).

The plates were next incubated at 37°C, and the number of colonies counted as log cfu /mL (Mahnot et al., 2019).

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2.3.2. Physicochemical Analysis of Fermented Coconut Sample

The pH of each of the samples was established using a digital pH meter (Eutech Instruments, Singapore) calibrated. The alcohol content was calculated by potassium dichromate method and ethanol standards 0.10% were used as the calibration standard and percentage v/v was read out. The quantity of reducing sugars was determined using DNSA method with measurements being taken at 540nm in universal spectrophotometer (Shimadzu, Japan). The reference was glucose, and the values presented in g/L (Deshpande and Nimbkar, 2018; Zhang and Li, 2019; Miller, 1959).

2.3.3. Sensory Evaluation of Fermented Coconut Sample

Sensory properties such as the taste, smell and colour were determined by use of a trained panel of 10 panel lists based on standard sensory evaluation procedures (Adubofuor, 2020). SM-1, SM-2, V and NP samples were added to coded glass beakers at room temperature. A hedonic scale was applied (9-point; 1 = dislike extremely, 9 = like extremely). The acceptability was worked out as the arithmetic mean of each of the attributes.

2.3.4. Antimicrobial Activity of Fermented Coconut Sample

The toddy samples were quantified against the pathogens of Escherichia coli (0157:H7), Staphylococcus aureus (ATCC 29213), Salmonella Typhi (ATCC 14028), and Corynebacterium sp (ATCC11045) using agar well diffusion technique on Mueller Hinton Agar (MHA) (Balouiri et al., 2015). The samples were added by 100 L of the sample into each of the Wells (6 mm) and the plates were incubated at 37°C after 24 h. The inhibition zones were measured in millimetres using a digital calliper.

2.3.5. Nutritional Analysis of Fermented Coconut Sample

The toddy was tested in the Tamil Nadu Test House Pvt. Ltd. (NABL-accredited, India) to determine the nutritional value. The energy content was determined by the use of the FAO method (FAO, 2003). The carbohydrate calculation was examined using the Indian Standard 1656:2007 (Bureau of Indian Standards, 2007) and estimation of dietary fibre was carried out using the AOAC 926.09 (AOAC, 1990). The fat analysis sources were ensured by keeping the IS 1479, Part II: 2018 (Bureau of Indian Standards, 2018) stable and protein analysis was executed through the IS 7219:1973 (Bureau of Indian Standards, 1973). The sugar content was measured with the FSSAI Manual of Methods (FSSAI, 2016). All the findings were presented in g/100 mL or kcal/100 mL according to the parameter under measurement.

2.3.6. Statistical Analysis

The experiments were repeated thrice and presented as means +- SD. Data obtained in microbial counts, physicochemical parameters, and sensory assessment were analysed using one-way analysis of variance (ANOVA). Statistical analysis was performed by using SPSS version 26.0 (IBM Corp., USA).

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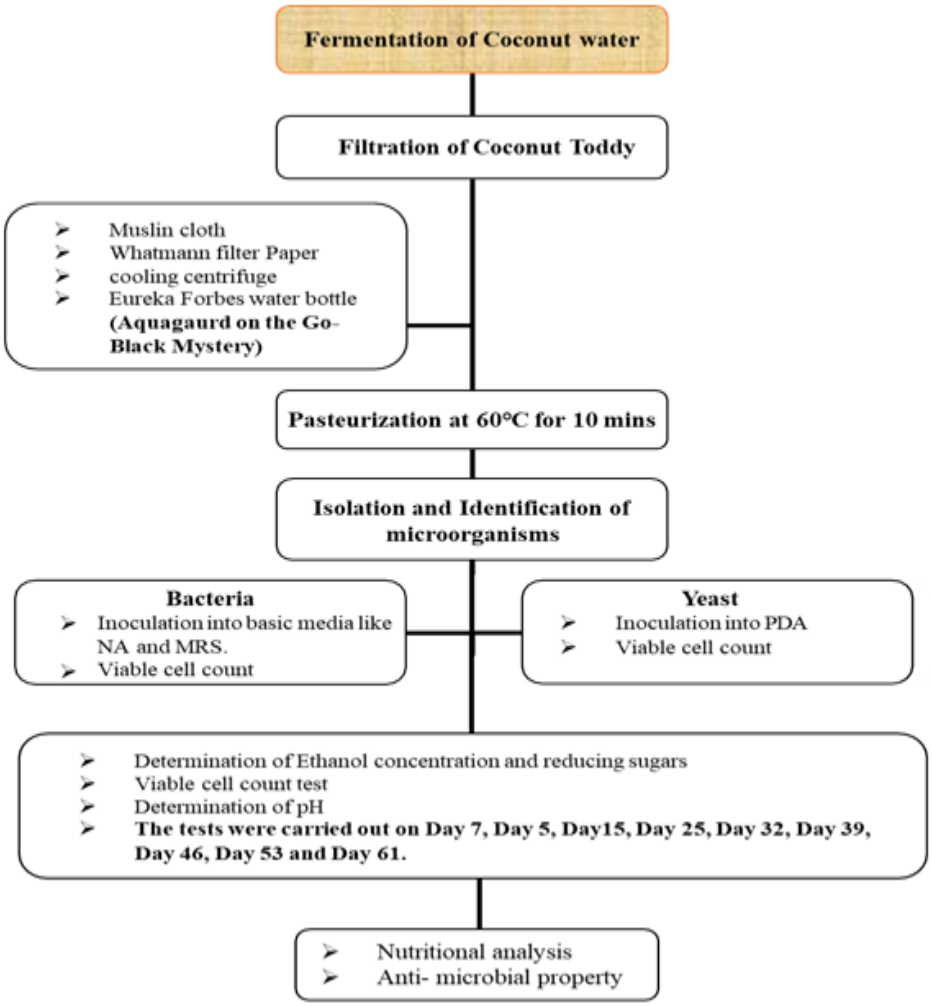

Figure 1: Fermentation, Filtration, Pasteurization, and Microbial Analysis of Coconut Toddy Experimental Workflow.

This flowchart shows the process of experiments in processing coconut water into the toddy through fermentation, filtration using other techniques, pasteurization at 60 o C with 10 minutes, and finally isolation and identification of microorganisms. The bacteria isolates were grown on NA and MRS culture media, and the yeasts on PDA culture media, after which viable cells count was assessed.

3. RESULTS

3.1. Characteristics of Collected Tender Coconut Sample Before and After Fermentation Process

Fresh, tender coconut water was taken and characterized before fermentation (Figure 2). The liquid was clear to cloudy and possessed a naturally sweet flavour thus justifying its

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selection as a toddy fermentation medium. The sensory properties are in line with the previous findings regarding the properties of fresh coconut water, which is clear and mildly sweet, which allows cultivating microbial fermentation.

After about 8 hours of fermentation, the toddy changed in colour subsequently becoming cream-colored (Figure 2D). This change was being credited to the metabolic activity of yeast which starts the breakdown of sugar and forming metabolites that change the physical properties of the drink. The partial fermentation which had taken place had given the aroma a mild character, which indicated that the ferment was not yet in a far-advanced state.

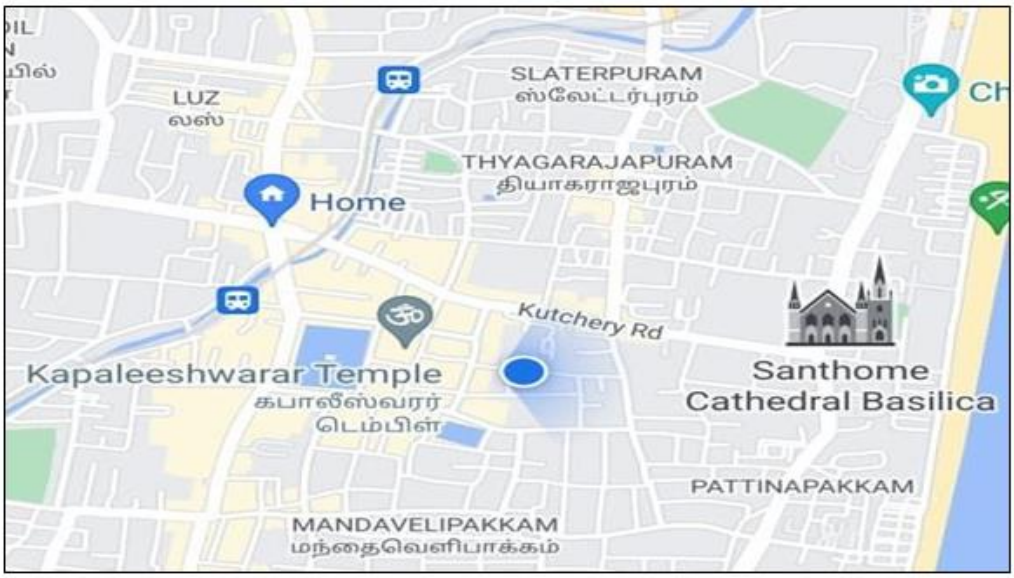

Figure 2: Collection Site and Representative Samples of Fresh Toddy

Figure 2 (a): Tender coconut Sample was collected from local street vendor in Mylapore

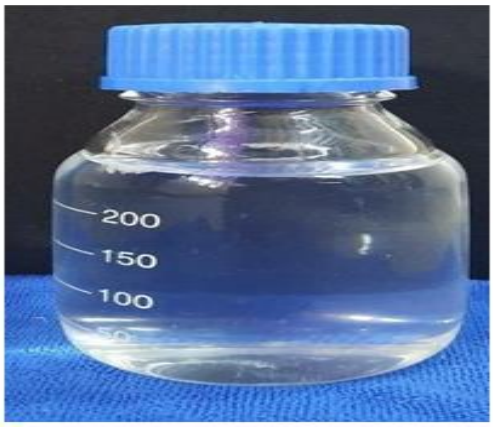

Figure 2 (b): Tender Coconut water

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Figure 2 (c): Fermented Coconut water/ Toddy

3.2. Filtration and Pasteurization of Collected Tender Coconut Sample After Fermentation Process

After fermentation the toddy was filtered in order to eliminate suspended substances, microbial loading. The result of this process was a more understandable and legible product thus enhancing its appearance. Filtration was therefore an important aspect in creating a better sensory appeal and at the same time reducing microbial contamination something that is important in the stabilization of products. To ascertain the safety microbiologically (without interfering with the sensory attributes), this toddy sample underwent Pasteurization. The method did not drastically change the smell, taste, or colour of the drink meaning that the thermal processing was sufficient in destroying the microbes without killing the natural stimuli organoleptic character of toddy.

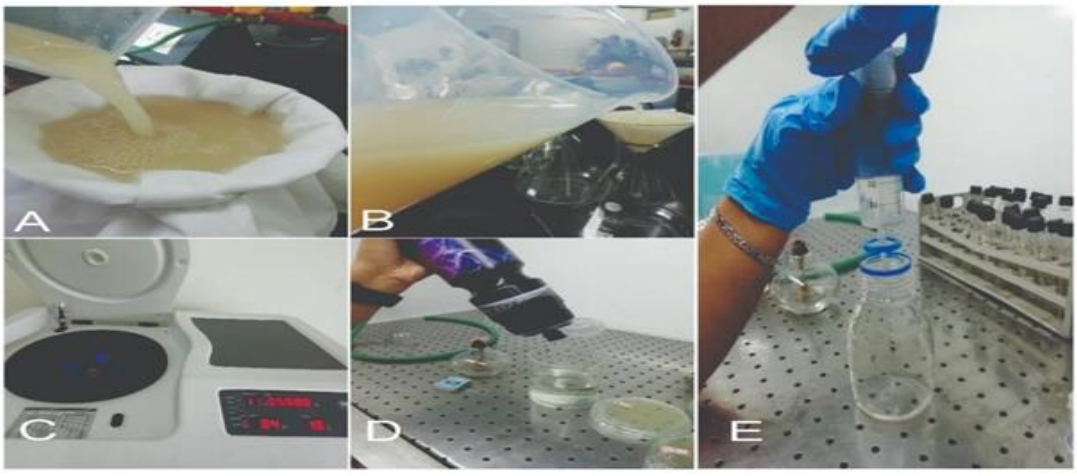

Figure 3: Processing and Preparation of Toddy Samples for Laboratory Analysis

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3.3. Quality Assessment of Toddy sample

3.3.1. Effect of Filtration and Pasteurization of Toddy sample

The pH of fresh coconut water was 6.0 but reduced to 5.38 at the end of the fermentation period, indicating the formation of organic acids. Further stabilization of the pH was by filtration and pasteurization to 5.08. The findings of the analysis of the microbial load demonstrated that the nutrient agar plates, before and after the fermentation was done, produced colonies that could not be enumerated.

This was a testament to the fact that there was high microbial activity during fermentation In MRS agar, colony counts increased by ten percent or 370 cfu /ml prior to fermentation and 419 cfu/ml later after fermentation whereas in PDA, colony counts increased by eight percent or 287 cfu/ml before and 340 cfu/ml after fermentation. Interestingly, after filtering and pasteurizing all the media indicated no growth of microbial. It can then be concluded that all the microbes were killed during this process.

3.3.2. Physiochemical and Microbial Analysis of Toddy sample

The effect of different preservatives in storage of toddy was determined. Sample S1 (0.05% sodium metabisulfite) showed no microbial growth with the pH value of 5.08 +/- 0.02 retained after 61 days. We kept alcohol between 2.08 +/- 0.02 (v/v), reducing sugars were kept at 4.72 +/- 0.02. Sample S2 (0.10% sodium metabisulfite) performed similar to S1 and identified that the preservative at both concentrations was working fine. Sample S3 (5 % vinegar) also exhibited stability without any loss in taste aroma and appearance of toddy, indicating the acceptability of this sample to use as a natural preservative. However, in contrast to Sample S4 (control without preservative), the changes were progressive during the storage. pH reduced to 4.62 as compared to 5.08 on day 61, and microbial growth was observed on the 53rd day. Alcohol level went up drastically, reaching 3.87%, and reducing sugars decreased correspondingly, to 3.75%, and it proves that we have active secondary fermentation and spoilage.

3.4. Anti-Microbial Property of Toddy sample

The toddy was assessed using antimicrobial activity against a few of the selected bacterial strains. The beverage represented the most significant inhibitory action against *Corynebacterium sp.*, and this suggests a powerful antimicrobial capacity in the beverage. Nevertheless, the minimal inhibition was noted against *Staphylococcus aureus*, so there was a selective antimicrobial spectrum. These findings confirm the importance of the acidic nature and the alcohol content of toddy, in inhibiting the growth of microbes.

3.5. Nutritional Analysis of Toddy sample

The nutritional profile of toddy was ascertained using NABL - accredited testing. The beverage had the lowest energy of 14.56 Kcal/100 g, thus showing that it is low in calories. The percentage of carbohydrates was 0.7319 g/100 g, and that of total sugar was surprisingly higher at 5.120 g/100 g which is the constituent of natural sugar present in coconut water. Protein content was determined to be 0.44 g/100 g and fat 1.097 g/100 g;

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fibre content was found to be negligible, 0.0019 g/100 g. Such values attest toddy as a low-calorie beverage that adds minimal macronutrients, as noted before in different studies about coconut-derived beverages.

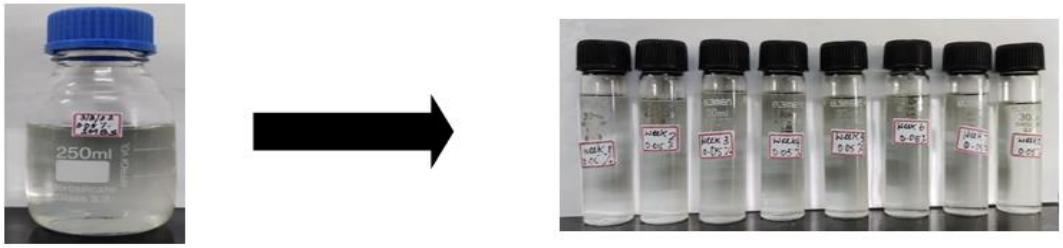

Figure 4 (a): Treatment with 0.05% Sodium Metabisulfite (SAMPLE SM-1)

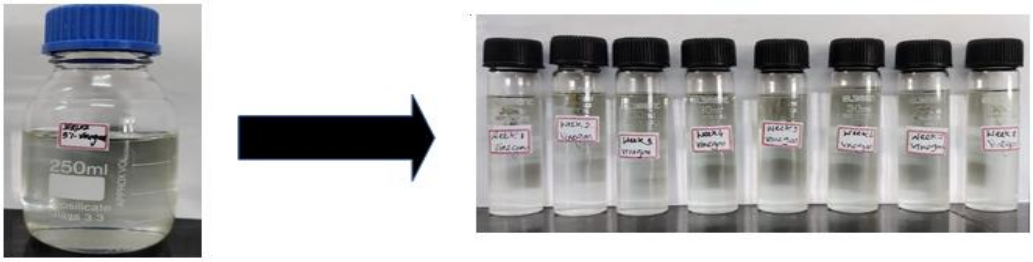

Figure 4 (b): Toddy treated with 5%White Vinegar (SAMPLE- V)

Figure 5: Microbial growth of Fermented Samples on Agar Plates

The representative image demonstrates fermented samples SM-1, SM-2 and V on agar plates. The differences in coloration and surface appearance indicate the differences in the growth of the microbes and metabolite production across the samples which indicates the microbial diversity and fermentation.

Table 1: Sensory evaluation of the prepared toddy sample

S. No	Properties	Appearance
1.	Colour	Clear and transparent
2.	Odour	Mild aroma
3.	taste	Sweet and light taste

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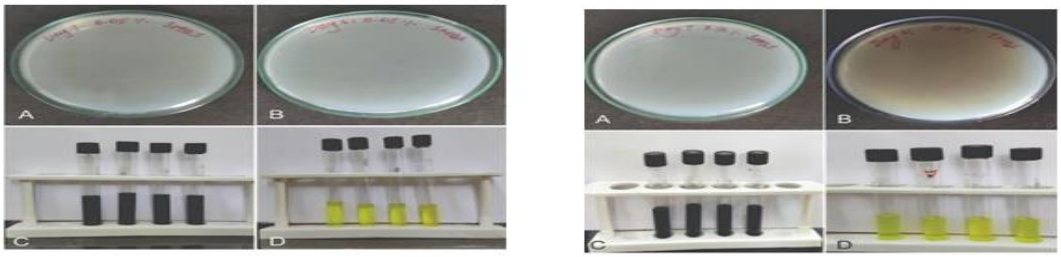

Figure 6: Comparative analysis of Fermented coconut sample parameters of samples

Table 2: Comparative analysis of storage and stability of toddy

Parameters	Day	No Preservative	SM1	SM2	White Vinegar
pH	7	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02
	15	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02	5.07 ± 0.02
	25	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02
	32	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02
	39	5.07 ± 0.02	5.07 ± 0.02	5.07 ± 0.02	5.07 ± 0.02
	46	5.06 ± 0.02	5.06 ± 0.02	5.06 ± 0.02	5.06 ± 0.02
	53	4.91 ± 0.02	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02
	61	4.62 ± 0.02	5.08 ± 0.02	5.08 ± 0.02	5.08 ± 0.02
Viable Count (cfu/ml)	7	Nil	Nil	Nil	Nil
	15	Nil	Nil	Nil	Nil
	25	Nil	Nil	Nil	Nil
	32	Nil	Nil	Nil	Nil
	39	Nil	Nil	Nil	Nil
	46	Nil	Nil	Nil	Nil
	53	11	Nil	Nil	Nil
	61	37	Nil	Nil	Nil
Alcohol (% v/v)	7	2.08 ± 0.02	2.08 ± 0.02	2.08 ± 0.02	2.08 ± 0.02
	15	2.08 ± 0.02	2.08 ± 0.02	2.07 ± 0.02	2.07 ± 0.02
	25	2.08 ± 0.02	2.07 ± 0.02	2.07 ± 0.02	2.08 ± 0.02
	32	2.08 ± 0.02	2.08 ± 0.02	2.08 ± 0.02	2.08 ± 0.02
	39	2.08 ± 0.02	2.08 ± 0.02	2.06 ± 0.02	2.08 ± 0.02
	46	2.07 ± 0.02	2.06 ± 0.02	2.06 ± 0.02	2.08 ± 0.02
	53	2.84 ± 0.02	2.08 ± 0.02	2.06 ± 0.02	2.08 ± 0.02
	61	3.87 ± 0.02	2.08 ± 0.02	2.06 ± 0.02	2.07 ± 0.02
Reducing Sugars (%)	7	4.72 ± 0.02	4.72 ± 0.02	4.72 ± 0.02	4.72 ± 0.02
	15	4.72 ± 0.02	4.72 ± 0.02	4.73 ± 0.02	4.72 ± 0.02
	25	4.72 ± 0.02	4.71 ± 0.02	4.71 ± 0.02	4.71 ± 0.02
	32	4.72 ± 0.02	4.72 ± 0.02	4.73 ± 0.02	4.71 ± 0.02
	39	4.72 ± 0.02	4.72 ± 0.02	4.73 ± 0.02	4.71 ± 0.02
	46	4.72 ± 0.02	4.73 ± 0.02	4.73 ± 0.02	4.71 ± 0.02
	53	4.18 ± 0.02	4.72 ± 0.02	4.73 ± 0.02	4.71 ± 0.02
	61	3.75 ± 0.02	4.72 ± 0.02	4.72 ± 0.02	4.71 ± 0.02

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Table 3: Anti-microbial property of coconut toddy

Table 3: Anti-microbial property of coconut toddy			
ORGANISM	ZONE OF INHIBITION (mm)		
	SM-1	SM-2	V
Staphylococcus aureus (ATCC 29213)	5	9	4
Escherichia coli (0157:H7)	12	17	9
Salmonella typhi (ATCC 14028)	6	12	6
Corynebacterium sps (ATCC11045)	15	18	13

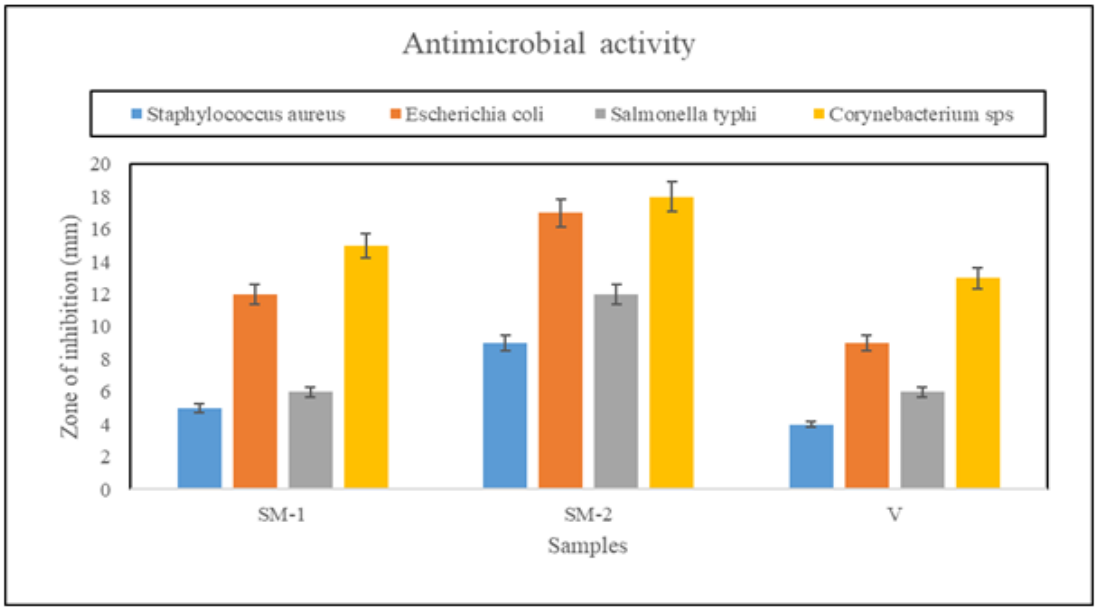

Table 4: Nutritional analysis of toddy samples

S. No	Parameter	Results
1	Energy	14.56 Kcal/100 g
2	Carbohydrate	0.7319 g/100 g
3	Total Fibre	0.0019 g/100 g
4	Total Fat	1.097 g/100 g
5	Total Protein	0.44g/100 g
6	Total Sugar	5.120g/100 g

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4. DISCUSSION

The fresh tender coconut water tested in the present study was reported to be colourless and moderately opaque and naturally sweet in flavour, which corresponds to previous reports of coconut and palm sap before fermentation as mildly sweet and nutrient-rich liquids (Baskaran & Radhakrishnan, 2024). This unfermented composition was a perfect substrate to the microbial activity specifically the yeasts and lactic acid bacteria which quickly transformed the physicochemical properties of the beverage upon fermentation. After 8 hours of collection, the toddy turned cream in colour with a slight yet, distinct smell, which can be attributed to the active proliferation of yeast and partial contentment of sugars. This kind of transformation of sensory properties has remained a consistent characteristic in the researches by palm sap, coconut sap, and other naturally fermentable exudates of plants.

These alterations are indicative of the biochemical conversion of fermentable sugars to ethanol, lactic acids and other organic acids and release of volatile compounds all of which make a difference in appearance, flavour and aroma. Filtration and light pasteurization produced transparent and clear samples of toddy without the significant change in taste or aroma. This underscores the topicality of these mild treatments in the harmonization of microbial stabilization with sensorial acceptability, which is a very important aspect of consumer perception. Studies on palm sap and other customary drinks have revealed that low-temperature thermal treatment (60-72^{o}) provides microbial protection without the sacrifice of volatile aroma compounds and bioactive phytochemicals (Hai et al., 2024). The treatments herein applied can therefore be marketed as clean label, consumer friendly preservation steps that are not only clear and stable but also with minimum loss of the traditional sensory properties.

Preservative's addition was another factor that contributed to the maintenance of microbial safety, as well as physicochemical stability of long-term storage. Within 61 days, sodium metabisulfite (0.05% and 0.10%) and 5 percent vinegar demonstrated the ability to stabilize pH, alcohol concentration (2.08% v/v) and reducing sugar content (4.72%). These results agree with the literature that shows that sodium metabisulfite presents antimicrobial and antioxidant effects in sugar-prone matrices (Alimohammadi et al., 2021). Surprisingly, vinegar which is also a natural source of acetic acid was also effective, making it an effective clean-label preservative that can be used instead of synthetic preservatives. As consumers are getting more interested in the minimally processed, preservative-free products, further use of vinegar might boost its market acceptance and underpin natural preservation trends in the beverage sector (https://www.mordorintelligence.com/industry-reports/vinegar-market). In untreated samples, on the contrary, the state became significantly worse. At day 61, the pH decreased (5.08 4.62), microbial growth was observed (day 53), ethanol concentration was almost doubled (3.87% v/v), and the reducing sugars were reduced significantly (to 3.75%). This curve reflects the uncontrolled fermentation of unpreserved toddy, which is in line with the report that palm toddy became strongly alcoholic and unpalatable two days

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after tapping (Sumerta et al., 2025). These tendencies in spoilage lead to the necessity of preservation to make toddy commercially viable, especially in order to sell it as a functional, slightly alcoholic and refreshing drink instead of a fast-fermenting product.

Toddy also contributes to its functionality with the added antimicrobial properties. The beverage exhibited selective inhibition behaviour on test organisms with the highest activity against *Corynebacterium sp*. and the lowest against the *Staphylococcus aureus*. This trend has been in line with findings of attributing antibacterial features of toddy to ethanol, organic acids, and phytochemicals produced on the fermentation process (Das & Tamang, 2023).

The low inhibition of S. aureus indicates species-specific resistance and indicates future studies on the antimicrobial activity of toddy components which can have potential in functional food, or antimicrobial nutraceuticals.

Nutritional analysis showed that toddy is a light refreshing, low-calorie drink (14.56 kcal/100 g) having small amounts of protein (0.44 g/100 g), fat (1.097 g/100 g), carbohydrate (0.7319 g/100 g), and total sugars (5.12 g/100 g) with minimal amount of dietary fibre. In comparison with coconut water that is seen as hydrating due to the presence of simple sugars in the form of minerals (Yong et al., 2009; Singh et al., 2020), today is the one with similar hydrating effects but with additional potential advantages, including functional fermentation-derived bioactives and a mild antimicrobial effect. The nutritional profile underpins the targeting of toddy as a functional beverage that may have other health usefulness other than being a hydrating beverage.

Taken together, these observations underscore the concept that a combination method of filtration, pasteurization and natural or mild chemical preservatives can be composed to greatly increase shelf life of toddy without sacrificing sensory qualities or safety. This is indicative of larger global trends in preserving food with minimal processing, natural antimicrobials and consumer-centric clean-label products. The proved successfulness of vinegar as a preservative is particularly remarkable, and it opens the opportunity of implementing sustainable and natural preservation methods in tropical areas where cold-chain logistics is at its weakest.

The next steps in research should be pilot-scale validation, investigation of plant-derived antimicrobial alternatives, and the characterization of the bioactive compounds that contribute to the antimicrobial effect of toddy. These studies would help to formulate safe, commercially viable, and consumer preferred fermented drinks both in local and international markets.

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