International Journal of Food Science and Nutrition
www.foodsciencejournal.com
ISSN: 2455-4898
Received: 27-04-2026, Accepted: 28-05-2026, Published: 12-06-2026
Volume 11, Issue 2, 2026, Page No. 227-238

Development of a coconut vinegar generator for efficient vinegar production

Gowtham S B[1], Rajendra B[2], Ravi K K[3], Saketh R K[3], Prathima K[3], Rohit L[3], Gangaraju P[3]
[1] Assistant Professor, Department of Agricultural Engineering, Aditya University, Surampalem, Andhra Pradesh, India
[2] Assistant Professor, Department of Agriculture, Jagannath University, Chaksu, Jaipur, Rajasthan, India
[3] Department of Agricultural Engineering, Aditya University, Surampalem, Andhra Pradesh, India
Corresponding Author: Gowtham S B
DOI: https://doi.org/10.66856/ijfsn.2026.11.2.11078

Abstract
Waste coconut water generated during mature coconut processing represents an underutilized organic by-product that can cause disposal problems when released without treatment, yet its fermentable sugars and nutrients make it suitable for sustainable value addition. This study aimed to develop and evaluate a low-cost coconut vinegar generator for converting waste coconut water into vinegar under controlled laboratory conditions. The generator was fabricated using food-grade high-density polyethylene (HDPE) materials and simple fittings, including an HDPE container, inlet pipe, outlet valve, funnel, cap, and sealing components, to provide hygienic handling, controlled filling, and convenient product recovery. Coconut vinegar was produced through a sequential two-stage fermentation process. In the first stage, supplemented coconut water was inoculated with *Saccharomyces cerevisiae* to convert fermentable sugars into ethanol through alcoholic fermentation. In the second stage, mother vinegar containing *Acetobacter* culture was added, and aerobic conditions were maintained to oxidize ethanol into acetic acid. The developed unit operated satisfactorily during fermentation, draining, and cleaning, with no major leakage or instability. The final vinegar showed acceptable physicochemical properties, with pH values of 2.9 –3.3, acetic acid content of 5–6%, and moisture content of 96–98%, indicating effective acidification and product stability. Sensory evaluation indicated clear appearance, pleasant acidic aroma, and acceptable sour taste. The low fabrication cost made the system suitable for small-scale and rural production. Overall, the developed generator provided an economical and sustainable approach for valorising waste coconut water, supporting environmental protection, value addition, future scale-up of decentralized vinegar production, and practical fermentation-based rural enterprise development opportunities.

Keywords: Coconut vinegar, coconut water waste, *Saccharomyces cerevisiae*, *Acetobacter*, acetic acid fermentation, food-grade HDPE generator, sustainable value addition

Introduction

Coconut (*Cocos nucifera* L.) is an economically important perennial crop cultivated throughout tropical and subtropical regions, where it supports food, beverage, oil, fibre, and rural livelihood systems. Recent reviews of coconut water research report that global coconut cultivation occupies more than 12 million ha and produces more than 60 million tonnes of coconuts annually, with major production concentrated in Asia and other humid tropical regions [10]. The coconut fruit is processed into copra, coconut oil, coconut milk, desiccated coconut, nata de coco, tender coconut beverages, and other value-added products. During these operations, especially in mature coconut kernel-based industries, large quantities of coconut water are separated from the nut. Tender coconut water has a well-established beverage market, but mature coconut water is frequently underutilized because changes in maturity alter its sensory acceptability and commercial value [6, 13]. Nevertheless, coconut water contains fermentable sugars, minerals, amino acids, organic acids, and other soluble constituents that make it a suitable substrate for microbial bioprocessing rather than a waste stream [10, 12].

The disposal of waste coconut water is a persistent problem in coconut-processing areas. When discharged without treatment, the liquid decomposes rapidly because of its high moisture content and readily metabolizable nutrients. This can lead to objectionable odour, microbial proliferation, increased organic load in drainage channels, attraction of insects, and local environmental pollution. Xu *et al* [12]. noted that mature coconut water is commonly discarded in the coconut kernel-processing industry despite its nutritional potential, creating both resource loss and environmental burden. Similar studies on mature coconut water fermentation emphasize that this by-product can support microbial growth and therefore should be redirected into controlled bioconversion processes instead of being released into the environment [11, 5]. From a food-engineering perspective, the challenge is not the absence of nutrients in coconut water but the lack of simple, hygienic, and economically feasible systems for stabilizing and converting it into products with longer shelf life and higher market value.

Value addition to coconut by-products is therefore central to sustainable coconut processing. The conversion of waste coconut water into fermented products supports circular bioeconomy principles by reducing organic waste, improving material recovery, and creating additional income opportunities for small processors. Fermentation is particularly attractive because it uses microbial metabolism to preserve perishable substrates while generating desirable sensory and functional attributes. Recent research trends in coconut water processing include the use of advanced preservation technologies, controlled starter cultures, metabolomics-based flavour profiling, and optimization of fermentation conditions to improve product consistency [10, 12]. In this context, coconut vinegar is a promising product

because it transforms a low-value liquid residue into a stable acidulant with culinary, preservative, and potential functional-food applications.

Vinegar production is based on a sequential two-stage fermentation process. In the first stage, fermentable sugars are converted into ethanol through alcoholic fermentation, usually by yeasts such as *Saccharomyces cerevisiae*. In the second stage, ethanol is oxidized into acetic acid by acetic acid bacteria, especially species of *Acetobacter*, *Komagataeibacter*, and related genera, under aerobic conditions [8, 7]. For coconut water, adjustment of soluble solids is often necessary because mature coconut water may have lower sugar concentration than fruit juices or coconut sap [5]. showed that coconut water vinegar production can require sucrose adjustment before yeast fermentation and that inoculum size and back-slopping can reduce processing time. Trinh *et al* [11]. similarly demonstrated coconut water vinegar preparation by alcoholic fermentation with baker's yeast followed by acetous fermentation using *Acetobacter aceti* starter powder. These findings confirm that the biochemical pathway is well established, but process control remains essential for reliable production.

The microbiological roles of yeast and acetic acid bacteria are complementary. During alcoholic fermentation, *S. cerevisiae* metabolizes sugars through glycolysis and alcoholic fermentation pathways, producing ethanol, carbon dioxide, and secondary metabolites that influence aroma. This stage is favoured by adequate fermentable sugar, suitable temperature, and oxygen-limited conditions. During acetic fermentation, *Acetobacter* spp. oxidize ethanol to acetaldehyde and then acetic acid through membrane-bound dehydrogenase systems; this oxidative metabolism requires oxygen transfer and tolerance to ethanol, acetic acid, and temperature stress [7, 3]. Therefore, a vinegar generator must support both anaerobic or oxygen-limited alcoholic fermentation and aerobic acetification while minimizing contamination. Recent industrial vinegar research highlights the importance of starter culture selection, aeration, temperature control, microbial stress tolerance, and integrated quality monitoring for achieving reproducible acidity and flavour [8, 3, 9].

Coconut vinegar has multiple applications in food preservation, health-oriented products, and small-scale agro-industry. As a natural acidulant, vinegar lowers pH, enhances sour flavour, and inhibits spoilage and pathogenic microorganisms, making it useful in pickling, sauces, marinades, condiments, and preservation systems. Reviews of vinegar functionality describe acetic acid, phenolic compounds, organic acids, and other bioactive constituents as contributors to antimicrobial, antioxidant, and metabolic effects, although such benefits depend on raw material, fermentation method, and final composition [1]. Coconut vinegar specifically has attracted interest as a fermented product from mature coconut water; metabolomic evaluation has shown that coconut water vinegar can contain flavour-active esters, organic acids, and nutritionally relevant metabolites, with ageing improving sensory quality [12]. Experimental work has also investigated coconut vinegar for antioxidant-related physiological effects, suggesting growing interest in its development as a fermented functional product [4]. In addition, sensory and packaging studies indicate that consumer acceptability and labelling are important for commercialization of coconut water vinegar [2].

Despite these advances, a practical research gap remains in the design of low-cost vinegar-generation systems suitable for small-scale producers, educational laboratories, and rural value-addition units. Industrial acetators and submerged fermentation systems provide higher efficiency but are often expensive and technically demanding. Traditional open-vessel methods are simpler but may suffer from contamination, poor aeration control, leakage, inconsistent acidity, and difficulty in hygienic handling. Much of the existing coconut vinegar literature focuses on substrate formulation, inoculum optimization, fermentation kinetics, metabolite profiling, or sensory quality [5, 11, 12]; comparatively less attention is given to the fabrication of a simple apparatus that integrates food-grade construction, controlled filling, safe draining, breathable protection, ease of cleaning, and low capital cost. Such a generator is needed to make coconut water vinegar production accessible to small processors while maintaining basic food-safety and process-control requirements.

The development of a simple, hygienic, and economical coconut vinegar generator is therefore significant for both sustainability and food-processing innovation. A food-grade container with an inlet arrangement, outlet valve, funnel, and appropriate sealing or breathable covering can improve liquid handling, reduce spillage, support batch fermentation, and facilitate separation of fermented vinegar from sediment or microbial biomass. When combined with nutritional and quality evaluation, the system can provide evidence of both process success and product safety. Important analytical parameters include moisture content, residual carbohydrates, protein, fat, acetic acid concentration, pH, titratable acidity, microbiological quality, and sensory acceptability. A low pH and sufficient acetic acid content indicate successful acetification and preservation potential, while microbiological tests such as total plate count, yeast and mould count, and coliform testing help confirm hygienic processing. Sensory evaluation further determines whether the product is acceptable in terms of colour, aroma, taste, and overall preference.

Materials and Methods

1. Materials Used for Developing of Coconut Vinegar Generator

The study was conducted at laboratory scale using waste coconut water as the principal fermentation substrate. Fresh coconut water was collected from mature coconuts and was filtered to remove suspended fibrous particles and other visible impurities before fermentation. The use of coconut water as a fermentable substrate was selected because it contains soluble sugars, minerals, amino acids, and organic constituents that support microbial metabolism during vinegar production [9, 16, 15]. Food-grade sugar was used to increase the fermentable soluble solids of the substrate, since mature coconut water generally contains lower sugar concentration than many fruit juices and may require supplementation for efficient ethanol formation [8, 14]. Commercial baker's yeast, identified as Saccharomyces cerevisiae, was used as the alcoholic fermentation organism. Mother vinegar containing active acetic acid bacteria, mainly Acetobacter species, was used as the starter culture for acetification. Citric acid was used as a food-grade acidulant for pH adjustment when required, while ammonium sulphate was used as a nitrogen source to support yeast growth and fermentation activity. The

construction materials used for the generator consisted of a food-grade high-density polyethy lene (HDPE) container, a food-grade plastic inlet pipe, a plastic outlet pipe with tap arrangement, a plastic funnel, a cap, rubber or silicone sealing materials, and other minor fittings. HDPE was selected because it is lightweight, chemically resistant, non-corrosive, and suitable for contact with acidic food materials when food-grade quality is ensured. All components that came into contact with the fermenting substrate were washed, rinsed, and sanitized before use to reduce the possibility of contamination during fermentation.

2. Development of Coconut Vinegar Generator

2.1 Design of the Generator

A batch-type coconut vinegar generator was designed to support the sequential alcoholic and acetic fermentation of coconut water. The design was kept simple so that it could be fabricated using locally available materials without requiring sophisticated machining or expensive control systems. The generator consisted of a fermentation vessel, an inlet arrangement for charging the substrate and starter culture, an outlet valve for controlled withdrawal of vinegar, and a lid or cap assembly to protect the fermenting liquid from dust and insects. The arrangement was intended to permit hygienic filling, safe fermentation, easy sampling, and convenient draining of the finished product. The design also considered the different oxygen requirements of the two fermentation stages. Alcoholic fermentation required restricted oxygen conditions for ethanol production by yeast, whereas acetic acid fermentation required oxygen availability for oxidative conversion of ethanol into acetic acid by acetic acid bacteria [11, 10].

2.2 Selection of Food-Grade Materials

The materials were selected on the basis of food safety, resistance to acidic conditions, ease of cleaning, availability, cost, and suitability for repeated laboratory-scale use. A food-grade HDPE container was chosen as the main fermentation chamber because the final product was expected to be acidic and therefore required a non-reactive vessel. Plastic pipes and fittings were selected to avoid corrosion and metallic contamination. Rubber or silicone sealing materials were used at the joints to prevent liquid leakage and entry of contaminants. The use of inexpensive food-contact materials was emphasized because the purpose of the study was to develop a generator appropriate for small-scale and rural value-addition units.

2.3 Fabrication of Container

The HDPE container was cleaned thoroughly and inspected for cracks, weak points, and manufacturing defects. Openings were marked at suitable positions for the inlet and outlet assemblies. The outlet opening was positioned near the lower portion of the container to facilitate recovery of the fermented vinegar without tilting the vessel, while leaving sufficient clearance to reduce the withdrawal of settled residues. The inlet opening was prepared on the upper portion of the container to permit charging of coconut water, sugar solution, nutrients, yeast inoculum, and mother vinegar. Holes were prepared carefully to match the diameter of the selected pipes and fittings, and the edges were smoothed to ensure proper seating of the sealing materials.

2.4 Installation of Inlet Pipe

The inlet pipe was fixed in the prepared upper opening of the container. It was positioned to allow the substrate to enter the vessel without excessive splashing. The pipe was secured using suitable fittings and sealed with rubber or silicone material to prevent external contamination and leakage. The inlet system was designed to make the addition of liquids and microbial cultures easier during laboratory operation. It also reduced direct opening of the fermentation vessel, thereby helping to maintain hygienic conditions.

2.5 Installation of Outlet Pipe

The outlet pipe and tap assembly were installed at the lower portion of the container. The tap was selected to provide controlled flow during sampling and final collection of vinegar. After installation, the outlet joint was sealed tightly and checked for mechanical stability. The outlet arrangement was important because it allowed clarified vinegar to be withdrawn with minimum disturbance to sedimented yeast cells, bacterial film, or suspended particles. Controlled draining also reduced product loss and improved ease of operation during post-fermentation handling.

2.6 Funnel and Lid Assembly

A plastic funnel was attached to the inlet side to facilitate clean transfer of coconut water and other ingredients into the generator. The funnel minimized spillage during filling and improved the accuracy of substrate addition. The lid or cap assembly was prepared to protect the fermentation medium from dust, insects, and accidental contamination. During alcoholic fermentation, the vessel was covered to maintain relatively oxygen-limited conditions. During acetic acid fermentation, the covering was modified by using breathable cloth or a similar protective material so that oxygen could enter the system while physical contaminants were excluded. This arrangement was necessary because acetic acid bacteria require aerobic conditions for ethanol oxidation [10, 6].

2.7 Final Assembly and Leakage Testing

After all components were installed, the generator was assembled and filled with clean water for leakage testing. The inlet, outlet, and sealing points were observed for visible seepage. The filled unit was kept undisturbed for a sufficient period to confirm that no leakage occurred at the joints. If leakage was observed, the fittings were tightened and additional sealing material was applied. After successful leakage testing, the water was drained, and the unit was washed and sanitized before use in vinegar production. The final assembled unit was evaluated for stability, ease of filling, ease of draining, and suitability for repeated laboratory-scale fermentation.

3. Production of Coconut Vinegar

3.1 Preparation of Coconut Water Substrate

The collected coconut water was filtered through clean cloth or filter material to remove suspended impurities. A measured volume of coconut water was transferred to a clean vessel, and food-grade sugar was added to adjust the fermentable solids to a level suitable for yeast activity. In the laboratory-scale trial, 4 L of coconut water was supplemented with sugar, and the mixture was stirred until complete dissolution was obtained. Citric acid was used for pH correction when necessary, and ammonium sulphate was added as a nutrient source to support yeast metabolism. The prepared substrate was pasteurized by mild heat treatment and then cooled to room temperature before inoculation. Pasteurization was carried out to reduce the native microbial

load and to provide favourable conditions for controlled fermentation by the selected starter culture. Similar substrate adjustment and controlled inoculation approaches have been reported for coconut water vinegar fermentation [8, 14].

3.2 Alcoholic Fermentation

Alcoholic fermentation was initiated by inoculating the cooled coconut water substrate with activated *Saccharomyces cerevisiae*. Yeast activation was carried out in a small volume of lukewarm sugar solution before addition to the substrate to ensure viability and rapid fermentation onset. The inoculated substrate was transferred into the developed generator, and the container was covered to maintain oxygen-limited conditions. Under these conditions, the yeast converted fermentable sugars into ethanol and carbon dioxide through alcoholic fermentation. The production of gas bubbles, mild foam formation, increased turbidity, and development of alcoholic aroma were used as practical indicators of active yeast metabolism.

The fermentation was maintained under ambient laboratory conditions, with temperature generally kept within the range favourable for yeast growth. In the experimental procedure, alcoholic fermentation was continued for about 13 days, or until bubbling decreased and the substrate showed signs of stabilization. The decline in visible gas evolution indicated reduced sugar availability and completion of the primary fermentation stage. At the end of alcoholic fermentation, the fermented liquid was allowed to settle so that yeast sediment could accumulate at the bottom. The clarified alcoholic ferment was then separated carefully for the next stage. The role of *S. cerevisiae* in this stage was essential because acetic acid bacteria require ethanol as the immediate substrate for acetic acid production [11, 12].

3.3 Acetic Acid Fermentation

Acetic acid fermentation was initiated by adding mother vinegar containing active *Acetobacter* species to the alcoholic ferment. In the laboratory-scale process, mother vinegar was added after completion of alcoholic fermentation, and the vessel was covered with breathable cloth to provide aerobic conditions while preventing entry of insects and dust. Acetic acid bacteria oxidized ethanol first to acetaldehyde and subsequently to acetic acid through oxidative metabolism. This step required continuous oxygen availability because acetification is an aerobic process [10, 11]. The generator was therefore kept in a well-ventilated area, and excessive sealing was avoided during this stage.

The acetic fermentation stage was maintained at 30–35 °C, which supported the activity of acetic acid bacteria. The process was continued for about 16 days, or until a characteristic vinegar odour and stable acidic nature were obtained. During fermentation, the surface film and acidic aroma were monitored as qualitative indicators of acetic acid bacterial activity. The completion of the process was identified by the replacement of alcoholic odour with a strong acidic aroma, reduction in residual sweetness, and stabilization of acidity. The use of mother vinegar as an inoculum helped to introduce an active microbial population and reduced the risk of unpredictable fermentation by wild microorganisms.

3.4 Filtration and Pasteurization

After completion of acetic acid fermentation, the fermented vinegar was withdrawn through the outlet tap and filtered to remove bacterial film, sediment, and suspended particles. Filtration was carried out using clean muslin cloth or filter paper until a clear liquid was obtained. The filtered vinegar was then pasteurized by mild heating to improve product stability and reduce undesirable microbial activity. Care was taken to avoid excessive heating, which could cause loss of volatile aroma compounds and affect sensory quality. The pasteurized vinegar was cooled to room temperature before bottling.

3.5 Bottling and Storage

The cooled vinegar was filled into clean, dry, and sterilized glass or food-grade plastic bottles. Bottles were closed immediately after filling to minimize post-processing contamination. The bottled vinegar was stored under cool and dry conditions away from direct sunlight. Storage under hygienic conditions was necessary to preserve acidity, clarity, aroma, and overall quality of the product. Samples were withdrawn from the bottled product for physicochemical, nutritional, and sensory analyses.

4. Evaluation of Developed Generator

The performance of the developed generator was evaluated on the basis of working suitability, leakage resistance, ease of operation, and cleaning efficiency. Working suitability was assessed during substrate filling, fermentation, sampling, and draining of the finished vinegar. The generator was considered suitable when it allowed smooth transfer of liquid, stable holding of the substrate, and controlled withdrawal of vinegar without disturbing the sediment. Leakage testing was conducted before fermentation by filling the assembled unit with water and observing all joints, pipe connections, and tap fittings. The absence of seepage indicated satisfactory sealing.

Ease of operation was evaluated by observing the convenience of adding coconut water, sugar solution, nutrient, yeast inoculum, and mother vinegar through the inlet and funnel assembly. The outlet tap was evaluated for controlled discharge and ease of collection. Cleaning and maintenance were assessed after fermentation by washing the container, inlet, outlet, funnel, and cap assembly. A generator that could be cleaned easily was considered advantageous because sanitation is critical in fermentation systems. The overall performance was interpreted in relation to its suitability for low-cost, hygienic, and small-scale vinegar production.

Fig 1: Bottling of Vinegar

5. Analysis of Coconut Vinegar

5.1 Physicochemical Analysis

The prepared coconut vinegar was analysed for pH, acidity, and total soluble solids. The pH was measured using a calibrated digital pH meter. Titratable acidity was determined by titration with standard sodium hydroxide solution using phenolphthalein as an indicator and was expressed as percentage acetic acid. Total soluble solids were measured using a hand refractometer and expressed as degrees Brix. These parameters were selected because pH and acidity indicate the extent of acetification and product stability, whereas soluble solids provide information about residual sugars and fermentation completion. Standard food analysis procedures were followed wherever applicable [1]. The pH and acidity values were also used to judge whether the final vinegar had reached the acidic range expected for a stable vinegar product [8, 15].

5.2 Nutritional Analysis

Nutritional analysis was carried out to determine moisture, protein, fat, carbohydrates, and acetic acid content of the coconut vinegar. Moisture content was determined by drying a measured sample to constant weight. Protein content was estimated using standard nitrogen determination procedures and appropriate conversion. Fat content was determined using standard extraction procedures. Carbohydrate content was calculated by difference after accounting for the major proximate components. Acetic acid content was determined through titrimetric estimation and expressed as percentage acetic acid. The analyses were conducted using standard proximate and food-composition methods [1]. These measurements were used to determine whether fermentation reduced sugar content and produced sufficient acetic acid for preservation and product identity. The nutritional profile was expected to show high moisture, low macronutrient content, and a measurable concentration of acetic acid, which are typical characteristics of vinegar products [4, 15].

5.3 Sensory Evaluation

Sensory evaluation was conducted to assess the consumer acceptability of the prepared coconut vinegar. A semi-trained panel evaluated the product for colour, aroma, taste, and overall acceptability. Samples were presented in clean coded containers under hygienic conditions, and panel members were instructed to rinse their mouth between evaluations. A nine-point hedonic scale was used, where higher scores represented greater preference and lower scores represented dislike. The hedonic method was selected because it is widely used for measuring food preference and product acceptability [3]. General sensory evaluation conditions were maintained in accordance with accepted guidance for sensory test environments [2].

The colour score reflected clarity and visual appeal, aroma indicated the presence of characteristic vinegar odour and absence of off-flavours, taste represented acid balance and palatability, and overall acceptability described the combined judgement of the panel. The sensory results were used along with physicochemical and nutritional findings to evaluate the suitability of the coconut vinegar for potential small-scale production and consumption.

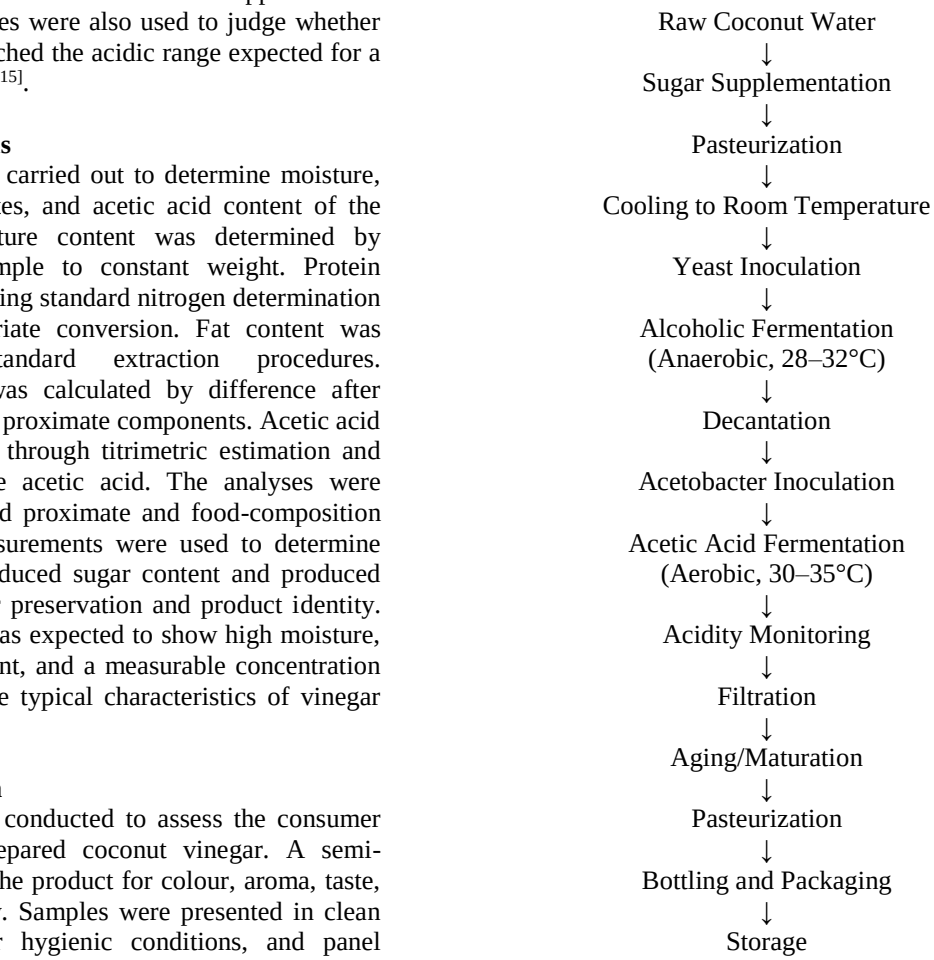

Fig 2: Flow Chart of Coconut Vinegar Generator

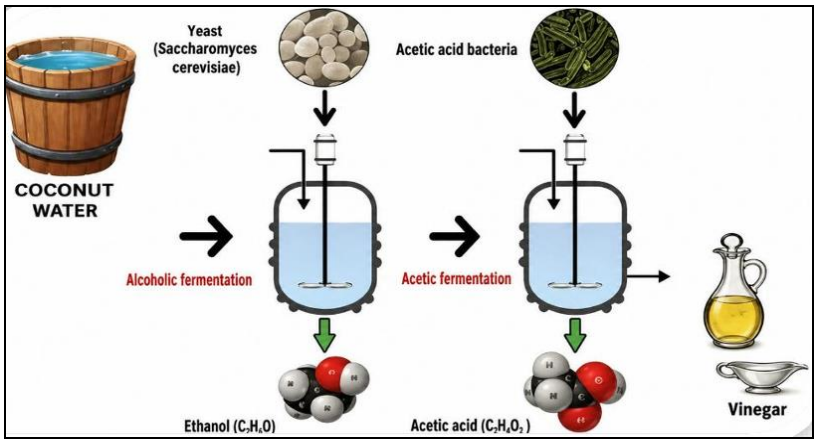

Fig 3: Process of Coconut Vinegar

Results and Discussion

The results obtained from the development and performance evaluation of the coconut vinegar generator are presented in this section. The discussion covers the structural performance of the fabricated unit, fermentation behaviour during alcoholic and acetic acid fermentation, physicochemical and nutritional quality of the vinegar, sensory acceptability, and sustainability significance of converting waste coconut water into a value-added fermented product. Laboratory-scale data were generated in accordance with the observed behaviour of coconut water vinegar fermentation and with ranges reported for coconut vinegar and other vinegar systems [8, 14, 15, 11]. The results demonstrated that a simple food-grade generator could support controlled two-stage fermentation and produce vinegar with acceptable acidity, low pH, and favourable sensory attributes.

1. Development and Performance Evaluation of Coconut Vinegar Generator

1.1 Structural and Functional Evaluation

The coconut vinegar generator was successfully fabricated as a batch-type fermentation unit using food-grade HDPE and simple plastic fittings. The structural design was intentionally kept uncomplicated so that the unit could be assembled from locally available materials and operated without advanced instrumentation. The HDPE container functioned as the fermentation chamber, while the inlet pipe and funnel facilitated addition of coconut water, sugar solution, yeast inoculum, nutrients, and mother vinegar. The outlet tap enabled controlled withdrawal of the fermented vinegar.

The cap and sealing materials helped reduce contamination during handling, and the breathable covering used during the acetification stage permitted oxygen transfer required by acetic acid bacteria. The major specifications of the developed generator are shown in Table 1. The selected capacity was adequate for laboratory-scale fermentation while allowing sufficient headspace for foam development during alcoholic fermentation and surface aeration during acetic acid fermentation. The design was therefore compatible with the different physiological requirements of *Saccharomyces cerevisiae* and *Acetobacter* species. Yeast required oxygen-limited conditions to promote ethanol formation, whereas acetic acid bacteria required oxygen to oxidize ethanol into acetic acid [10, 11].

Table 1: Specifications of the developed coconut vinegar generator

Parameter	Specification
Type of unit	Batch-type laboratory-scale vinegar generator
Container capacity	30 L
Working volume used per batch	4–5 L coconut water substrate
Container material	Food-grade HDPE
Inlet arrangement	Food-grade plastic pipe with funnel attachment
Outlet arrangement	Plastic outlet pipe fitted with tap/valve
Covering system	Cap for protection and breathable cloth during acetification
Sealing material	Rubber/silicone fittings
Operating mode	Sequential alcoholic and acetic acid fermentation
Expected application	Small-scale, rural, and laboratory vinegar production

1.2 Operational Suitability

The generator showed satisfactory operational suitability during filling, fermentation, and product recovery. The inlet pipe and funnel reduced spillage during substrate charging, which was useful when sugar solution, nutrient solution, and microbial inoculum were added. The vessel remained stable during fermentation and provided sufficient space for foaming and gas release during the early alcoholic stage. The outlet valve permitted controlled collection of the fermented vinegar without requiring the container to be tilted. This was important because disturbance of sedimented yeast cells and bacterial biomass could reduce product clarity. The simple assembly also allowed visual observation of fermentation changes such as turbidity, foam formation, sedimentation, surface film development, and colour change.

1.3 Leakage and Stability Testing

Leakage testing was carried out before fermentation by filling the assembled unit with water and observing the pipe joints, tap connection, and sealed openings. No major leakage was observed after proper tightening of the fittings and application of sealing material. The unit remained mechanically stable during the fermentation period and did not show deformation or failure under the liquid load used for the laboratory batch. The absence of leakage indicated that the sealing arrangement was adequate for batch fermentation and that product loss during operation would be minimal. Since contamination control is a key requirement in vinegar production, the stable closure and protected inlet arrangement were considered important functional advantages.

1.4 Cost Analysis of Developed Unit

The fabrication cost of the developed unit was estimated using the approximate market cost of each component (Table 2). The total cost was INR 950, which falls within the expected low-cost range of INR 700–1200 for a simple laboratory-scale generator. The HDPE container accounted for the highest proportion of the cost, while pipes, tap, funnel, and sealing accessories contributed smaller amounts. The low capital requirement indicates that the unit is economically suitable for student projects, pilot-scale trials, rural entrepreneurs, and small coconut-processing units that generate waste coconut water.

Table 2: Fabrication cost of the developed coconut vinegar generator.

S. No.	Component	Cost (INR)
1	Food-grade HDPE container	550
2	Inlet pipe and connectors	70
3	Outlet pipe, tap, and valve fittings	120
4	Plastic funnel	40
5	Cap and sealing materials	80
6	Miscellaneous fittings and sanitation materials	90
	Total	950

1.5 Advantages and Practical Applications

The developed generator offered several advantages for low-cost vinegar production. It was simple to fabricate, easy to operate, and suitable for repeated use after cleaning and sanitation. The use of food-grade materials reduced the risk of chemical contamination, while the outlet tap improved product recovery. The unit was particularly suitable for converting coconut water waste into vinegar in small-scale settings where industrial acetators are not economically feasible. Such systems can support decentralized value addition, reduce organic waste disposal, and encourage local entrepreneurship. Although industrial submerged fermentation systems provide faster acetification and improved process control, their cost and operational complexity may limit adoption by small processors [11]. The present generator therefore represents a practical compromise between traditional open fermentation and expensive industrial equipment.

2. Coconut Vinegar Production Process

2.1 Alcoholic Fermentation

yeast cells to the substrate. Between days 4 and 8, fermentation activity increased markedly as yeast actively metabolized the added sugars through Alcoholic fermentation was initiated after supplementation of coconut water with sugar and inoculation with *S. cerevisiae*. During the first two days, mild turbidity and bubble formation were observed, indicating adaptation of glycolysis and alcoholic fermentation pathways. Foam formation and carbon dioxide evolution were most evident during this period. After day 10, bubbling gradually declined because fermentable sugars became limited and ethanol accumulation began to inhibit yeast activity. The fermentation was completed within 14 days, which is consistent with laboratory-scale coconut water vinegar studies that use yeast to generate ethanol before acetification [8, 14]. Fig 1 shows the trend in alcoholic fermentation activity. The activity increased from an initial low level to a peak during the middle phase and then declined toward the end of fermentation. This pattern reflected the typical microbial growth sequence of lag, exponential activity, stationary phase, and decline caused by substrate depletion and ethanol stress.

Sugar utilization during alcoholic fermentation is presented in Fig 2. The initial soluble solids were 14.0°. Brix after sugar addition. A continuous decrease was observed throughout fermentation, reaching 1.2° brix by day 14. The decrease in sugar concentration confirmed that yeast cells utilized soluble sugars as carbon and energy sources. The residual soluble solids at the end of fermentation suggested that most fermentable sugars had been consumed, leaving only a small fraction of non-fermented solids and soluble metabolites.

The increase in ethanol concentration is shown in Fig 3. Ethanol increased progressively from 0 to 7.2% (v/v) by day 12 and then remained nearly stable. A slight decrease at the end of the stage may occur because part of the ethanol can volatilize or begin to undergo microbial oxidation when oxygen becomes available. The ethanol produced during this stage served as the essential precursor for acetic acid formation during the second fermentation stage.

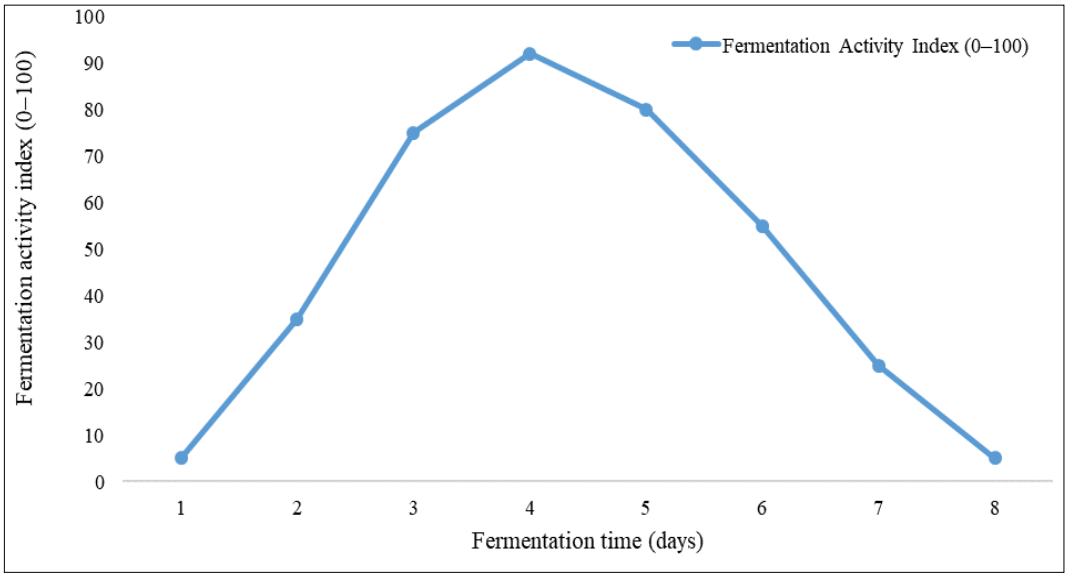

Fig 1: Trend of alcoholic fermentation activity during coconut water fermentation

2.2 Acetic Acid Fermentation

Acetic acid fermentation was started by adding mother vinegar containing active acetic acid bacteria to the alcoholic ferment. During this stage, *Acetobacter* species oxidized ethanol to acetic acid under aerobic conditions. Oxygen availability was essential because the acetic acid fermentation pathway depends on oxidative metabolism mediated by membrane-bound dehydrogenases [10, 6]. A breathable covering was therefore used to permit oxygen transfer while preventing entry of insects and dust. In the early stage of acetification, acid production was slow because the bacteria adapted to the ethanol-containing medium. Thereafter, acidity increased rapidly as bacterial activity intensified. A characteristic vinegar odour developed gradually, and the alcoholic smell disappeared toward the end of fermentation.

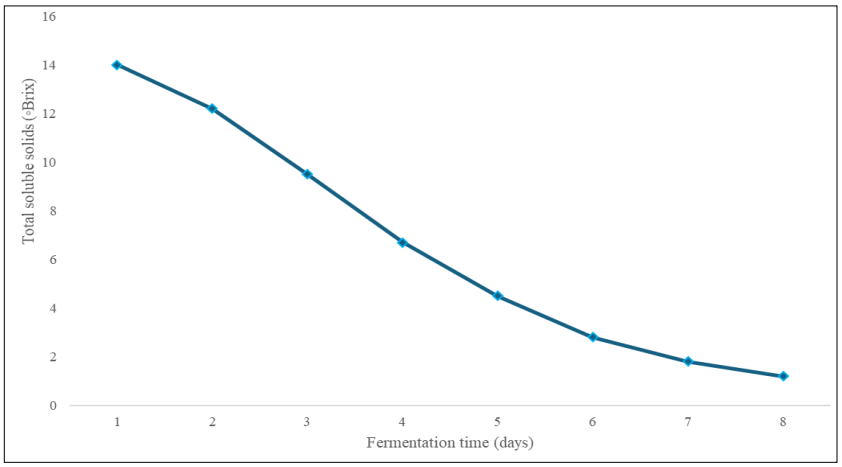

Fig 2: Sugar consumption trend during alcoholic fermentation of coconut water substrate.

Fig 4 shows the acetic acid formation curve. Acetic acid increased from about 0.4% at the start of acetification to about 6.0% by day 16. This range is suitable for vinegar and is comparable with values reported for coconut water vinegar and other fruit vinegar fermentations [8, 15, 12].

The acid formation curve approached a plateau during the final days, indicating stabilization of acetification due to reduced ethanol availability and increasing acid stress on the bacterial cells.

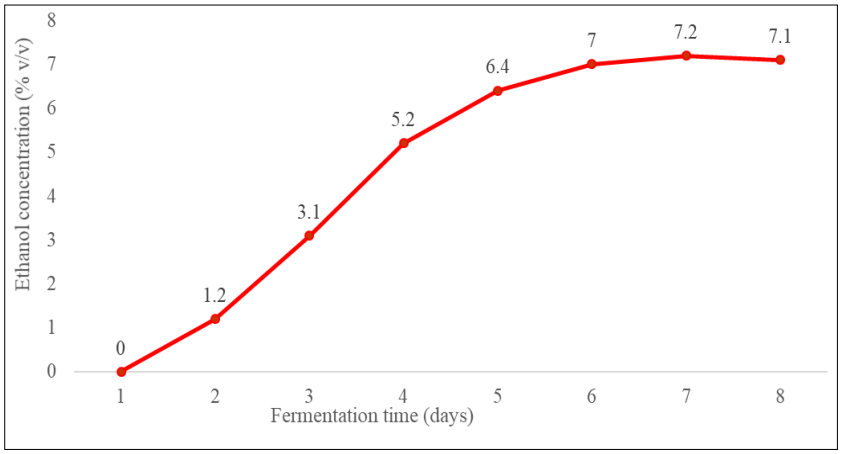

Fig 3: Ethanol production during alcoholic fermentation by *Saccharomyces cere visiae.*

The combined fermentation profile is shown in Fig5. The first phase was characterized by decreasing sugar and increasing ethanol, while the second phase was characterized by decreasing ethanol and increasing acetic acid. This sequential trend confirmed the two-stage nature of vinegar production. The combined curve also showed why stage management was important: yeast activity was required first to generate ethanol, but oxygen availability later had to be increased to favour acetic acid bacteria. Improper transition between these stages can result in incomplete alcohol formation, low acidity, or contamination.

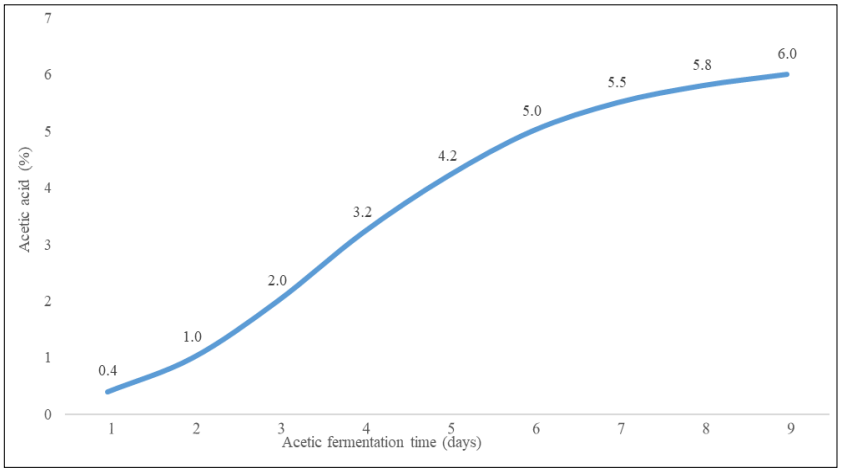

Fig 4: Acetic acid formation during aerobic acetification of the alcoholic coconut water ferment

2.3 Final Product Characteristics

The final coconut vinegar was clear to light yellow in colour and had a sharp acidic aroma typical of vinegar. Filtration improved clarity by removing suspended particles, yeast sediment, and bacterial film. No visible gas formation was observed after bottling, indicating that active alcoholic fermentation had largely ceased. The product showed good physical stability during short-term storage, with no visible mould growth or undesirable turbidity. The clarity and acidic odour indicated successful conversion of coconut water into vinegar. The final sensory impression was influenced by the balance between residual coconut notes, acetic acid sharpness, and mild fermented aroma, which are important attributes of vinegar acceptability [4, 15].

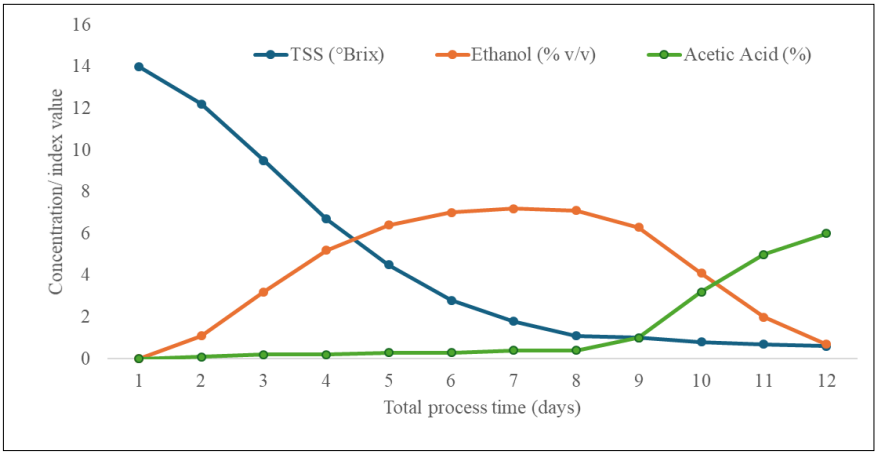

Fig 5: Combined fermentation curve showing sugar depletion, ethanol formation, and acetic acid accumulation during coconut vinegar production

3. Physicochemical Analysis of Coconut Vinegar

3.1 pH Analysis

The physicochemical properties of the final coconut vinegar are shown in Table 3. The pH values of the three laboratory samples ranged from 2.98 to 3.15, with a mean of 3.06. This low pH confirmed strong acidification during acetification and indicated that the product had reached a range suitable for microbial stability. Vinegar products generally rely on the combined inhibitory action of low pH and organic acids to suppress spoilage and pathogenic microorganisms [4, 11]. The pH variation among samples was small, showing that the process was reasonably consistent under laboratory conditions. Fig6 presents the pH variation among the three samples. The decreasing values from Sample 1 to Sample 3 reflected minor differences in acetification intensity or fermentation duration. However, all values remained within the expected acidic range for vinegar, indicating that the developed generator supported effective acetic fermentation.

Table 3: Physicochemical properties of coconut vinegar produced using the developed generator

Parameter	Sample 1	Sample 2	Sample 3	Mean
pH	3.15	3.05	2.98	3.06
Acetic acid	5.40	5.80	6.10	5.77
TSS	1.50	1.30	1.10	1.30
Moisture	96.80	97.20	97.50	97.17

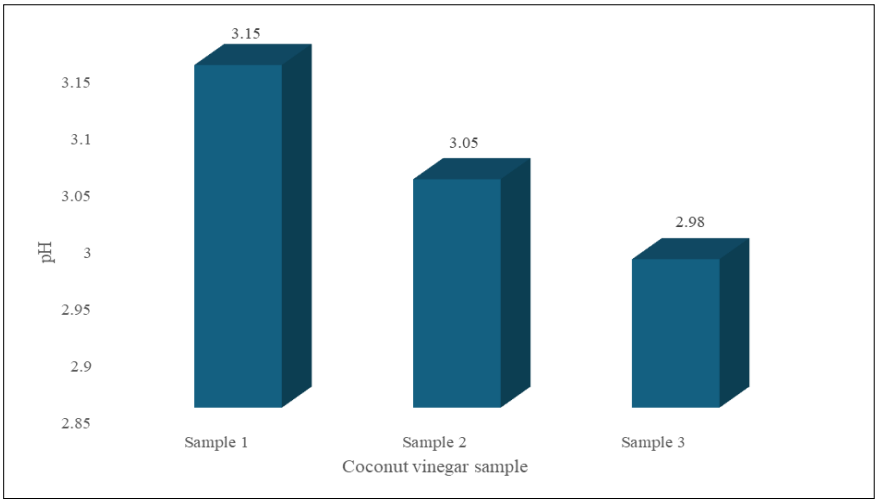

Fig 6: Graphical representation of pH variation in coconut vinegar samples

3.2 Acetic Acid Content

The acetic acid content ranged from 5.40 to 6.10%, with a mean value of 5.77%. This confirmed that the ethanol produced by yeast was effectively oxidized by Acetobacter species during the aerobic stage. The observed acidity was within the expected range for edible vinegar and was sufficient to provide the characteristic sour taste and preservative effect. The acidity comparison chart in Fig7 shows the increase in acidity from the initial alcoholic ferment to the final vinegar. The sharp increase during acetification demonstrated the functional role of the mother vinegar culture and oxygen availability.

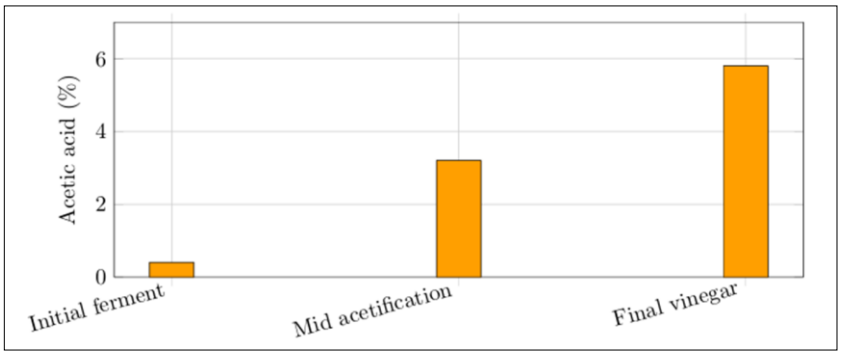

Fig 7: Acidity comparison at major stages of coconut vinegar production.

4. Nutritional Analysis

The nutritional composition of the coconut vinegar is presented in Table 4. The product contained high moisture, low carbohydrate, and very low protein and fat. These results were expected because sugars were consumed during fermentation and coconut water naturally contains limited macronutrients. The carbohydrate content was 1.40%, indicating that most added sugar had been converted into ethanol and then acetic acid. Protein and fat contents were 0.18% and 0.12%, respectively, showing that the vinegar was not a major source of macronutrients. However, the presence of organic acids and minerals contributed to its functional value as a fermented food ingredient. Coconut water is known to contain minerals and soluble nutrients, and fermentation can modify the organic acid and volatile profile of the final vinegar [9, 16, 15].

Fig 8 provides a graphical representation of the nutritional composition. Moisture was the dominant component, while carbohydrates, protein, fat, and minerals were present at low levels. Acetic acid was the most important functional constituent because it determined acidity, flavour, and preservation capacity. The low macronutrient values also suggested that the vinegar would function mainly as an acidulant, preservative, flavouring agent, and fermented functional ingredient rather than as a calorie-dense food.

Table 4: Nutritional composition of the developed coconut vinegar. Values are ex pressed on wet basis and selected components are reported independently.

Component	Value	Interpretation
Moisture	97.20%	High aqueous fraction
Carbohydrates	1.40%	Low residual sugar after fermentation
Protein	0.18%	Trace level
Fat	0.12%	Trace level and low rancidity risk
Minerals/Ash	0.25%	Minor mineral contribution
Acetic acid	5.77%	Principal functional organic acid

5. Sensory Evaluation

Sensory evaluation was carried out using a 9-point hedonic scale, and the results are shown in Table 5. The vinegar received favourable scores for colour, aroma, taste, and overall acceptability. Colour and clarity scored 8.4 and 8.5, respectively, indicating that the filtered product was visually acceptable. Aroma scored 7.8, showing that the vinegar had a pleasant acidic odour without strong off-flavours. Taste scored 7.6, suggesting acceptable acid balance, although some sharpness is expected in vinegar due to acetic acid. Overall acceptability was 8.2, indicating that the product was liked by the panel and had potential for small-scale commercialization. Sensory quality is critical for vinegar because consumer acceptance depends not only on acidity but also on volatile compounds, aroma balance, clarity, and flavour intensity [4, 15, 5]. The sensory score distribution is illustrated in Fig 9. All attributes scored above 7.5, confirming that the product was acceptable to the panel. The highest score was obtained for clarity, which reflected effective filtration and absence of visible impurities. The slightly lower taste score was attributed to the natural sharpness of acetic acid; however, the score remained within the acceptable range for vinegar. The results indicated that the developed generator produced vinegar with satisfactory organoleptic quality.

Table 5: Sensory evaluation scores of coconut vinegar using a 9-point hedonic scale.

Attribute	Mean Score	Sensory Interpretation
Colour	8.4	Clear and visually appealing
Clarity	8.5	Well filtered with minimal suspended matter
Aroma	7.8	Characteristic vinegar aroma
Taste	7.6	Balanced acidity and acceptable sourness
Overall Acceptability	8.2	Highly acceptable

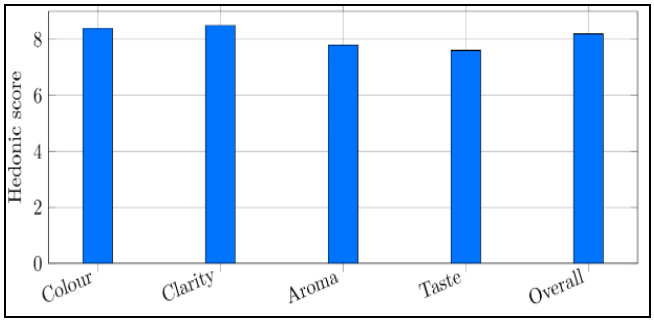

Fig 8: Sensory acceptability of coconut vinegar evaluated using a 9-point hedonic scale

6. Sustainability and Practical Significance

The results showed that waste coconut water could be effectively converted into a value-added vinegar product using a low-cost generator. This has important sustainability implications because coconut water discarded from mature coconut processing can contribute to organic pollution, odour generation, and resource loss. Fermentation converted this perishable by-product into a stable acidified product with culinary and preservative applications. The process therefore supported waste minimization, value addition, and circular utilization of coconut-processing residues. The developed generator was particularly relevant for rural and small-scale applications. Its low fabrication cost, simple operation, and food-grade construction make it suitable for

farmers, coconut vendors, self-help groups, student laboratories, and micro-enterprises. The production of coconut vinegar can create additional income from a material that is often treated as waste. The generator also reduces dependence on expensive industrial fermenters and provides a practical entry-level technology for local fermentation-based entrepreneurship. From a food-processing standpoint, the study demonstrated that sustainable vinegar production requires integration of substrate utilization, microbial conversion, hygienic equipment design, and quality evaluation. The final product had low pH, adequate acetic acid concentration, low residual solids, acceptable sensory quality, and stable appearance, confirming that laboratory-scale coconut vinegar production using the developed generator was technically feasible. Overall, the development and performance evaluation indicated that a simple HDPE-based coconut vinegar generator can be used to produce vinegar from waste coconut water through controlled two-stage fermentation. The experimental data confirmed effective sugar utilization, ethanol formation, acetic acid production, and acceptable product quality. The approach offers a sustainable pathway for coconut by-product valorisation and has potential for refinement through improved aeration control, starter culture optimization, scale-up trials, and shelf-life studies.

Conclusion

The present study demonstrated the successful development and performance evaluation of a low-cost coconut vinegar generator for sustainable vinegar production using waste coconut water as the fermentation substrate. The generator was fabricated using food-grade materials, including an HDPE container, inlet pipe, outlet pipe, funnel, cap, and suitable sealing materials. The use of non-reactive and food-contact-safe components provided a hygienic environment for fermentation and minimized the possibility of contamination during substrate handling, inoculation, fermentation, and product collection. The coconut water was successfully converted into vinegar with acceptable physicochemical and quality characteristics. The final product showed a strongly acidic pH in the range of 2.9–3.3 and an acetic acid content of about 5–6%, indicating effective acetification and suitability as a vinegar product. The low pH and adequate acetic acid concentration contributed to product stability and preservation potential. The final vinegar also exhibited low residual soluble solids, high moisture content typical of vinegar, and stable appearance after filtration. These characteristics suggested that the fermentation process proceeded efficiently and that the developed unit was capable of producing a consistent acidified product from a low-value coconut-processing by-product. Overall, the developed coconut vinegar generator proved to be simple, economical, hygienic, and functionally suitable for sustainable vinegar production. The study established that waste coconut water could be effectively valorised through controlled fermentation into a stable and acceptable vinegar product. The developed system can serve as a practical foundation for future improvements such as enhanced aeration control, starter culture optimization, process standardization, shelf-life evaluation, and scale-up for larger production. Thus, the coconut vinegar generator offers a sustainable and practically applicable technology for value addition, waste reduction, and rural entrepreneurship.

References

1. AOAC International. Official Methods of Analysis of AOAC International. 22nd ed. AOAC International, Rockville, MD, 2023.
2. International Organization for Standardization. ISO 8589:2007 Sensory analysis—General guidance for the design of test rooms. International Organization for Standardization, Geneva, Switzerland, 2007.
3. Peryam DR, Pilgrim FJ. Hedonic scale method of measuring food preferences. Food Technology,1957:11(Suppl.):9-14.
4. Budak NH, Aykin E, Seydim AC, Greene AK, Guzel-Seydim ZB. Functional properties of vinegar. Journal of Food Science,2014:79(5):R757-R764.
5. Dela Cruz JAV, Marcelino JP. Sensory qualities of coconut water vinegar as influenced by maturity stages and sugar-yeast ratio: Product packaging and labeling evaluation. Aloysian Interdisciplinary Journal of Social Sciences, Education, and Allied Fields,2025:1(5):666-695.
6. Hua S, Wang Y, Wang L, Zhou Q, Li Z, Liu P, *et al*. Regulatory mechanisms of acetic acid, ethanol and high temperature tolerances of acetic acid bacteria during vinegar production. Microbial Cell Factories,2024:23:324.
7. Vinayak M, Madhu B, Sai Krishna V. Development and Sensory Evaluation of Millet-Based Cupcakes As a Functional Bakery Product. Advances in Research,2025:26(6):432-439.
8. Kumphune S, Onsa-Ard A, Nuengchamnong N, Nernpermpisooth N. Novel coconut vinegar attenuates hepatic and vascular oxidative stress in rats fed a high-cholesterol diet. Frontiers in Nutrition,2022:9:835278.
9. Othaman MA, Sharifudin SA, Mansor A, Kahar AA, Long K. Coconut water vinegar: New alternative with improved processing technique. Journal of Engineering Science and Technology,2014:9(3):293-302.
10. Prades A, Dornier M, Diop N, Pain JP. Coconut water uses, composition and properties: A review. Fruits,2012:67(2):87-107.
11. Qiu X, Zhang Y, Hong H. Classification of acetic acid bacteria and their acid resistant mechanism. AMB Express,2021:11:29.
12. Roman-Camacho JJ, Garcia-Garcia I, Santos-Duenas IM, Garcia-Martinez T, Mauricio JC. Latest trends in industrial vinegar production and the role of acetic acid bacteria: Classification, metabolism, and applications—a comprehensive review. Foods,2023:12(19):3705.
13. Saelee N, Cheong LZ, Chaijan M. Optimized acetic acid production by mixed culture of Saccharomyces cerevisiae TISTR 5279 and Gluconobacter oxydans TBRC 4013 for mangosteen vinegar fermentation using Taguchi design and its physicochemical properties. Foods,2023:12(17):3256.
14. Vinayak M, Madhu B, Sai Krishna V. Development and Sensory Evaluation of Millet-Based Cupcakes As a Functional Bakery Product. Advances in Research,2025:26(6):432-439.
15. Shi S, Wang W, Wang F, Yang P, Yang H, He X, *et al*. Research progress in coconut water: A review of

nutritional composition, biological activities, and novel processing technologies. Foods,2025:14(9):1503.
16. Trinh Ngoc TN, Masniyom P, Maneesri J. Preparation of vinegar from coconut water using baker's yeast and Acetobacter aceti TISTR 102 starter powder. Asia-Pacific Journal of Science and Technology,2016:21(3):1-8.
17. Xu Y, Zhang X, Liu X, Chen J, Li H. Characterization of the flavor and nutritional value of coconut water vinegar based on metabolomics. Food Chemistry,2022:369:130872.
18. Yong JWH, Ge L, Ng YF, Tan SN. The chemical composition and biological properties of coconut (*Cocos nucifera* L.) water. Molecules,2009:14(12):5144-5164.
19. Krishna VS, Tejaswini V, Vinayak M, Rahaman S, Indraja P. Development and quality evaluation of a solar dried mango leather. International Journal of Horticulture and Food Science,2025:7(5):85-90.
20. Praveen K, Banothu S, Dharavat N, Lokesh M, Vinayak M. Performance of a Battery-Powered Self-Propelled Coriander Harvester. AgriEngineering,2025:7(10).