

Characterization and evaluation of nipa palm (*nypa fruticans wurmb*) vinegar using controlled temperature fermentation process

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Abstract: Traditional vinegar fermentation processes are often associated with prolonged production times and inconsistent product quality. To address these limitations, a controlled-temperature fermentation system was developed using an Arduino-based automation platform. This system enables precise temperature regulation and real-time pH monitoring, supporting optimal fermentation conditions. The prototype has a 10-liter capacity and maintains a temperature range of 27°C–32°C throughout the process. Vinegar produced using this system underwent proximate analysis to determine its compositional quality. Results indicated acceptable levels of key components, including acetic acid (2.52 g/100 g), protein (<0.10 g/100 g), ash (0.76 g/100 g), and carbohydrates (3.30 g/100 g). Sensory evaluation was conducted using a 9-point Hedonic scale. Panelists rated the vinegar's irritation intensity with a mean score of 7.6 (very strong), odor quality at 5.9 (slightly pleasant), taste quality at 7.0 (moderately pleasant), appearance quality at 5.3 (neutral—either clear or cloudy), and overall acceptability at 8.1 (very acceptable). The controlled fermentation process significantly reduced production time to just six days, representing an 80% improvement in efficiency compared to conventional batch-type fermentation methods. The results indicate that the Arduino-controlled system contributes to improved consistency in product quality and significantly reduces the fermentation time required for vinegar production.

Keywords: controlled fermentation process, Arduino-based systems, proximate analysis, 9-point hedonic scale

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1 Introduction

Nypa fruticans Wurmb, commonly known as nipa palm, is a unique and ancient palm species that thrives in mangrove ecosystems and is characterized by an underground, horizontally growing stem with dichotomous branching. It is widely distributed across Southeast Asia and is ecologically and economically

significant. In the Philippines, nipa palm covers approximately 8,000 hectares, making it one of the most abundant mangrove-associated palms in the country. Owing to its availability and versatility, rural communities have increasingly cultivated nipa palms for livelihood purposes, particularly for the production of sap-based products such as toddy, vinegar, and sugar, which contribute to local income generation and

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sustainable coastal resource utilization (Manzano et al., 2024). However, the fermentation process is the main challenge in Nipa vinegar production. Additionally, fermentation significantly affects the final characteristics of the vinegar produced (Luzón-Quintana et al., 2021).

Fermentation is defined as the chemical process by which molecules such as glucose are broken down anaerobically. Anaerobic fermentation has been applied to many important industrial processes, such as ethanol production by yeasts, lactic acid preservation of foods, and anaerobic digestion of organic matter in ruminant cultivation and waste treatment. There are existing processes used for vinegar production: the Orleans process (slow process), the quick process (generator process), and the submerged culture process (Bhat et al., 2014). The quick and submerged culture processes were developed for commercial vinegar production. Each method has its own differences and challenges during fermentation. The Orleans process, or traditional method, is considered one of the oldest and slowest methods for producing high-quality vinegar. In this method, holes in the wooden barrel are left exposed and covered with thin coverings, and the fermentation lasts for about 1 to 3 months at 21°C to 29°C.

While this method produces vinegar with superior sensory qualities, it is labor-intensive, time-consuming, and susceptible to human error due to manual monitoring. In contrast, the submerged fermentation process introduces oxygen into the culture, allowing aerobic fermentation that typically lasts only 24–48 hours. This approach provides various advantages in terms of speed, productivity, and scalability, making it more suitable for commercial applications. The need for developing such a controlled and automated method stems from both economic and operational reasons: it reduces labor costs, minimizes inconsistencies associated with human supervision, and ensures continuous, efficient production without compromising product quality.

Vinegar fermentation is critically dependent on

three primary factors: substrate supply, oxygen supply, and temperature (Gullo et al., 2006). Improper control of these factors can halt acetic acid production. Additionally, secondary factors like starter culture selection, fermenter design, and working conditions can influence the yield and rate of conversion to vinegar (Tesfaye et al., 2002). Conventional methods of vinegar production often lack precise temperature control, leading to inconsistencies in yield and quality. To address this, the development of a fermenter with a controlled temperature is recommended. Thus, this study developed a controlled-temperature fermenter, characterizing and evaluating Nipa palm vinegar to establish a more reliable and efficient method for producing high-quality Nipa vinegar. Furthermore, vinegar produced from conventional methods, and the designed fermenter was compared to assess the potential for improving Nipa sap vinegar production in Oriental Mindoro.

2 Methodology

2.1 Experimental site

The study was conducted at the Mindoro State University – Institute of Agricultural and Biosystems Engineering laboratory facility, 5205, Victoria, Oriental Mindoro, Philippines, 13009°32" N, 121011°22" E in February 2023 - May 2024.

2.2 Production process of Nipa vinegar in controlled temperature fermenter machine

The quality of Nipa vinegar is primarily influenced by the raw materials used and the control of fermentation conditions, particularly temperature and oxygen supply. Poor-quality inputs or inadequate process control can lead to undesirable microbial activity, resulting in off-flavors and reduced acetic acid production. The block diagram to produce Nipa vinegar using a controlled-temperature fermenter machine is shown in Figure 1.

Figure 1 illustrates the mass balance of the Nipa vinegar production process using the developed fermenter machine. Fresh Nipa sap was collected from a single Nipa plantation area in the City of Calapan,

Oriental Mindoro, Philippines to ensure sample homogeneity. Ten liters of Nipa sap were used per sample. The collected sap initially underwent filtration to remove impurities, after which it was subjected to fermentation in the developed controlled-temperature fermenter machine. Following fermentation, a second filtration process was conducted to further purify the

product.

The resulting vinegar samples were then subjected to proximate analysis to determine their acetic acid, protein, ash, and carbohydrate contents. Sensory evaluation was also conducted using a nine-point (9-point) hedonic scale to assess irritation intensity, odor, taste quality, appearance, and overall acceptability.

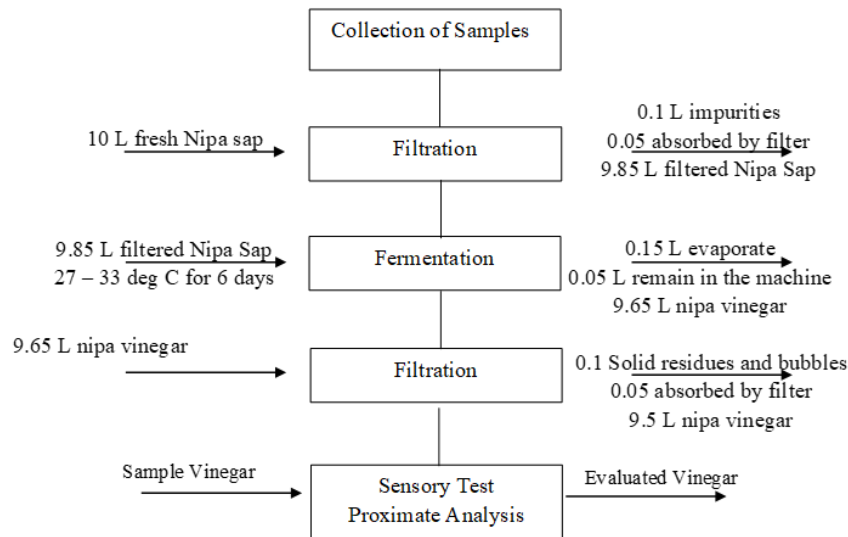


Figure 1 Block diagram for production of Nipa vinegar in controlled temperature fermenter machine

2.3 Design and construction of controlled temperature nipa palm vinegar fermenter

The controlled temperature Nipa palm vinegar fermenter was designed and constructed to ensure optimal fermentation conditions for high-quality vinegar production. It integrates temperature and pH

sensors to monitor and maintain ideal fermentation parameters. The system consists of six main components including fermenting chamber, discharge chute, heating coil, supporting frame, air pump, and control panel within a compact structure measuring 60 cm × 50 cm × 75 cm as shown in Figure 2.

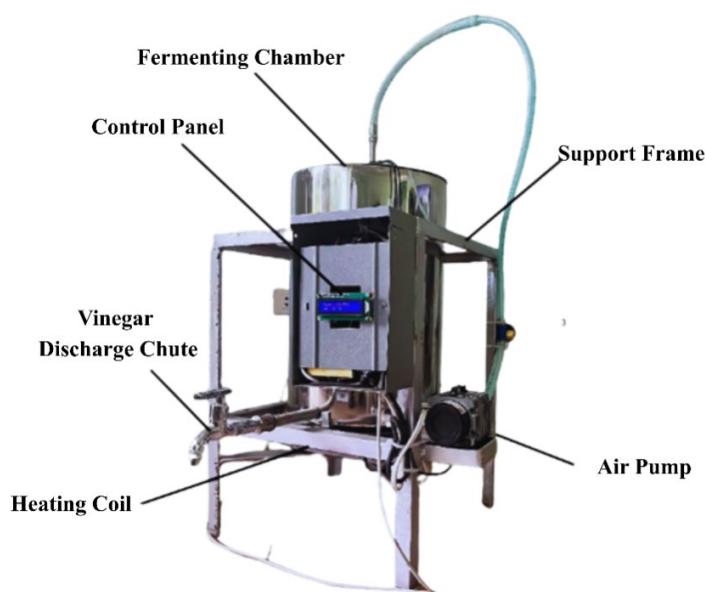


Figure 2 Design of controlled temperature nipa palm vinegar fermenter

2.4 Temperature control system

The temperature-controlled Nipa vinegar fermenter was developed using an Arduino Uno microcontroller as the central control unit shown in Figure 3. The system received input data from thermal sensors and pH sensors to continuously monitor the temperature and acidity levels inside the fermentation chamber. These parameters were displayed in real time on a Liquid Crystal Display (LCD) module, allowing on-site monitoring of fermentation conditions. A Global System for Mobile Communications (GSM) module was integrated into the system to provide real-time notifications to the operator via Short Message Service (SMS). Alerts were sent whenever irregular conditions were detected or when optimal fermentation parameters were achieved. In addition, a data logger was installed to record sensor data continuously over time. All recorded data were stored on an SD card for subsequent retrieval and trend analysis.

The system was powered through a C-type power plug connected to a standard wall outlet. A 12 V, 3 A step-down transformer converted high-voltage alternating current (AC) into 12 V direct current (DC) to supply power to high-load components. A 12 V to 5 V step-down module further reduced the voltage to safely power the Arduino Uno and other sensitive electronic sensors. For safety, a fuse was installed in the power circuit to protect the system from electrical surges and potential damage to electronic components. A 5 V relay, controlled by the Arduino Uno, was used to trigger a 12 V relay responsible for controlling the heater coil. When the thermal sensor detected that the fermentation temperature had dropped below the desired setpoint, the Arduino activated the relay to turn the heater on. An air pump, controlled via the AC power side and an external switch, was incorporated to provide adequate oxygenation and circulation within the fermenting medium, thereby supporting efficient microbial activity during fermentation.

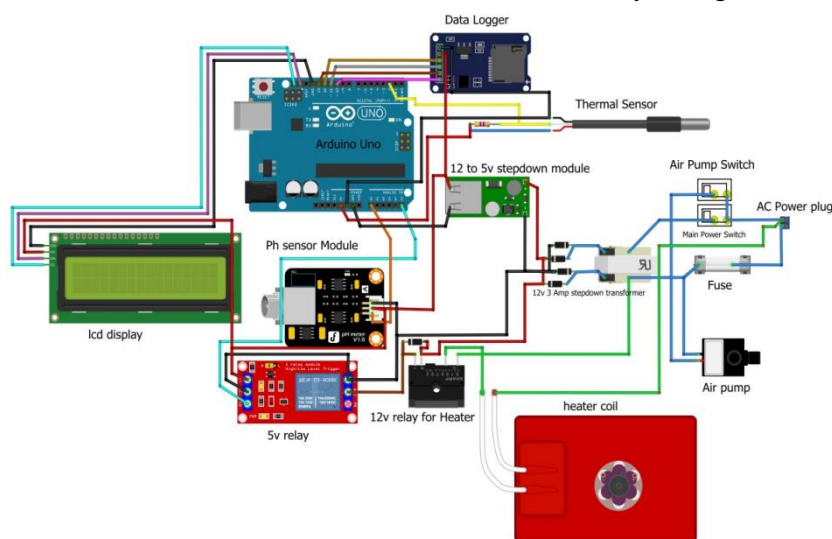


Figure 3 Nipa vinegar temperature controlled fermenter circuit board diagram

2.5 Operation procedure for controlled temperature for vinegar production

The operation of the temperature-controlled nipa palm vinegar fermenter began with system inspection, calibration of sensors, and sterilization of the fermenter chamber to prevent contamination. Fresh nipa sap was collected, filtered to remove impurities, and transferred into the sealed fermenter. Temperature inside the fermentation chamber was monitored using

a built-in stainless-steel thermal sensor, while pH was measured using an immersed stainless-steel pH probe. The desired fermentation temperature range (27.0°C–32.0°C) was programmed into the Arduino Uno microcontroller, not the sensors themselves. A closed-loop control system was implemented such that when the detected temperature fell below 27.0°C, the Arduino activated the heater via a relay, and when the temperature exceeded 32.0°C, the heater was

automatically switched off. Real-time temperature and pH values were displayed on an LCD and recorded at regular intervals using an SD-card data logger.

The Arduino system was programmed using the Arduino Integrated Development Environment (IDE) to handle sensor data acquisition, temperature regulation, data logging, and GSM-based alerts. Threshold values for optimal and critical fermentation conditions were embedded in the program, enabling automated SMS notifications to the operator when irregular conditions occurred or when the target acidity level was reached. Aeration was provided as needed using an air pump to support acetic acid bacteria activity. Fermentation was terminated once the desired acidity was achieved, after which the vinegar was drained, filtered for clarity, and stored in sterilized bottles for subsequent analysis and use.

2.6 Data collection and analysis

The study analyzed the effects of temperature and oxygen supply on Nipa vinegar production by comparing vinegars produced using the traditional batch-type method and a controlled-temperature fermenter to a commercially available Nipa vinegar. Samples were collected after only 6 days of fermentation, yielding 9.7 L and 9.5 L of vinegar from

10 L of fresh Nipa sap for the batch-type and controlled-temperature methods, respectively. In contrast, the commercial vinegar had undergone 150 days of fermentation. One-liter samples from each method were submitted to SGS Philippines, Inc. for laboratory analysis to determine acidity (as acetic acid), crude fat, protein content, and ash content, serving as the basis for proximate composition and sensory evaluation.

3 Results and discussion

3.1 Acidity as acetic acid

Acidity, measured as acetic acid concentration, determines the strength and sharpness of a vinegar sample's taste, the higher the acidity, the stronger the flavor. Table 1 presents the acetic acid content of the three vinegar samples. The commercially available Nipa vinegar had the highest acetic acid concentration at 4.30 g/100g, followed by the vinegar produced using the controlled temperature fermenting machine at 2.52 g/100g, and the batch-type method at 1.38 g/100g. Notably, the acetic acid level from the controlled temperature method falls within the acceptable range of 0.32% to 5.09%.

Table 1 Level of acidity as acetic acid of commercially available vinegar, batch type produced vinegar and controlled temperature fermentation produced vinegar.

Vinegar production process	Level of acidity per 100g
Commercially available vinegar (CAV)	4.30 g/ 100 g
Batched-type produced vinegar (BPV)	1.38 g/ 100g
Controlled temperature fermentation produced vinegar (CTFPV)	2.52 g/ 100g

3.2 Protein content

Proteins are composed of amino acids; the hydrogen bonds formed between hydrogen and oxygen atoms within amino acids are responsible for maintaining a protein's structure. When these hydrogen bonds are disrupted typically by exposure to acidic or high-heat environments protein denaturation occurs, resulting in the loss of the protein's natural structure. Laboratory results presented in Table 2 indicate that the protein content in all three vinegar samples was reported as <0.10 g/100 g. This value falls below the minimum detection limit of the testing

method, suggesting that the actual protein content may be even lower or undetectable. This low or undetectable protein level supports the conclusion that the samples are indeed vinegar. As explained by Harvard School of Public Health (2017), the acidic nature of vinegar can disrupt ionic bonds in proteins, leading to denaturation consistent with the observed results.

3.3 Ash content

Ash determination helps ensure that no hazardous minerals are present in a sample, as ash content can influence the taste, texture, and stability of foods.

Additionally, it serves as an indicator for possible acid adulteration. The ash content determined in the three vinegar samples is presented in Table 3. Results show that ash levels range from 0.76 g/100g to 0.78 g/100g, which fall within the acceptable range of 0.14% to 7% as specified by Judith et al. (2021).

An ash content below 0.18% may indicate the presence of unfermented material in vinegar. However,

it is important to note that the safe ash content for human consumption can be significantly higher exceeding 7%. Therefore, based solely on ash content, all vinegar samples appear to be free from adulteration and safe for consumption. Nonetheless, further analysis may be necessary for a more definitive assessment.

Table 2 Level of protein content commercially available Nipa vinegar, batch type produced Nipa vinegar and controlled temperature fermentation produced Nipa vinegar

Vinegar production process	Level of protein per 100g
Commercially available vinegar (CAV)	<0.10 g/ 100 g
Batched-type produced vinegar (BPV)	<0.10 g/ 100 g
Controlled temperature fermentation produced vinegar (CTFPV)	<0.10 g/ 100 g

Table 3 Level of ash content commercially available Nipa vinegar, batch type produced Nipa vinegar and controlled temperature fermentation produced Nipa vinegar

Vinegar production process	Level of ash content per 100g
Commercially available vinegar (CAV)	0.78 g/ 100 g
Batched-type produced vinegar (BPV)	0.77 g/ 100g
Controlled temperature fermentation produced vinegar (CTFPV)	0.76 g/ 100g



Figure 4 Level of sensory analysis of the vinegar produced from three processes

3.4 Sensory analysis

The sensory analysis, conducted using a 9-point Hedonic Scale, is presented in Figure 4. This evaluation was performed after the completion of proximate analysis to ensure the safety and suitability of the vinegar samples for sensory testing. The respondents consisted of vinegar vendors and producers from Calapan City, Oriental Mindoro. Each respondent was provided with 5 mL of each vinegar sample for evaluation, and plain water was used for

mouth rinsing between samples to minimize sensory carryover.

The results showed that commercially available vinegar consistently obtained the highest mean scores across all sensory attributes, including irritation intensity ($\bar{x} = 8.7$), odor ($\bar{x} = 7.2$), taste ($\bar{x} = 8.2$), appearance ($\bar{x} = 7.4$), and overall acceptability ($\bar{x} = 8.7$). Vinegar produced using the controlled-temperature fermenting machine followed closely, demonstrating higher sensory ratings than the batch-

type fermentation method in all evaluated attributes. Specifically, the controlled-temperature vinegar achieved mean scores of $\bar{x} = 7.6$ for irritation intensity, $\bar{x} = 5.9$ for odor, $\bar{x} = 7.0$ for taste, $\bar{x} = 5.3$ for appearance, and $\bar{x} = 8.1$ for overall acceptability, while the batch-type vinegar consistently scored the lowest. These findings indicate that controlled-temperature fermentation enhances vinegar quality more effectively than traditional batch fermentation within the same six-day fermentation period.

3.5 Performance evaluation of the controlled temperature fermenter machine

The performance of the controlled temperature fermenter machine was evaluated based on the quality of the produced Nipa vinegar through chemical analysis, proximate composition, and sensory evaluation, alongside the monitoring of ambient temperature. The machine, with a capacity of 10 liters, was constructed using food-grade materials and featured a discharge chute, aerator, and centrally positioned diffuser to ensure uniform heat distribution. The desired fermentation temperature of 27°C–32°C was consistently maintained through the integration of a heating coil and temperature sensor, while a pH sensor provided accurate monitoring of the acidity level throughout the process, enabling a reduced fermentation period of only six days. On the first day, the fresh Nipa sap exhibited a sweet odor and a pH of 5.89, consistent with the findings of Saengkrajang and (2021), who reported that fresh sap typically falls within a pH range of 5.5 to 5.9. As fermentation progressed, the pH steadily decreased and the odor shifted from sweet to alcoholic and eventually to sour, indicating successful alcohol and subsequent acetic acid formation. By the sixth day, the final product exhibited a pH of 2.91, confirming the effective completion of the fermentation process and the production of vinegar.

4 Conclusion

Based on the tests, observations, and data gathered, it was concluded that the integration of the Arduino-based system provided accurate and convenient

control of storage temperature and real-time pH monitoring throughout the fermentation process. The combined usage of rice hull and R Foil as insulating materials proved to be efficient, as actual heat loss through the walls of the fermenter was significantly lower than the computed theoretical values. Moreover, the fermenting machine successfully produced Nipa palm vinegar that met acceptable quality standards within just six days which represented an 80% reduction in fermentation time compared to the traditional batch-type method. These findings highlight the strong potential of the system for industrial application, offering a scalable and energy-efficient approach to vinegar production. Therefore, the developed system promotes both economic viability and environmental sustainability in the controlled production of Nipa palm vinegar by reducing processing time, minimizing human intervention, and utilizing locally available and sustainable materials.

5 Recommendation

It is recommended to extend the duration of vinegar storage and testing to evaluate its long-term stability, sensory attributes, and physicochemical changes over time. Future studies should also consider exploring microbial profiling during the fermentation process and assessing shelf-life performance under various storage conditions. Additionally, scaling up the fermenter system for pilot or commercial-level production could further validate its applicability and economic viability for broader Nipa vinegar production in coastal regions like Oriental Mindoro.

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