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A Study on the Potential of Natural Liquid Electrolytes from Lime Peel, Starfruit, and White Vinegar for Bio Batteries

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A B S T R A C T

The purpose of this study is to evaluate the performance of bio-batteries utilizing natural liquid electrolytes made from white vinegar, lime peel, and star fruit. The bio-battery uses copper (Cu) and zinc (Zn) electrodes to function according to galvanic cell principles. With an overall average efficiency of 50% in all test intervals (5, 10, 15, and 30 minutes), composition 47, which consists of 35 ml of lime peel liquid extract, 35 ml of starfruit liquid extract, and 10 ml of white vinegar liquid, is the ideal composition for the bio battery liquid electrolyte. The results show that the electrical power generated ranges from 0.0007 to 0.0008 W, with an average acidity level (pH) of 2.15 and an average conductivity of 3.85 µs/cm. Ion mobility and electrochemical reactions were significantly affected by the electrolyte's characteristics, particularly its high conductivity and low pH. While additional tweaking is required to increase the bio battery's efficiency and electrical power production. This study demonstrates the promise of organic waste as an eco-friendly alternative energy source.

Contribution to Sustainable Development Goals (SDGs):
SDG 7: Affordable and Clean Energy
SDG 13: Climate Action

1. INTRODUCTION

1.1. Research Background

The use of electrical energy is an important and fundamental aspect of human life in the current modern era. Electrical energy is used not only for lighting but also to support various activities, including operating household appliances, communication technology, medical equipment, and industrial processes. Along with population growth and technological development, the demand for electrical energy continues to increase significantly. However, this increased demand has not been matched by the availability of sustainable energy sources; to date, most electrical energy still relies on non-renewable sources, namely fossil fuels such as coal, petroleum, and natural gas [1].

The continuous use of fossil fuels not only depletes resources but also harms the environment. Greenhouse gas (GHG) emissions from burning fossil fuels are the main cause of global warming and climate change. Additionally, waste from conventional energy use can pollute soil, water, and air, affecting human health. Therefore, the development of alternative energy sources that are environmentally friendly, sustainable, and easily accessible is an urgent need [2].

One technology that can be developed as an alternative energy solution is the bio-battery. A bio-battery is an electrochemical device that operates based on galvanic cell principles, generating electrical energy through reduction and oxidation (redox) reactions between two electrodes with different potentials. Generally, the electrodes used are zinc (Zn) as the anode and copper (Cu) as the cathode. In this system, zinc is oxidized by releasing electrons, while copper is reduced by accepting electrons, thereby producing an electric current that flows in a closed circuit [3, 4].

The primary benefit of biobatteries is the use of electrolytes made from organic materials, including fruits and agricultural waste. These substances include organic acids that ionize in solution, generating H^+ ions that act as electrical conductors, such as acetic acid, citric acid, and oxalic acid. Because of their comparatively high organic acid content, organic wastes like lime peel and starfruit could be used as natural electrolytes in biobatteries. Furthermore, using white vinegar as a source of acetic acid can increase the solution's acidity and free-ion concentration, thereby increasing the electrolyte's conductivity. [5-8].

Several previous studies have shown that a lime solution, as a bio-battery electrolyte, can produce a voltage up to 1.47 V under certain conditions, such as a solution volume of 40 mL and a maximum concentration of 15%. Furthermore, the efficiency of fruit-waste-based bio-batteries was reported to reach a maximum of approximately 32.47%. This indicates that organic materials have sufficient potential as alternative energy sources, although they still require further optimization [9].

However, bio-batteries still have limitations, particularly low electrical power output and lower system efficiency than conventional batteries. Factors such as electrolyte type, ion concentration, tingkat keasaman (pH), electrode area and distance, and electrolyte volume greatly affect bio-battery performance. Therefore, further research is needed to optimize these parameters, especially with relation to the electrolyte material's volume composition.

In this study, variations in the composition volume of material electrolytes comprising lime peel extract, starfruit extract, and white vinegar were examined. These variations were made to determine the effect of material composition ratios on bio-battery performance, including the generated voltage, current, and power. In this study, other variables such as electrode type (Zn and Cu), electrode area, inter-electrode distance, and electrolyte volume were kept constant, so that the measurement results were influenced only by variations the volume of each electrolyte used [10].

Additionally, this study considers environmental aspects using the Life Cycle Assessment (LCA) approach with cradle-to-gate system boundaries, which evaluates the environmental impact from raw material extraction through the finished product. LCA analysis was conducted using SimaPro software to obtain a general overview of the environmental impact of the developed bio-battery.

Based on this background, this study aims to analyze the effects of variations in the composition of organic waste-based electrolytes on bio-battery performance, including voltage, current, power, and system efficiency. This research is expected to contribute to the development of environmentally friendly and economical alternative energy technologies and to support the optimal utilization of organic waste.

1.2. Literature Review

1.2.1. Current Conditions

The development of bio-batteries based on natural electrolytes has become an increasingly important research topic in renewable energy studies, particularly because they can utilize organic materials, agricultural waste, and local biomass resources as ionic-conducting media. Previous studies have shown that fruits, vegetables, and organic waste containing organic acids can function effectively as electrolytes in simple electrochemical systems.

The utilization of sweet orange peel (Citrus sinensis) as a liquid electrolyte material in bio-batteries has been studied. Orange peel contains citric acid, which ionizes in aqueous solution, producing H^+ ions that act as charge carriers. Using zinc (Zn) and copper (Cu) electrodes, the bio-battery produced an average voltage of 0.81 V and an electric current of 0.049 mA. These findings confirm that orange peel waste has significant potential as an environmentally friendly natural electrolyte for small-scale bio-battery applications [11-13].

Research on the effect of vinegar concentration as an electrolyte solution on voltage and current generated in bio-battery systems has been conducted. Household vinegar contains acetic acid (CH_3COOH), a weak acid that partially dissociates in water to release H^+ ions. Research results showed that increasing vinegar concentration led to proportional increases in both voltage and current. Furthermore, vinegar is considered safe, inexpensive, readily available, and environmentally friendly, making it suitable for educational and laboratory-scale renewable energy experiments [14].

A solid-state biobattery prototype has been created utilizing cassava pulp, NaCl, and starfruit (Averrhoa carambola) extract. Because of its high concentrations of organic acids, including ascorbic acid, citric acid, and oxalic acid, starfruit was selected.

NaCl was added to increase ionic conductivity, while cassava pulp functions as a solid electrolyte matrix. The prototype produced a maximum voltage of 0.610 V and a maximum current of 2.17 mA. This study shows that agricultural waste can be transformed into functional materials for sustainable energy storage systems [15-17].

Research analyzing the efficiency of bio-batteries derived from various fruit and vegetable waste, including rotten tomatoes, bilimbi, bananas, and papaya, has been conducted. The study emphasized the effect of fermentation on increasing acid concentration and the number of free ions. Using a Zn–Cu electrode configuration, rotten tomatoes produced the highest voltage of 1.345 V, followed by bilimbi at 1.2825 V. These results confirm that the fermentation process increases electrolyte effectiveness due to increased concentration of organic acids and electrically conductive ions [18-20].

Based on previous research, most existing studies focus on single-source natural electrolytes, such as orange peel, vinegar, bilimbi fruit, or certain fruit waste materials. Research on the combined use of lime peel, bilimbi fruit, and white vinegar as mixed liquid electrolytes in a single bio-battery system remains limited. Therefore, this research is novel in its evaluation of the electrochemical performance of mixed local organic acid electrolyte systems within a sustainable bio-battery framework.

1.2.2. Renewable Energy and Global Energy Challenges

The global energy crisis, increasing energy demand, and greenhouse gas emissions have become major challenges in sustainable development. Dependence on fossil fuels such as coal, petroleum, and natural gas not only depletes non-renewable resources but also contributes significantly to carbon dioxide (CO_2) emissions and environmental degradation. Consequently, the development of renewable and environmentally friendly energy sources is becoming increasingly important [21].

Renewable energy uses natural resources such as solar, wind, hydropower, geothermal, and biomass. One promising biomass-based energy technology is the bio-battery, an electrochemical device that converts chemical energy from biological materials into electrical energy. Bio-batteries offer environmental advantages because they can utilize organic waste as electrolytes.

Organic waste such as orange peels, tomatoes, starfruit, bananas, mangoes, and papayas contains active compounds including citric acid, ascorbic acid, oxalic acid, and acetic acid. These compounds can ionize in solution, producing ions that conduct electricity. In addition to generating electrical energy, using organic waste as an electrolyte material contributes to waste reduction and the utilization of value-added biomass.

Therefore, bio-batteries using natural electrolytes not only support renewable energy development but also promote circular economy principles and low-carbon technologies.

1.2.3. Concept and Working Principles of Bio-Batteries

A bio-battery is an environmentally friendly electrochemical device that operates on galvanic-cell principles. Electrical energy is generated through redox reactions between two different electrodes immersed in an electrolyte solution. In most bio-battery systems, zinc (Zn) acts as the anode, while copper (Cu) functions as the cathode [22].

Natural electrolytes function by providing ions that facilitate charge transfer in the electrochemical system. Lime peel contains citric acid; starfruit contains oxalic acid, citric acid, and ascorbic acid; and white vinegar contains acetic acid. These compounds ionize in aqueous solutions, releasing H^+ ions that support electrochemical reactions.

The ionization reactions of several organic acids are as follows:
Citric acid: $C_6H_8O_7 \rightarrow C_6H_7O_7^- + H^+$
Ascorbic acid: $C_6H_8O_6 \rightarrow C_6H_7O_6^- + H^+$
Acetic acid: $CH_3COOH \rightarrow CH_3COO^- + H^+$

The higher the concentration of free ions in the electrolyte solution, the greater the bio-battery's conductivity and electrical performance. Therefore, electrolyte composition, acidity, electrode surface area, and inter-electrode distance are important parameters that affect bio-battery performance.

1.2.4. Electrolytes in Bio-Batteries

Electrolytes are essential components in bio-batteries because they enable ionic conduction in the electrochemical system. Natural electrolytes generally come from materials containing organic acids that dissociate in water, producing H^+ ions and their corresponding anions.

The effectiveness of electrolytes depends on several factors, including pH, ion concentration, ion mobility, temperature, and chemical stability. Solutions with lower pH values generally contain higher concentrations of H^+ ions, resulting in better electrical conductivity [23].

Several studies have shown that adding sodium chloride (NaCl) can increase electrolyte conductivity by introducing additional Na^+ and Cl^- ions into the solution. These ions facilitate charge transfer and reduce internal resistance, thereby increasing voltage and current output. As a result, electrolyte optimization plays a crucial role in improving bio-battery performance [24-25].

1.2.5. Potential of Lime Peel as Electrolyte

Lime peel (Citrus aurantifolia) is an organic waste material with significant potential as a bio-battery electrolyte due to its high levels of citric acid, flavonoids, phenolic compounds, and essential oils. Citric acid easily ionizes in water to release H^+ ions, while other bioactive compounds can contribute to electrochemical stability.

The acidic properties of lime peel make it suitable for galvanic cell systems. Previous studies on orange peel have shown that citrus-based extracts can generate voltages up to 0.81 V with Zn and Cu electrodes. Since lime peel generally has higher acidity than sweet orange peel, it is expected to exhibit comparable or superior electrochemical performance.

Beyond its electrochemical properties, lime peel use supports sustainable waste management and biomass valorization, making it a promising renewable electrolyte material [26].

1.2.6. Acid Content of Starfruit

Starfruit (*Averrhoa carambola*) is known for its high acidity, with a pH ranging from 2.5 to 3. This fruit contains high concentrations of oxalic acid, citric acid, and ascorbic acid, making it highly suitable as a natural electrolyte source.

Oxalic acid has two carboxyl groups that easily ionize, producing a large number of conductive ions. Citric acid and ascorbic acid further enhance acidity and ionic conductivity. Experimental studies show that starfruit extract can produce voltages approaching 0.9 V per cell in Zn–Cu bio-battery systems.

Starfruit can also be combined with other electrolyte materials, or NaCl can be added to increase free ion concentration, reduce internal resistance, and improve voltage stability [27].

1.2.7. White Vinegar as Electrolyte

White vinegar is an aqueous solution containing approximately 4–8% acetic acid. Although acetic acid is classified as a weak acid, it can partially dissociate in water, releasing H^+ and CH_3COO^- ions that support electrochemical reactions in bio-batteries.

White vinegar offers several advantages as an electrolyte, including low cost, easy availability, safety, and biodegradability. In simple bio-battery systems, white vinegar can produce voltages ranging from 0.6 to 0.8 V per cell, depending on acid concentration, electrode type, electrode surface area, and inter-electrode distance.

The addition of NaCl can further increase conductivity by increasing the number of free ions in the solution. As a result, white vinegar is a practical and environmentally friendly electrolyte material for bio-battery applications [28].

1.2.8. 1.2.8 Environmentally Friendly Bio-Batteries Based on Local Natural Electrolytes

Bio-batteries utilizing lime peel, starfruit, and white vinegar represent a promising approach to developing renewable energy technology based on local natural resources. These materials contain organic acids that release H^+ ions, thereby supporting electrochemical processes in galvanic systems.

From a sustainability perspective, bio-batteries based on natural electrolytes offer several advantages. The materials are cheap, easily available, biodegradable, and safe for the environment. Additionally, the use of agricultural and household waste contributes to waste reduction and resource efficiency.

Bio-batteries also align with sustainable development goals related to clean energy, responsible production, and low-carbon technology development. Although their electrical output is still lower than that of conventional commercial batteries, bio-

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batteries have considerable potential for educational applications, low-power electronic devices, and future research in renewable energy [29].

1.2.9. 1.2.9 SNI IEC 60086-1:2015 Standard as Evaluation Reference

SNI IEC 60086-1:2015 is the Indonesian national standard adopted from the International Electrotechnical Commission (IEC) standard for primary batteries. This standard regulates electrical performance, testing methods, safety aspects, labeling, and environmental conditions for battery evaluation.
Although the bio-battery developed in this study is not a commercial primary battery, this standard can still serve as a reference framework for evaluating fundamental performance parameters. These parameters include open circuit voltage (OCV), working voltage under load, current output, electrical power, voltage stability, and operational duration.
Electrical power can be calculated using the following equation:
$P = V \times I$ (1)

Performance testing can be conducted by connecting the bio-battery to a low-power load, such as an LED lamp, while recording voltage changes over time. The generated data can be used to create discharge curves and evaluate voltage stability.

Safety observations are also important and include monitoring electrolyte leakage, gas formation, corrosion, electrode discoloration, and abnormal odors. Since bio-batteries use natural, biodegradable materials, their environmental and health risks are much lower than those associated with conventional batteries containing toxic heavy metals such as mercury, cadmium, and lead.

Thus, the developed system can be classified as a Zn–Cu organic acid biobattery. The application of SNI IEC 60086-1:2015 provides a more systematic and measurable framework for evaluating the performance and feasibility of environmentally friendly bio-batteries [30].

2. MATERIALS AND METHODS

2.1. Materials and Equipment

The materials used in this study include:
1. Lime peel
2. Starfruit
3. White vinegar
4. Zinc (Zn) plate as anode
5. Copper (Cu) plate as cathode

Additionally, supporting materials such as bio-battery containers, connecting cables, and insulation materials were also used.
The equipment used includes:
1. Digital multimeter (avometer) for measuring voltage and current
2. pH meter for measuring the solution acidity level
3. Conductivity meter for measuring solution conductivity
4. Measuring cylinder for volume measurement
5. Blender and sieve for the material extraction process
6. Assembly equipment such as soldering tools, scissors, and other tools

This equipment was used to support the manufacturing, testing, and accurate measurement of bio-battery performance.

2.2. Research Procedure

The research procedure was conducted through several stages as follows:

2.2.1. Material Preparation

Lime peel and starfruit were cleaned of dirt, then cut into small pieces to facilitate the extraction process. White vinegar was used as an additional material without further processing.

2.2.2. Electrolyte Preparation

Lime peel and starfruit were ground separately in a blender. The resulting mixture was then filtered through cloth to obtain a liquid extract that would be used as an electrolyte.

2.2.3. Electrolyte Composition Variation

Lime peel extract, starfruit, and white vinegar were mixed in various volume ratios to produce several electrolyte samples.

Table 1. Electrolyte Volume Composition of each Material

No	Lime peel (mL)	Starfruit (mL)	White Vinegar (mL)
1	80	0	0
2	75	2,5	2,5
3	70	5	5
4	65	7,5	7,5
5	60	10	10
6	55	12,5	12,5
7	50	15	15
8	45	17,5	17,5
9	40	20	20
10	35	22,5	22,5
11	30	25	25
12	25	27,5	27,5
13	20	30	30
14	15	32,5	32,5
15	10	35	35
16	5	37,5	37,5
17	0	80	0
18	2,5	75	2,5
19	5	70	5
20	7,5	65	7,5
21	10	60	10
22	12,5	55	12,5
23	15	50	15
24	17,5	45	17,5
25	20	40	20
26	22,5	35	22,5
27	25	30	25
28	27,5	25	27,5
29	30	20	30
30	32,5	15	32,5
31	35	10	35

32	37,5	5	37,5
33	0	0	80
34	2,5	2,5	75
35	15	15	70
36	7,5	7,5	65
37	10	10	60
38	12,5	12,5	55
39	15	15	50
40	17,5	17,5	45
41	20	20	40
42	22,5	22,5	35
43	25	25	30
44	27,5	27,5	25
45	30	30	20
46	32,5	32,5	15
47	35	35	10
48	37,5	37,5	5

2.2.4. *Bio-Battery Assembly*

Each electrolyte mixture was placed into bio-battery containers. Zinc (Zn) and copper (Cu) electrodes were then installed in each container at a specified distance apart to form a bio-battery cell system.

2.2.5. *Performance Measurement*

Measurements were conducted on:

1. Electrical voltage (V)
2. Electric current (mA)
3. Electrical power (W)

Measurements were conducted using a multimeter at several time intervals: 5, 10, 15, and 30 minutes. Measurements were performed both under no-load conditions and with load to more comprehensively assess system performance.

2.2.6. *Electrolyte Characterization*

In addition to electrical parameters, the following measurements were also conducted:

1. Solution pH to determine acidity level
2. Conductivity to determine the ability of a solution to conduct electricity

2.2.7. *Experiment Repetition*

Each experiment was conducted three times to obtain more accurate data and reduce the possibility of measurement errors.

2.3. *Data Analysis*

Measurement data were analyzed to determine the relationship between electrolyte composition and bio-battery performance. The main parameters analyzed include voltage, current, electrical power, and system efficiency.

Electrical power calculation was performed using the equation:

$P = V \times I$

Where:

- P is power (W)
- V is voltage (V)
- I is current (A)

Bio-battery efficiency was calculated using the equation:

Efficiency (%) = (P_load / P_no load) × 100% (2)

Additionally, the effects of pH and solution conductivity on bio-battery performance were analyzed. The data obtained were presented in tables and graphs to facilitate the interpretation of the results.

Descriptive analysis was used to explain the relationships among variables and to examine changes in bio-battery performance over time and with variations in electrolyte composition. Comparisons between samples were conducted to determine the electrolyte composition that produces optimal performance.

2.4. *Environmental Impact Analysis (LCA)*

This study also used the Life Cycle Assessment (LCA) approach to evaluate the environmental impact of the bio-battery manufacturing process. The approach used was cradle-to-gate, which covers the entire process from raw material collection and electrolyte extraction to bio-battery assembly. The distribution, use, and end-of-life disposal stages were not included in the analysis. Evaluation was conducted using SimaPro software to calculate and analyze the environmental impact of each electrolyte composition.

3. RESULT AND DISCUSSION

3.1. *Chemical Characteristics of Electrolyte Solution*

The bio-battery electrolyte solutions used in this study were generally acidic, with low pH values. This indicates a high concentration of hydrogen ions (H^+) in the solution. This acidity arises from various organic acids in the electrolyte, including acetic acid, citric acid, ascorbic acid, and oxalic acid.

The presence of H^+ ions plays an important role in supporting electrochemical reactions, particularly by accelerating oxidation at the zinc (Zn) electrode and enabling electron flow to the copper (Cu) electrode. Thus, the electrolyte solution's acidity directly contributes to bio-battery performance.

The pH of the electrolyte solution ranged from 1.64 to 2.63, with an average of around 2.05. This range indicates that the solution is highly acidic, optimally supporting oxidation and reduction reactions in the bio-battery system.

Additionally, the solution's electrical conductivity ranged from 2 μS/m to 1625 μS/m, with an average of approximately 38.08 μS/m. This conductivity is influenced by the number of dissolved ions in the solution. The higher the ion concentration, the greater the solution's ability to conduct electric current, which ultimately improves bio-battery system performance.

3.2. *Characteristics of Voltage and Electric Current*

Measurement results showed that the voltage generated by the bio-battery ranged from 0.55 V to 0.78 V. The highest voltage was obtained with a specific electrolyte composition, while the lowest value was observed with other mixture variations. This indicates that differences in electrolyte composition affect the electrochemical potential formed at the electrodes.

The electric current generated ranged from 1.12 mA to 3.98 mA. The highest current was produced by certain compositions with higher ion content, while the lowest current was obtained by

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compositions with lower ion concentrations. This indicates that the electric current is strongly influenced by the electrolyte solution's ability to conduct electricity.

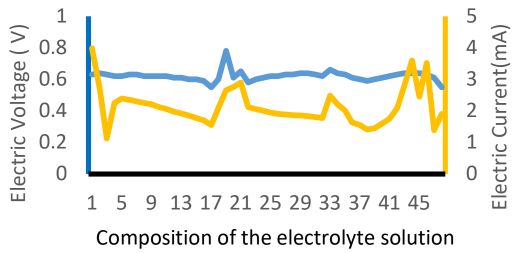

Figure 1. Voltage and current (5 minutes no load)

Figure 1 shows that the voltage was relatively stable in the 0.6–0.7 V range with small fluctuations. Conversely, the electric current exhibited greater fluctuations and was generally unstable. This phenomenon indicates that electric current is more sensitive to changes in electrolyte composition than voltage.

3.3. Bio-Battery Electrical Power

The electrical power generated by the bio-battery ranged from 0.0007 W to 0.0025 W. The electrical power that is quite stable is in the 47th composition, namely between 0.0007 to 0.0008 W. The highest power was observed at certain electrolyte compositions that produced relatively high voltage and current, while the lowest power occurred in mixtures with lower current and voltage.

Electrical power calculation follows the relationship:
$P = V \times I$

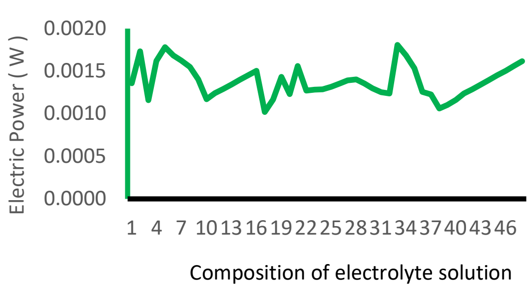

Figure 2. Electrical power (30 minutes no load)

Based on Figure 2, the electrical power pattern shows a fluctuating trend. Initially, power values were relatively low and stable, then increased at certain compositions to a maximum before decreasing again. This indicates an optimal composition that yields the best performance in the bio-battery system.

3.4. Power and Efficiency Analysis

A power and efficiency analysis was conducted to evaluate the bio-battery's ability to generate electrical energy and its energy utilization efficiency. Based on the test results, the bio-battery's power output ranged from 0.0007 to 0.0025 W. System efficiency was calculated based on the ratio of power under load to power without load. The higher the efficiency, the better the system's ability to conserve energy during use. The calculated bio-battery power and efficiency at minute 5 are shown in Table 2.

Table 2. Power and efficiency of bio-battery (at the 5th minute)

No.	Power Without Load (W)	Power With Load (W)	Efficiency (%)
1	0.0025	0.0007	28
2	0.0017	0.0007	41
3	0.0007	0.0007	100
4	0.0014	0.0007	50
5	0.0015	0.0007	47
6	0.0015	0.0007	47
7	0.0014	0.0007	50
8	0.0014	0.0007	50
9	0.0014	0.0006	43
10	0.0013	0.0006	46
11	0.0013	0.0006	46
12	0.0012	0.0006	50
13	0.0012	0.0006	50
14	0.0011	0.0006	55
15	0.0011	0.0006	55
16	0.001	0.0005	50
17	0.0009	0.0006	67
18	0.0013	0.0006	46
19	0.0021	0.0008	38
20	0.0017	0.0007	41
21	0.0019	0.0007	37
22	0.0012	0.0006	50
23	0.0012	0.0006	50
24	0.0012	0.0006	50
25	0.0012	0.0006	50
26	0.0012	0.0006	50
27	0.0012	0.0006	50
28	0.0012	0.0006	50
29	0.0012	0.0006	50
30	0.0012	0.0006	50
31	0.0011	0.0005	45
32	0.0011	0.0005	45
33	0.0016	0.0009	56
34	0.0014	0.0008	57
35	0.0013	0.0007	54
36	0.001	0.0007	70
37	0.0009	0.0007	78
38	0.0008	0.0006	75
39	0.0009	0.0006	67
40	0.001	0.0006	60
41	0.0011	0.0006	55
42	0.0013	0.0006	46
43	0.0018	0.0006	33
44	0.0023	0.0005	22
45	0.0016	0.0005	31
46	0.0022	0.0004	18
47	0.0008	0.0008	100
48	0.001	0.0006	60
Average			51

Based on Table 2, bio battery efficiency values show significant variation, ranging from 18% to 100%. The highest efficiency value (100%) occurred in the 47th electrolyte solution combination, indicating that power with load equals power without load. This condition indicates no significant energy loss, although the generated power is relatively small.

Conversely, the lowest efficiency of 18% indicates significant energy loss in the system. This is likely caused by high internal resistance, unbalanced electrochemical reactions, and low solution conductivity at certain electrolyte compositions.

In general, most data shows efficiency in the range of 40% to 60%, indicating that the bio-battery performs fairly consistently but not optimally. This variation in efficiency indicates that electrolyte composition significantly affects system performance.

The average bio-battery efficiency at 5 minutes is 51%, indicating system performance at that time point. However, based on overall test data at various time intervals (5, 10, 15, and 30 minutes), the average efficiency is 55.42%. This difference indicates that bio-battery performance changes with testing time.

This indicates that system efficiency is not constant but is influenced by electrochemical reaction dynamics and by changes in ion concentration in the electrolyte solution during testing.

Additionally, efficiency variation reflects the effects of internal resistance and the stability of electrochemical reactions on bio-battery performance. The higher the internal resistance, the greater the energy loss in the system, resulting in decreased efficiency.

3.5. 3.5 Life Cycle Assessment (LCA)

This study aims to evaluate the environmental impact of bio-battery production using lime peel, starfruit, and white vinegar, employing a cradle-to-gate Life Cycle Assessment (LCA) approach. The functional unit was defined as one bio-battery produced under laboratory-scale conditions, including electrolyte solution preparation and bio-battery system assembly. System boundaries cover four main stages: raw material collection, washing, extraction, and assembly, while the use and end-of-life treatment phases were excluded from the analysis. Environmental impacts were assessed using the Eco-indicator 99 method for impact categorization and the IPCC GWP 100a method for evaluating carbon emissions.

The life cycle inventory includes all material and energy inputs and emissions generated during each stage of the production process. At the raw material collection stage, lime peel, bilimbi, and white vinegar were obtained from local markets and transported by motorcycle, while supporting materials such as copper, zinc, and battery containers were transported over long distances by diesel-powered vehicles. These transportation activities contribute to emissions of CO_2, CO, NOx, HC, and particulates from fuel consumption. During the washing stage, 3 kg of lime peel and 3 kg of bilimbi were cleaned with approximately 1 liter of water to remove contaminants, resulting in a small amount of wastewater with relatively low environmental impact. The extraction stage involves mechanically processing raw materials to produce electrolyte solutions and requires approximately 0.7 kWh of electrical energy. This stage produced approximately 1.5 liters of lime peel extract and 2.4 liters of bilimbi extract, and it also contributed to carbon emissions from electricity consumption. The assembly stage involves integrating electrolyte solutions with copper (Cu) and zinc (Zn) electrodes, battery containers, cables, and soldering materials, all of which require electrical energy during soldering.

Life cycle impact assessment results show that the extraction stage contributed the largest share to environmental impact, approximately 64–69% of total impact. This dominance is mainly due to electricity consumption and processing activities such as grinding and filtering, which require significant energy input. The assembly stage accounted for approximately 27–30% of the total impact, mainly due to the use of copper and zinc, which have high embodied energy and carbon footprints associated with their production processes. The raw material collection stage accounted for approximately 6–7% of the total impact, primarily due to transportation emissions, while the washing stage contributed less than 1%, indicating a negligible environmental impact compared to other stages. Based on the IPCC GWP 100a method, total carbon emissions from the bio-battery system were estimated at 1,79 kg CO_2-eq, with the extraction stage being the largest contributor, followed by assembly, transportation, and washing.

Interpretation of these results highlights that the extraction process is the most critical stage in terms of environmental impact due to its high energy consumption and processing intensity. Therefore, improving extraction efficiency and reducing electricity use are important strategies to minimize environmental impact. The assembly stage also makes a significant contribution due to the use of metal electrodes, suggesting that alternative materials or recycled metals can be considered to reduce environmental burden. Although bio-batteries use natural materials and organic waste—making them potentially more environmentally friendly than conventional batteries—results show that energy use and material sourcing still play an important role in the overall environmental footprint. Compared to conventional batteries, bio-batteries offer advantages in renewable materials and reduced hazardous waste; however, further optimization is needed to improve their sustainability performance.

Overall, findings indicate that bio-batteries can be categorized as conditionally environmentally friendly technology. Although they provide environmental benefits by using organic waste, improvements are still needed, particularly to reduce energy consumption during extraction, optimize material use, and adopt more sustainable production processes. These improvements are essential for strengthening environmental performance and supporting the development of bio-batteries as a viable alternative energy technology.

4. CONCLUSION

Electrolyte solutions made from lime peel, starfruit, and white vinegar are acidic because they contain organic acids such as citric acid and acetic acid, which produce high levels of H^+ ions. This high level of H^+ ions increases the solution's electrical conductivity, thus supporting the electrochemical reactions in the biobattery. The lower the pH and the higher the conductivity, the better the biobattery's performance in generating electrical energy. A biobattery with an electrolyte mixture of lime peel, starfruit, and white vinegar produces fluctuating voltage, current, and power, but tends to be optimal at certain compositions. The voltage produced is higher when unloaded, but when a load, such as an LED, decreases due to energy consumption. Nevertheless, the biobattery can still power the LED, although its intensity decreases due to reduced electrochemical reactions and ion concentration in the solution. The results of a Life Cycle

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Assessment (LCA) indicate that a biobattery made from lime peel, starfruit, and white vinegar has the potential to be a more environmentally friendly alternative energy source, as it uses organic waste. The greatest environmental impact occurs during the material extraction and assembly stages of the biobattery system. This is primarily due to the use of electrical energy and metal materials such as copper, zinc, and lead.

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