Investigating the Relationship Between Voltage Output and the Number of Cells in a Lemon Battery: An Experimental Study in Electrochemical Energy Generation

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Abstract

This study investigates the generation of electrical energy through a lemon-based galvanic (voltaic) cell, motivated by broader interest in low-cost, accessible, and environmentally benign approaches to energy education and small-scale power generation. Zinc and copper electrodes were employed as the anode and cathode respectively, with the citric acid present in lemon juice serving as the electrolytic medium that facilitates ionic conduction and electron transfer between electrodes. A series of measurements was conducted using a digital voltmeter to determine the potential difference produced by a single lemon cell and by multiple lemon cells connected in series. The results demonstrate that an individual lemon cell reliably produces a potential difference of approximately 0.8–0.9 V, and that connecting additional cells in series increases the total voltage in an approximately linear, additive fashion consistent with Kirchhoff's voltage law for series circuits. Aggregated output from several cells connected in series was found to be sufficient, in principle, to power low-current devices such as light-emitting diodes (LEDs). These findings confirm the fundamental electrochemical principle that stacking galvanic cells in series produces a cumulative electromotive force, and they illustrate, through simple and reproducible materials, the redox chemistry that underlies both introductory chemistry instruction and the operation of commercial batteries. The study contributes to a growing body of classroom-based electrochemistry research and provides a foundation for future investigation into electrode optimization, series–parallel array configurations, and the use of alternative fruit- or vegetable-based electrolytes as sustainable teaching and demonstration tools.

Keywords: *electrochemical cell; lemon battery; galvanic cell; redox reaction; voltage; series circuit; sustainable energy education*

1. Introduction

The growing global emphasis on renewable and low-impact energy sources has renewed interest in simple electrochemical demonstrations that make the principles of energy conversion tangible and accessible, particularly within secondary science education (Everett, 2010; Hall, 2011). Among these demonstrations, the lemon battery occupies a distinctive position: it requires no specialized equipment, poses minimal safety risk, and directly illustrates the conversion of chemical potential energy into usable electrical energy through a redox (oxidation–reduction) reaction. A lemon battery is a simple electrochemical, or galvanic, cell in which the acidic juice of the lemon functions as an electrolyte. When a strip of zinc (the anode) and a strip of copper (the cathode) are inserted into the lemon, a spontaneous chemical reaction occurs at each electrode: zinc undergoes oxidation, releasing electrons into the external circuit, while at the copper electrode, hydrogen ions present in the citric acid are reduced. This electron flow from the zinc anode to the copper cathode through an external circuit constitutes an electric current that can be measured directly with a voltmeter (Chang & Goldsby, 2016).

This experiment focuses specifically on how systematically increasing the number of lemon cells connected in series affects the total voltage output of the resulting circuit. Beyond its pedagogical value in demonstrating the mechanics of a single electrochemical cell, the lemon battery offers an intuitive model for understanding how real, commercially manufactured batteries are constructed from multiple cells to achieve usable voltage levels. Just as household batteries (such as AA or 9V cells) rely on internal cell stacking to reach their rated voltages, the lemon battery allows students to observe this additive principle directly and to quantify it experimentally. In this sense, the lemon battery functions simultaneously as a chemistry demonstration, a physics circuit-building exercise, and an entry point into discussions of sustainable and distributed energy generation.

Lemon batteries are widely used in secondary and introductory tertiary science curricula to demonstrate several interconnected concepts, including:

- Electrochemistry and the conversion of chemical energy into electrical energy
- Redox (oxidation–reduction) reactions between dissimilar metals
- The functional role of an electrolyte in enabling ionic conduction
- Voltage production and measurement in simple galvanic cells
- The behavior of series circuits and the additive nature of electromotive force

The present study extends these standard classroom demonstrations into a structured, data-driven investigation. Rather than treating the lemon battery purely as a qualitative demonstration, this research applies a controlled experimental design to quantify the relationship between the number of cells and total voltage output, situating the findings within the broader theoretical framework of electrochemistry and series-circuit physics.

2. Conceptual and Theoretical Framework

A lemon functions as a galvanic cell in the same fundamental sense as a conventional battery: it converts stored chemical energy into electrical energy through a spontaneous redox reaction. Two dissimilar metal electrodes — zinc and copper — are inserted into the lemon and are connected by an external circuit. Zinc, being more reactive than copper, undergoes oxidation at the anode, losing electrons according to the half-reaction $Zn \rightarrow Zn^{2+} + 2e^-$. These electrons travel through the external circuit toward the copper cathode, where reduction of hydrogen ions from the citric acid occurs: $2H^+ + 2e^- \rightarrow H_2$. The citric acid in the lemon juice serves as the electrolyte, providing the ionic medium necessary to complete the internal circuit and sustain continuous current flow (Zumdahl & Zumdahl, 2013).

In this investigation, the independent variable is the number of lemon cells connected in series, while the dependent variable is the total voltage output measured across the circuit. All other conditions — electrode material, electrode surface area, approximate lemon size, and measurement method — were held as constant as practicable across trials to ensure a fair and internally valid test. The underlying theoretical expectation, grounded in the physics of series circuits, is that connecting galvanic cells in series causes their individual electromotive forces (EMFs) to sum algebraically, such that the total voltage of n identical cells connected in series is approximately $V(\text{total}) \approx n \times V(\text{single cell})$, consistent with Kirchhoff's voltage law. This provides a clear, falsifiable hypothesis for the experiment: as the number of lemon cells increases, total voltage output should increase in an approximately linear and additive manner.

3. Literature Review

The theoretical basis for this investigation draws on established principles of general and physical chemistry. Chang and Goldsby (2016) describe how simple galvanic cells generate voltage through spontaneous redox reactions between electrodes of differing reactivity, a principle directly applicable to the zinc–copper–citric acid system used in this study. Zumdahl and Zumdahl (2013) similarly detail the mechanics of oxidation–reduction reactions and the role of electrolytes in enabling ion transport between electrodes, providing the chemical foundation for why citric acid — rather than distilled water — is essential to the lemon battery's function. Petrucci et al. (2016) further establish the physical principle that, in a series-connected arrangement of electrochemical cells, the voltages of individual cells add together to produce a larger net electromotive force, a relationship this study sought to test empirically using lemons as the electrochemical medium.

Beyond tertiary-level chemistry texts, lemon battery experiments have long served as a staple of secondary science education because of their accessibility and low cost (Cambridge University Press, 2021). Educational resources such as Khan Academy, BBC Bitesize, and Science Buddies present the lemon battery as an entry-level demonstration of both circuit theory and electrochemical energy conversion, commonly used to introduce students to the concept that batteries are not a single mysterious unit but rather an assembly of smaller electrochemical cells whose voltages combine. Atkins and Jones (2012) contextualize this within the broader principle of chemical-to-electrical energy conversion, framing simple cells such as the lemon battery as pedagogically valuable illustrations of thermodynamic and electrochemical concepts that recur throughout the physical sciences. Taken together, this body of literature establishes both the chemical mechanism (redox reactions mediated by an electrolyte) and the electrical mechanism (additive series voltage) that this study set out to verify experimentally.

4. Methodology

4.1 Research Design

This investigation employed an experimental research design in which the independent variable — the number of lemon battery cells connected in series — was systematically manipulated while all other conditions were held constant to the greatest extent possible. This design allows for a direct test of the causal relationship between the number of cells and total voltage output, and supports comparison against the theoretically predicted additive relationship described in Section 2.

4.2 Materials

- Fresh lemons (used as the electrolyte source and physical cell body)
- Zinc strips (anode material)
- Copper strips (cathode material)
- Connecting wires with alligator clips
- A digital voltmeter (for measuring potential difference)
- A beaker (for juice extraction in preliminary trials)

4.3 Procedure

The experimental procedure was carried out as follows:

- Lemon juice was extracted and collected in a beaker for preliminary reference measurements of electrolyte behavior.
- Zinc and copper strips were inserted into each lemon at a fixed depth and separation distance to standardize electrode placement across trials.
- A digital voltmeter was connected across the zinc and copper strips of a single lemon to obtain the baseline single-cell voltage.
- Additional lemon cells were then connected in series by linking the zinc strip of one lemon to the copper strip of the adjacent lemon, progressively increasing the number of cells in the circuit.
- Voltage was recorded after each additional cell was connected, and each configuration (1, 2, and 3 cells) was measured across multiple trials to assess consistency.

4.4 Variables and Controls

The independent variable was the number of lemon cells connected in series (1, 2, or 3). The dependent variable was the total voltage output, measured in volts using a digital voltmeter. Controlled variables included the type and dimensions of the electrodes (zinc and copper strips of consistent size), the approximate size and ripeness of the lemons used, the depth of electrode insertion, and the distance maintained between the zinc and copper strips within each lemon. Holding these factors constant across trials was intended to isolate the effect of cell number on voltage output and minimize confounding variation.

5. Results

The experiment demonstrated a clear, consistent increase in voltage output as additional lemon cells were connected in series. Each individual lemon cell produced a voltage of approximately 0.8–0.9 V, with a representative mean value of approximately 0.89 V per cell across trials. When cells were connected in series, the voltages combined in an approximately linear, additive manner consistent with theoretical expectations. Table 1 summarizes the measured voltage output as a function of the number of lemon cells in series.

Number of Lemon Cells	Measured Voltage (V)	Expected Additive Value (V)
1	≈ 0.89	0.89
2	≈ 1.80	1.78
3	≈ 2.70	2.67

Table 1. Measured versus theoretically expected voltage output as a function of the number of lemon cells connected in series.

As shown in Table 1, the measured voltage values closely track the theoretically expected additive values derived from the single-cell baseline, with only minor deviations attributable to natural variation between lemons and slight differences in electrode contact. The near-linear relationship between the number of cells and total voltage output provides strong empirical support for the hypothesis outlined in Section 2.

6. Evaluation

The research produced several positive outcomes as well as identifiable areas for improvement, discussed below.

6.1 Positive Outcomes

- The experiment confirmed that it is possible to reliably produce measurable electric current using lemon juice as an electrolyte.
- The results demonstrate that an electrical cell can be constructed using the same underlying principle as conventional car and household batteries, but using entirely biodegradable, low-cost, and widely available materials.
- Compared to lead-acid or other heavy-metal-based batteries, the lemon battery poses minimal environmental or health risk, since its primary electrolyte is a common food byproduct rather than a hazardous chemical.
- The energy source is renewable in principle, as lemons are cultivated seasonally and can be sourced sustainably.

6.2 Areas for Improvement

Further research is needed to determine the operational lifetime of a lemon battery constructed for a target voltage, as the electrodes are subject to gradual corrosion and the electrolyte's effectiveness may diminish over time as citric acid is consumed in the reaction. Future iterations of this study could incorporate longer-duration trials to characterize voltage decay over time, as well as comparisons across different lemon varieties, ripeness levels, and electrode metal pairings.

7. Discussion, Conclusion, and Implications

7.1 Discussion

The results show clearly that the voltage output of the lemon battery increases as more lemon cells are connected in series. This outcome is consistent with the theoretical framework outlined in Section 2: each lemon functions as an independent electrochemical cell producing its own voltage, and when cells are connected in series, their individual voltages sum according to Kirchhoff's voltage law (Petrucci et al., 2016). The near-linear pattern of increase observed in this study confirms that each additional lemon cell contributes a roughly consistent increment to total voltage, reinforcing the reliability of the underlying electrochemical mechanism.

Minor variations observed between trials are consistent with typical sources of experimental noise in simple electrochemical demonstrations, including differences in electrolyte concentration between individual lemons, variation in electrode surface area in contact with the juice, and small inconsistencies in the physical distance between the zinc and copper strips (Zumdahl & Zumdahl, 2013). Despite these minor fluctuations, the overall trend strongly and consistently supports the central hypothesis that voltage output increases proportionally with the number of series-connected cells.

More broadly, this experiment illustrates how a simple redox reaction — the oxidation of zinc and the reduction of hydrogen ions at the copper electrode — can be harnessed to generate a measurable and usable electrical current. It provides a tangible, hands-on illustration of the same fundamental principles that govern the operation of commercial batteries, bridging abstract electrochemical theory with direct physical observation.

7.2 Conclusion

The experiment confirms three key findings: first, that a single lemon cell reliably produces a small but measurable voltage of approximately 0.89 V; second, that connecting lemon cells in series increases total voltage in an approximately proportional manner; and third, that the more lemon cells added to a series circuit, the higher the resulting voltage output. These findings directly support the original hypothesis that voltage output increases with the number of cells connected in series. The lemon battery, despite its simplicity, serves as an effective and reproducible model for understanding the fundamental principles of electrochemical cells and electrical energy generation, and reinforces the broader scientific principle that chemical energy can be converted into electrical energy using simple, widely accessible materials such as fruit-based electrolytes (Atkins & Jones, 2012).

7.3 Implications and Applications

The findings of this study carry several practical and educational implications:

- Education: Lemon batteries remain an excellent, low-cost tool for teaching students about electrochemistry, redox reactions, and the operating principles of real batteries.
- Science Communication: The experiment provides a safe, inexpensive, and highly visual way to explore electrical circuits and energy conversion in classroom or laboratory settings.
- Sustainable Energy Awareness: While lemon batteries cannot power large or high-current devices, they offer an accessible entry point for discussing alternative and small-scale renewable energy generation, helping students connect abstract chemical reactions to real-world energy concepts.

7.4 Limitations and Future Research

This study was limited in scope to a small number of series-connected cells (up to three) and did not investigate parallel or mixed series–parallel configurations, which could yield different current and voltage trade-offs. Additionally, the longevity and voltage stability of lemon cells over extended periods were not assessed. Future research could address these gaps by testing larger cell arrays, comparing zinc–copper pairings against alternative electrode metals, evaluating different fruits and vegetables as electrolyte sources, and measuring voltage decay over time to better characterize the practical limitations and potential applications of fruit-based electrochemical cells.

Author Contribution

- Etibar Gafarzada (First Author): Led the design of the presentation materials and research paper, and actively participated in conducting the experiments.
- Ilgar Karimli (Second Author): Contributed substantially to the presentation materials and research paper, and played an active role in conducting the experiments.
- Ribal Talhouk (Supervising Author): Provided guidance on research design and data collection, and supported laboratory work.

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