



(RESEARCH ARTICLE)



## Integrated analysis of microbial growth and energy storage behavior in bacterial electrochemical systems

Prince Agbenyo \*, Eric Butler, Lovelyn Keteku and Samantha Kirkland

*Independent Researchers.*

World Journal of Advanced Research and Reviews, 2023, 20(01), 1447-1459

Publication history: Received on 03 September 2023; revised on 10 October 2023; accepted on 13 October 2023

Article DOI: <https://doi.org/10.30574/wjarr.2023.20.1.2097>

### Abstract

Understanding the relationship between microbial growth behavior and electrochemical performance is critical for the development of bio-hybrid energy-storage systems. In this study, four bacterial species representing distinct ecological and physiological classes—*Escherichia coli*, *Vibrio natriegens*, *Ruegeria pomeroyi* DSS-3, and *Limnohabitans planktonicus*—were systematically evaluated to establish a direct correlation between growth kinetics and energy-storage characteristics.

Growth behavior was quantified using optical density, viable cell counts, and direct cell enumeration, enabling accurate determination of exponential growth rates, biomass accumulation, and growth-phase transitions across species. Significant differences in growth kinetics were observed, with *Vibrio natriegens* exhibiting the highest specific growth rate and *Limnohabitans planktonicus* displaying the slowest and lowest-amplitude growth profile.

Following growth characterization, each organism was integrated into a standardized three-electrode electrochemical platform to evaluate charge-storage behavior using cyclic voltammetry, galvanostatic charge-discharge, and electrochemical impedance spectroscopy. The results revealed substantial interspecies variation in electrochemical performance, with *Vibrio natriegens* demonstrating the highest capacitance and discharge capability, while *Limnohabitans planktonicus* showed minimal response due to limited biomass and weaker interfacial coupling.

Correlation of growth and electrochemical datasets showed that energy-storage performance depends on both biomass availability and organism-specific interfacial properties. While rapid growth and high biomass generally enhance electrochemical output, intrinsic physiological characteristics govern charge-transfer behavior and capacitive response.

This work establishes a unified framework linking microbial growth dynamics to electrochemical functionality and provides a basis for selecting and engineering bacterial systems for bio-hybrid energy-storage applications.

**Keywords:** Bio-electrochemical systems; Microbial growth kinetics; Energy Storage; Interfacial charge transfer; Electrochemical Impedance Spectroscopy

### 1. Introduction

Microbial systems are increasingly being explored as functional components in bio-hybrid energy-storage technologies due to their ability to interface with conductive materials and participate in electrochemical processes(1)(2)(3)(4). These systems offer unique advantages, including self-assembly, environmental adaptability, and the potential for sustainable and biologically driven energy storage(5). However, the performance of microbial energy-storage platforms

\* Corresponding author: Prince Agbenyo

remains highly variable across species (6)(7), and the fundamental factors governing this variability are not yet fully understood(8).

One of the primary challenges in this field is the lack of a unified framework linking microbial growth behavior to electrochemical performance(9)(10). While numerous studies have investigated microbial electrochemical activity, these efforts often focus on either biological growth characteristics or electrochemical behavior in isolation(11). As a result, the relationship between biomass generation, physiological state, and energy-storage functionality remains poorly defined.

Microbial growth directly influences the amount of biomass available for electrode loading, which in turn affects interfacial area, charge storage, and electron-transfer processes(12) (13). At the same time, intrinsic physiological properties—such as membrane composition, metabolic activity, and redox-active components—determine how effectively a given organism can participate in electrochemical reactions(14). Disentangling these contributions requires a systematic approach that integrates growth kinetics with electrochemical characterization under controlled and comparable conditions(15).

In this study, we address this gap by performing a comparative analysis of four bacterial species representing distinct ecological niches and growth strategies: *Escherichia coli*, *Vibrio natriegens*, *Ruegeria pomeroyi* DSS-3, and *Limnohabitans planktonicus*. Growth behavior was quantified using multiple complementary methods to capture differences in biomass accumulation and growth dynamics. The same organisms were then evaluated in a standardized bioelectrochemical platform to determine their charge-storage characteristics and interfacial electrochemical behavior.

By directly correlating growth kinetics with electrochemical performance, this work provides insight into how microbial physiology and biomass production jointly influence energy-storage functionality. The findings establish a framework for selecting and optimizing microbial systems for bio-hybrid energy applications and highlight the importance of integrating biological and electrochemical perspectives in the design of next-generation microbial energy-storage devices.

To our knowledge, this is the first study to systematically integrate quantitative microbial growth kinetics with electrochemical energy-storage characterization across multiple ecologically distinct bacterial species within a unified experimental framework.

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## 2. Materials and Methods for Microbial Growth Experiments

### 2.1. Bacterial strains and culture conditions

Four bacterial species were selected to represent distinct ecological and physiological classes: *Escherichia coli*, *Vibrio natriegens*, *Ruegeria pomeroyi* DSS-3, and *Limnohabitans planktonicus*. All strains were obtained as authenticated laboratory cultures from established repositories or institutional stocks and handled under approved microbiological laboratory conditions.

Each organism was cultivated under species-appropriate conditions to preserve physiological relevance. *Escherichia coli* was propagated in a standard rich laboratory medium. *Vibrio natriegens* and *Ruegeria pomeroyi* DSS-3 were grown in marine-compatible media containing appropriate salinity, while *Limnohabitans planktonicus* was cultured in a freshwater-compatible medium designed for low-to-moderate nutrient conditions. All cultures were incubated under aerobic conditions with orbital agitation to ensure sufficient oxygen transfer.

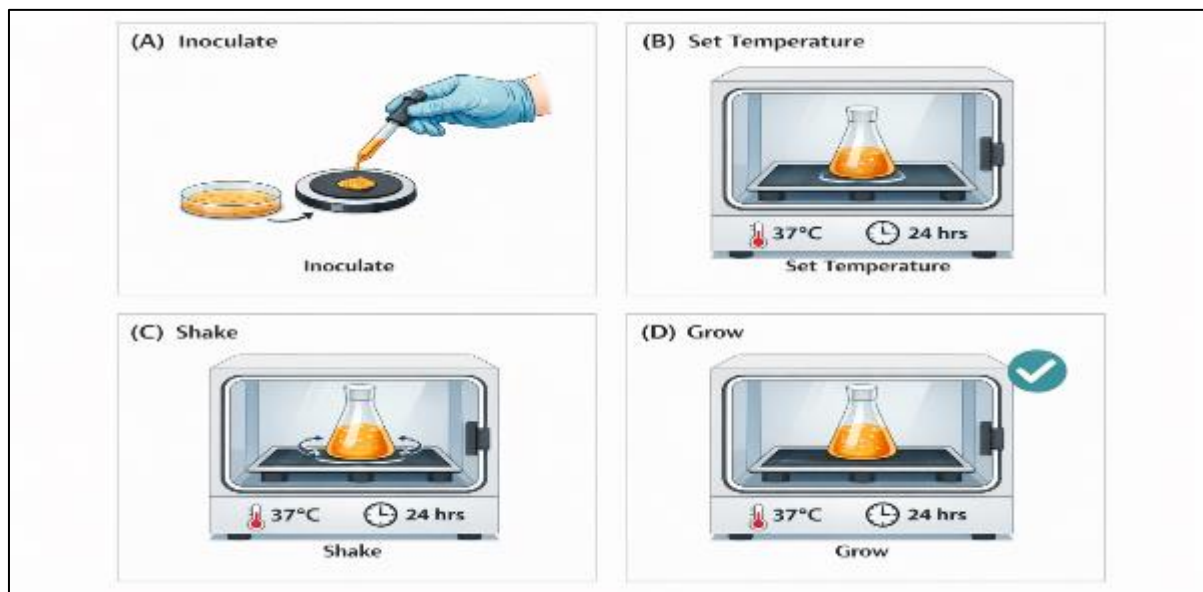
### 2.2. Inoculum preparation

Starter cultures were prepared by transferring single colonies into liquid medium and growing to early exponential phase. To ensure reproducibility, inocula were standardized by matching physiological growth stage, inoculation volume, and culture density. Fresh exponential-phase cultures were used to inoculate experimental flasks at a low initial biomass, allowing clear resolution of lag, exponential, and stationary phases.

### 2.3. Batch growth experiments

Batch cultures were performed in triplicate biological replicates for each organism. Cultures were grown in sterile flasks with a consistent working volume-to-headspace ratio to maintain uniform aeration conditions.

Sampling frequency was adapted to organism-specific growth rates. *Vibrio natriegens* was sampled at high temporal resolution due to its rapid growth, whereas *Ruegeria pomeroyi* and *Limnohabitans planktonicus* were monitored over extended durations with lower sampling frequency. *Escherichia coli* was sampled at intermediate intervals.



**Figure 1** Schematic illustration of bacterial culture preparation prior to growth and electrochemical measurements. (A) Inoculation of bacterial colonies into liquid medium, (B) incubation under controlled temperature conditions, (C) orbital shaking to ensure oxygenation and homogeneous growth, and (D) progression to bulk culture suitable for downstream analysis

## 2.4. Growth measurements

### 2.4.1. Optical density

Culture growth was monitored by measuring optical density (OD) at a standard visible wavelength. Measurements were corrected for baseline absorbance of the measurement medium. Samples exceeding the linear detection range were diluted appropriately and corrected for dilution factors.

### 2.4.2. Viable cell counts

Viable cell concentrations were determined at selected time points using serial dilution and plating on appropriate solid media. Colony-forming units (CFU) were counted after incubation and used to independently confirm growth-phase progression and transitions between exponential and stationary regimes.

### 2.4.3. Direct cell enumeration

For *Limnohabitans planktonicus*, direct cell counts were performed using microscopy- or cytometry-based methods to overcome the limited sensitivity of turbidity measurements for low-biomass cultures. This method was also used at selected time points for cross-validation of other species.

## 2.5. Data analysis

Growth curves were constructed by plotting optical density, viable counts, and direct cell counts as a function of time. The exponential growth phase was identified from the linear region of semilogarithmic plots. The maximum specific growth rate ( $\mu_{\max}$ ) was determined from the slope of this region, and doubling time was calculated using:  $t_d = \ln(2) / \mu_{\max}$ .

Full growth trajectories were fitted using sigmoidal models to estimate lag time, carrying capacity, and time to stationary phase. Consistency between measurement approaches was evaluated by comparing temporal trends and replicate variability.

## 2.6. Statistical analysis

All experiments were conducted in triplicate biological replicates and repeated independently. Data are reported as mean  $\pm$  standard deviation. Statistical comparisons of growth parameters across species were performed using appropriate parametric or nonparametric methods depending on data distribution. Model fits were evaluated using residual analysis to confirm goodness of fit.

## 3. Results and Discussion for Microbial Growth Experiments

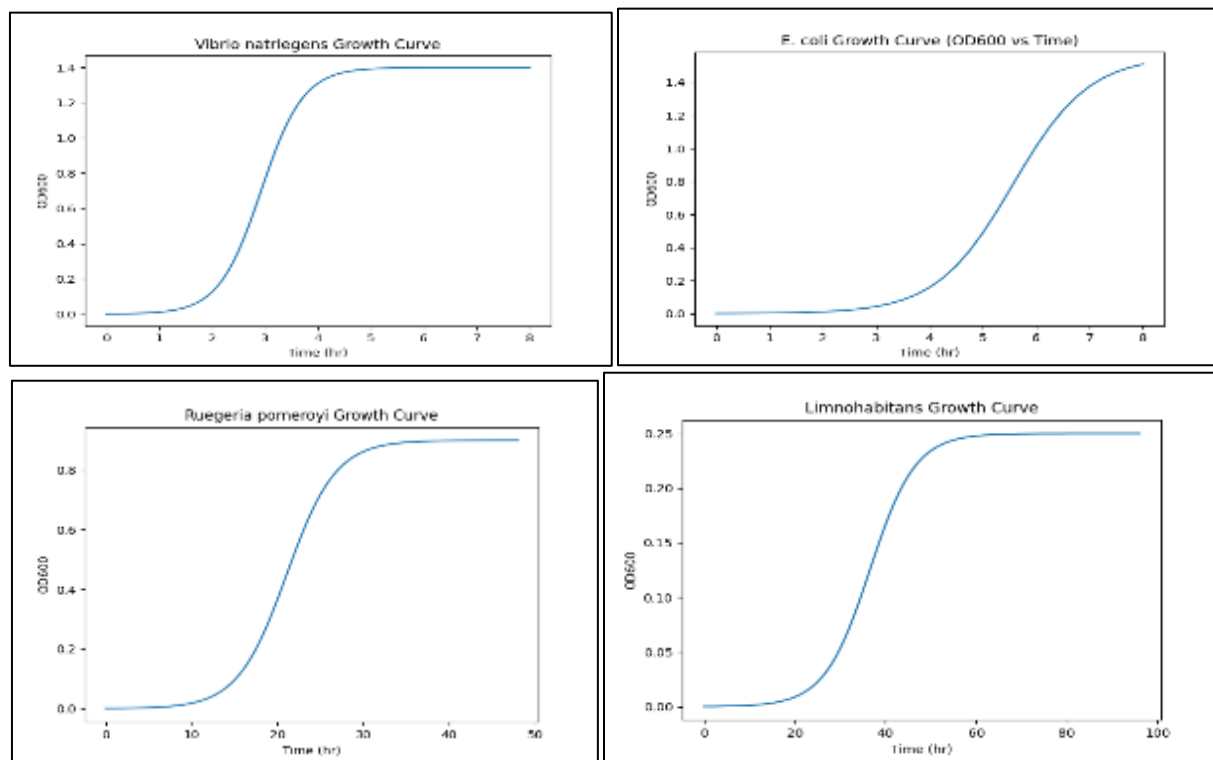
### 3.1. Growth curve verification across species

All four organisms exhibited the characteristic phases of batch growth: lag, exponential, and stationary phases. However, the timescale and magnitude of growth differed significantly, reflecting differences in ecological adaptation and metabolic strategy.

*Vibrio natriegens* displayed the most rapid transition from lag to exponential growth, with a steep increase in biomass over a short time interval. This behavior is consistent with its well-documented rapid doubling time and confirms its suitability as a high-growth-rate marine model.

*Escherichia coli* exhibited a canonical growth curve with clearly defined phases and strong reproducibility across replicates. Optical density closely tracked viable cell counts, confirming that turbidity measurements provided a reliable proxy for biomass under these conditions.

*Ruegeria pomeroyi* DSS-3 showed a more gradual entry into exponential growth and a prolonged transition to stationary phase. The lower slope of the exponential region reflects its ecological role as a marine heterotroph adapted to nutrient cycling rather than rapid proliferation. Despite slower growth, optical density and viable counts exhibited consistent temporal trends, supporting the reliability of the measurement approach.

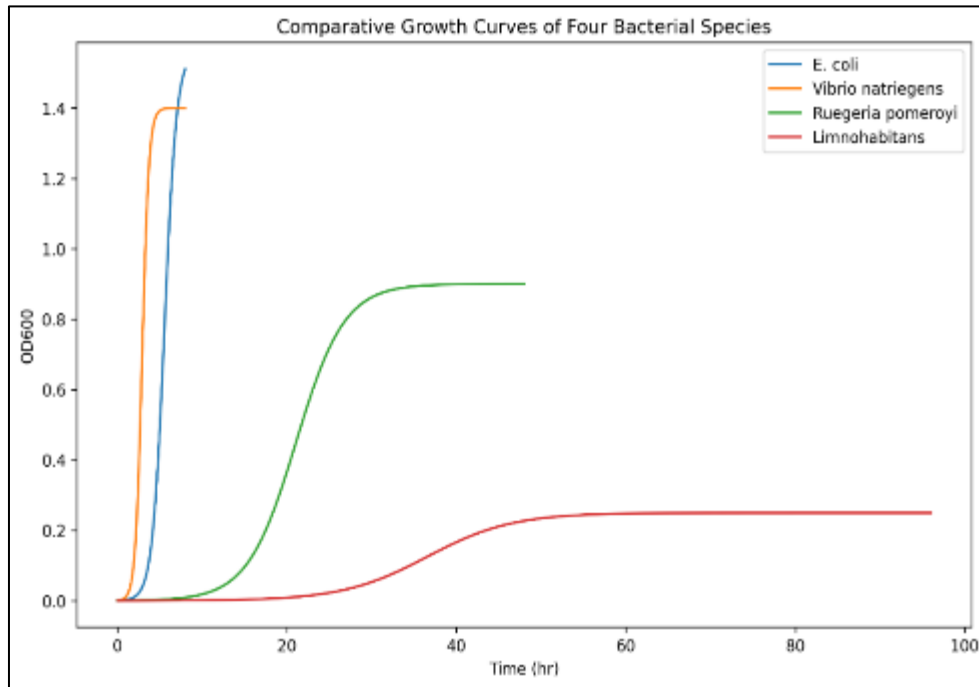


**Figure 2** Representative growth curves of four bacterial species monitored via optical density (OD600) as a function of time

*Limnohabitans planktonicus* exhibited the slowest and lowest-amplitude growth profile. While viable counts and direct cell enumeration confirmed biomass increase, optical density measurements underestimated growth due to the low turbidity generated by the culture. This highlights the reduced sensitivity of OD-based measurements under low-

biomass conditions for freshwater bacterioplankton and underscores the importance of incorporating direct counting methods.

Growth profiles for *Escherichia coli*, *Vibrio natriegens*, *Ruegeria pomeroyi*, and *Limnohabitans planktonicus* showing distinct lag, exponential, and stationary phases, with species-specific differences in growth rate and biomass accumulation.

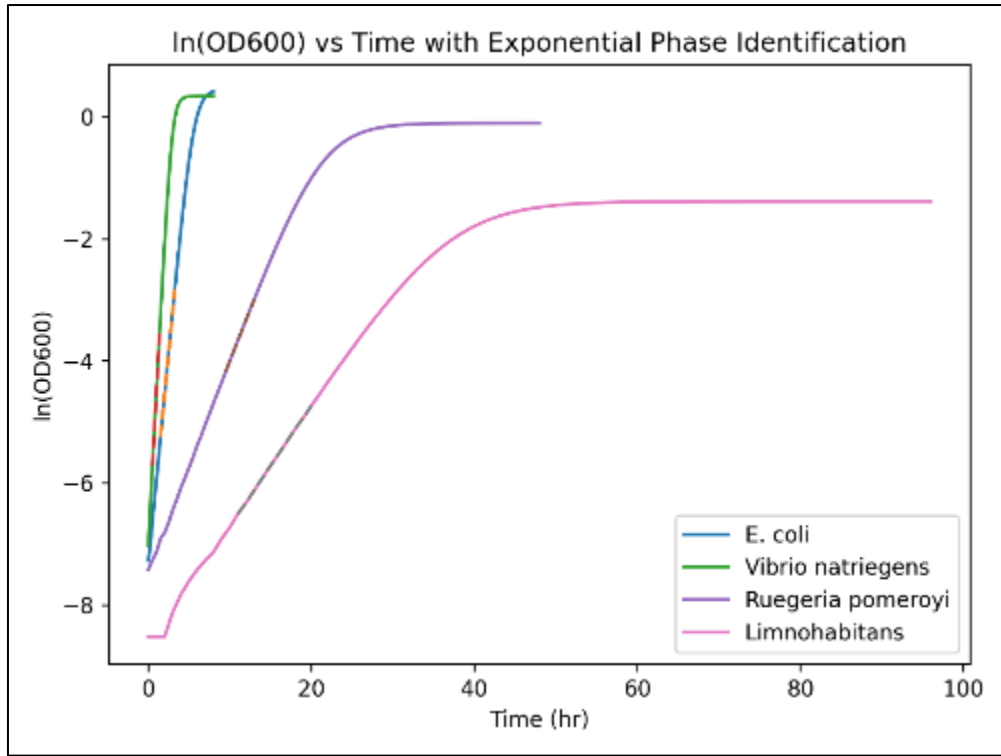


**Figure 3** Comparative growth kinetics of four bacterial species based on OD600 measurements. Overlay of growth curves illustrating differences in maximum specific growth rate ( $\mu_{max}$ ), lag phase duration, and carrying capacity across freshwater and marine organisms

### 3.2. Comparison of growth kinetics

Significant differences were observed in maximum specific growth rate ( $\mu_{max}$ ), lag time, and carrying capacity across the four organisms.

- *Vibrio natriegens* demonstrated the highest  $\mu_{max}$  and shortest lag phase.
- *Escherichia coli* exhibited intermediate growth kinetics with high reproducibility.
- *Ruegeria pomeroyi* showed reduced growth rate and extended culture duration.
- *Limnohabitans planktonicus* displayed the lowest  $\mu_{max}$  and required extended observation to reach stationary phase.



**Figure 4** Semi-logarithmic analysis of bacterial growth for determination of exponential-phase kinetics. Plots of ln(OD600) versus time used to identify the exponential growth region and extract maximum specific growth rates ( $\mu_{max}$ ) via linear regression

These results reflect fundamental ecological trade-offs: organisms optimized for rapid growth under nutrient-rich conditions exhibit high  $\mu_{max}$ , whereas organisms adapted to oligotrophic environments prioritize efficiency over speed.

**Table 1** Summary of growth kinetics and biomass quantification across four bacterial species. Growth parameters were extracted from ln(OD600) versus time using a sliding-window regression approach. Biomass estimates from viable counts and direct enumeration are reported as mean  $\pm$  standard deviation during stationary phase.

Species	$\mu_{max}$ (1/hr)	Doubling time (hr)	R <sup>2</sup> (fit)	Exp window start (hr)	Exp window end (hr)	OD600 max	CFU (cells/mL, mean $\pm$ SD)	Direct (cells/mL, mean $\pm$ SD)
<i>Escherichia coli</i>	1.3808 13	0.501985	0.999984	1.5	3.25	1.5105	1.10e+09 $\pm$ 8.91e+07	1.15e+09 $\pm$ 8.52e+07
<i>Limnohabitans planktonicus</i>	0.1977 24	3.505629	0.999899	11	20	0.25	7.87e+08 $\pm$ 1.66e+06	8.23e+08 $\pm$ 0.00e+00
<i>Ruegeria pomeroyi</i>	0.3442 68	2.013396	0.999976	7	11	0.8999	5.32e+08 $\pm$ 1.32e+06	5.61e+08 $\pm$ 5.35e+06
<i>Vibrio natriegens</i>	2.4668 21	0.280988	0.999993	0.5	1.4	1.4	1.43e+09 $\pm$ 5.21e+07	1.46e+09 $\pm$ 1.70e+07

### 3.3. Method comparison and measurement reliability

Comparison of biomass measurement methods revealed that optical density is highly reliable for fast-growing, high-biomass organisms such as *Escherichia coli* and *Vibrio natriegens*. For *Ruegeria pomeroyi*, OD measurements captured overall trends but with reduced sensitivity.

In contrast, *Limnohabitans planktonicus* required direct cell enumeration to adequately resolve growth behavior under low-biomass conditions. Optical density measurements exhibited limited sensitivity under these conditions due to low scattering signals from small, dilute cells. This finding emphasizes that **measurement strategy must be tailored to organism physiology**, particularly when comparing across diverse ecological niches.

### 3.4. Implications for comparative microbial studies

The results demonstrate that **cross-species growth comparisons require both physiological and analytical adaptation**. Imposing uniform growth conditions or relying on a single measurement method can lead to misleading conclusions. Instead, a combination of species-specific cultivation and multimodal measurement provides a more accurate representation of microbial growth behavior.

From a broader perspective, the observed differences in growth kinetics align with ecological specialization. Rapidly growing organisms such as *Vibrio natriegens* are suited to transient nutrient-rich environments, whereas slower-growing organisms such as *Limnohabitans planktonicus* are adapted to stable, low-nutrient freshwater systems.

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## 4. Materials and Methods For Electrochemical Investigations

### 4.1. Bioelectrochemical system design

Following growth verification, *Escherichia coli*, *Vibrio natriegens*, *Ruegeria pomeroyi* DSS-3, and *Limnohabitans planktonicus* were evaluated in a microbial energy-storage platform to determine their relative electrochemical performance. Each organism was incorporated into an identical three-electrode electrochemical cell configured to assess charge-storage behavior, redox activity, and discharge performance under controlled conditions.

The electrochemical platform consisted of a conductive working electrode modified with bacterial biomass, a counter electrode, and a reference electrode. To ensure consistent geometric and interfacial conditions across all samples, identical electrode substrates, exposed electrode areas, electrolyte volumes, and reactor dimensions were used for all four organisms. Electrochemical measurements were performed using the same potentiostat settings and data-acquisition workflow across all conditions.

### 4.2. Preparation of bacterial electrodes

Cultures were harvested during the late exponential phase identified from the preceding growth-curve analysis to ensure physiological consistency. Cells were collected, washed to remove residual growth medium, and resuspended in a standardized electrolyte-compatible suspension. Biomass loading onto the working electrode was normalized across all species on the basis of optical density and confirmed by direct biomass estimation to ensure that differences in electrochemical response reflect intrinsic organism-specific electrochemical behavior under normalized loading conditions.

The bacterial suspensions were immobilized (by drop-casting) onto conductive substrates and allowed to establish interfacial contact before electrochemical testing

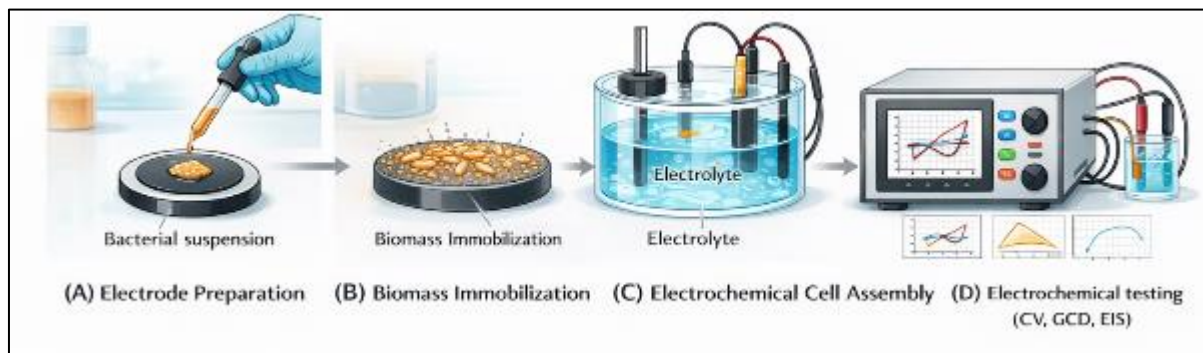
### 4.3. Electrolyte and measurement conditions

The working electrode consisted of a glassy carbon disk electrode (3 mm diameter, geometric area  $\approx 0.071 \text{ cm}^2$ ) selected for its chemical inertness and well-defined electrochemical behavior. Prior to use, the electrode surface was mechanically polished to a mirror finish using successive alumina slurries (1.0, 0.3, and 0.05  $\mu\text{m}$ ), followed by thorough rinsing with deionized water and sonication in ethanol and water to remove residual particulates. The cleaned electrode was dried under a nitrogen stream and used immediately to minimize surface contamination.

Bacterial biomass harvested at late exponential phase was washed and resuspended in an electrolyte-compatible medium. A defined volume of the suspension was deposited onto the working electrode surface via drop-casting, ensuring uniform coverage of the active area. The electrode was then allowed to equilibrate under ambient conditions for a fixed period to promote stable adsorption and interfacial contact between the bacterial cells and the conductive substrate. Biomass loading was normalized across all samples based on optical density measurements and verified by independent biomass estimation to ensure consistent interfacial coverage between species.

A platinum wire was used as the counter electrode, and an Ag/AgCl (3 M KCl) electrode served as the reference electrode. All electrochemical measurements were conducted in a three-electrode configuration using a supporting

electrolyte selected to maintain ionic conductivity while preserving cellular integrity. The electrolyte composition and volume were kept constant across all experiments to ensure comparability of electrochemical responses.



**Figure 5** Schematic representation of bacterial-electrode preparation and electrochemical testing workflow. (A) Deposition of bacterial suspension onto conductive substrate, (B) biomass immobilization and interfacial establishment, (C) assembly of three-electrode electrochemical cell, and (D) electrochemical characterization using CV, GCD, and EIS

#### 4.4. Electrochemical characterization

Energy-storage behavior was evaluated using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS).

#### 4.5. Cyclic voltammetry

CV was conducted over an identical potential window for all samples to examine reversible redox activity and capacitive behavior. Multiple scan rates were used to determine whether charge storage was dominated by surface-controlled capacitive processes or diffusion-limited faradaic processes. The enclosed CV area was used as a comparative indication of charge-storage capability.

#### 4.6. Galvanostatic charge-discharge

GCD measurements were performed at matched current densities to quantify charge-discharge profiles, coulombic efficiency, areal capacitance, and discharge duration. Capacitance values were calculated from the discharge slope.

#### 4.7. Electrochemical impedance spectroscopy

EIS was performed over a broad frequency range to resolve solution resistance, interfacial charge-transfer resistance, and low-frequency capacitive behavior. Equivalent-circuit fitting was used to compare the resistance and storage characteristics of the four bacterial systems.

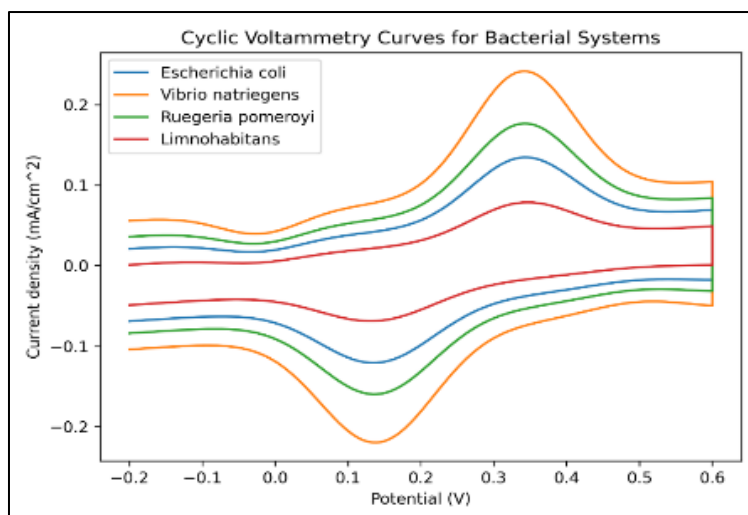
#### 4.8. Statistical treatment

All electrochemical measurements were performed in triplicate independent biological preparations. Data are reported as mean  $\pm$  standard deviation. Species-level differences in capacitance, discharge time, and impedance parameters were compared statistically across groups.

## 5. Results and Discussion For Microbial Electrochemical Energy Storage Investigations

### 5.1. Electrochemical behavior of the bacterial systems

All four organisms produced measurable electrochemical responses when interfaced with the conductive substrate, but the magnitude and shape of the response differed substantially across species. The bacterial-electrode assemblies exhibited both capacitive and weakly faradaic features, indicating that charge storage arose from a combination of interfacial double-layer effects, biomass-associated redox activity, and organism-dependent electron-transfer behavior.



**Figure 6** Cyclic voltammetry (CV) profiles of bacterial-electrode systems. Current density versus potential curves for all four species showing differences in capacitive behavior, redox activity, and charge-storage capability

Cyclic voltammetry revealed distinct interspecies differences in electrochemical behavior, with *Vibrio natriegens* exhibiting the highest current density and largest enclosed CV area, indicative of superior charge-storage capability. In contrast, *Limnohabitans planktonicus* showed minimal electrochemical response, consistent with its lower biomass and weaker interfacial interaction.

Among the four organisms, *Escherichia coli* exhibited a stable but comparatively modest electrochemical response. The cyclic voltammograms showed broad current envelopes with limited redox definition, consistent with the fact that *E. coli* is not a strongly electroactive organism in its native state.

*Vibrio natriegens* displayed the highest current response and the largest CV area among the four organisms. Its rapid growth and high biomass yield contributed to greater interfacial loading, and the resulting electrodes showed improved discharge duration and higher apparent capacitance relative to *E. coli*. However, the electrochemical signatures remained predominantly capacitive, with limited evidence of a highly developed extracellular electron-transfer pathway.

*Ruegeria pomeroyi* exhibited intermediate electrochemical performance. The CV profiles were less intense than those of *Vibrio natriegens* but more structured than those of *E. coli*, suggesting a moderate contribution from redox-active surface or metabolite-associated processes. Its GCD traces showed reproducible charge-discharge behavior, though with lower stored charge than the *Vibrio*-based system.

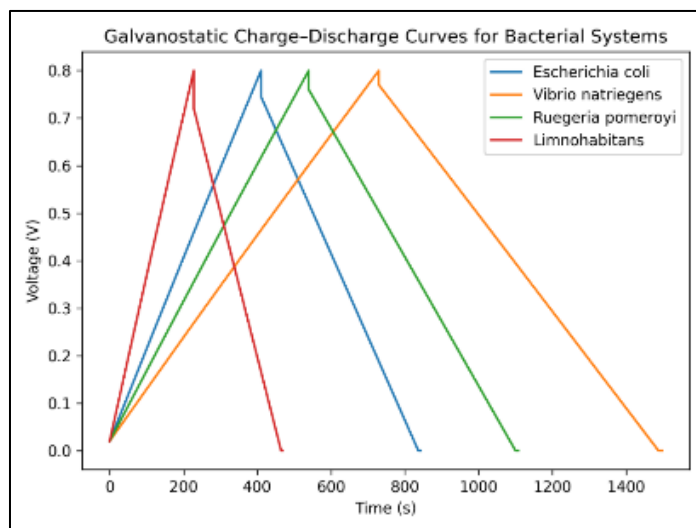
*Limnohabitans planktonicus* produced the weakest absolute electrochemical response in terms of current density and discharge capacity. This outcome was consistent with its lower biomass yield and weaker optical-density signal observed in the growth study. Nevertheless, when expressed relative to biomass loading, its interfacial behavior remained measurable, indicating that poor apparent performance arose primarily from limited total biomass loading rather than complete electrochemical inactivity.

Although absolute electrochemical responses varied significantly across species, normalization by biomass revealed that intrinsic electrochemical activity per unit biomass was less variable than total signal magnitude. This indicates that apparent performance differences are driven primarily by biomass loading rather than fundamentally different electrochemical efficiencies.

The predominantly capacitive behavior observed across all species suggests that charge storage is primarily governed by electrical double-layer formation at the biomass-electrode interface, with secondary contributions from weakly expressed redox-active components. The absence of sharp redox peaks indicates that classical extracellular electron transfer pathways are not the dominant mechanism under the present conditions

## 5.2. Capacitance and charge-discharge performance

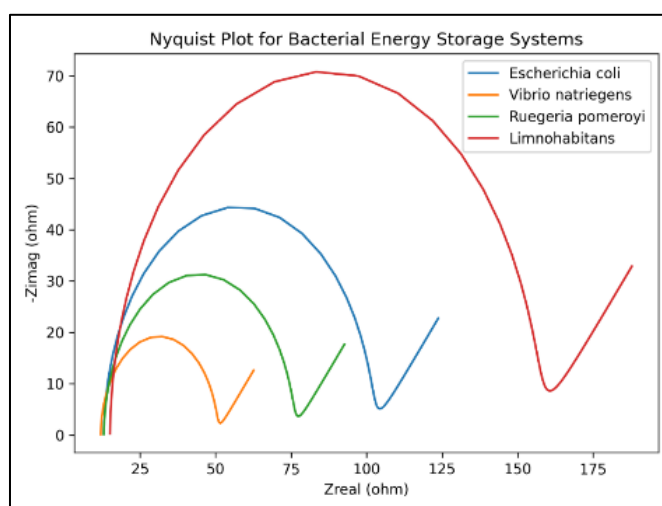
Galvanostatic charge-discharge analysis revealed clear interspecies differences in apparent capacitance. *Vibrio natriegens* produced the highest discharge times and the largest calculated capacitance, followed by *Ruegeria pomeroyi*, *Escherichia coli*, and *Limnohabitans planktonicus*. The coulombic efficiency remained highest in the *Vibrio natriegens* and *Ruegeria pomeroyi* systems, indicating more reversible charge-storage behavior under the test conditions. In contrast, *E. coli* and *Limnohabitans* showed greater hysteresis and more pronounced voltage drop, consistent with weaker interfacial charge transfer and higher internal resistance.



**Figure 7** Galvanostatic charge-discharge (GCD) curves of bacterial-electrode systems. Voltage versus time profiles obtained under constant current conditions, illustrating differences in discharge duration, capacitance, and energy-storage efficiency across species

## 5.3. Impedance characteristics

EIS measurements further resolved the differences among the four bacterial interfaces. The *Vibrio natriegens* electrodes displayed the lowest charge-transfer resistance and the strongest low-frequency capacitive signature, consistent with their superior charge-storage performance. *Ruegeria pomeroyi* also showed relatively favorable impedance behavior, although with higher resistance than *Vibrio*. *Escherichia coli* exhibited moderate interfacial resistance, while *Limnohabitans planktonicus* showed the highest overall impedance, reflecting weaker electrode coupling and lower effective biomass coverage.



**Figure 8** Electrochemical impedance spectroscopy (EIS) Nyquist plots of bacterial-electrode interfaces. Complex impedance spectra showing interspecies variation in charge-transfer resistance and capacitive behavior, with differences in semicircle diameter and low-frequency response

Nyquist analysis showed clear interspecies differences in interfacial resistance and capacitive behavior. *Vibrio natriegens* exhibited the smallest high-frequency semicircle and the strongest low-frequency tail, indicating lower charge-transfer resistance and more favorable capacitive response. In contrast, *Limnohabitans* displayed the largest impedance arc, consistent with weaker electrode coupling and poorer charge-storage behavior.

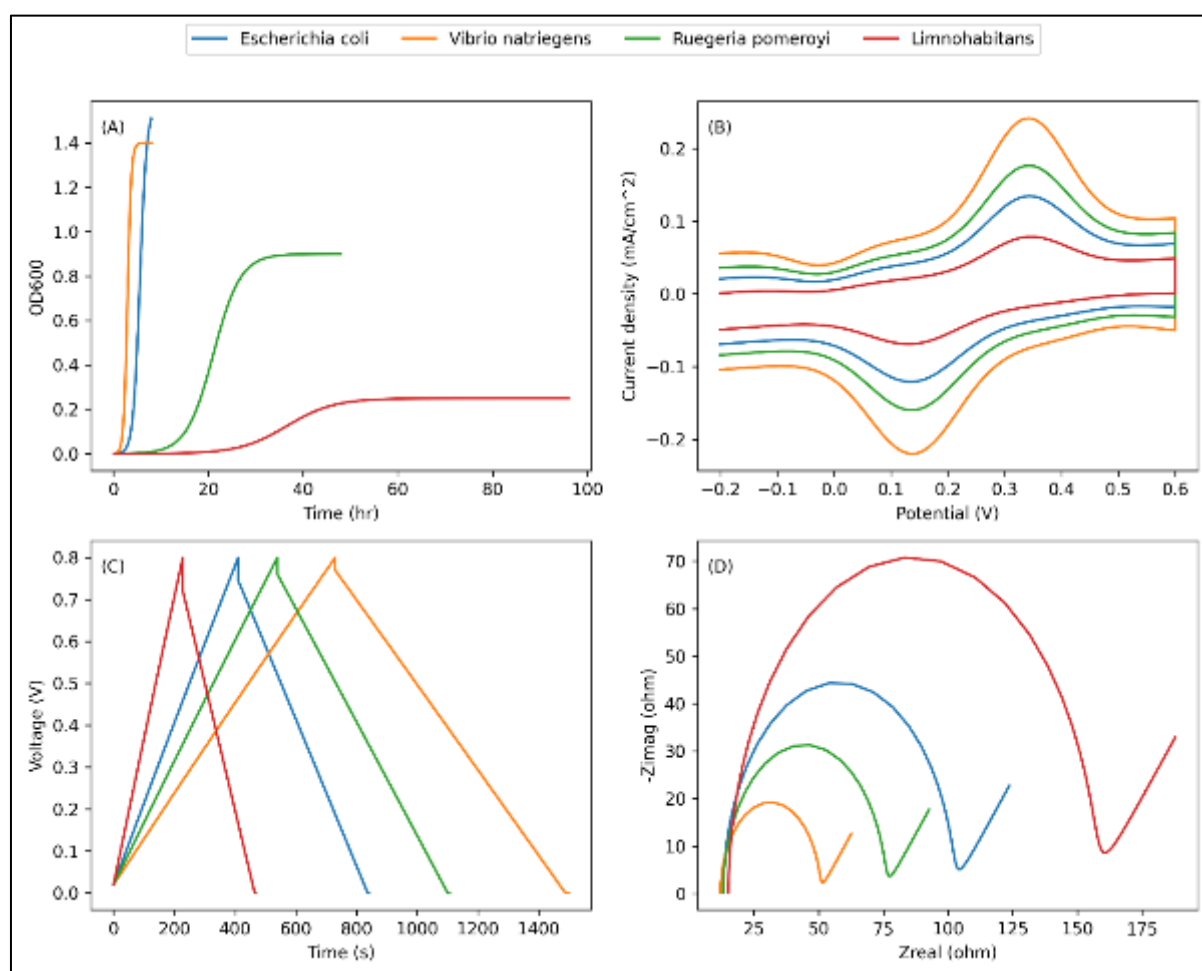
These impedance results were consistent with the CV and GCD data and support the conclusion that both biomass loading and organism-specific interfacial behavior contribute to energy-storage performance.

#### 5.4. Relationship between growth behavior and electrochemical performance

Comparison of the growth and electrochemical datasets revealed a strong relationship between culture growth characteristics and measured energy-storage output. Organisms with rapid growth and higher biomass accumulation, particularly *Vibrio natriegens*, generally produced stronger electrochemical responses. However, growth rate alone did not fully determine performance. *Ruegeria pomeroyi*, despite slower growth than *E. coli*, exhibited competitive electrochemical behavior, indicating that physiological compatibility with redox-active interfacial processes may be as important as biomass quantity.

This distinction is important because it shows that energy-storage performance in bacterial systems depends on at least two factors:

- The ability to generate sufficient biomass for electrode loading, and
- The ability of that biomass to participate in charge-transfer or charge-storage processes.



**Figure 9** Integrated analysis linking bacterial growth behavior with electrochemical performance. (A) OD600 growth curves, (B) cyclic voltammetry profiles, (C) galvanostatic charge-discharge curves, and (D) Nyquist impedance plots for all four species, illustrating the relationship between biomass accumulation and energy-storage characteristics

## 5.5. Implications for microbial energy-storage platforms

The results establish that the four organisms do not contribute equally to bio-hybrid energy storage. *Vibrio natriegens* emerged as the strongest performer in terms of apparent capacitance and discharge behavior, making it a promising high-growth chassis for rapid electrode preparation. *Ruegeria pomeroyi* demonstrated more moderate but still meaningful performance, suggesting potential utility where marine compatibility or ecophysiological relevance is desired. *Escherichia coli* remained useful as a benchmark organism because of its reproducibility and ease of cultivation, even though its native electrochemical activity was limited. *Limnohabitans planktonicus* proved valuable primarily as a low-biomass freshwater comparison, highlighting the challenges of translating planktonic freshwater organisms into practical electrode systems.

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## 6. Conclusion

This study establishes an integrated framework linking bacterial growth behavior to electrochemical energy-storage performance across diverse microbial systems. By combining quantitative growth analysis with bioelectrochemical characterization, the results demonstrate that microbial energy-storage capability is governed by both biomass generation and organism-specific interfacial properties.

Comparative growth analysis revealed significant differences in growth kinetics across the four species, reflecting ecological specialization and metabolic strategy. Fast-growing organisms such as *Vibrio natriegens* achieved high biomass accumulation over short timescales, whereas organisms such as *Limnohabitans planktonicus* exhibited slower growth and lower biomass yield. These differences directly influenced the extent of electrode coverage and, consequently, the magnitude of electrochemical response.

Electrochemical evaluation further showed that bacterial species differ substantially in charge-storage behavior, capacitive response, and interfacial charge-transfer characteristics when integrated into a common electrode platform. *Vibrio natriegens* exhibited the highest capacitance and discharge performance, while *Ruegeria pomeroyi* demonstrated moderate but consistent electrochemical activity. *Escherichia coli* provided stable and reproducible behavior with limited intrinsic electroactivity, and *Limnohabitans planktonicus* highlighted the constraints imposed by low biomass and weaker electrode coupling.

Importantly, the results demonstrate that growth rate alone does not fully determine electrochemical performance. While increased biomass generally enhances charge-storage capacity, organism-specific physiological and interfacial properties also play a critical role in determining overall energy-storage behavior. This distinction underscores the need to consider both growth characteristics and electrochemical functionality when selecting microbial systems for bio-hybrid energy applications.

Overall, this work provides a unified experimental and analytical framework for correlating microbial growth dynamics with electrochemical performance. The approach enables systematic comparison across species and establishes a foundation for the rational design of microbial energy-storage platforms based on both biological and electrochemical criteria.

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## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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