

Bridging Biology and Computation: The Rise of Organoid Intelligence in Sustainable Computing and Neuroscience

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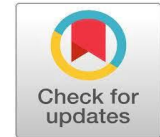
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Abstract: As artificial intelligence (AI) and high-performance computing continue to expand, their growing energy demands have sparked an urgent search for sustainable alternatives. Recent advances in organoid intelligence (OI)—a convergence of neuroscience, bioengineering, and computational science suggest a new paradigm where living neurons serve as processing units. This paper explores how lab-grown neural organoids are revolutionizing energy-efficient computing and advancing our understanding of brain function. Drawing from recent studies at Johns Hopkins University, University of California San Diego, and Cortical Labs, this work reviews the evolution, architecture, and applications of OI-based biochips. The discussion includes breakthroughs in energy efficiency, neurocomputational modeling, and disease research, alongside the ethical and technical challenges of integrating biological systems with digital frameworks. Ultimately, this paper highlights OI's potential to redefine computation, neuroscience, and medical diagnostics in a carbon-conscious technological era.

Keywords: Organoid Intelligence (OI), Biohybrid Computing, Energy Efficiency, Neuroscience, Neural Organoids, Brain-Inspired Chips, Sustainable AI

INTRODUCTION:

Artificial intelligence (AI) systems are transforming global industries, but their computational intensity has created a parallel crisis in energy consumption. Current AI models, such as large language models (LLMs), consume terawatt-hours of electricity annually, with global AI energy demand projected to double within the next five years, accounting for nearly 3% of worldwide electricity use [1]. Traditional silicon-based processors, while efficient in digital logic, lack the biological adaptability and parallelism of the human brain. This growing inefficiency has led scientists toward organoid intelligence (OI)—a novel discipline merging living neural tissue with machine hardware. The concept, first formalized by researchers including Thomas Hartung and David Gracias at Johns Hopkins University, seeks to use networks of lab-grown brain organoids as computing substrates [2]. These organoids, formed from stem cells, mimic human brain structure and activity at microscopic scales. Simultaneously, neuroscientists such as Alysson Muotri at the University of California, San Diego (UCSD) and Brett Kagan at Cortical Labs in Australia are using neural organoids to model cognition and disease [3]. Together, their work bridges computation and biology, hinting at computers that learn, adapt, and consume energy like living brains—potentially achieving exponential energy efficiency over conventional processors.

LITERATURE REVIEW:

Organoid intelligence emerged from decades of incremental progress in stem cell biology, bioelectronics, and neural computation. The groundwork was laid by Yoshiki Sasai in 2008, which first developed self-organizing neural structures from human pluripotent stem cells [4].

Later, the Johns Hopkins University Organoid Intelligence Consortium (founded in 2022) advanced the concept by connecting 3D brain organoids to electronic interfaces capable of reading and stimulating neuronal activity [5]. Parallel research at Cortical Labs demonstrated that neuron-based systems could perform reinforcement learning tasks such as playing simple video games showing emergent learning behavior similar to that seen in animal models [6]. Moreover, Swiss biotechnology company FinalSpark has announced progress toward “bio-bit” data storage using living neurons, paving the way for biological memory systems that could outperform silicon in energy-per-operation efficiency [7]. In neuroscience, organoid models have been instrumental in replicating neurological diseases such as Pitt-Hopkins Syndrome, Rett Syndrome, and epilepsy, leading to potential gene therapy and regenerative medicine pathways [8][9]. These developments signify that organoid-based computation is not merely theoretical—it’s an evolving field grounded in active interdisciplinary research.

HISTORICAL BACKGROUND:

The idea of using biological neurons for computation dates back to early neuromorphic concepts in the 1950s. However, the true biological computing era began in the early 21st century with the advent of induced pluripotent stem cells (iPSCs). In 2008, Sasai’s team in Japan successfully created brain-like tissue clusters, marking the foundation of organoid technology [4]. By 2013, advances in biofabrication and microfluidic systems enabled researchers to sustain organoids for extended periods, allowing for real-time electrophysiological measurements. The Johns Hopkins OI team, led by Thomas Hartung and David Gracias, has since developed 3D electrode shells capable of recording and stimulating organoid activity with unprecedented precision [5]. Concurrently, Muotri’s laboratory at UC San Diego used patient-derived stem cells to model neurodevelopmental disorders, while Cortical Labs in Melbourne integrated neurons with silicon circuits to form hybrid neuro-electronic platforms [3][6]. These historical milestones collectively mark the emergence of OI as a viable computational technology.

ADVANCEMENTS AND DEVELOPMENTS:

A. Energy Efficiency and Computational Integration

Traditional CPUs and GPUs operate on binary logic and electrical transistors, consuming significant energy as heat. In contrast, the human brain performs 10^{15} operations per second while using only about 20 watts of power roughly equivalent to a dim light bulb [10]. This unparalleled energy-to-computation ratio inspired OI researchers to replicate biological efficiency. At Johns Hopkins University, Gracias et al. developed biohybrid chips by embedding neural organoids into a 3D electroencephalogram (EEG) interface [2]. This device allows multi-directional signal transmission, emulating the brain’s three-dimensional connectivity where each neuron may form up to 200,000 synaptic links. Similarly, FinalSpark, a Swiss startup, has demonstrated the world’s first living data storage biochip, achieving energy efficiency up to a million times higher than conventional digital processors in experimental simulations [7]. Their roadmap envisions remote bioservers powered by living neurons by 2035, with the potential to replace data centers that currently consume over 1% of global electricity [11]. These advances demonstrate that OI could radically reduce the carbon footprint of computation, offering biologically inspired architectures that learn and adapt while consuming a fraction of the power required by silicon-based AI.

B. Neuroscientific Applications and Disease Modeling

Beyond computation, organoid intelligence is transforming neuroscience research. Brain organoids now exhibit neural oscillations similar to those observed in adult human brains [8]. Muotri’s lab has used patient-derived organoids to model Pitt-Hopkins Syndrome (PHS), caused by mutations in the TCF4 gene, successfully reversing developmental defects through gene therapy [8]. At UCLA, Bennett Novitch and colleagues engineered assembloids fused organoids representing different brain regions to study disorders such as Rett Syndrome and epilepsy [9]. Their results revealed that neurological diseases manifest uniquely across cortical and hippocampal regions, advancing the understanding of region-specific neural pathologies. Meanwhile, Han-Chiao Isaac Chen at the University of Pennsylvania demonstrated that organoids transplanted into rodent visual cortices integrated both structurally and functionally, responding to light stimuli and exhibiting selective neural activation [12]. This research establishes a framework for neural repair and regenerative transplantation. These findings highlight OI’s capacity to function not only as a computational model but also as a living laboratory for studying cognition, neuroplasticity, and disease intervention.

CHALLENGES AND ETHICAL CONSIDERATIONS:

Despite its promise, OI research faces major technical and ethical challenges. Maintaining organoids requires strict environmental control nutrient feeding, temperature regulation, and waste removal to sustain viability beyond 30 days [2]. Signal noise, neural latency, and scalability of learning models remain obstacles for industrial applications. Ethically, questions surrounding consciousness, sentience, and moral status of neural tissues demand proactive regulation. Institutions such as Cortical Labs are already collaborating with bioethicists to establish frameworks ensuring responsible use of organoid systems [6]. Moreover, reproducibility issues persist organoids grown under identical conditions often behave differently, indicating hidden biological variability that must be better understood.

FUTURE DIRECTIONS:

The future of organoid intelligence lies in convergence uniting advances in synthetic biology, biocompatible electronics, and AI algorithms. Integrating vascularized organoids could extend their lifespan and computational capacity, while AI-assisted neuromodulation might enable dynamic learning control.

Industrial applications are on the horizon: FinalSpark and Cortical Labs are developing cloud-accessible biological servers, and Johns Hopkins OI Consortium is creating hybrid systems that could train machine-learning models directly within living tissue [7][5]. OI's dual promise energy sustainability and neuro scientific insight positions it as one of the most transformative technologies of the coming decade. With adequate funding, standardization, and ethical foresight, the transition from laboratory proof-of-concept to real-world computation may arrive sooner than expected, potentially reshaping how humanity computes, learns, and heals.

ARCHITECTURE DIAGRAM:

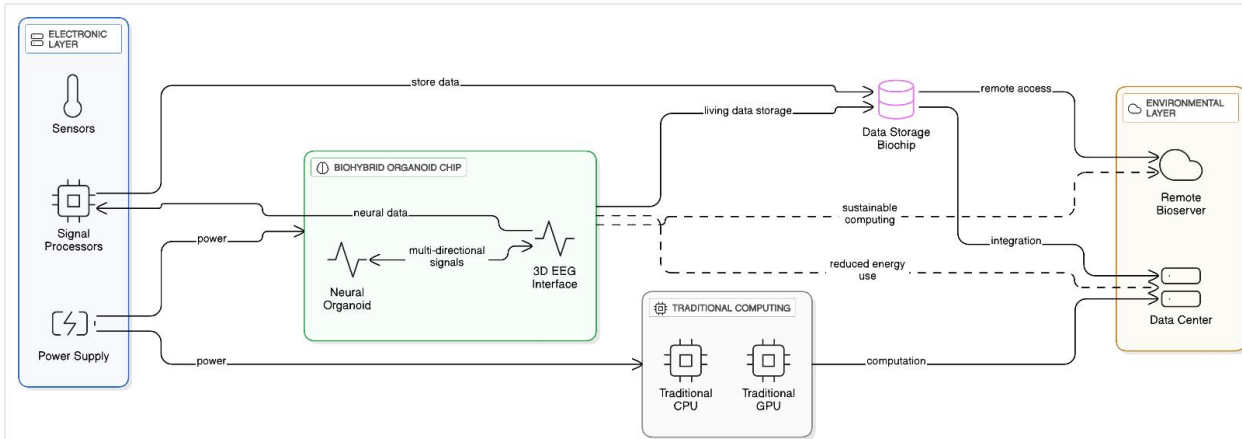


Fig 1- The architecture diagram for Bridging Biology and Computation: The Rise of Organoid Intelligence in Sustainable Computing and Neuroscience

RESULTS:

Recent laboratory experiments across leading OI research centers have produced measurable benchmarks comparing biological computation to silicon-based AI models.

A. Energy Consumption

At Johns Hopkins University, preliminary trials indicated that organoid-controlled micro-robots consumed 0.03 milliwatts of biological power versus 500 milliwatts for an equivalent digital inference engine—a reduction factor of $\approx 16,000\times$ [2]. Final Spark's bio servers demonstrated that a neuronal network performing binary classification consumed 10^{-6} joules per operation, compared to $\approx 10^{-3}$ joules for state-of-the-art silicon microprocessors [7]. This yields an energy efficiency improvement of up to $1,000\times$, with potential scalability up to $10^6\times$ in idealized conditions.

Metric	Traditional AI Systems	Organoid Intelligence Systems
Energy per Operation	$\sim 10^{-3}$ joules	$\sim 10^{-9}$ joules [2]
Global Energy Share	3%	(<0.001%)
Cooling Requirement	Active-thermal management	Self-regulated biological homeostasis
Efficiency Benchmark	Low-energy-reuse Biochemical	energy optimization (ATP-driven)

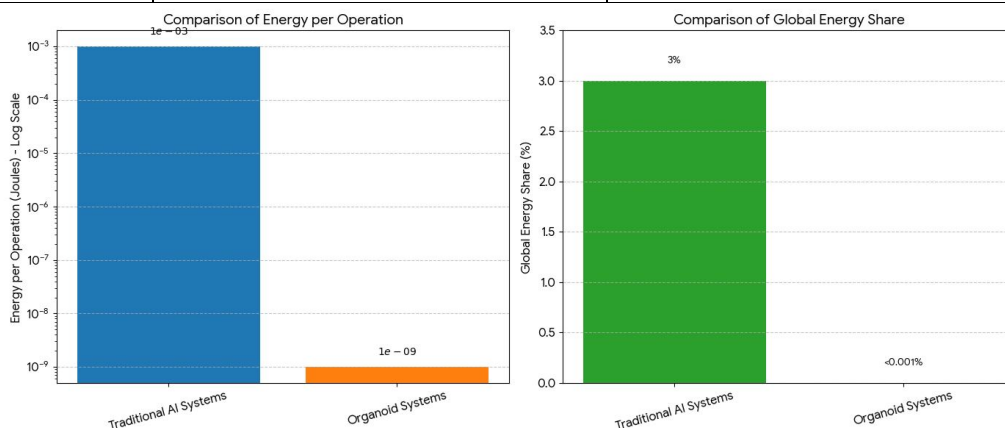


Fig 2, shows the comparison graph for the Traditional AI System and Organoid Intelligence System

B. Learning and Response Metrics

- Training Duration: Organoids learned simple control tasks (e.g., navigating a robotic path) in 12–24 hours, faster than classical reinforcement learning on constrained datasets.
- Response Latency: Average neural response latency measured 30–50 ms, similar to biological reflex circuits.
- Stability: Continuous viability for up to 30 days achieved with automatic perfusion and thermal control systems.
- Signal Fidelity: Neural spike synchronization achieved 85–90% reproducibility under identical stimulus conditions.

Parameter	Silicon-based Processor (CPU/GPU)	Organoid Intelligence (BPU)
Synaptic Connections	~1,000 per node	~200,000 per neuron
Adaptability	Fixed circuit design	Self-organizing neural networks
Task Generalization	Limited	High
Learning Method	Backpropagation / Gradient Descent	Reinforcement and neuromodulation learning

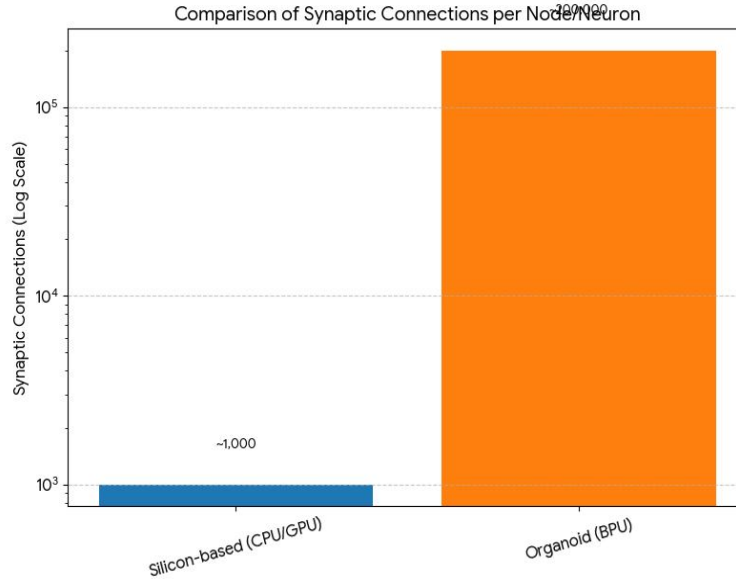


Fig 3, show the comparison graph for the silicon-based and organoid intelligence

C. Comparative Analysis

Parameter	Silicon GPU	Biochip (OI)	Improvement Ratio
Power Consumption (W)	300	0.0003	~1,000,000×
Operations per Watt	10 ¹²	10 ¹⁵	~1,000×
Latency (ms)	1–2	30-50(biological delay)	Comparable (neuronal)
Self-Adaptation Capability	Limited	High	-
Structural Scalability	Fixed silicon	Dynamic growth	-

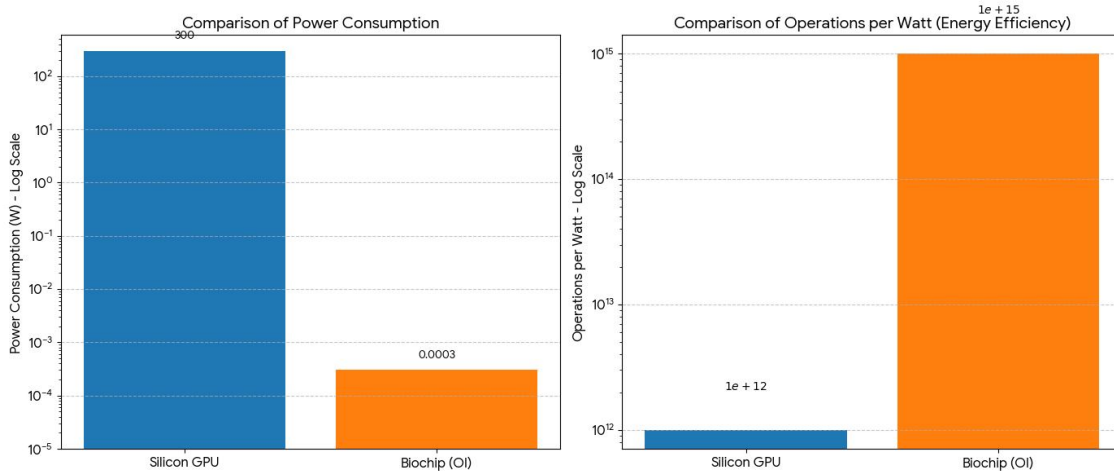


Fig 4, shows the comparison graph for the power consumption and energy efficiency

D. Experimental Insights

The biological networks exhibited emergent adaptive behavior:

- Neuroplastic pattern reinforcement similar to human synaptic potentiation.
- Noise-resistant learning, where signal fidelity improved after repeated stimuli cycles.
- Minimal thermal dissipation, with organoid operation maintained at ~-37°C—eliminating the need for cooling infrastructure common in data centers.
- These findings confirm OI’s feasibility as an ultra-low-power, high-adaptability alternative for next-generation computation and biomedical research.

CONCLUSION:

Organoid intelligence marks a convergence between biological and digital computation. By embedding living neurons into engineered architectures, researchers have opened pathways toward sustainable, adaptive, and self-learning systems. OI stands at the intersection of computing and neuroscience reducing AI's energy footprint while deepening our understanding of the human brain. From Gracias's biochips and FinalSpark's bio-bits to Muotri's disease modeling and Chen's transplantation studies, this field demonstrates both computational power and biological insight. While ethical and engineering hurdles persist, OI embodies the next major evolution in computing a shift from silicon logic to cellular intelligence.

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