Energy inputs and biological work

Grant Kinkead
Independent Researcher, Melbourne, VIC, Australia
grant@kinkead.au

***Abstract*—Energy inputs and biological work are related but cannot be treated as interchangeable quantities. Light supplies energy for photosynthesis, while plant cells depend on the resulting metabolic processes, together with respiration, to maintain an ATP supply. Crop biomass provides a further, system-level measure of biological production, although it does not reveal every step between energy input and growth. This paper synthesises controlled lighting studies, a cellular ATP experiment and reviews of root-zone physiology and controlled-environment production. The evidence connects incident light with crop growth under tested conditions and shows, in one plant species, that light-dependent cytosolic ATP accumulation also depends on mitochondrial respiration. It further indicates that oxygen availability can constrain root function. These relationships explain why increasing an energy input need not yield a proportional increase in biological output. The available studies largely concern hydroponic crops, indoor production or a non-crop plant; they do not directly establish an energy-to-work account for an entire aquaponic ecosystem. The most defensible interpretation is therefore a causal account of supported plant processes, accompanied by explicit limits on its extension to other organisms and whole-system performance.**

I. Introduction

Energy inputs and biological work describe different points in a causal chain. A plant can receive more light without converting every additional unit into an equivalent gain in biomass. In a controlled study of two purslane cultivars, changing photosynthetic photon flux altered growth, but the relative fresh-weight gain from an additional increase in light declined at the highest tested interval [1]. The result makes input alone an inadequate description of biological production. It also raises the central question of this paper: which processes connect supplied energy to useful biological activity, and which conditions limit the observable response?

Lighting studies approach that question at the crop scale by considering both the energy used to provide light and the plant response to the resulting light environment. A study combining lighting design with crop cultivation related lighting choices to photosynthetic performance and dry weight, while identifying trade-offs involving electrical energy-use efficiency [2]. Such work can show whether a particular input arrangement is associated with growth, but crop measurements by themselves cannot explain how energy becomes available inside cells. An account of biological work must therefore connect the external input with a physiological mechanism rather than equating electricity consumed, light delivered and biomass produced.

A cellular experiment supplies part of that missing connection. In Physcomitrium patens, illumination increased cytosolic ATP; blocking photosynthetic electron transport abolished that increase, and respiratory perturbations changed ATP accumulation [3]. These observations support a link between photosynthetic energy input and cellular energy supply, while remaining specific to the investigated species and tissue. This paper first distinguishes inputs, cellular processes and crop outcomes, then synthesises the available evidence and its practical limits. Its scope is the supported causal explanation of plant biological work, not a claim that the same measurements account for every organism or energy pathway in an aquaponic ecosystem.

II. Background and Scope

The evidence addresses biological work at several scales, each with a different explanatory strength. Measurements of cytosolic ATP respond more directly to changes in cellular energy supply than crop dry weight does, because dry weight is an accumulated outcome rather than a measurement of the intervening metabolic steps. The Physcomitrium experiment tested this closer link by altering photosynthetic electron transport and respiration while observing ATP accumulation [3]. It supports a mechanism in which light-dependent processes contribute to energy available in the cytosol, with respiration also important. It does not, however, quantify how much of a crop's eventual biomass results from any particular ATP response.

Crop experiments provide the complementary outcome evidence. In hydroponic lettuce of the tested cultivar, higher photosynthetic photon flux density was associated with greater shoot and root biomass, and total incident light was positively associated with shoot dry weight [4]. The purslane study likewise found that responses to increasing light differed by cultivar and that the marginal fresh-weight response fell over its highest tested interval [1]. Together, these observations establish that light input matters to biological production while cautioning against a universal conversion rule. Their different species, treatments and response measures also make a single transferable input-to-biomass ratio unjustified.

A further distinction concerns the energy required to create and maintain the growing environment. Reviews of hydroponic operation and controlled-environment crop production discuss energy requirements, including lighting and climate control [5], [6]. Those requirements matter when interpreting the input side of the relationship, but an account of operating energy demand is not itself evidence of cellular work or proportional crop gain. The literature considered here consequently has a gap between detailed plant measurements and whole-system accounting. In particular, these sources do not directly measure

the combined biological work of plants, fish and microorganisms in aquaponics, so conclusions about that complete ecosystem require separate evidence.

III. Core Concepts and Mechanisms

The first useful distinction is between supplied energy and biologically available energy. Lighting equipment consumes energy to establish a light environment, whereas photosynthetic processes determine how a plant responds to that environment. A hydroponics review identifies energy requirements and operational trade-offs, but offers limited direct evidence that would convert a stated operating input into a measured quantity of biological work [5]. The cellular ATP experiment narrows this gap: its light-induced ATP response disappeared when photosynthetic electron transport was blocked [3]. The implication is causal, not merely terminological: accounting for an input requires identifying the physiological step through which it can support activity.

Oxygen availability introduces a second constraint on biological work. A review focused on strawberry plants in nutrient-film systems describes how restricted dissolved oxygen affects ATP production and root function, while also considering root disease in that particular setting [7]. Read alongside the finding that respiratory perturbations changed cytosolic ATP accumulation in Physcomitrium, this supports treating respiration as part of the explanation rather than assuming light supply alone determines usable cellular energy [3]. The two sources examine different plants and conditions; together they establish a relevant physiological relationship, not an aquaponics-specific oxygen threshold or a quantified effect on whole-system output.

Root-zone conditions also affect how far an energy-based explanation can be extended. A viewpoint on aeroponic production relates oxygen, carbon dioxide and temperature in the root zone to plant physiology and growth, but its proposed mechanisms and production context limit direct transfer to other systems [8]. These conditions are relevant because plant growth reflects more than incident light, even when light is the input being varied. The controlled lettuce study demonstrates a biomass response to light under its tested conditions, not independence from the surrounding root environment [4]. Biological work is therefore best understood as an observed response supported by interacting processes, with the strength of each proposed connection judged against its actual evidence.

IV. Evidence Synthesis

The strongest causal link in the supplied evidence lies between illumination and cellular ATP behaviour. Blocking photosynthetic electron transport abolished light-induced cytosolic ATP increases in the studied plant, while changing respiration altered the accumulation that remained possible under the experimental conditions [3]. At a different scale, the lighting-design study relates the provided light environment to photosynthetic performance and cultivated crop dry weight [2]. The studies are complementary rather than interchangeable: one tests an intervening cellular process and the other examines production under particular lighting arrangements. Neither alone determines the fraction of supplied electrical energy ultimately represented by biological work across a complete production system.

Evidence for crop production also shows why the relationship should not be described as a fixed conversion. Lettuce biomass rose with higher tested photon flux, and shoot dry weight was positively related to total incident light [4]. Purslane responded to changes in flux too, yet its cultivars differed and the marginal fresh-weight gain declined at the upper tested increase [1]. Lighting design added another dimension by relating crop performance to the arrangement of the light environment and identifying trade-offs with electrical energy-use efficiency [2]. Taken together, these findings support a conditional pathway from light input to growth, not a claim that more energy always produces a proportionate biological return.

The root-zone evidence helps explain why conditionality matters without proving a single, integrated mechanism for every setting. Restricted dissolved oxygen is associated with impaired ATP production and root function in the strawberry nutrient-film context [7]. Aeroponic work discusses additional root-zone factors, including carbon dioxide and temperature, but some of its mechanistic propositions remain tied to that production approach [8]. Combined with the cellular evidence for a respiratory contribution to ATP accumulation [3], these sources make it reasonable to examine both light delivery and conditions supporting respiration. They do not justify importing measured outcomes from strawberries, aeroponics or moss directly into aquaponic performance estimates.

V. Practical Implications and Limitations

An assessment of energy inputs and biological work should keep its measurements distinct. Energy consumed in lighting or climate control describes provision of the growing environment, whereas incident light, ATP behaviour and crop biomass describe different stages or outcomes of biological response [3], [4], [6]. Treating those quantities as if they were the same would conceal the mechanism connecting them. The lettuce findings make total incident light relevant to interpreting biomass within the tested conditions, while the cellular experiment makes ATP supply relevant to explaining how light-dependent processes can support activity. Neither measure, on its own, establishes the biological return on all operating energy.

Input choices must also be interpreted against the particular response being sought. In purslane, the reduction in marginal fresh-weight gain at the highest tested light increase warns against projecting a lower-intensity response indefinitely [1]. A lighting-design study found relationships among crop performance, light distribution and electrical energy-use efficiency that involved trade-offs rather than one uniformly favourable outcome [2]. These results warrant comparing input and biological response over the actual operating conditions under consideration. They do not establish an optimum light level

for aquaponic plants, because the reported responses belong to specific crops, lighting arrangements and experimental environments.

The principal validation gap is whole-ecosystem evidence. The accepted studies directly address plant cells, crop growth, root-zone physiology and the energy demands of controlled environments, but do not jointly measure the biological activity of all aquaponic organisms against the system's energy inputs [3], [4], [6], [8]. Strawberry nutrient-film evidence is informative about oxygen-dependent root function, yet its disease context prevents an unqualified extension to aquaponics [7]. A future system-level account would need measurements that distinguish external inputs, plant responses and the contributions of other organisms. Until such evidence is available, the present synthesis explains supported plant pathways but cannot quantify total aquaponic biological work.

VI. Conclusion

Energy input becomes meaningful in biological terms only when its connection to an observed process or outcome is specified. The supplied evidence links light-dependent processes to cytosolic ATP accumulation in one plant, relates incident light to biomass in tested crops and identifies oxygen-dependent root function as a relevant constraint [3], [4], [7]. It also shows that biological response can differ across cultivars and tested light levels, while provision of the growing environment carries energy demands of its own [1], [6]. Biological work should therefore not be inferred directly from the amount of energy supplied.

The highest-value next step is to test these relationships together in the system for which a whole-ecosystem explanation is wanted. Existing cellular, crop and root-zone studies provide a defensible plant-centred causal framework, but their distinct species and settings leave the combined contributions of aquaponic organisms unmeasured [3], [4], [8]. Until direct evidence closes that gap, an account of energy inputs and biological work can explain why plant production depends on both energy supply and physiological conditions, while remaining explicit about what it cannot establish for the ecosystem as a whole.

Acknowledgment

The author used artificial intelligence tools to assist with manuscript drafting and revision, and with LaTeX and bibliography preparation. The author reviewed all AI-assisted output and remains responsible for the final content.

References

[1] A. V. Gediminas Kudirka, R. S. Kristina Laužikė, and G. Samuolienė, "Photosynthetic photon flux density effects on portulaca olearacea in controlled-environment agriculture," *Plants*, 2023.

[2] K. Saito and E. Goto, "Lighting design optimization in a plant factory using an optical simulation and differential evolution," *Horticulturae*, 2025.

[3] A. M. Vera-Vives, P. Novel, K. Zheng, S. ling Tan, and M. Schwarzländer, "Mitochondrial respiration is essential for photosynthesis-dependent atp supply of the plant cytosol," *New Phytologist*, 2024.

[4] P. L. Palsha, M. W. van Iersel, R. W. Dickson, L. Seymour, M. Yelton, K. Qin, and R. S. Ferrarezi, "Strategic light use efficiency optimization of hydroponic lettuce exposed to different photosynthetic photon flux densities," *Agronomy*, 2024.

[5] R. S. Velazquez-Gonzalez, A. L. Garcia-Garcia, E. Ventura-Zapata, J. D. O. Barceinas-Sanchez, and J. C. Sosa-Savedra, "A review on hydroponics and the technologies associated for medium- and small-scale operations," *Agriculture*, 2022.

[6] C. Vatistas, D. D. Avgoustaki, and T. Bartzanas, "A systematic literature review on controlled-environment agriculture: How vertical farms and greenhouses can influence the sustainability and footprint of urban microclimate with local food production," *Atmosphere*, 2022.

[7] S. Scott and C. Villouta, "Dissolved oxygen limitation and pythium root rot in strawberry nft systems: Mechanisms, research gaps, and prospects for substrate-free production," *Frontiers in Plant Science*, 2026.

[8] B. M. Eldridge, L. R. Manzoni, C. A. Graham, B. Rodgers, J. R. Farmer, and A. N. Dodd, "Getting to the roots of aeroponic indoor farming," *New Phytologist*, 2020.