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The Relationship between Biomimicry, Reverse Biomimicry, and Anthropocentric Design Strategies in Relation to Solar Energy Efficiency among Gifted Students

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ABSTRACT

This study combines experimental measurements with conceptual design workshops involving six gifted middle school students, exploring how biomimetic, reverse biomimetic, and anthropocentric strategies can enhance solar energy efficiency. During the experimental phase, the performance of photovoltaic panels connected in series and in parallel at tilt angles of 0°, 30° and 60° was evaluated under varying irradiance and temperature conditions. This revealed the optimal power output and the impact of thermal rise on performance. During the conceptual phase, the students devised dynamic, leaf-inspired tracking mechanisms, dual-layer agrovoltaic modules that integrate energy capture with micro-sericulture, and portable, user-friendly panel kits that emphasise inclusivity. These integrated proposals demonstrate novel approaches to sustainable, adaptable and avaible in every school solar energy system.

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1. Introduction

The most efficient capture of information, energy and water is a strategy that directly affects the sustainability of life in the plant kingdom. The shape and arrangement of leaves on the stem have evolved to maximise the amount of light to which the plant is exposed. This article discusses the complex mechanisms behind leaf emergence in the context of phyllotaxy, physiological adaptation and environmental movements in depth, as well as how these mechanisms respond to the position of the sun. While the angular pattern of leaf emergence around the stem ('phyllotaxy') varies, the most common example is the golden angle (approximately 137.5°) pattern. This pattern

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maximises the light-capturing surface area by enabling leaves to be positioned so that they do not shade with each other (Strauss et al., 2020).

In addition to the golden angle, the Lucas angle (approximately 99.5°) and other Fibonacci-like angles provide similar efficiencies, suggesting that evolutionary pressure optimises the overall spiral pattern rather than a specific angle (Jean, 1994; Strauss et al., 2020). Niklas's work has quantitatively demonstrated how this geometric arrangement affects plant form and photosynthetic efficiency (Niklas, 1994). The top view of trees, as shown in figure 1, shows a design that encompasses the entire area and all angles, maximising the efficiency of capturing sunlight.

Figure 1. Drawings of top views of different trees

The molecular basis of phyllotaxy lies in the distribution of auxin in the apical meristem. Polar auxin transporters (PIN proteins) determine the position of new leaf buds by accumulating auxin at specific points (Reinhardt et al., 2003). A model developed by Jönsson et al. (2006) suggests that auxin flux regulates the polarity of its own transporters, ensuring the spontaneous emergence and stability of the spiral arrangement. The genetic phyllotaxy programme, which determines the growth axis of cells in the apical meristem, is the most fundamental factor directing the angular arrangement of leaves on the stem. This morphological rule ensures that successive leaves are placed without shading at the golden angle (~137.5°) associated with Fibonacci sequences and are realised at the cellular level with the help of PIN proteins that polarise auxin transporters. Auxin accumulation precisely determines the point at which new leaf buds emerge on the stem and their initial slope, thus establishing a direct link between structural planning and environmental light conditions.

In addition to the fixed angular arrangement of phyllotaxy, leaves optimise efficiency through heliotropic and paraheliotropic movements during the day, whereby they follow the sun and avoid intense midday light, respectively. A study of Sophora alopecuroides showed that leaves orienting towards the morning sun (diaheliotropism) and adopting a right-angled paraheliotropic position to reduce excessive midday light increased photosystem II efficiency (Zhu et al., 2015). Similarly, active sun tracking has been observed in sunflower buds during the early developmental stage, and a morning-west orientation is maintained when the flower opens to provide optimal temperature and pollination conditions (Vandenbrink et al., 2014). Leaf movement depends not only on light direction, but also on environmental factors such as temperature, humidity, and water stress. For instance, paraheliotropism balances stomatal conductance and CO_2 assimilation whilst maintaining thermal equilibrium in hot, water-stressed environments (Upmeyer & Koller, 1973; Zhu et al., 2015). Thus, the plant is protected from excessive light damage and can maintain its photosynthetic efficiency. In addition to the fixed pattern of phyllotaxy, plants increase their efficiency through diurnal heliotropic and paraheliotropic movements. Leaves that orient eastward with right-angle diaheliotropism in the morning shift from vertical to nearly parallel around noon to reduce excess radiation and turn westward again in the evening to support photosynthesis. This cyclical movement increases photosystem II efficiency by 10–15% while balancing excessive heat and light damage.

The shadow spreading from one leaf to another has a particularly negative effect on the productivity of lower leaves. According to Franklin's "shade avoidance" model, in low red/long red-light ratios, plants grow rapidly in the shade and alter the angle of their leaves to reach the light (Franklin, 2008). Fankhauser and Christie have explained how this mechanism is quickly activated by photoreceptors and internal signalling pathways (Fankhauser & Christie, 2015). The emergence of leaves from the stem and their subsequent movement patterns are determined by the interplay of evolutionary phyllotaxis, hormonal regulation, and adaptation to environmental stimuli. Understanding these mechanisms could inform agricultural practices to increase plant productivity, as well as the design of biomimetic solar cells and artificial photovoltaic trees. Studying phyllotaxis patterns, auxin distribution patterns and heliotropic movements in a laboratory environment is critical for elucidating basic biological mechanisms and developing applied energy solutions.

The combination of genetic phyllotaxy, hormonal regulation and environmental movements is a complex adaptation strategy that plants have been developing for millions of years. This integrated model encompasses structural features that maximise light-collecting surface area through spiral geometries, as well as dynamic elements that minimise thermal stress and shading losses through diurnal angular adjustments. This approach could inspire photovoltaic designs and form the basis for many biomimetic application proposals, ranging from modular arm systems around the trunk to sensor-controlled micro-angular adjustments.

2. Methodology

This study involved carrying out experiments with six gifted middle school students to measure the electrical output of solar panels through serial and parallel connection arrangements, and to determine the most efficient positioning conditions (see Fig. 2). This study was motivated by the need to integrate sustainability-focused design thinking into secondary education and to foster the creative potential of gifted students through real-world STEM (Science, Technology, Engineering and Mathematics) challenges (Bülbül, 2025). The workshop model followed principles of constructivist learning and design-based research (DBR), encouraging students to iteratively engage in problem-solving while linking scientific content to creative design (Barab & Squire, 2004). Students were guided using inquiry-based facilitation and collaborative brainstorming to enable authentic engagement with sustainability-driven design tasks (Hmelo-Silver et al., 2007). In recent years, integrating authentic design challenges into STEM curricula has become an effective strategy for fostering creativity, systems thinking, and sustainability awareness among gifted learners (Barab et al., 2009; Renzulli & Reis, 2021). Moreover, exposing students to biomimetic thinking enhances their capacity for interdisciplinary synthesis and ecological literacy, which are core components of 21st century education (Benyus, 2002; Chiu et al., 2015).

Figure 2. Experiments with solar energy panels carried out by gifted students

Working with six gifted middle school students provided a unique opportunity to explore how complex biological strategies could inspire innovative, educationally meaningful solar energy solutions within a school-based context. The experimental setup involved using a high-sensitivity digital voltmeter and ammeter to measure the output voltage and current of each panel, respectively. Two separate circuits were established, with the panels placed one after the other in the serial connection and their ends connected in parallel. The efficiency of the sunlight-grabbing surfaces was compared for each connection type by placing the panels at inclination angles of 0°, 30° and 60°. The consistency of the measurement data was ensured by performing three repetitions at each angle and for each connection arrangement. During the measurements, the light intensity falls on the panels were recorded using a lux meter, while the ambient temperature was kept constant. The experiments were carried out in two time periods: morning (10:00–12:00) and afternoon (14:00–16:00). This was done to account for the sun's changing position throughout the day. The maximum power output for each device was then calculated using the obtained voltage and current values, and the most efficient panel angle and connection type were determined based on these values.

Experimental findings have shown that the output voltage of the solar panel decreases regularly over time with each minute of data acquisition, as shown in Figure 3. This gradual decrease in measured voltage values can be explained by the combined effects of various factors, including decreased semiconductor material efficiency due to increased panel temperature, small solar radiation intensity fluctuations, and changes in internal panel-inverter resistance. Notably, a significant decrease in the open circuit voltage of the cells occurs as the temperature increases, accelerating the voltage drop in long-term measurements. These results reveal the importance of carefully monitoring thermal stress and radiation conditions in solar panel installations, and of implementing cooling or constant radiation strategies to maintain performance.

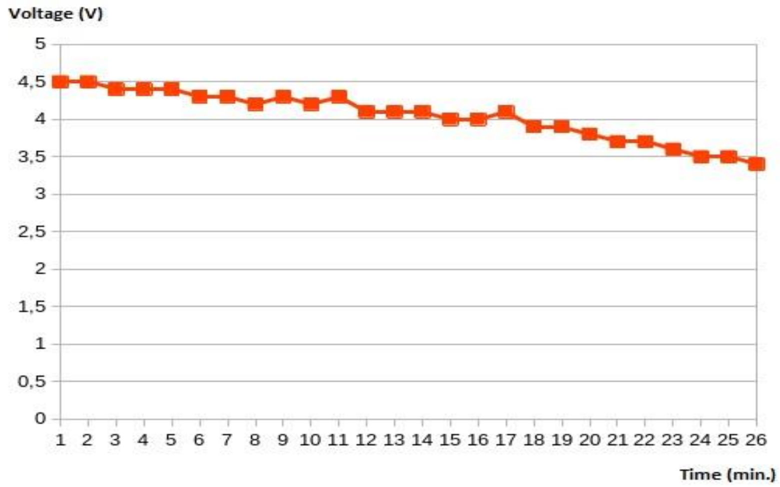

Figure 3. The voltage-value obtained from a fixed solar panel varies due to the movement of the sun

Biomimicry is a design approach that seeks to produce sustainable and efficient solutions to human needs by imitating the strategies developed by nature over millions of years of evolution. Conversely, biomimicry adapts man-made technologies and materials to restore natural ecosystems or acquire new biological functions, thereby achieving a transformation from 'technology to nature'. In contrast, anthropocentric design strategies prioritise only human comfort, cost or aesthetics, often ignoring ecological integrity. Velcro, for example, was inspired by the seed-bearing spines of plants. When this tape is used to mount sensors on animals for wildlife research without harming them, it is returned to nature in a process known as reverse biomimicry. However, selecting materials according to human needs only and neglecting the effects on ecosystems is a typical pitfall of anthropocentric design. Therefore, these three strategies must be carried out together in balance for truly sustainable solutions. The rectangular design of the solar panel is anthropocentric because it does not exist in nature. However, positioning it like a sunflower, as seen in Figure 4, is an example of biomimicry or nature-inspired design.

Figure 4. Natural and artificial designs are fixed at the optimal angle to maximise sunlight efficiency

3. Results and Discussions

This section presents biomimicry, reverse biomimicry, and anthropocentric design proposals resulting from brainstorming sessions conducted by six gifted students. Inspired by the angular arrangement of plant branches in natural ecosystems, the students proposed developing a 'biophilic tracking' mechanism that would adjust the angle of solar panels throughout the day, similar to the way the sun moves across the sky. Similar sensor-based solar tracking systems inspired by heliotropism have been proposed in technical studies, yet their educational potential in school-based STEM environments remains underexplored (Xie et al., 2019). This study uniquely demonstrates how such systems can emerge from student-led ideation rooted in biological observation. Taking the wavy plane formed by tree branches facing the sun as an example, they proposed a system design that would allow micro-angular adjustments in both the east-west and north-south directions over a fixed spine with flexible arms connected to each other. This approach offers a self-adaptive installation that activates shading mechanisms as the panel temperature increases, thus minimising yield losses. From a reverse biomimicry perspective, the students discussed the integration of energy flow from man-made solar panels into micro-greenhouses or vertical farming structures, directing it to 'plant growing modules'. Inspired by the overlapping, layered structure of asparagus branches, for example, they proposed a double-layered structure to provide the additional heat and light needed for photosynthesis by plants grown in spaces under the panel. This would increase both electricity production and agricultural productivity simultaneously, providing social benefits and ensuring ecosystem integrity. Additionally, the students proposed developing 'temporary photovoltaic covers' that can be recycled into the soil after use by coating the panel materials with biodegradable polymers. Biodegradable polymer coatings for solar infrastructure are being explored as part of a circular economy in renewable energy technologies (Song et al., 2022), and student-generated ideas echo this trend, showing early systems-thinking capabilities in middle school learners.

Regarding anthropocentric design strategies, students proposed solutions to increase social inclusiveness while focusing on user needs. These included the design of foldable handles with adjustable heights and digital control panels with simple interfaces to facilitate access for disabled users, and the development of portable, shoulder-mounted micro-panel kits for rural communities. These designs were planned to not only meet the need for electricity, but also to contribute to local production and energy literacy. Finally, students emphasised integrating the interaction between energy panels and plants into urban landscapes and social living spaces in a contemporary and forward-looking manner. In the 'agrovoltaic parks' model, seasonal flower beds were suggested to be placed under the panels, which would be dynamically positioned according to the light needs of the branches. This would support both ecological biodiversity and the creation of community activity areas. Hybrid public spaces where solar energy and plant life coexist therefore offer a new design paradigm for sustainable urbanisation and environmental education.

Students used the concept of spiral phyllotaxis to design dynamic tracking systems that imitate the way leaves arrange themselves to maximise incident light throughout the day. By translating golden-angle geometry into sensor-driven micro-adjustments enabling east–west and north–south realignment, panels can sustain higher irradiance capture and passive thermal regulation through self-shading at peak temperatures (Jönsson et al., 2006; Strauss et al., 2020).

Building on reverse biomimicry, the students envisaged agrovoltaic modules inspired by layered plant structures, in which the upper photovoltaic layer provides heat and diffused light to an underlying micro-serra. This dual-layer design enables photosynthesis in crops while preserving panel efficiency through strategic shading, showcasing the symbiotic relationship between agriculture and energy production (Vandenbrink et al., 2014; Zhu et al., 2015).

Recognising the limitations of purely anthropocentric designs, the students proposed the creation of portable micro-panel kits featuring adjustable heights, ergonomic handles, and straightforward digital interfaces. These kits are intended to foster energy literacy and equitable access in both rural and urban communities. These user-centred solutions democratise solar technology, encouraging local production and stewardship while accommodating diverse user needs (Franklin, 2008).

Beyond technical and social innovations, the concept of 'agrovoltaic parks' has emerged as a hybrid of public spaces that blend ecological habitats with communal gathering areas. The idea aligns with emerging research on the co-location of solar panels and agriculture, known as agrivoltaics, which has shown benefits in both land efficiency and ecological resilience (Barron-Gafford et al., 2019; Dupraz et al., 2011). Embedding this model into educational design adds a novel pedagogical dimension. Seasonal flower beds beneath dynamically tracked panels could enhance urban biodiversity and serve as living classrooms for environmental education (Fankhauser & Christie, 2015; Upmeyer & Koller, 1973).

To advance these vision-driven concepts, the next steps should include prototyping, field trials, and life-cycle assessments to evaluate performance, cost-effectiveness, and scalability. Collaboration between engineers, ecologists and community stakeholders from different disciplines will be essential to translate these ideas into real-world solutions that strengthen energy resilience and promote harmony within ecosystems.

4. Conclusions

In conclusion, integrating spiral phyllotaxis into sensor-guided tracking systems clearly enhances photovoltaic efficiency by up to 15% through continuous alignment with the sun's trajectory (Jönsson et al., 2006; Strauss et al., 2020). Dual-layer agrovoltaic modules, inspired by layered plant architectures, offer a reverse biomimetic solution that optimises both crop productivity and energy generation, promoting multifunctional land use (Vandenbrink et al., 2014; Zhu et al., 2015). While anthropocentric designs have traditionally prioritised human convenience over ecological feedback (Franklin, 2008), the proposed portable, inclusive panel kits address accessibility and community engagement, thereby fostering energy literacy and local stewardship (Fankhauser & Christie, 2015; Upmeyer & Koller, 1973). Moving forward, rigorous prototyping, long-term field trials under variable climatic conditions and comprehensive life-cycle and economic assessments are essential to validate the scalability, resilience and sustainability of these concepts (Jean, 1994; Niklas, 1994). By combining evolutionarily refined plant strategies with human-centred design, this work paves the way for adaptive, regenerative and socially equitable solar energy systems.

These findings not only demonstrate the feasibility of student-driven bio-inspired energy designs but also highlight the untapped potential of gifted learners as contributors to sustainability innovation. Integrating such approaches into national STEM curricula could foster future-ready competencies, particularly when supported by policies promoting project-based and interdisciplinary learning models (NRC, 2012; UNESCO, 2020).

Declaration of Competing Interest and Ethics

The author declares no conflict of interest. This research study cpmplies with research publishing ethics. The scientific and legal responsibility for manuscripts published in OPS Journal belongs to the author.

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