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Biological Insights into Energy Storage Technologies

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Abstract

In the face of increasing energy demands and environmental concerns, the search for sustainable and efficient energy storage technologies has intensified. This review presents a holistic survey of innovative solutions by examining biological approaches. The study proceeds through three thematic sections: Biological Fuel Cells and Battery Systems, Photosynthesis and Solar Energy Storage, and Energy Generation at the Cellular Level. The first section, Biological Fuel Cells and Battery Systems describes the integration of biological processes into energy storage mechanisms. The use of biological systems and their contribution to the development of environmentally friendly and high performance energy storage technologies are discussed. In the 2nd section, Photosynthesis and Solar Energy Storage are very prominent in sustainability and energy efficiency issues in terms of both energy production and energy source food production while reducing carbon dioxide with photosynthesis-based energy storage methods. Energy production at the cellular level is discussed in the last section, Adenosine triphosphate (ATP), which is necessary for the cell to perform processes such as growth, reproduction and response to environmental stimuli, is characterized as the primary fuel. ATP production is carried out by mitochondria in animal cells and chloroplast in plant cells. Energy storage at the cellular level is carried out by molecules such as glycogen and lipids in animal cells and starch in plant cells. Considering all three issues, it has been observed that biological-based energy storage methods have numerous advantages in terms of sustainability and energy efficiency. In application areas where engineering approaches are at the forefront, it is thought that it may be possible to design more sustainable and highly energy efficient energy production systems by gaining new perspectives with biology-based simulation studies.

Keywords: Energy Storage System; Bio-battery; Bio-fuel cell; Photosynthesis Energy; Cellular Level Energy.

1. INTRODUCTION

Energy production, which has been one of the most important issues of the past decades, has emerged as a problem of meeting energy needs with increasing population and developing technology. Therefore, the importance of prioritizing studies on energy storage is gaining interest over the years [1]. To eliminate challenges such as the limited fossil fuel reserves of modern fossil fuel-dependent culture, and global warming caused by the combustion of fossil fuels, many alternative storage systems have been developed considering the storage of energy as biomass [2]. To the best of our knowledge, despite discussions on energy storage occurring across biological, chemical, and physical realms in various studies, there appears to be a notable absence of a comprehensive review specifically

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focusing on the biological aspect in the literature [3]. Hence, integrating biological principles into energy storage systems could offer a novel perspective, making it imperative to conduct further research to broaden the scope of biologically inspired applications, which are currently limited in number.

A battery is a system consisting of one or more electrochemical cells that allow chemically-stored energy [3,4]. Many different research studies have been carried out in battery technology, including reduction-oxidation (redox) reactions in the electrolyte placed between two electrodes, one positive and one negative [4,5]. It is acknowledged that ongoing research endeavors will persist in this domain. The increasing energy demand has led to the concept of renewable batteries with advantages such as energy storage, flexible shape, the ability to use renewable biocatalysts, room temperature operation, and readily available fuel sources. It is known that with the invention of bio-batteries, it is possible to reduce the damage to nature caused by traditional batteries made of metal [6].

The process whereby sunlight is utilized to generate high-energy carbohydrates, which eventually form fossil fuels over millions of years, is referred to as natural photosynthesis. However, energy storage methods are insufficient to meet the growing and diversifying needs of the society. Therefore, new methods for harnessing natural photosynthesis to store, transport, and use energy on demand have become one of the major global focuses [7]. Energy storage methods realized with the help of photosynthesis-based bio-inspired techniques have been extensively studied and have shown promising results in solar cell technology. The future scope of solar energy conversion systems is to adapt the results of bio-inspirations and to further improve the operation and performance of solar cells with the production of solar cells with higher promising incident light absorption and power conversion rates [8].

The last thematic issue that will be discussed in this study the expression of energy storage methods with cellular energy production. When cellular energy production is examined, ATP (Adenosine triphosphate) and ADP (Adenosine diphosphate) conversion should be taken into account. The rate of change between these two concepts according to energy use can be explained similarly to the working principle of a battery. In mammalian cells, ADP and phosphate are converted into ATP by reactions such as glycolysis and oxidative phosphorylation. This conversion of ATP can be described as analogous to the charging of a battery. The conversion of ATP to ADP manages the energy required in the cellular process, can be simulated as the discharge process of the battery [9]. Considering this scenario, it appears feasible to elucidate the cellular energy storage method and conventional energy storage methods in a similar manner.

The motivation of this study can be expressed as a study on biological storage methods, which are mentioned as one of the energy storage methods in the literature but have not been classified in detail [1-3]. In this way, it is thought to classify the micro and macro-scale bio-supported energy storage systems used by comparing them. During literature research, the leading biological energy storage studies are classified as biological battery systems, photosynthetic solar storage, and cellular storage [10,17]. In this study, we discussed the these aforementioned topics and evaluate the concepts of energy efficiency, and sustainability at both micro and macro levels in the context of biological systems. In this way, the comparison of conventional fuel cells and batteries with biological fuel cells, and batteries will provide an overview of the methods of photosynthetic energy storage and the concept of ATP in energy storage at the cellular level.

2. Biological Insights into Energy Storage Technologies

In this section, we will classify energy storage systems from a biological point of view and discuss energy storage mechanisms and energy concepts in detail in sub-headings such as Biological Battery and Fuel Cell Systems, Photosynthesis and Storage with Solar Energy, and Cellular Level Energy Production.

2.1 Biological Fuel Cells and Batteries Systems

In this section, biological fuel cells (bio-fuel cells) and biological batteries (bio-batteries), which have different working principles but have a lot in common, will be described in detail. In addition, the definitions, mechanisms, and comparisons of electrical conversion systems with conventional methods are shared in detail under different headings in this section.

2.1.1 Description of Bio-Fuel Cells and Bio-Batteries

Bio-batteries and bio-fuel cells operating at low temperatures, which have the potential to be environmentally friendly, and suitable for cooperation with renewable energy sources, have a lot in common due to their reliance on biologically derived materials [10].

Bio-fuel cells are bio-electrolysis-based energy conversion devices that utilize enzymes or microorganisms to convert chemical energy into electrical energy. In these systems, electron transfer can take place directly with the help of enzymes or in different structures supported by electrodes [10]. Bio-fuel cells are highly advanced systems that have been developed in recent years based on the cooperation of microbiological cells, organelles such as mitochondria and enzymes [11,12]. Szczupak [13] obtained a living organism that can generate sustainable electrical energy with the help of biofuel cells placed inside mussels. In this way, electrified mussels integrated into batteries were observed to activate devices using the energy produced live.

Bio-batteries can be defined as systems that use biological materials to mimic the energy generation processes of conventional batteries in living organisms. These systems commonly generate electricity from carbohydrates using enzymes as catalysts [10]. Although agricultural products such as sugar-containing fruits and plants, citrus fruits have been proposed as bioenergy sources, some studies have also suggested the use of plant-based wastes such as non-agricultural fruit and vegetable peels, and corn stalks that do not trigger food consumption-related issues [14,15]. Togibasa [14] aimed to develop a affordable, simple, and practical bio-battery from tropical almonds, which have a low risk of food shortage due to their abundance in the region where they are produced.

2.1.2 Mechanisms of Bio-Fuel Cells and Bio-Batteries

Bio-batteries can be characterized as systems that have anode (-) cathode (+) and electrolyte parts, similar to conventional batteries that produce useful forms of energy using renewable energy technologies [8]. Bio-batteries are designed to generate electricity by considering indirect galvanic cell design. Khan and Obaid [15] used a sugar digesting hydrogenase enzyme containing an anode and an oxygen reducing laccase enzyme containing a cathode in their study.

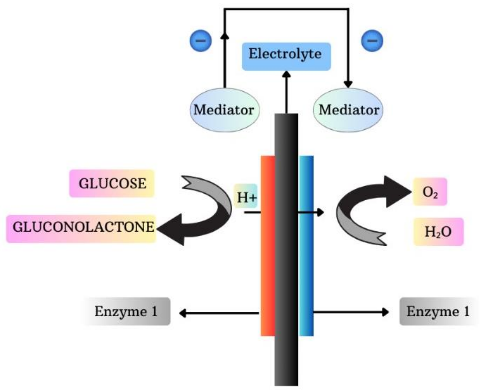

Figure 1. An example of a bio-battery working mechanism.

The working mechanism of the battery starts with the production of hydrogen and electron ions from sugar at the anode. These ions pass to the cathode with the help of the carrier and react with oxygen to form water. Energy is produced thanks to the movement of the released electrons. Figure 1 shows the the working principle of an example bio-battery.

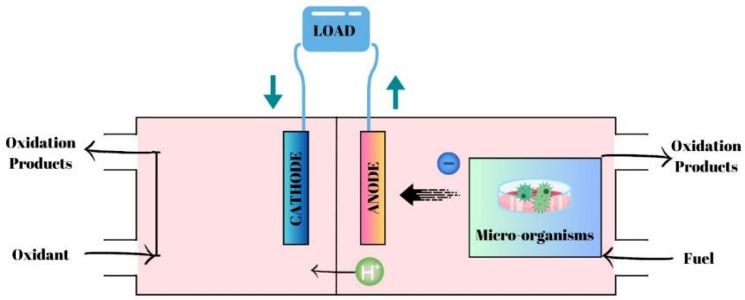

Figure 2. Working mechanism of Bio-Fuel Cells.

The working mechanism of bio-fuel cells is that microorganisms produce electrochemical active materials through fermentation and metabolism and electrons are transported from the anode side to the cathode side with the help of the biocatalytic system. Figure 2 represents the the working mechanism of bio-fuel cells. Energy storage can be achieved through the movement of free electrons. In addition, various types of bacteria and algae such as Escherichia coli, Enterobacter aerogenes, and Clostridium butyricum offer an advantage to the use of hydrogen production in fuel cells [16,17].

2.1.3 Comparison of Bio-Fuel Cells and Bio-Batteries with Conventional Methods

The literature review uncovered that research on applications of bio-fuel cells and bio-batteries is relatively limited, leaving ample room for development in various areas. In both energy storage methods, the concepts of sustainability and energy efficiency emerge when we want to compare bio-based and traditional methods. Since organic materials are used in bio-supported fuel cells and batteries, they do not cause the formation of greenhouse gasses with the use of fossil fuels as in traditional methods. In addition, compared to traditional methods, bio-supported fuel cell and battery systems can be classified under biomass renewable energy technology, which can be expressed with natural and renewable supported organic material. In this context, it can be argued that bio-supported energy storage systems are more prominent in terms of sustainability compared to traditional storage methods. [7,16].

If the concept of energy efficiency is taken into account in traditional methods and bio-assisted methods in fuel cell and battery systems, it will be observed that the amount of energy produced is higher in traditional methods. Since bio-assisted batteries and fuel cells can produce energy directly using biochemical reactions, it can be anticipated that energy efficiency will be higher in bio-assisted systems due to fewer energy losses.

2.2 Photosynthesis and Storage with Solar Energy

To date, the type of energy obtained through renewable energy methods is mostly electrical energy. Electrical energy has two disadvantages: the difficulty of storage, and the lower density of stored electricity compared to other fuels. This situation pushes us to design systems that can produce fuel from solar energy. The only biological reaction on our planet that can produce fuel from solar energy is photosynthesis. Photosynthesis refers the synthesis using light. This reaction, which produces carbohydrates and oxygen using carbon dioxide and water, has the potential to be a solution to the greenhouse gas effect and global warming crisis. Produced carbohydrates provide most of the energy needed to support all life on Earth. Moreover, the source of the fossil fuels we currently consume is primitive photosynthetic activities. Currently, photosynthesis is estimated to produce more than 100 billion tons of dry biomass annually, this is equivalent to a hundred times the weight of the total human population on our planet and an average annual energy storage rate [18]. Due to its high energy capacity utilization, scientists are looking for new ways to harness and artificially mimic photosynthesis.

2.2.1 Natural Photosynthesis

Photosynthesis is the reaction in which phototrophic organisms such as plants and algae use solar energy to strip electrons from water and reduce carbon dioxide in the air to carbohydrates. Oxygen formed as a result of the oxidation of water makes the air breathable. The fact that we can now breathe is an indication that these reactions continue. Synthesized carbohydrates provide a large portion of the energy needed to support life on Earth. Moreover, the reason for the formation of the fossil fuels we use most is (unfortunately) primitive photosynthetic activity.

We can examine the photosynthesis reaction in two parts. These parts are light-dependent reactions and dark, that is, light-independent reactions. Light-dependent reactions use solar energy to power the synthesis of the energy splitter adenosine triphosphate (ATP) and reduced nicotinamide adenine dinucleotide phosphate (NAPD). Subsequent dark reactions consume these chemicals during the enzymatic reduction of carbon dioxide to carbohydrates. Depending on the dark reaction chain, the efficiency for plants is a maximum of 6%, and for some microalgae grown in small bioreactors, the rate is even higher at 5–7% [19]. Unfortunately, for most crops, actual productivity is often less than 1%. Since the overall efficiency of converting solar energy into electricity with standard silicon-based solar cells is usually 10-20%, instead of producing energy directly using the photosynthesis reaction, we use materials produced as a result of the reaction or develop artificial photosynthesis reactions.

2.2.2 Energy Storage Via Natural Photosynthesis Method

Energy storage systems with the natural photosynthesis method use the product resulting from the photosynthetic reaction, that is, the stored form of light energy by phototrophic organisms. The end product of photosynthesis is called Biomass [18]. Wood and other forms of biomass can be converted into other biofuels such as ethanol biogas and syngas and used to generate heat and electricity when needed.

2.2.3 Artificial Photosynthesis

Artificial photosynthesis is a technology that mimics the natural process of photosynthesis. In this process, chemical energy is stored using inputs such as sunlight, water and carbon dioxide (CO_2). Artificial photosynthesis is usually carried out by photochemical or electrochemical methods that convert sunlight into electrical energy or chemical bond energy. In energy storage systems in artificial photosynthesis, the products resulting from photosynthesis can be changed by genetic modification to the phototrophic organism, catalysts can be used to increase production or artificial surfaces can be created to imitate the photosynthesis reaction. Among the current projects being worked on in the artificial photosynthesis technique:

In energy storage technologies supported by biological systems, the storage of energy through microalgae photosynthesis is becoming increasingly significant. Large amounts of biomass and lipid materials such as triacylglycerol can be obtained with microalgae species developed using genetic engineering techniques and metabolic engineering. It has a great impact on improving the economy of microalgae-based biodiesel [20]. Photosynthetic-derived fuel is a promising renewable and carbon-neutral alternative energy reserve. While microalgae provide raw materials for renewable biofuels such as biodiesel, methane, hydrogen, dimethyl furan and ethanol, they can also be used in lands that are not suitable for agriculture by using salt water and wastewater [21]. Many microalgae species are rich in oils, and the biomass of microalgae usually doubles within 24 hours. Effective use of solar energy will provide a great solution to the current energy shortage and environmental pollution caused by non-renewable energy consumption. Therefore, natural simulation of photosynthesis will become an important aspect of using solar energy to produce clean energy. Microalgae can capture solar energy, fix carbon dioxide through photosynthesis, convert light energy into chemical energy and store it in the form of fat in cells [21]. As a result, by using microalgae, we can naturally convert the energy in sunlight into fuel during the photosynthesis process.

The possibility of energy storage through photosynthetic membranes designed by utilizing biological systems is another important issue to be considered. The aim here is to exploit the photocatalytic properties of engineered surfactants in soft (soap film-based) compartments for oxygen-fuel (i.e. carbon monoxide, CO) production and separation.

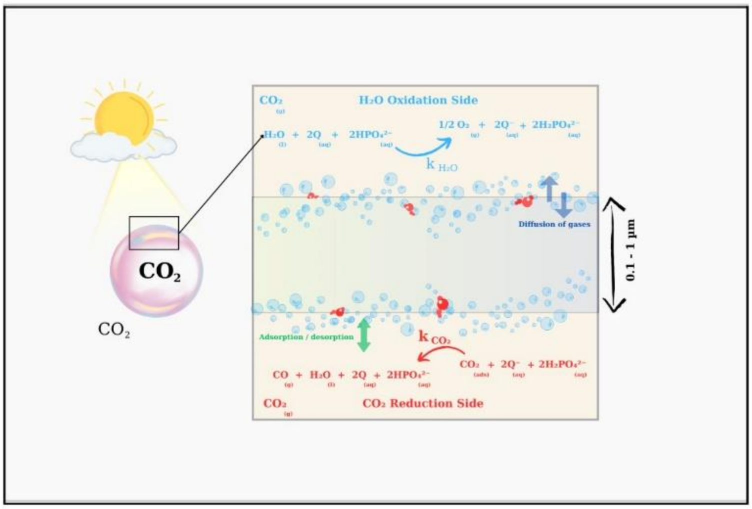

Figure 3. Physicochemical Model of a Reactive Soap Film.

Soap films consist of a water core stabilized by surfactant molecules that self-assemble at gas-liquid interfaces [22]. Figure 3 shows the Physicochemical Model of a Reactive Soap Film. Ideally, a soap film membrane allows molecular catalysts to naturally assemble on the water surface, thus preventing the photocatalytic surface from decreasing in effectiveness due to microbubble formation, thus keeping oxygen and fuel separated for long periods. In the envisioned configuration, the soap film membrane separates two CO_2-filled regions to carry out two half-reactions, the oxidation of water and the reduction of carbon dioxide, in two opposing monolayers of surfactant. These last two half-reactions form part of the desired overall photochemical reaction that converts carbon dioxide into a useful fuel using solar energy.

2.3 Cellular Level Energy Production

Cellular energy production is a fundamental process that fuels the myriad activities of all living organisms, from the simplest to the most complex. Energy production is a cornerstone of life, enabling organisms to carry out certain processes such as growth, reproduction, and response to environmental stimuli. Adenosine triphosphate (ATP) is the primary fuel, also “energy currency”, for that has been efficiently converted via nutrients through a series of intricate biochemical pathways [23]. ATP serves as a versatile energy storing agent owing to the presence of phosphate groups, providing the energy required for cellular processes such as biosynthesis, muscle contraction, active transport, and DNA/RNA synthesis. Cellular level energy production involves multiple interconnected biological pathways, primarily glycolysis, the citric acid cycle (also known as the Krebs cycle), and oxidative phosphorylation [24]. These pathways collectively enable the efficient generation of ATP from substrates such as glucose and fatty acids. Mitochondria are known as the “powerhouse” of the cell and play a central role in maintaining the energy production in normal mammalian cells through cellular respiration. By facilitating glycolysis, the citric acid cycle, and oxidative phosphorylation, mitochondria efficiently generate ATP to meet the energy demands of the cell. ATP synthesis relies on electron flow across the mitochondrial membranes to the specific molecular mechanisms. This electron transfer flow generates a proton gradient across the internal mitochondrial membrane, creating a proton motive force. The flow of protons back across the membrane through ATP synthase drives the synthesis of ATP [25]. The close association between mitochondria and ATP production highlights the importance of these organelles in cellular energy metabolism and overall cellular function. Plants can generate ATP through cellular respiration, similar to mammalian cells. Different then mammalian cells, plants possess electron transport in unique organelles called chloroplast. Electrons enter the chain from the water during photosynthesis, and carbon dioxide reduces to carbohydrates and produces ATP [26]. However, ATP production in plants is complemented by photosynthesis, a process unique to plants and some microorganisms.

In addition to energy production, energy storage is also a critical process in both mammalian cells and plants. ATP cannot be stored in large amounts within the mammalian cells because of the high rapid turnover and demand. Turnover process is tightly regulated via cells to meet the energy demands. ın case of excess ATP generation, cells can use glycogen and lipids, high-energy compounds that can quickly regenerate ATP in case of a need [27]. Similar to mammalian cells, ATP is not stored in large quantities within plant cells. Instead, plants maintain a dynamic equilibrium between ATP synthesis and consumption. Excess energy in plants is stored primarily as starch, a polysaccharide composed of glucose molecules. Starch serves as a long-term energy reserve and is stored in specialized storage organs such as tubers, seeds, and roots. Lipids also serve as an energy storage form in plants, particularly in oil-rich seeds and fruits. Triglycerides are stored in lipid droplets and can be mobilized for energy production when needed.

3. CONCLUSION

In this study, the concepts in biological systems are the diversity of energy storage methods, energy efficiency and sustainability, comparison with conventional (physical and chemical) methods, increasing the use of biological approaches, and enabling the understanding of energy storage at the micro-scale as well as at the molecular or cellular level. The problem of the study is that in the literature, energy storage methods are mostly classified and studied as physical storage such as thermal and magnetic kinetic and chemical storage methods such as hydrogen, battery, and fuel. Since biological scale classification and studies on energy storage methods are limited, a classification study was wanted to be carried out in this field.

The overall investigation of biological energy storage systems in terms of sustainability is as follows:

The concept of sustainability is highly important in energy storage systems where environmental damage is reduced, such as the use of clean energy technologies, the protection of natural resources, and the reduction of greenhouse gas emissions. When the concept of sustainability is taken into account in fuel cell and battery systems, it is a negative situation that the production of normal fuel cells and batteries involves production processes that adversely affect the environment, such as mining. Bio-fuel cells and bio-batteries, on the other hand, are produced from natural and environmentally friendly materials, which is an important advantage in terms of sustainability. In addition, bio-fuel cells and bio-batteries have more sustainable features compared to normal systems, such as the possibility of producing biological organisms with the use of renewable energy sources and containing biodegradable or recyclable materials. The use of agricultural products containing sugar and protein for electricity production in bio-batteries and bio-fuel cells poses a risk for the reduction of food products. However, the use of vegetable wastes such as corn stalks, fruit and vegetable peels for the glucose requirement of batteries contributes to the formation of a sustainable environment as it will reduce the formation of waste.

Energy storage systems based on photosynthesis can store energy in various forms such as electricity, biofuel or chemicals. Carbon neutral systems are available and can be installed in areas that are not suitable for agriculture, such as saltwater and wastewater. Considering these features, photosynthesis-based systems attract attention with their sustainability even among renewable energy systems. Since it uses carbon dioxide as raw material during production, it improves the air quality of the region. It has the potential to be a band-aid against greenhouse gases and global warming, which are the bleeding wounds of our age. Although there are serious problems in studies on living cells such as algae and plants, keeping their living environments at optimum levels and obtaining products from sunlight at levels as low as 7%, it is likely that engineering solutions will be found soon.

In the concept of sustainability at the cellular level, it is thought that concepts such as the use of energy in the cell when needed and the formation of harmful products will be at the forefront. It is known that CO2, which is the final product of respiration in living cells, creates a greenhouse gas effect. It can be stated that the use of CO2 as a primary source of photosynthesis performed by plant cells is important for sustainability in terms of both energy source and gas reduction. In addition, with the help of energy storage products such as stored lipids, glycogen, and starch, the sustainability of the energy required for the growth, reproduction and development of the cell is ensured.

The overall investigation of biological energy storage systems in terms of energy efficiency is as follows:

The concept of energy efficiency examines the efficient use of resources in energy storage technologies, less energy losses, less waste, cheaper costs, etc. Reducing energy losses is said to be an important parameter considering the increasing energy demand and cost for more effective storage of energy resources in a highly efficient way. Although bio-fuel cells and bio-batteries have more advantages over conventional batteries in terms of sustainability, the opposite is the case when energy efficiency is taken into account. It can be said that the energy efficiency of conventional fuel cells and batteries are considerably higher than bio-batteries in terms of their higher energy interpretation and longer life.

The sun's rays exceed our current energy needs by 7000 times. Unfortunately, due to the losses incurred in capturing and storing this energy, the energy obtained is far below the current potential. The only biological reaction that can use solar energy is photosynthesis. Although photosynthetic organisms can capture the sun's rays regardless of wavelength, they can only use red photons to reduce carbon dioxide, so other wavelengths of radiation are first reduced to the red wavelength for use. The energy left over from the reduction is converted into heat energy. In the photosynthesis reaction, the efficiency of producing glucose with energy from red photons is 33%. When the energy loss during the conversion of the sun's rays into red photons is taken into account, this rate varies from organism to organism and decreases to approximately 4.5%. The energy stored by photosynthesis on Earth is thought to be quite large, and the global efficiency of natural photosynthetic reactions is 0.1%, given the annual amount of energy that falls on our planet from the sun. The systems studied to increase the efficiency rates are called artificial photosynthesis systems. In the study on genetically modified algae, which is one of the artificial photosynthesis systems, it is seen that this efficiency increases to 7%.

It has been observed that energy efficiency at the cellular level highly depends on the organisms, and the respective organelle, and the energy storage method. While the organelle that produces energy in animal cells is mitochondria, it is chloroplast in plant cells. As an energy storage method, glycogen can be quickly broken down into smaller branches as glucose in animal cells, and lipid, which can be considered as a long term energy storage unit, and starch can be broken down into glucose when energy is needed, providing a sustainable energy source for the plant. Thus, cellular level energy efficiency can be counted as higher than energy production and storage. While cellular level energy efficiency in biological organisms is indeed remarkable, it's important to recognize that comparing it directly to energy production and storage systems in non-biological contexts may not be entirely straightforward. In conclusion, studying and learning from nature can inspire innovations in energy technology and contribute to more sustainable and efficient energy solutions.

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Conflict of interest

All authors declare that they have no conflicts of interest.

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