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Utilizing Spirulina in Combination with Concentrated Solar Thermal Technology for Sustainable Biofuel Production and Enhancing Cultivation Efficiency - A Review

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Abstract

Biofuels reduce greenhouse emissions by 30-50% when compared with fossil fuels. However, nearly half of the biofuels have greater environmental costs than petrol. So, it is needed to have new cost effective and eco-friendly technology for fulfill of our energy demand. Solar energy, the most abundant and exploitable renewable energy resource is regarded as a major energy source for the future. Nevertheless, solar irradiation is characterized by relatively low energy density, intermittency and uneven distribution. Storage of solar energy for usage during non-solar times is required to match supply and demand rates in today's society. In this context, the application of solar energy for converting into storable, transportable, and energy-dense fuels (i.e., solar fuels) is an attractive option, with the advantage of contributing to promoting the commercialization of solar power technologies. This narrative review aims to describe and delineated on comprehensive summary of solar assisted Spirulina cultivation for biofuel production, including concentrating solar thermal technology and strategies to enhance the cultivation of spirulina.

Keywords: Spirulina, Microalgae, Biofuel, Cultivation

Introduction

The international standard of the energy sector has been concerning in its immediate and long-term environmental impact. More specifically, the continuing environmental and ecological effects of mediums *viz.* fossil, fuels and coal output have influenced phenomenon such as global warming and the greenhouse effect. However, private and public energy corporations have experienced slow transitions into renewable energy. The undeniable root of this lagging changeover comes from world energy demands in growing populations. Although the most renewable techniques of energy delivery have been hydropower and biomass, these methods are unable to sustain mass populations due to its small-scale output systems. The economical magnitude of biomass and hydropower is costly, due to its geographical limitations (i.e., costly land expansion).[1]

Furthermore, due to the finite availability of biomass, satisfying full energy demands alone is not possible. Additionally, when considering small scale biomass energy generation, net energy is easily lost due to the system's high energy needs. Moreover, the combustion of extraneous or usable biomass can harm the environment by discharging carbon dioxide, encouraging possible climatic change. As a result, energy sustainability, consistency, and environmental efficiency, are not fulfilled. Similarly, the high yielding biofuel industry poses a plethora of economic drawbacks. The biofuel sector presents a demanding cost of production in contrast with the fossil fuel industry. The ecological facet of biofuel and biomass extraction is also penetrated by the ineffectiveness of monoculture and the use of fertilizers.[1]

Economically, both fossil fuel and coal production are the most sufficient fields of immediate energy availability and output. The frame of renewable energy is hindered technologically, as it is limited by surrounding environmental conditions. More specifically, technologies, such as solar cells/solar panels are constrained by the sunlight exposure in specific regions. The limitations of the renewable and nonrenewable energy sector create economical barriers, oftentimes being excluded from developing countries. Studies have presented a close correlation between both economic growth and energy availability.[1] Due to the economic circumstances of 3rd and 2nd world countries, continuous access to both non-renewable and renewable energies is constricted, due to financial limitations of large capacity/quantity. Contrary to non-renewable energy types, renewable sources do not suffice the energy market and the economy due to high initial costs and inconsistency.[2] The economic and technological impediments of large-scale and non-intuitive renewable energy sources can be most magnified in impoverished and developing nations. However, individual houses and facilities experience frequent power outages due to irregular Electricity production. The central drawback of irregularity lies in large-scale energy inconsistency. In other words, developing countries are oftentimes deprived of a smart grid system which provides stable energy flow to individual facilities, departments, and residents.

As concerns increase worldwide regarding the rapid depletion of fossil fuels, the resulting greenhouse gas emissions and global warming, renewable energy sources have attracted more and more attention for gradually replacing fossil fuels.[3,4] Solar energy is by far the largest renewable energy source exploitable - Continuous solar radiation reaches the Earth at a rate of 173,000 TW. Nevertheless, solar irradiation is characterized by relatively low energy density, intermittency and uneven distribution.[5] In order to match the energy demand of today's society, solar energy needs to be stored for usage during off-solar periods. The conversion of solar radiation into storable, transportable, and energy-dense fuels (i.e., solar fuels) is an attractive option that could help to promote the commercialization of solar power technologies.[6-8] With this scenario, current narrative review of literature study was carried with the main purpose to describe and delineate on comprehensive summary of solar assisted Spirulina cultivation for biofuel production, including concentrating solar thermal technology and strategies to enhance the cultivation of spirulina.

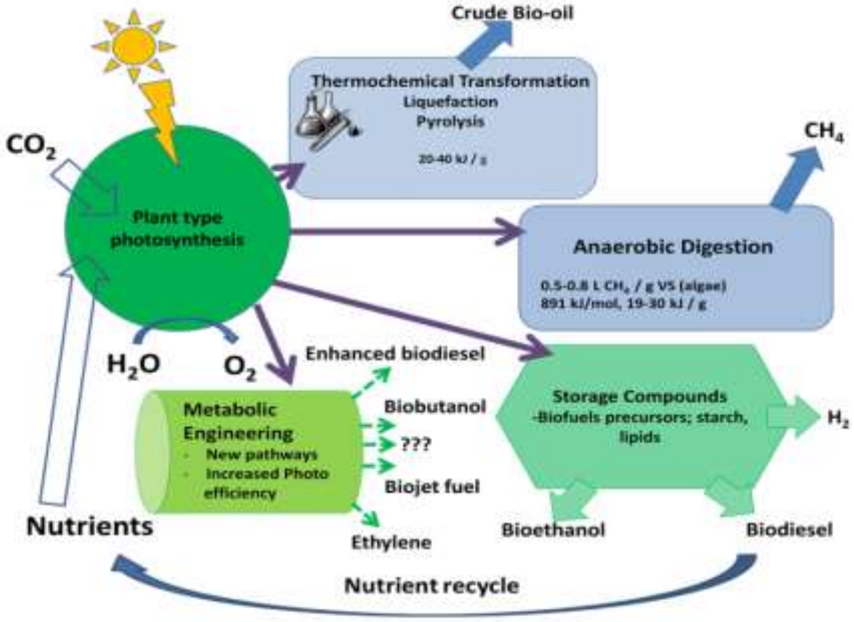
Biological solar cells

Biological solar cells have been of particular research interest, due to the integration of metabolism and its implications in energy production. This system amalgamates a single species of live microbial organisms, such as anaerobic bacteria. However, biological materials such as Eukaryotic organisms (plantae) can be exploited through their photosynthetic and respiratory properties. Most importantly, the metabolic pathways can be manipulated by exploiting extraneously discharged electrons and protons in the media. As an alternative energy source, microbial fuel cells advantage the sectors of energy and environmental sustainability by catalyzing naturally produced energy in growable living conditions (e.g., bioreactor and photobioreactor). Traditionally, the system houses three divisions/containments- an isolated anode chamber, an isolated cathode chamber, and a semipermeable proton exchange membrane. In addition, the two electrodes (anode and cathode) are interconnected with conductive wires to form a fully attached simple circuit. The circuitry system is then completed by the particle transfer of the proton exchange membrane (PEM). Combining these three components forms a bioelectrochemical system. As bacteria is submerged into the anode chamber, freely electrons penetrate through the wall of the semipermeable membrane into the cathode containment, outputting electrical current. The proton exchange membrane constantly transports hydrogen ions to harness electricity. However, due to the vulnerability of these biological sources (regular pond bacteria) it is prone to contamination. Therefore, achieving a much more stable and adaptable microorganism is necessary. In addition, the metabolic processes of natural bacteria (mostly found in pond ecosystems) have varying metabolic processes. Thus, seeking a microorganism with great photosynthetic processes and cell respiration is necessary.

Research into the potential of algae as a fuel source is moving quickly, despite serious debate over its heavy reliance on water. Scientists continue to demonstrate algae's power potential - from a building powered entirely by algae to an algae carbon capture facility of the most interesting research projects currently underway. In addition to the electricity generated from solar and wind power, biofuel is an attractive renewable energy source, especially for systems such as transportation, which require liquid forms of energy. The aquatic microalgal biomass is considered to be one of the best-suited feedstocks for this purpose, and it does not require arable land area. Moreover, a wide range of the potential applications of the microalgal biomass (food, medicine, agriculture, etc.) makes it more promising in the view of marketability. However, to become economically viable for mass production, the fundamental issue of limited biomass yield, although one-order higher than terrestrial plants, must be resolved.[9]

Microalgae

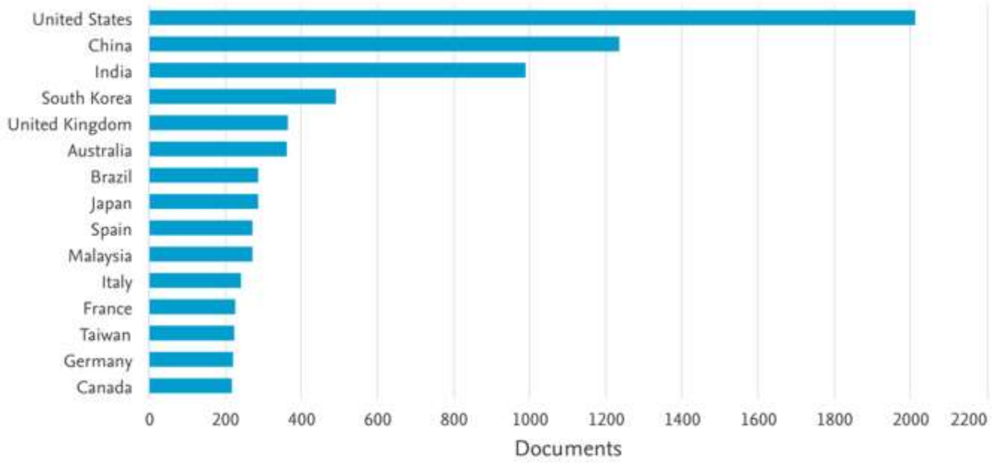
Microalgae, small, unicellular organisms that carry out plant type photosynthesis, possess several characteristics that make them attractive as potential biofuels producers.[10-13] Their autotrophic capabilities lend an element of flexibility in comparison to conventional fuels. As discussed in more detail below, algae can serve as feedstocks in a variety of processes that can produce fuels or fuel precursors (Figure 1).



Source: Hallenbeck *et al.*, 2016[14]

Figure 1: Showing solar biofuel production using microalgae

Microalgae supported by basic nutrients, use captured solar energy and plant-type photosynthesis to split water and fix carbon dioxide. A variety of fuels can be made from the newly fixed carbon. The harvested algal biomass can be converted to bio-oil through hydrothermal liquefaction or pyrolysis or to methane through anaerobic digestion. Alternately, different algal storage materials can be converted to various fuels including ethanol, biodiesel, and hydrogen. Metabolic engineering could be used to enhance yields or to produce novel fuel compounds. The details on use of algal biofuels across the globe was represented in Figure 2.



Source: Zuorro et al., 2020[15]

Figure 2: Number of publications on algal biofuels and their country of origin

Arthrospira platensis

Arthrospira platensis (usually named "Spirulina") (Microalgae) is a blue-green cyanobacteria that can be naturally found in different aqueous media such as fresh and seawater, brackish water, marshes, sable and soil.[16] The natural proliferation of this photosynthetic microorganism in warm lakes of Mexico and Tchad as well as its harvest and massive consumption as food by earlier populations has been reported since the 15th century.[17] Spirulina is nowadays widely commercially produced (Figure 2). At the beginning of this decade, an optimistic estimation of the global annual production neared 10,000 tons.[18] Some studies have related the ingestion of this microorganism to nutritional and therapeutic benefits such as hepatoprotective[19] and anti-inflammatory effects.[20] In fact, Spirulina has a high protein content (up to 70% dw)[21] and is also naturally rich in vitamins (B_{12}, E), provitamins (β-carotene), minerals (iron, magnesium) and antioxidants such as phycocyanine.[22] Besides, the composition of Spirulina includes other substances such as lipids and polysaccharides that have an interest in other domains, ranging from green chemistry (i.e., biomaterials, bio fertilizers) to energy. Some studies have in fact observed the aptitude of the Spirulina biomass to be used as a feedstock for biogas,[23] biodiesel[24] and hydrogen production.[25] Besides, some authors have pointed out encouraging results related to the biosorption capacity of Spirulina to remediate water contaminated with synthetic dye at batch laboratory scale.[26]

Figure 3: Commercial culturing of spirulina in pots and tanks

Furthermore, to supply their metabolic needs for inorganic carbon, these microorganisms are able to uptake dissolved CO_2 which is an additional feature to counteract climate change. However, within a global context of environmental deterioration (i.e., greenhouse effect, ecosystems pollution, exhaustion of limited resources), and the quest for the development of a sustainable industry, the operations related to growing microalgae processes need to demonstrate high yields as well as viable environmental performances compared to those attained by the manufacture of conventional or equivalent products.

Microalgae are considered to have great potential due to; (i) their ability to be grown on
marginal lands, (ii), their use of wastewater as a medium for growth, often thereby effecting wastewater treatment as well, (iii) their very fast growth rates as compared to land plants, often doubling their biomass in a single day or less, and (iv) their ability to sequester flue gas emissions under appropriate conditions.[27] Depending on the production methods used, microalgae can provide a suite of commercially useful co-products.[28,29] In addition to triglyceride production for biofuels, the co-production of other even more valuable compounds, such as essential fatty acids and animal feeds, could bolster the economics of the whole process at the beginning when fuel production is modest. However, scale up and production costs must be considered to truly ascertain commodity values under present market conditions.[30] In some instances, when biofuel production is ramped up to scale, these valuable co-products could lose market value.

Microalgae carry out plant type photosynthesis, converting captured solar energy into chemical energy through the fixation of CO_2. Although only specific products are naturally made, environmental, biochemical and molecular manipulations potentially greatly expand the scope, leading to practically limitless possibilities. A variety of biofuels are possible through different processes. Total algal biomass can be converted through direct thermochemical transformation to bio-oil, or through anaerobic digestion, to methane. Pyrolysis treatment under varying temperature regimens appears to have some potential for oil production. According to some, oil yields may range from 20-50 % of the total ash free dry weight in some algae.[31] Alternatively, algae can be induced to produce high levels of storage compounds, starch or lipids, which can, when appropriately extracted and converted, be turned into the biofuels, bioethanol or biodiesel. A variety of novel methods for extraction and conversion remain to be explored including the use of enzymes to aid in extraction by weakening the cell wall.[32] Finally, future metabolic engineering [33,34] could produce improved strains with the ability to produce higher levels of natural biofuels, or endowed with the capacity to produce novel fuels, or fuel precursors, such as ethylene, biobutanol, hydrogen, or biojet fuel.

However, there are a number of serious challenges to implementation of microalgal-based biofuels production on a practical level. These range from uncertainties on how to effectively and efficiently culture algae on a large scale, how to maintain the desired culture in the face of alien species, how to carry out low-cost, energy efficient harvesting, and the best methods for conversion to biofuels.[35]

Concentrated solar energy

The utilization of concentrated solar energy to propel thermochemical conversions is one potential route for the production of solar fuels.[36] According to different types of reactants, the technique map can be divided into non-carbonaceous routes and carbonaceous routes. Non-carbonaceous routes involve solar splitting H_2O and CO_2 through direct thermolysis or multi-step thermochemical cycles, producing combustible gases H_2 and CO. As direct thermolysis is a strongly endothermic reaction, an extremely high temperature is needed (usually >2,200°C), resulting in stricter operation conditions and inevitable irreversible loss in the product separation process. Multistep thermochemical cycles can automatically separate the product and greatly lower the reaction temperature, among which the two-step thermochemical cycle is the most favored for its simplicity. Numerous studies had focused on the ideal layout of the solar receiver-reactor,[37] and the development of new catalysts.[38] Despite being hopeful, the conversion efficiency of solar splitting of H_2O and CO_2 remains a significant obstacle.[39] Additionally, carbonaceous routes can be taken by using methane,[40] biomass or coal as feedstocks. The production of syngas (H_2 and CO) can be achieved from solar thermochemical gasification, cracking or reforming processes, and it could be further synthesized into useful hydrocarbon fuels by Fischer-Tropsch synthesis (FTS). With water-gas shift (WGS) reaction or carbon capture and sequestration applied, solar hydrogen can be produced from any of these processes as well.

On the other hand, biofuels produced from microalgae hold the promise of a much small footprint. Although actual large scale production figures are not available, a rough approximation can be made using reasonable extrapolations from existing data. Thus, if a microalgal production system could produce 20 gm/dL, and 30% of this could be converted to liquid fuel, the land area required for total transportation fuel replacement would be 4.47 x 105 km^2. As well, the International Institute for Sustainable Development has concluded that the benefits to climate and CO_2 reduction from replacing petroleum fuels with biofuels like ethanol are essentially zero. Therefore, more advanced biofuels are needed that can meet these challenges.

Thus, use of biomass-derived biofuels has become attractive because biomass is abundant in nature, low-cost, biodegradable, and a source of renewable carbon. Biomass can be used as a renewable source of carbon for production of fuels or chemical precursors from thermochemical transformations, such as combustion, gasification, and pyrolysis. Among the thermochemical processes, pyrolysis stands out mainly because of its ability to generate products (solids, liquids, and gases) with greater added value that could be used as fuels or chemicals of interest for other industrial activities. Even though lignocellulosic biomass is the most used raw material to produce bio-oil, new raw materials are being evaluated in the pyrolysis process. In this respect, microalgae have shown great potential as a source of biomass in pyrolysis processes given their great diversity of species and good environmental adaptability, allowing their cultivation in systems that do not compete for arable land. According to some studies, another advantage of using microalgae as a raw material in pyrolysis is the fact that the bio-oil obtained by their thermochemical conversion has a higher heating value and less viscosity than the bio-oil produced from lignocellulosic biomass.

Microalgae and cyanobacteria are a diverse group of photosynthetic microorganisms that naturally grow in lakes, rivers, and oceans. Microalgae offer several advantages over plant-based biofuels such as (i), high growth rate, (ii) use of non-arable lands, (iii) can be grown in wastewater, (iv) high consumption of CO_2, and (v) their production can be directed toward the synthesis of several compounds of commercial interest. To obtain biomass with a high concentration of specific metabolites is one the cornerstones of microalgae biotechnology. Several authors have proved that specific culturing conditions such as nutrient concentrations in the medium, photobioreactor configuration, environmental conditions (temperature and illuminance), agitation and pH directly influence the cellular composition, resulting in the final concentration and productivity of the strain, as well as the variation in the content of specific metabolites (lipids, carbohydrates, proteins and of other components). The transformation of algal biomass into biofuels is not new. Several studies have covered different areas on the strain selection, culture method, and transformation into biofuel, which is the critical link in the production chain towards obtaining sustainable biofuels from microalgae.

One possible solution to achieve the potential of algae as a feedstock for biofuels is the application of catalytic-based processes such as torrefaction and Hydrothermal Liquefaction (HTL), pyrolysis, and gasification. Among the challenges of a pyrolysis system is the reactor design and its heating system. In conventional pyrolysis, use of an electrical heater or combustion of external fuels generally imply high-energy consumption and costly production. This problem can be softened by incorporating solar heating devices in the pyrolysis system. Thus, solar pyrolysis emerges as an interesting process as it combines concentrated solar energy and biomass to generate fuel and chemicals. Concentration of solar radiation in this process occurs through solar concentrators. These optical devices can operate reflexively, similar to parabolic mirrors or refractive lenses (e.g., Fresnel lenses). Some studies on solar pyrolysis have reported satisfactory results regarding application of this technology in biomass conversion.

Energies of using microalgae as a raw material in pyrolysis is the fact that the bio-oil obtained by their thermochemical conversion has a higher heating value and less viscosity than the bio-oil produced from lignocellulosic biomass. Bio-oil obtained by pyrolysis can have some undesirable characteristics because of its chemical composition, such as low high heating value and high acidity and viscosity. The presence of oxygenated compounds in the composition of pyrolysis oil is the characteristic that most contributes to these negative factors. For these reasons, this product must undergo deoxygenation processes so that it can be integrated into refineries and meet the specifications of finished fuels. One way to improve the quality of the fuel generated is to change the reaction routes through addition of catalysts.

In recent decades, layered double hydroxides (LDHs in the following) received increased attention due to their wide-ranging applications and the relative ease of their availability and functional modification. LDHs also have considerable potential in health care: they can be applied as antacids, medicine stabilizers, and even used as catalysts of base-catalyzed transformations in their layered forms or, more frequently, after calcination (then, the layered structure is lost). However, few studies have outlined layered double hydroxides (LDHs) as possible catalysts for improvement in biomass pyrolysis oil characteristics. Maree and Heydenrych showed that MgAl-LDH significantly reduced the concentrations of ketones and oxygenated aromatics in electrostatic precipitator oils and increased the concentration of aliphatics.

Hydrocalumite is a type of double lamellar hydroxide composed of calcium and aluminum neatly distributed within its hexagonal structural layers, interspersed with carbonate. When subjected to the calcination process at different temperatures, it generates mixed oxides, favoring their application as basic catalysts. These materials have already been applied as catalytic precursors in the isomerization of 1-butene and transesterification of oils for biodiesel production. However, there are still no records regarding their application in deoxygenation of bio-oil obtained by microalgae pyrolysis.

Among the challenges of a pyrolysis system is the reactor design and its heating system. In conventional pyrolysis, use of an electrical heater or combustion of external fuels generally imply high-energy consumption and costly production. This problem can be softened by incorporating solar heating devices in the pyrolysis system. Thus, solar pyrolysis emerges as an interesting process as it combines concentrated solar energy and biomass to generate fuel and chemicals. Concentration of solar radiation in this process occurs through solar concentrators. These optical devices can operate reflexively, similar to parabolic mirrors or refractive lenses (e.g., Fresnel lenses). Some studies on solar pyrolysis have reported satisfactory results regarding application of this technology in biomass conversion.

Zeng et al. studied wood pyrolysis impregnated with Cu and Ni using a solar concentration system composed of a heliostat and a parabolic disk. The studies were carried out at temperatures from 600 ◦C to 1600 ◦C at heating rates of 10 and 50 ◦C/s and a thermochemical decomposition time of 5 min. The results showed that the increase in temperature favored the gas yield but caused a decrease in the solid and liquid yields.[41]

Hijazi et al. performed catalytic and non-catalytic pyrolysis of tire strips using Fresnel lenses at a temperature range from 550 to 570 ◦C at the focal point. The assays were developed using heterogeneous photocatalysts. The authors evaluated the effects of use of pure titanium dioxide (TiO_2) catalysts, as well as Pd/TiO_2, Pt/TiO_2, and $TiO_2/Bi_2O_3/SiO_2$ on the gas yield. They observed that the amount of gas produced increased by 7% with addition of TiO_2 and 21% with use of palladium supported on titanium dioxide at a reaction time of 15 min. However, no records were found on the use of Fresnel lenses in thermochemical processes with a focus on bio-oil production and upgrading.[42]

Cyanobacteria and especially Spirulina platensis are recognized as abundant resources of lipids and poly-unsaturated fatty acids (PUFA). The main valorization of these lipids has been biofuel production.[43] Effective methods to extract lipids from Cyanobacteria have been developed, extending their application potential.[44]

Strategies to enhance production of Spirulina biomass

High production costs are the major limitation for commercialization of algal biofuels. Strategies to maximize biomass and lipid production are crucial for improving the economics of using microalgae for biofuels. Selection of suitable algal strains, preferably from indigenous habitats, and further improvement of those ‘platform strains’ using mutagenesis and genetic engineering approaches are desirable. Conventional approaches to improve biomass and lipid productivity of microalgae mainly involve manipulation of nutritional (e.g., nitrogen and phosphorus) and environmental (e.g., temperature, light and salinity) factors. Approaches such as the addition of phytohormones, genetic and metabolic engineering, and co-cultivation of microalgae with yeasts and bacteria are more recent strategies to enhance biomass and lipid productivity of microalgae.[45] Improvement in culture systems and the use of a hybrid system (i.e., a combination of open ponds and photobioreactors) is another strategy to optimize algal biomass and lipid production. In addition, the use of low-cost substrates such as agro-industrial wastewater for the cultivation of microalgae will be a smart strategy to reduce production costs. Such systems not only generate high algal biomass and lipid productivity, but are also useful for bioremediation of wastewater and bioremoval of waste CO_2.

Conclusion

In conclusion, a well-known technology, pyrolysis exhibits the proper concentration of bio-oil, char, and syngas, as well as reasonable quality and macroalgal biomass. Because dried biomass is required for this technology, it might be more interesting. Solar pyrolysis can be used as a sustainable process to produce biofuel from a renewable energy source without burning other fuels or using electricity. To increase algal biomass and lipid productivity and boost the economics of microalgae-based biofuel production, multifaceted strategies incorporating various approaches should be used.

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