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Review

Zero-waste algal biorefinery for bioenergy and biochar: A green leap towards achieving energy and environmental sustainability☆

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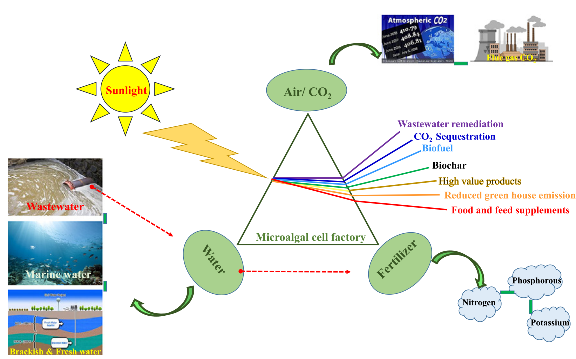
HIGHLIGHTS

- Analysis of the trends and developments of biofuel and bio-product from microalgae
- Microalgae provide an edge over lignocellulosic and solid waste based feedstock.
- "Zero waste discharge" concept with process integration is presented.
- Parallel synthesis of high value product and biochar as a co-product

GRAPHICAL ABSTRACT



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ABSTRACT

In spite of tremendous efforts and huge investments on resources, biodiesel from oleaginous microalgae has not yet become a commercially viable and sustainable alternative to petro-diesel. This is mainly because of the technological and economic challenges hovering around large scale cultivation and downstream processing of algae, water and land usage, stabilized production technology, market forces and government policies on alternative energy and carbon credits. This review attempts to capture and analyse the global trends and developments in the areas of biofuel and bio-product of microalgae and proposes possible strategies that can be adopted to produce biofuel, biochar and bio-products utilizing wastewater in a bio-refinery model. The strategies include "Zero waste discharge" concept with process integration, wherein microalgae is grown strategically using different wastewater combined with flue gas in cultivation system for simultaneous production of 'high-value-low-volume' product and 'low-value-high-volume' product with sharing of the remnant biomass to produce biochar. In addition, the CO_2 present in the atmosphere is captured and sequestered long term in the form of biochar would help to attain carbon negativity, while remediating wastewater and balancing energy requirements. Therefore, "Zero waste discharge" concept holds the potential to make the process a sustainable one, while gaining on the carbon credits.

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☆ Notes: The authors declare no competing financial interest.
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Contents

1. Introduction

An impending energy crisis due to rapid depletion of fossil fuel resources and unabated environmental damage resulting from the emission of greenhouse gases (GHG) are some of the drivers in recent years to focus research attention on carbon neutral renewable energy. With the current energy production and consumption trends (Sen, 2008), it is unlikely that we will have traditional oil reserve after 2050. More importantly, even if we still have the oil reserve, the associated environmental pollutions with the release of GHG emission including CO_2 would plunge the global climatic conditions at its' abysmal (Sen, 2008). Biodiesel derived from energy crops is a potential renewable and carbon neutral alternative to petroleum diesel. However, biodiesel derived from oil crops, waste cooking oil and animal fat is unlikely to fulfill the existing demand for transport fuels (Yen et al., 2013). Over the past few years microalgae have emerged as the most promising feedstock for biodiesel and other biofuel production because of their higher photosynthetic efficiency, high growth rate and ability to convert atmospheric CO_2 into complex value added molecules (Chisti, 2007). For instance, 100 t of algal biomass fixes around 183 t of CO_2 and production of fuels from microalgae can be carbon neutral (Yen et al., 2013).

Microalgae can also transform nutrients present in wastewater into biomass; potential decrease in otherwise manual harvesting cost; solid carbon material that can be derived through pyrolysis can aid in contaminant removal. Moreover, while saving on contaminant remediation and possible minimization of fresh water usage for biomass production, microalgal lipid can be also transformed into biodiesel in a bio-refinery concept (De Bhowmick et al., 2015). Microalgae derived biofuel production, however, appears to be too costly. The major bottleneck seems to be the net energy gain versus requirement and horrendous capital investment (De Bhowmick et al., 2018a). Therefore, the algal research community has shifted their focus from single-centric product formation to parallel synthesis of multiple products in a biorefinery model leading a methodical approach that will exploit both the up- and downstream processing (De Bhowmick et al., 2018a).

Though numerous studies are available on microalgae biorefinery; however, report on systematic comparative strategies to produce multiple products while minimizing on energy is limited. Considering the immense potential of microalgae as a feedstock for bioenergy and bioproduct development, through this article we make an attempt to provide a review of the existing and emerging strategies to adopt different techniques (process integration) to minimize the energy consumption and produce multiple products particularly carbon neutral and carbon negative energy in a bio-refinery model with zero waste discharge.

Here, we propose the strategies to maximize the biomass production by using low-cost medium such as waste waters, incorporating flue gas supply as a source of CO_2 and inexpensive easy cultivation systems while minimizing the energy use. Additionally, another approach could be the use of microalgal remnants (devoid of lipid) in combination with other lignocellulosic biomass for biochar (a biomass-derived carbonaceous material) production as a co-product along with biofuel and high value product development in a bio-refinery model. The possibility of annexing microalgal remnants to the existing lignocellulosic biomass such as rice husk and pine saw dust upon pyrolysis was thought to enhance the biochar quality and was proved by our study (De Bhowmick et al., 2018b). Therefore, achieving high biomass production using low-cost, economical resources and minimal energy for multivariate product development along with biofuel appears to be win-win scenario, while curbing the environmental pollution.

2. Energy outlook: current scenario

Considerable growth in transportation sector and requirement of fuel along with 30% increase in world's population has thrown up new challenges to the world scientific community (Slade and Bauen, 2013). World Energy Council indicated that fossil fuel accounted for 82% of the primary energy production, while renewable (other than large hydro), nuclear and hydro accounted for 11%, 5% and 2% of the total primary energy production respectively (International Energy Agency (IEA), 2011). The International Energy Agency (IEA) in Paris estimated

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