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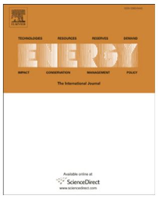

Design and optimization of artificial cultivation units for algae production

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ABSTRACT

This paper focuses on finding the optimum design of artificial cultivation units for biomass production depending on geographical location and kind of algal species selected for growth. Here, the optimum is defined as the design that yields the lowest net present sink for the lifetime of the cultivation unit. Models are developed for tubular, column, and flat plate photobioreactors by considering diurnal pattern of sunlight and temperature fluctuations. As part of the case study, algae growth is modeled for 10 years in each cultivation unit using two species and four locations, resulting in twenty-four optimization problems. Each optimization model is implemented in GAMS 23.6.5 and the solution is obtained using CONOPT (version 3.14W) solver. The results indicate that algae species with higher oil content requires smaller reactor volume to produce the desired amount of biomass. The results also reveal that the geographical location with higher incident solar irradiance may not necessarily be the optimal location for algae culturing because higher irradiance may lead to cell damage, and hence, lower growth rates. Among the options considered in the case study, the design of tubular photobioreactor for culturing *Phaeodactylum tricornutum* at Hyderabad, India yields the minimum net present sink.

1. Introduction

Excessive usage of fossil fuels has not only led to depletion of world reserves but also emission of greenhouse gases [1]. These concerns have enhanced the interest in developing first generation biofuels extracted from food crop feedstocks including soy beans, palm, canola, and rape seeds using conventional technologies [2]. First generation biofuels, however, are limited in their ability to meet the existing demand for transport fuels besides causing a tremendous strain on global food markets and endangering hunger [3]. To accommodate some of these short falls, second generation biofuels emerged from non-food crop feedstocks including wheat straw, corn stover, and wood using advanced technologies [4]. These biofuels might still not be abundant enough to replace more that 20–25% of our total transportation fuels because of concerns over competing land use. The major draw backs associated with first and second generation biofuels are addressed by third generation biofuels derived from algae [5].

The main advantage of algae is that they create their own food through photosynthesis by combining light, carbon dioxide, and water. This food is then stored as carbohydrates and lipids. Majority of algal species exhibit much higher growth rates and productivities than conventional forestry, agricultural crops, and aquatic plants, which makes it possible to use algae to fulfill the overall fuel demand while using limited land resources [6] and [7]. Furthermore, algae can be cultivated in saline water on non-arable land [8]. One of the common uses of algal biomass is to produce biodiesel because lipid or oil content present in algae may be quite high, with individual species containing anywhere between 2% and 40% on a dry weight basis [9] and [10]. The most common production route for biodiesel includes the following steps: the cultivated cells are separated from the growth medium and dried, the lipid content of the cells is extracted, and subsequently biodiesel is produced via transesterification reaction. Algae-based biodiesel is highly biodegradable and contains no sulfur; hence, it is seen as a clean and more environmentally-friendly fuel source [8]. Considering these benefits, algae appears to be a viable alternative feedstock for producing biodiesel that is capable of meeting the demand for transportation fuels.

Abbreviations: PBR, photobioreactor; MARR, minimum acceptable rate of return; DA, dry algae biomass; WIA, water present in algae biomass; WW, waste water; WRD, water remain in dryer; trans, transesterificator; BD, biodiesel; MeOH, methanol; gly, glycerol; LBTD, lower bound tube diameter; UBBC, upper bound biomass concentration; LBCD, lower bound column diameter; LBFPW, lower bound flat plate width; UBFPL, upper bound flat plate length.

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Nomenclature

Greek symbols

ρ	density of water (g m^{-3})
μ	viscosity of water (g m^{-1} s^{-1})
σ	surface tension (g s^{-2})
ϑ	kinematic viscosity of water (m^{2} s^{-1})

Parameters

g	acceleration due to gravity (m s$^{-2)}$
Sc	solar constant (μE m^{-2} s^{-1})
Cp	specific heat (J g^{-1}°C^{-1})
$EmpA$	empirical constant for interior and coastal regions
η_{dryer}	efficiency of dryer
$\eta_{\mathrm{extractor}}$	efficiency of extractor
η_{trans}	efficiency of transesterificator
Demand	biodiesel demand (g y^{-1})
n_T	number of tube diameters of separation
$[O_2]_{out}$	outlet concentration of dissolved oxygen (g m^{-3})
$[O_2]_{in}$	inlet concentration of dissolved oxygen (g m^{-3})
T_{max}	maximum temperature attained at a location in a day (°C)
T_{min}	minimum temperature attained at a location in a day (°C)
Latitude	latitude (degree)
Longitude	longitude (degree)
Time zone	time zone
$EqCost$	equipment cost of a node at a location ($ m^{-3})
$ElCost$	electric cost of pump ($ kWh^{-1})
$\%_s$	percentage of dry algae present in algae species (%)
OC	lipid content present in an algae species (dry weight basis)
Ka	extinction coefficient of algae biomass (m^{2} g^{-1})
I_k	species dependent constant (μE m^{-2} s^{-1})
n	empirical constant
Ul_{max}	maximum permissible liquid velocity inside the PBR (m h^{-1})
sunrise time	time of sunrise (h)
θ	daily zenith angle at a location (radians)
I_t	extraterrestrial solar radiation on horizon surface (μE m^{-2} s^{-1})
I_o	incident solar radiation on horizontal surface (μE m^{-2} s^{-1})
T_{surr}	surrounding temperature (°C)

Variables

Z	objective function ($)
O	mass flow rates of reactant or product entering or leaving transesterificator or extractor at a location for a species in a year (g y^{-1})
N	mass flow rates of reactant or products entering or leaving PBR at a location for a species in a year (g y^{-1})
X	mass flow rates of reactant or product entering and leaving PBR at a location for a species and at certain times (g h^{-1})
$\dot{m}$	mass flow rate of products produced in PBR at a location for a species and at certain times (g h^{-1})
I_{avg}	average irradiance inside the PBR (μE m^{-2} s^{-1})
$Ø_{\mathrm{eq}}$	length of the light path from the surface to any point in the PBR (m)
BC	biomass concentration (g m^{-3})
T_{reactor}	reactor temperature (°C)
A_S	Surface area of the cultivation unit (m^{2})
μ_{max}	maximum specific growth rate (day^{-1})
μ	specific growth rate (h^{-1})
PrV	volumetric productivity of the PBRs (g m^{-3} h^{-1})
PrV_{O2}	volumetric rate of oxygen generation by photosynthesis (rate of photosynthesis) (g m^{-3} h^{-1})
V	volume occupied (m^{3})
Ul	velocity of fluid flow in PBR (m h^{-1})
A_C	Cross sectional area of the cultivation unit (m^{2})
Re	Reynolds number
$HØ$	Hydraulic diameter of PBR (m)
PP	Power of pump (kW)
ϕ	tube diameter (m)
TL	length of solar loop of a tubular PBR (m)
A	Land area occupied by tubular PBR (m^{2})

Variables related to column PBR

dC	column diameter (m)
ε	gas hold up
Ug	superficial gas velocity (m h^{-1})
dB	bubble diameter (m)
CH	height of column PBR (m)

Variables related to flat plate PBR

W	width of flat plate (m)
FPH	height of flat plate (m)
FPL	length of flat plate (m)
ε	gas hold up
Ug	superficial gas velocity (m h^{-1})
Ub	bubble rise velocity (m h^{-1})
Ra	Rayleigh number

Subscripts

s	species
l	location
Pi	process i ($P1$, $P2$, $P3$, $P4$, and $P5$ represent the series of processes involved in biodiesel production)
c	component
y	year
d	day of the year
t	time of the day
in	stream flowing in to unit operation
out	stream flowing out from unit operation
max	maximum
min	minimum

Despite their inherent potential as a source of biofuel, algae-based applications have scarcely reached industrial scale. The main reason underlying such a low practical implementation is the high costs associated with algae cultivation [11]. Practical methods for cultivating algae in large scale are open ponds and closed photobioreactors (PBRs) [12]. Open ponds are less efficient when compared to PBRs [13] because of the difficulty to control contamination, temperature fluctuations, and evaporative losses.

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