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Algal biorefinery-based industry: an approach to address fuel and food insecurity for a carbon-smart world

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Abstract

Food and fuel production are intricately interconnected. In a carbon-smart society, it is imperative to produce both food and fuel sustainably. Integration of the emerging biorefinery concept with other industries can bring many environmental deliverables while mitigating several sustainability-related issues with respect to greenhouse gas emissions, fossil fuel usage, land use change for fuel production and future food insufficiency. A new biorefinery-based integrated industrial ecology encompasses the different value chain of products, coproducts, and services from the biorefinery industries. This paper discusses a framework to integrate the algal biofuel-based biorefinery, a booming biofuel sector, with other industries such as livestock, lignocellulosic and aquaculture. Using the USA as an example, this paper also illustrates the benefits associated with sustainable production of fuel and food. Policy and regulatory initiatives for synergistic development of the algal biofuel sector with other industries can bring many sustainable solutions for the future existence of mankind.

Keywords: algal biofuel; food insecurity; aquaculture; coproducts; integrated algal biofuel; biorefinery

FOOD AND FUEL: TWO MAJOR FUTURE CHALLENGES

Food security is a growing concern worldwide, with more than one billion people lacking sufficient dietary energy.[1] An emission-mediated climate change will significantly affect future food production and caloric availability, increasing the prevalence of child malnutrition.[2] However, while the productive agricultural land on our planet is decreasing due to extreme climate and unpredicted weather (attributed mainly to increasing greenhouse gas (GHG) emissions), the world population and food demand are growing.[3,4] GHG-mediated climate change is causing irreversible damage (e.g., species loss, sea-level rise, increased ambient temperature, irregular weather pattern, ocean acidification and oceanic phytoplankton depletion) to our planet.[5] The GHG emission and world population trends in developed and developing countries are shown in Fig. 1(A) and (B), respectively.

Since increased GHG emission is directly connected to energy production, production of clean renewable energy has become a global focus and has inspired countries to approve biofuel-promoting legislation. The USA mandated that 36 billion gallons (in 2008, the USA consumed ∼140 billion gallons of gasoline, so 36 billion gallons represents ∼25% replacement of gasoline consumption) of conventional and advanced biofuel be produced by 2022,[6,7] whereas the European Union introduced a binding target of 10% renewable biofuel energy in transport by 2020.[8] Similar legislation is underway in China, India, and Brazil, suggesting a major change in the energy sector. The projected biofuel production in developed and developing countries is illustrated in Fig. 1(C).

THE VICIOUS INTERPLAY OF FOOD, FUEL AND GREENHOUSE GAS EMISSIONS

Current biofuel projections are based on feedstock such as corn, soya bean and sugar cane, which are also food commodities.[9] Energy and agricultural markets are closely linked, and due to their size the movements in energy markets affect agriculture more than vice versa. In 2007, biofuel production used 5% of the world's cereal production, 9% of the world's oil production, and 10% of the sugar cane production.[3] In 2008, 20–22% of US corn crop was fermented to bioethanol.[10] Higher corn prices resulted from biofuel mandates and subsidies encouraged farmers to plant fewer acres of wheat and soya beans. This resulted in increases in wheat and soya bean prices. In addition, corn is the chief feed grain for the beef, poultry, and pork industries. Feed accounts for 60% of the operational cost in these industries and producers were forced to pay higher prices for feeding their animals, which they eventually passed on to the consumers.[11] Pressure from the biofuel industry might further worsen an already exacerbated global food security issue.[12] During the last 3 years, the price of wheat and corn has tripled and the price of rice increased fivefold, pushing 75 million more people into poverty.[13] The World Bank has estimated that food prices have already risen by 83%, and riots for food have already

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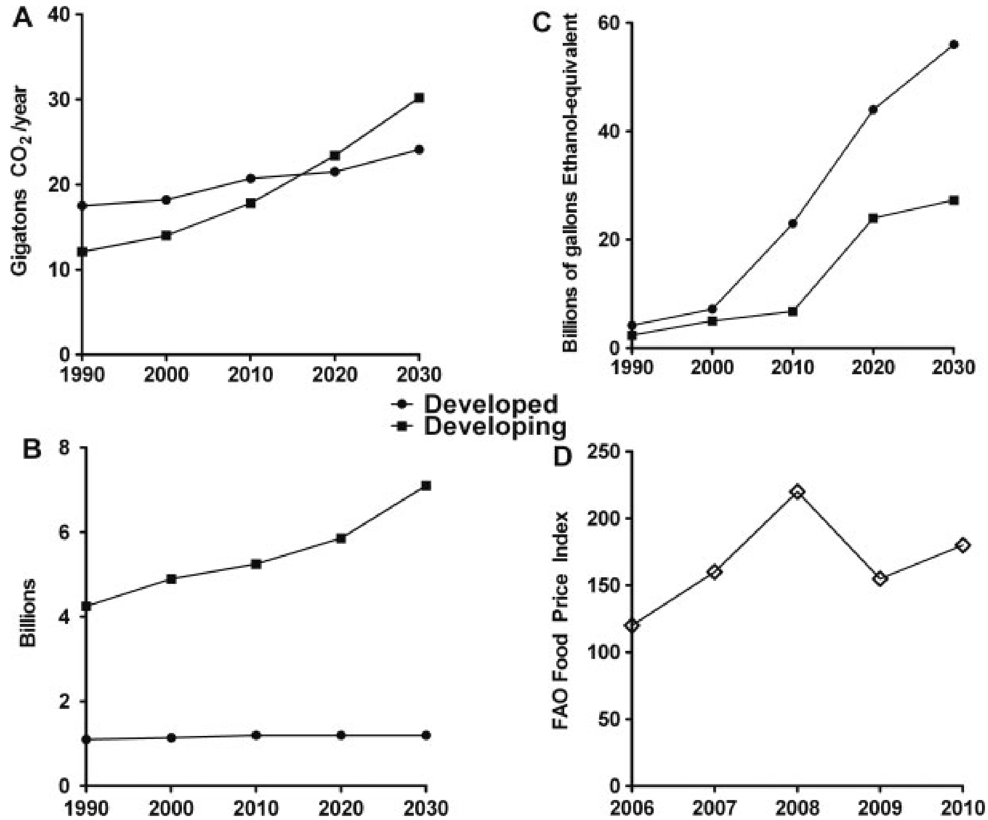

Figure 1. (A) Global trends in GHG emissions, (B) population growth and (C) biofuel production; (D) the trend in FAO Food Price Index from 2006 to 2010.

broken out in half a dozen countries because of extreme food shortages. Instabilities and oscillations in the Food and Agriculture Organization (FAO) food price index (FFPI) between 2006 and 2010 imply a growing trend (Fig. 1(D)). The FFPI continued to increase after 2006 and peaked in 2008, averaging 220–57% more than in 2007.[14] Prices of nearly all food commodities have risen since the beginning of the year, supported by a persistent, tight supply-and-demand situation. There are several factors behind the food price spikes in 2008. The high price of oil is manifested in increased fertilizer and fuel costs, thereby increasing demand for meat and dairy products in the developing world. This has necessitated more feeding grain for the livestock sector. Adverse weather conditions (such as the recent 6-year Australian drought) have decimated rice production. Diversion of crops for biofuel production and domestic policy responses in developing countries, such as export taxes, bans, and other restrictions, have also resulted in higher food prices.[15] There was a declining trend in FFPI in 2009 owing mainly to the lower international crude oil price, and in 2010 the FFPI again shows an increasing trend. There is substantial evidence that a rapid expansion of liquid biofuel production for transport from food crops has an upward effect on food prices.[16–18] Another effect linked to a rapid expansion of biofuel production based on food crops is the emergence of additional land claims for food production. Although biofuel is only one of the many drivers of high food prices, there is an increasing fear that developing biofuel based on food crops could reduce the production of basic food ingredients. A shift in land usage and crop utilization for biofuel will have global repercussions, signifying the pressing need for more food production for the planet's growing population, with optimal use of our remaining natural resources.

Another limitation of sustainable food production in a 'carbon-emission-constrained' planet is related to GHG emission of food production systems.[19] Atmospheric CO_2 presently adds about 63% of the gaseous component responsible for anthropogenic climate change. The mean global atmospheric CO_2 concentration increased from 280 ppm in the 1700s to 380 ppm in 2005, at a progressively faster rate each decade.[20,21] This growth is primarily attributable to the CO_2 emissions from fossil fuel combustion and industrial processes, and the CO_2 flux from land use change – mainly land clearance.[21] Among the average GHG emissions from various human activities, food production contributes a significant 15% and there is a growing concern to reduce the carbon footprint of agriculture-based food producion and processing.[22] Excessive use of fossil fuel-based irrigation and synthetic fertilizers for increasing production, as practiced in the past, are not viable options.[4] Livestock accounts for 15–18% of worldwide GHG emissions, with direct methane emission from ruminant guts and indirect carbon required for the production of feed-grade grain, fertilizer and meat processing.[23] Similarly, the global increase in fuel-intensive fisheries – another major food production sector – has led to a substantial increase in CO_2 emissions from fishing vessels. Global fisheries burned almost 42.4 million tons of fuel in 2000, representing about 1.2% of the global oil consumption. These fishing fleets emitted more than 130 million tons of CO_2 into the atmosphere, at an average rate of 1.7 tons of CO_2 per ton of live weight of fish landed.

There is a growing need for a sustainable food systems approach to address the importance of multiple scales and levels in food security debates and discussions. A sustainable food system can be defined as productive, responsive to changing demands, resource efficient and with limits on GHG emission, with strict energy efficiencies along the entire food chain.[24] Two major criteria laid out as key future sustainability principles for biofuels concern the interrelatedness of biofuel with food and GHG emission. First, biofuels will contribute to climate change mitigation by significantly reducing the life cycle of GHG emissions in comparison to fossil fuels; and second, biofuels will ensure the right to adequate and improved food security in food-insecure regions.[25]

The inherent interrelationship between future demand for food and fuel in a GHG emission-constrained planet with an increasing population (Fig. 1) brings the main challenges for regulators and policy planners, namely: *Can fuel and food crops be co-managed and co-optimized sustainably? Are there policy initiatives to foresee a synergistic development of agricultural food and energy crops?* This paper discusses a framework to integrate the algal biofuel sector, a booming biofuel industry, with other industries such as livestock, lignocellulosic and shrimp production industries, taking the USA as an example, to illustrate the benefits of sustainable production of fuel and food.

ALGAL BIOFUEL SECTOR

Scope and advantages of algal biofuel in the USA

The assessments of production potential, environmental impacts of biomass facility production and carbon sequestration have revealed that biofuels based on traditional feedstocks will comply marginally with various sustainability criteria. This has instigated the need for rapid development of advanced feedstocks such as switch grass, algae and woody mass. However, terrestrial-based bioenergy production systems are now facing issues related to indirect emission[26] and carbon debt from land clearance[27,28] and are becoming a sustainability hurdle for further expansion.[29] Microalgal biomass production offers a number of advantages over conventional biomass production, including higher productivity, use of otherwise nonproductive land, reuse and recovery of waste nutrients, use of saline or brackish waters, and reuse of CO_2 from power plant flue gas or similar sources.[30,31] A key attraction of algae for biofuel feedstock production is the potential for high annual oil productivity per unit of area. Resource studies have shown that corn (18 gallons of oil per acre) and soya (48 gallons of oil per acre) require 1.5 billion and 570 million acres of land area, respectively, to produce enough oil to replace half of the 44 billion gallons of petroleum and diesel currently used in the USA for transportation. Conversely, algae (5000 gallons of oil per acre) would require only 5.5 million acres of land to replace the same amount of fossil fuel. Although the theoretical maximum production rate of 50 000 gallons per acre has been proposed by many studies, 5000 gallons per acre is a conservative algal production rate using current technologies. The USA has optimum resources and technological know-how to develop a sound commercial algal biofuel sector and, recently, investors have shown particular interest in algae-based biofuel.[32,33] More recently, industry leaders such as Shell, Chevron, ExxonMobil, and British Petroleum have invested substantial resources (∼$1 billion) in developing algal based biofuels not only because of the positive sustainability indexes but also because of the prospects of scalability.

Algal biorefinery and integrated sequential biomass processing

As algae produce many valuable products, developing integrated algal processing (IAP) for the sequential production of various products from the same algal biomass can substantially reduce the cost of production, which in turn will make it a profitable enterprise. For example, as the first step in an IAP concept, harvested algal mass and culture water can be processed for recombinant protein production. In the second step, the algal oil and algal meal can be processed. From the algal oil, high-value omega-3 fatty acids, such as docosahexaenoic acid and eicosapentaenoic acid, can be separately processed.[34] The rest of the oil can be used for biofuel production. A significant amount of glycerin is the end byproduct of biodiesel production, and recent studies have shown that glycerin, in turn, may be effectively utilized to grow more algal mass for the production process.[35] Alternatively, glycerin can also be used as a raw material for the bioproduction of chemicals such as 1,3-propanediol via microbial or algal enzymatic methods.[36,37] Algal biomass can yield many coproducts from the same biomass and this multiproduct paradigm makes it a perfect candidate for the biorefinery concept. A biorefinery involves biomass conversion processes and equipment to produce fuel, power, and value-added chemicals from organic material. This facility is analogous to modern petroleum refineries, which produce multiple fuels and products from crude petroleum.[38] By producing various coproducts such as recombinant protein, omega-3 fatty acids and biodiesel in a sequential biomass processing, an algal biorefinery takes advantage of the various components in raw material and their intermediates therefore maximizing the value derived from the biomass feedstock.[39]

ALGAL BIOREFINERY-BASED INDUSTRIAL ECOLOGY

The various coproducts derived from algal biorefinery can feed various industries (Fig. 2). For example, cheap recombinant antiviral (e.g., cyanovirin, griffithsin, interferon) and antibody production could be of use to pharmaceutical industries manufacturing sustainable and cheap drugs and vaccines. Similarly, coproducts such as glycerin can be an input to the industrial chemical sector. Integrated approaches to cross-feed products and byproducts between these industries can contribute to the co-development of many sectors.[40] The biorefinery framework can also yield value-added coproducts which can be used directly or indirectly in the food production sector.[41,42] For example, it is estimated that 100 million tons of protein will be additionally produced from biomass-based biofuel feedstock as a coproduct in the future.[40] These nutrient-rich coproducts can be directly used to feed undernourished children in underdeveloped countries or indirectly used as an animal feed ingredient for producing meat, milk and dairy products. However, a multisector restructuring for a new industrial ecology needs to be developed to encompass the value chain of different products, coproducts, byproducts and services from the booming algal biorefinery industries.[43] The food production sector will also be a part of this concept. In the following sections, three integrated industrial scenarios are described in detail to further substantiate the merits of a biorefinery-based industrial ecology in fuel and food production.

Integration of algal biofuel with livestock industry

Scope and size of the livestock industry in the USA

Livestock production operations in the USA vary widely in both the mode and scale of production. There are individual farms spanning small-scale production facilities with few animals, to large, intensive production facilities with hundreds of animals. In 2009, the USA meat and milk industries generated a mammoth

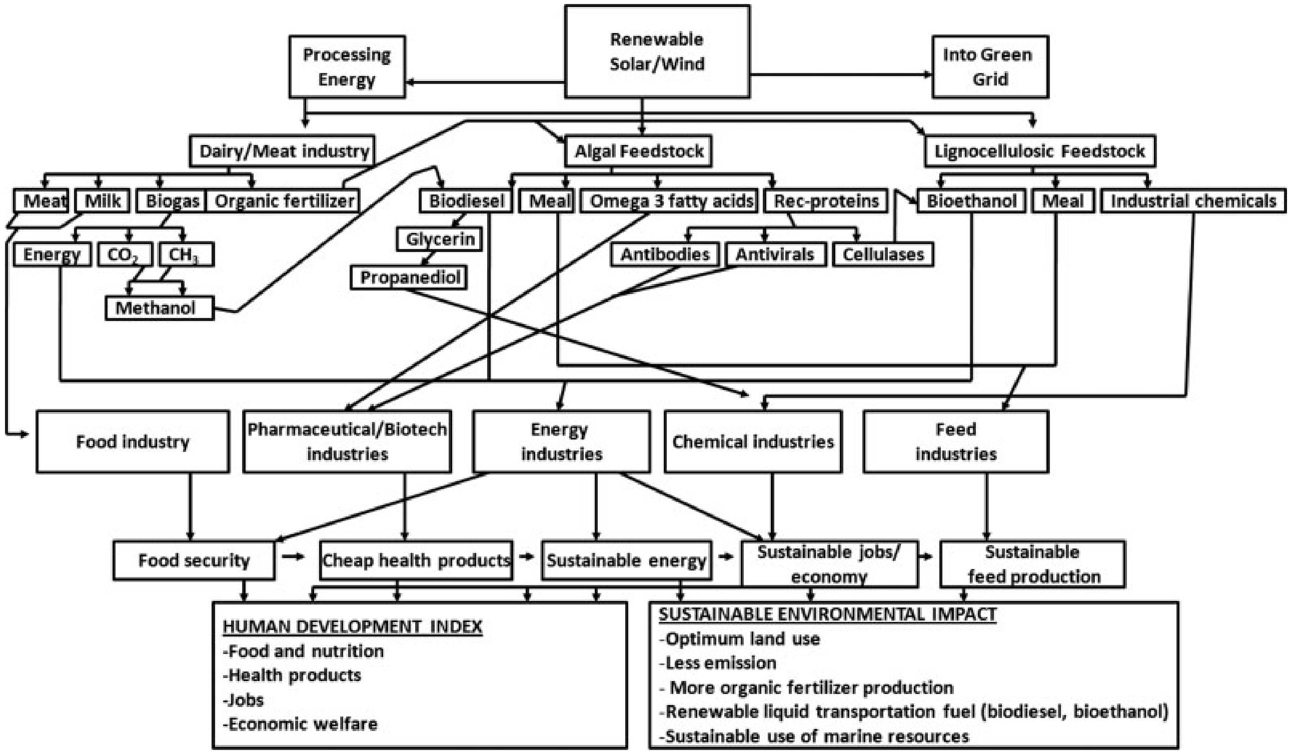

Figure 2. Byproducts from biofuel industries can feed into other industries for sustainable production of food, fuel and high-value coproducts.

49 billion pounds of meat (26 billion pounds of beef and 23 billion pounds of pork) and 190 billion pounds of milk, respectively, with a combined value of \$70 billion.[44]

The main livestock industry categories are establishments primarily engaged in raising:

- cattle, milking dairy cattle, or feeding cattle for fattening;
- hogs and pigs; these establishments may include farming activities, such as breeding, farrowing, and the raising of weaning pigs, feeder pigs or market-size hogs;
- sheep, lambs and goats, or feeding lambs for fattening;
- animals for sale or production (except those listed above), including horses and other equines, rabbits and other fur-bearing animals and associated products.

All livestock-producing establishments covered nearly 530 million acres of land. Cattle ranching and farming establishments comprise the overwhelming majority of all establishments by accounting for 77.9% of all livestock establishments. In the USA in 2003, there were 785 672 cattle ranching and farming establishments. Of these, approximately 89% were categorized as beef cattle establishments, including feedlots. The remaining 11% were categorized as dairy cattle and milk production facilities. In 2003, the average beef cattle establishment was nearly 635 acres in size. Establishments raising dairy cattle with milk production averaged approximately 356 acres.[45,46] Cattle ranching and farming establishments accounted for approximately \$60 billion of sales in 2003. Of that \$60 billion, beef cattle establishments had sales of approximately \$38 billion (approximately 65% of sales), while dairy cattle and milk production accounted for the remaining \$21 billion. Hog and pig farming comprised approximately 4.6% of all the livestock-producing establishments in the USA in 2003. These establishments accounted for nearly \$14 billion in total sales, or approximately 14% of total livestock-producing establishment sales in 2003. Ranked by the number of cattle and calves sold, the top ten producing states controlled 65% of US beef production in 2008. Texas was the largest beef-producing state, accounting for 16% of 2008 sales. Other major states included Kansas, Nebraska, Oklahoma, Colorado, Iowa, California, South Dakota, Missouri, Wisconsin, and Montana. The hog-farming sector is concentrated among the top five producing states that together supply about 60% of US pork production. Iowa accounted for a significant share of hog sales. The top five dairy cattle states controlled more than 50% of all US milk production in 2008.[47] Wisconsin and California were the leading dairy producing states, with 30% of volume milk sales. A significant recent shift in the industry is a trend toward fewer and larger livestock operations. Agriculture Census data highlight the ongoing shift from many small, diversified farms toward fewer large-scale, year-round, intensive breeding and feeding operations.[46]

Challenges of the livestock industry in the USA

The livestock industry faces a raft of sustainability challenges in addition to climate change, such as intensive livestock operations using large quantities of water, concern about waste from factory farming methods and the 'energy' inefficiency of meat as a foodstuff (the environmental damage caused by clearing forests for pasture or inputs used in rearing livestock). One of the major sustainability issues with livestock production is the excess nutrients in water (i.e., phosphorus and nitrogen), which can result in or contribute to low levels of dissolved oxygen, eutrophication, and toxic algal blooms. These conditions may be harmful to human health, and may adversely affect the suitability of the water for other uses. Animal waste includes the fecal and urinary wastes of livestock and poultry, process water and the feed, bedding, litter, and soil with which fecal and urinary matter and process water become intermixed. Manure and wastewater from animal feeding operations have the potential to contribute pollutants such as nutrients, organic matter, sediments, pathogens, heavy metals, hormones, antibiotics, and ammonia to the environment. Solids deposited in water bodies can accelerate eutrophication through the release of nutrients over extended periods of time.[44] Contamination of groundwater can be a problem if runoff results from the misapplication or over-application of manure to land or if storage structures are not built to minimize seepage. As animal feed sometimes contains heavy metals, the possibility for harmful accumulations of metals on land where manure is improperly or over-applied is possible. Within a livestock production establishment, pesticides may be applied directly to livestock or to structures to control pests, including parasites, vectors, and predators. Pesticides may harm the environment by eliminating or reducing populations of desirable organisms, including endangered species.[44]

The use of pollution prevention technologies and environmental controls can substantially reduce the volume and concentration of contaminants. Waste minimization generally encompasses any source reduction or recycling that results in either the reduction of total volume or the toxicity of hazardous waste. The primary pollution outputs include animal wastes, bedding, wastewater from flushing and wash down of housing areas, and air emissions (e.g., methane, ammonia, and odors). The main impacts of these outputs are soil and water contamination stemming from waste spills, improper storage, and runoff.[44]

Another major issue that currently needs pressing policy actions is the methane production from livestock industry.[48] Livestock accounts for a significant amount of worldwide GHG emission and more than a third of all methane emissions – around 900 billion tons every year – are produced by methanogen bacteria that live in the digestive system of ruminants. By volume, methane is 20 times more powerful at trapping solar energy than carbon dioxide, making it a potent GHG. There have been suggestions that, to help combat global warming, a cap be placed on the number of animals in the meat industry because of their methane production. However, in a ‘protein-demanding future’, this is not a viable option.

Algal biodiesel production needs substantial amounts of methanol for the processing of oil into diesel. This is an important premise because methanol is traditionally produced from fossil fuel-based feed stocks. Thus renewable supply of nonfossil-based methanol is important for sustainable algal biodiesel production and marketing. This is where the dairy and beef industries can be integrated into the biofuel sector. Anaerobic digestion of manure has the potential to eliminate most of these emissions while conserving nutrients and also coproducing renewable energy and methane. This methane can be converted to nonfossil-based methanol, which can meet future demand from the algal biodiesel industry (Fig. 2). Similarly, the organic fertilizer produced from manure can in turn be used for rearing algae without the sustainability issues of synthetic fertilizer. Basic research in livestock nutrition to address these challenges is also pivotal for this industry. A study reported that a substantial reduction in the amount of methane released by animals is achieved by including 2% fish oil in the diet of cattle.[49] The fish oil affects the methane-producing bacteria in the rumen gut, leading to reduced emissions. If omega-3 in fish oil is responsible for these effects, the algal-derived omega-3 from the algal biofuel industry could also be used to fortify the feed to reduce GHG emission from the livestock industry.

Use of nutrient-rich wastewater from the livestock industry can be treated and used for algal production, thereby reducing environmental pollution and deriving an economic incentive by using nutrient-rich wastewater for productive use. Feeding omega-3 fatty acid-rich feeds and algal meal in livestock intended for meat and milk production will increase the nutrient value of the meat and milk produced. Alternatively, omega-3 produced from the algal sector can be used to fortify milk. The benefits of marine-based feed ingredients in livestock feed is a growing area of nutrition research. An algal supplementation level of about 10 g kg^{-1} of dry matter intake proved effective in reducing milk fat content and in modifying the milk fatty acid composition toward increased conjugated linolenic acid (CLA) and docosahexaenoic acid concentrations.[50] Another study found that algal meal could be used to increase the concentration in rumen contents of *trans*-18 : 1 isomers that serve as precursors for CLA biosynthesis in the tissues of ruminants.[51] Dietary supplementation with fish meal or n-3 fatty acids in early-lactating dairy cows significantly increased uterine n-3 fatty acid concentrations.[52] A related study demonstrated that dietary supplementation with fish meal or n-3 polyunsaturated fatty acids in early-lactating dairy cows significantly increased milk yield with no change in milk composition.[53]

Integration of algal biofuel sector with lignocellulosic industry

Scope of lignocellulosic biofuel industry in the USA

A series of policies in the USA have supported development of biofuels, including the Biomass Research and Development Act of 2000, the Energy Policy Act of 2005, the Energy Independence and Security Act (EISA) of 2007, and the 2002 and 2008 Farm Bills. EISA requires increased biofuel production and additional funds to promote cellulosic and advanced biofuel production. The Renewable Fuel Standard increases to 36 billion gallons by 2022. The mandate includes specific allocations, including 21 billion gallons of advanced biofuels – essentially renewable fuels other than ethanol derived from corn starch that meet certain GHG emission reductions. Of the 21 billion gallons of advanced biofuels, at least 16 billion gallons must be from cellulosic biofuel.[54]

The effects of biofuel production based on food crops have led to calls for growing nonfood crops for transport biofuel production which would not have an upward effect on food prices nor lead to the replacement of nature. Nonfood crops proposed in this context are mainly crops that can provide lignocellulosic biomass for transport biofuel production. These include grasses such as *Miscanthus* and switchgrass (*Panicum virgatum* L.), and woody crops such as willow.[55,56] In view of mounting criticism of ‘first-generation’ transport biofuels made from sugar, starch, oils and fats, there is increasing interest in ‘second-generation’ biofuels. These are made from lignocellulosic biomass. Lignocellulose is a composite of cellulose, hemicellulose and lignin, and roughly corresponds to plant fibers. Cellulose and hemicellulose can be enzymatically converted into ethanol, which can be included in petrol. Lignocellulose can also be gasified and then converted into biodiesel. Harvest residues such as straw and corn stalks are a convenient source of lignocellulose for biofuel production.[57,58] They can be easily gathered during harvest operations, and there are large amounts thereof – worldwide, about 4 billion tons each year. Indeed, many plans for second-generation transport biofuels assume that in the future harvest residues will be a major ingredient of the main feedstock. Enzyme hydrolysis of forest waste and switchgrass is considered a viable third-generation feedstock in the USA. Apart from switchgrass-based crops, many states in

Table 1. Biomass resources for the ten standard Federal regions (as established by Office of Management and Budget, Circular A-105) in the USA. Renewable resource information from Milbrandt[84] were taken to prepare the table and biomass is represented as thousand tons per year

Region	States in the Region	Biomass
R1	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont	8 239
R2	New Jersey, New York, Puerto Rico, Virgin Islands	7 643
R3	Delaware, District of Columbia, Maryland, Pennsylvania, Virginia, West Virginia	8 219
R4	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee	100 142
R5	Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin	95 582
R6	Arkansas, Louisiana, New Mexico, Oklahoma, Texas	44 666
R7	Iowa, Kansas, Missouri, Nebraska	82 667
R8	Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming	35 619
R9	Arizona, California, Hawaii, Nevada	15 636
R10	Alaska, Idaho, Oregon, Washington	26 401

the USA have a vast potential for other cellulosic feedstocks, and the biomass potential of regions in the USA is shown in Table 1.

The cellulosic and lignocellulosic bioethanol industry is still in its infancy and has many technological and infrastructure constraints.[55] The success of this industry depends on the availability of inexpensive sources of cellulases/hemicellulases to hydrolyze cellulose and hemicellulose. Three types of cellulases are needed to convert cellulose into glucose: endoglucanase, exoglucanase or cellobiohydrolase, and glucosidase. Cellulases are currently the third largest industrial enzyme worldwide because of their use in cotton processing, paper recycling, detergent enzymes, juice extraction and animal feed additives. However, cellulases will become the largest volume industrial enzyme, if ethanol, butanol, or some other fermentation product of sugars, produced from biomass by enzymes, becomes a major transportation fuel. Currently, industrial cellulases are produced from aerobic cellulolytic fungi such as *Hypocrea jecorina* or *Humicola insolens* (Cooney and Emers). This is due to the ability of engineered strains of these organisms to produce extremely large amounts of crude cellulase (over 100 g L^{-1}) with relatively high specific activity of their crude cellulases on crystalline cellulose, and the ability to genetically modify these strains to tailor the set of enzymes they produce to give optimal activity for specific uses.

Algal production of proteins can reduce the cost by about 1000–5000 times compared to other expression platforms. The current cost of production of proteins in algae is estimated to be \$0.002 g^{-1}, compared to \$0.05 in plant expression systems.[59] Integrated sequential processing of algal biomass for multiple products such as recombinant proteins, biodiesel, and unsaturated fatty acids has already been proposed.[40] Genetically modifying algal strains such as *Chlamydomonas* and *Dunaliella* to stably express cellulases/hemicellulases opens the door for integrating enzyme production as a coproduct from the algal biofuel sector, which in turn can be fed to the enzymatic hydrolysis step in cellulosic-based feedstock processing (Fig. 2). Algal biofuel production is in the order of millions of gallons of culture water, with tons of biomass turnover per day, which can bring down the cost of production (estimated to be \$0.0002) of cellulases/hemicellulases to a level unachievable by other current production platforms.[40] These purified enzymes can be stored until pumped into the cellulosic feedstock for hydrolysis (Fig. 3).This is an example where the algal and lignocellulosic sectors can synergistically contribute to commercial viability.

Integration of algal biofuel sector with aquaculture in the USA

Scope and challenges of aquaculture in the USA

Aquaculture is the fastest-growing food sector globally and holds great promise for closing the nutritional gap for much of the world's population.[60] Further, the aquaculture-based animal production system has several advantages over other animal protein production systems (Table 2). However, intensive aquaculture also has several sustainability issues associated with it.[61] The reliance on use of wild-caught fish in aquaculture feeds, which could deplete food supplies for other marine life and the aquaculture industry itself over time, is a major sustainability issue.[62,63] The emergence of drug-resistant bacteria due to indiscriminate use of antibiotics in aquafeed for disease control and growth promotion has been a major public health issue related to mariculture. The use of coastal and marine resources for aquaculture poses environmental threats, including spread of disease from farmed to wild fish and nutrient discharge of effluents into surrounding waters. The future development of shrimp aquaculture should be focused on underutilized, environmentally insensitive areas. The rapidly expanding shrimp aquaculture industry poses one of the gravest threats to the world's remaining mangrove forests, which have lost a fifth of their area since 1980.[64,65] Mangrove depletion also robs the planet of its much needed carbon sinks to combat GHG emissions. Thus the need for future expansion of seafood production in environmentally insensitive areas is also a must.

Instead of depending largely on fish farming to meet demand, the USA has relied on high levels of seafood imports. In the USA, one of the world's fastest-growing seafood markets, the gap between demand and supply is even more pronounced, contributing in excess of \$8 billion to the seafood trade deficit. Per capita consumption of seafood in the USA has jumped to 16.3 pounds – its highest level in more than 20 years – and is expected to continue rising. America's aquaculture industry currently meets only a meager 5–7% of domestic demand for seafood.[66] Generally, more and more consumers are recognizing fish and shellfish as an excellent source of health-promoting high-quality protein and omega-3 fatty acids,[67] which is increasing the demand for seafood. Further, elderly populations are consumers of seafood because of the health benefits of fish in many degenerative diseases and enhancement of health by reducing the risk of cardiovascular diseases. The USA saw a rapid growth in its elderly population during the 20th century. The number of Americans aged 65 and older climbed above 34.9 million in 2000, compared to 3.1 million in 1900. Between 1990 and 2020, the population aged 65–74 is projected to grow by 74%.[68] This growing elderly population will

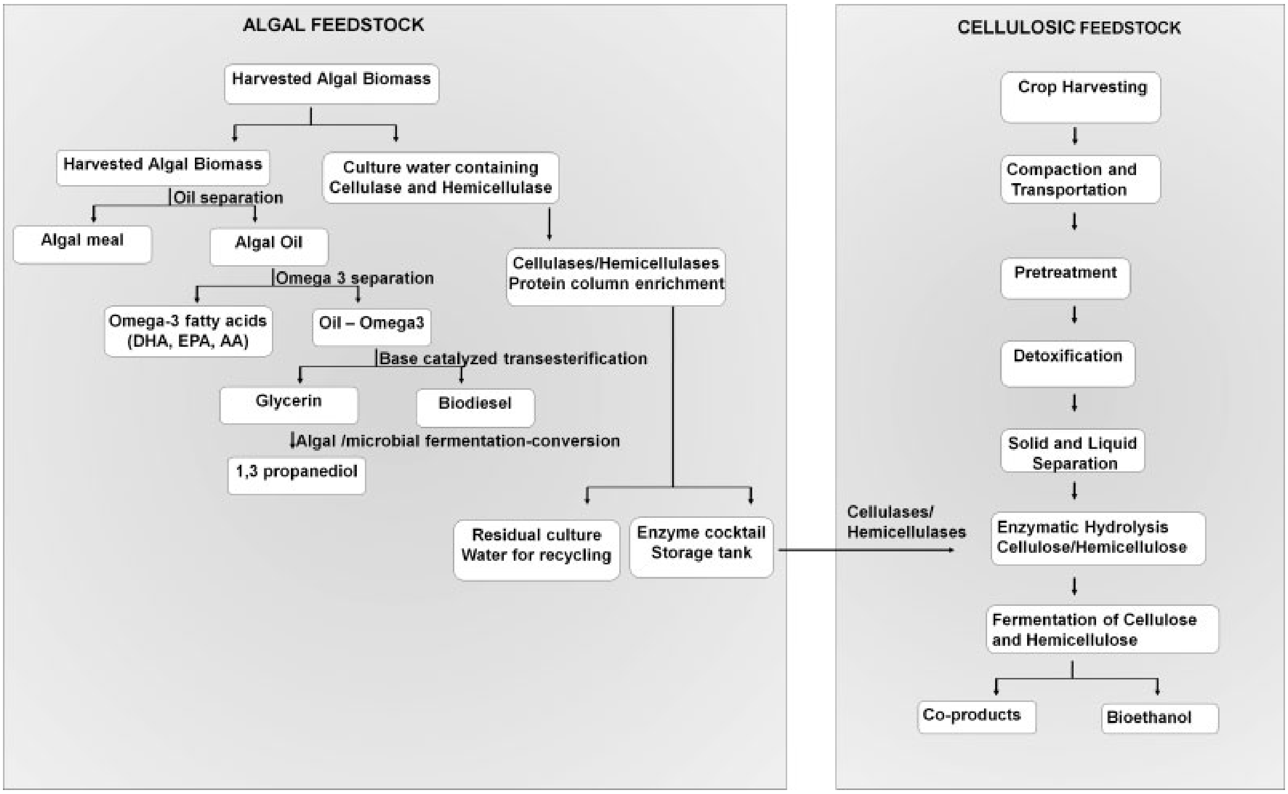

Figure 3. Box diagram of coprocessing of algal and cellulosic feedstocks for biofuel production.

Table 2. Comparison of fish and shellfish meat production with other terrestrial meat production systems. Source: Global Aquaculture Alliance

Production system	FCR[a]	LUE[b]	CF[c]	HBI[d]
Beef	9.0	45.0	14.0	1
Pork	3.5	873.0	4.8	1
Poultry	2.0	7946.0	1.8	2
Fish/shellfish	1.8	7941.0	2.0	3

[a] FCR, food conversion ratio (kg of feed required to produce kg^{-1} of meat).
[b] LUE, land use efficeincy (kg ha^{-1} a^{-1}).
[c] CF, carbon footprint (kg^{-1}).
[d] HBI, health benefit index – an index based on availability, digestibility and health benefits of nutrients such as protein, lipid, micronutrients, vitamins; 1 = good; 2 = very good; 3 = excellent.

add an additional demand for seafood in the coming decades, suggesting the crucial need for local production and marketing of seafood. Aquaculture industry is the most promising sector for integration with the growing algal biofuel industry in the USA because of the benefits and scope accrued.

Scope and benefits of integrating algal biofuel with shrimp production in the USA

Shared use of finite natural resources

The land and water required for growing future food and fuel harvest are finite. At present, these two major natural resources are competing for enhancing production in food and fuel.[39,40] Thus the primary constraint in the future food and fuel scenario is a dearth of these natural resources and the need for their optimal use. Any wasteful use of these resources will be a highly costly affair from a sustainability perspective. The renewable energy and related resources information in the USA indicate that the major renewable energy sources – solar, wind, and geothermal – are aggregated in a 'corridor' comprising the regions located in New Mexico, Arizona and Colorado, as well as parts of Utah, Texas and Nevada.[39] Further, substantial saline groundwater resources (∼15 billion acre-feet of brine) that cannot be used for traditional agriculture or drinking water can be optimally used for algal, shrimp and fish culture. These resources are within several huge aquifers in this proposed corridor.[69,70] Most of these states also possess vast stretches of underdeveloped semiarid land suitable for large-scale biomass production from feedstocks such as algae. The arid climatic conditions coupled with plentiful sunlight and saline water in the region can support a strong integrated algal biofuel industry. The resources in these areas are also highly suited for aquaculture (e.g., shrimp production). Hence developing integrated algal biofuel and shrimp production by cross-feeding products and byproducts would increase the viability and sustainability of both sectors while optimally sharing the natural resources.

Optimum use of coproducts from algal biofuel sector into shrimp production

Fishmeal and fish oil, which make up the bulk of the ingredients in diets for farmed carnivorous fish, are obtained from finite sources that are fully exploited or, in some cases, overfished.[61] Between 1950 and 2003, the amount of fish and shellfish landed by capture fisheries destined for reduction into meals, oils and other nonfood purposes increased from 3 million tons to 21.4 million tons. Overfishing of the world's oceans has depleted fish stocks, leading to a shortage of small fish such as anchovies, herring and mackerel, and, as a consequence, there is an imbalance in the marine ecosystem.[61] As a result, governments all over the globe are taking drastic measures to mitigate this problem. Beyond diminishing supplies of fish, there is also growing concern over pollutants such as dioxins, mercury, and polychlorinated biphenyls in the world's oceans that are causing the fish oil and fishmeal produced from these resources to be similarly polluted.[62] A challenge in fish nutrition is to generate end products with high levels of health-promoting long chains of omega-3 fatty acids for the consumer, while reducing the use of fish oils.[70] Omega-3 oils have a high market demand in both the human nutraceutical and animal feed industries. This growing concern is another driving force for the marketing of non-marine-based omega-3 oils and alternative feed ingredients.[71,72] Algae naturally produce substantial amounts of omega-3 and at least a fraction of this component can be carved from the extracted lipid intended for biofuel production. Algal meal is a rich source of high-quality protein, vitamins, micronutrients (trace elements) and carotenoids, which can be used directly in aquafeeds.[63,73] Policy initiatives for the meaningful integration of aquafeed industries with the algal biofuel production sector can bring many sustainable deliverables to society, such as a renewable supply of aquafeed ingredients. Substituting algal meal and oil in animal feeds is substantial with respect to indirect energetic offsets and GHG reduction, taking into account that fishmeal/oil production is one of the most energy- and GHG-intensive process (e.g., fishing, transportation, fishmeal/oil production and distribution).[74] These are important because solutions for sustainable animal farming for food security are vital for the future (Fig. 4).

Use of antibiotics in aquaculture is banned in many countries owing to the emergence of drug-resistant microbes.[75] However, losses due to disease problems are a major issue in this sector. The economic impact of infectious diseases in the mariculture sector is overshadowed by their tremendous threat to global food security. Usually, the appearance of disease (such as white spot syndrome virus and vibriosis) is associated with loss of harvest for shrimp farmers, and a staggering 30% of global production is lost annually. Disease problems have decimated shrimp farming industries in many parts of Asia and South America, and account for nearly $3 billion of economic loss annually. Loss of food produce is a major threat to a resource-constrained future. Lack of new production avenues will affect future food supply with a growing population and loss of food produce.[1] In an operational regime that prohibits antibiotics, use of robust approaches to disease control are of paramount importance for the continued growth of this industry.[76] Recently, studies have found that simultaneous treatment of antibacterial cationic peptides can obviate the emergence of resistance and can be sustainably used as therapeutics for mariculture.[77] Pathogen-specific antibodies and antivirals such as PmAV can help to ward off specific infections and thereby reduce the loss of aquaculture produce. However, the key to success of this approach is the cheap supply of peptides, antibodies, and other protein antivirals. These therapeutic agents can be inexpensively produced in algal species intended for biofuel production as a byproduct, which in turn can sustainably be used by mariculturists to ward

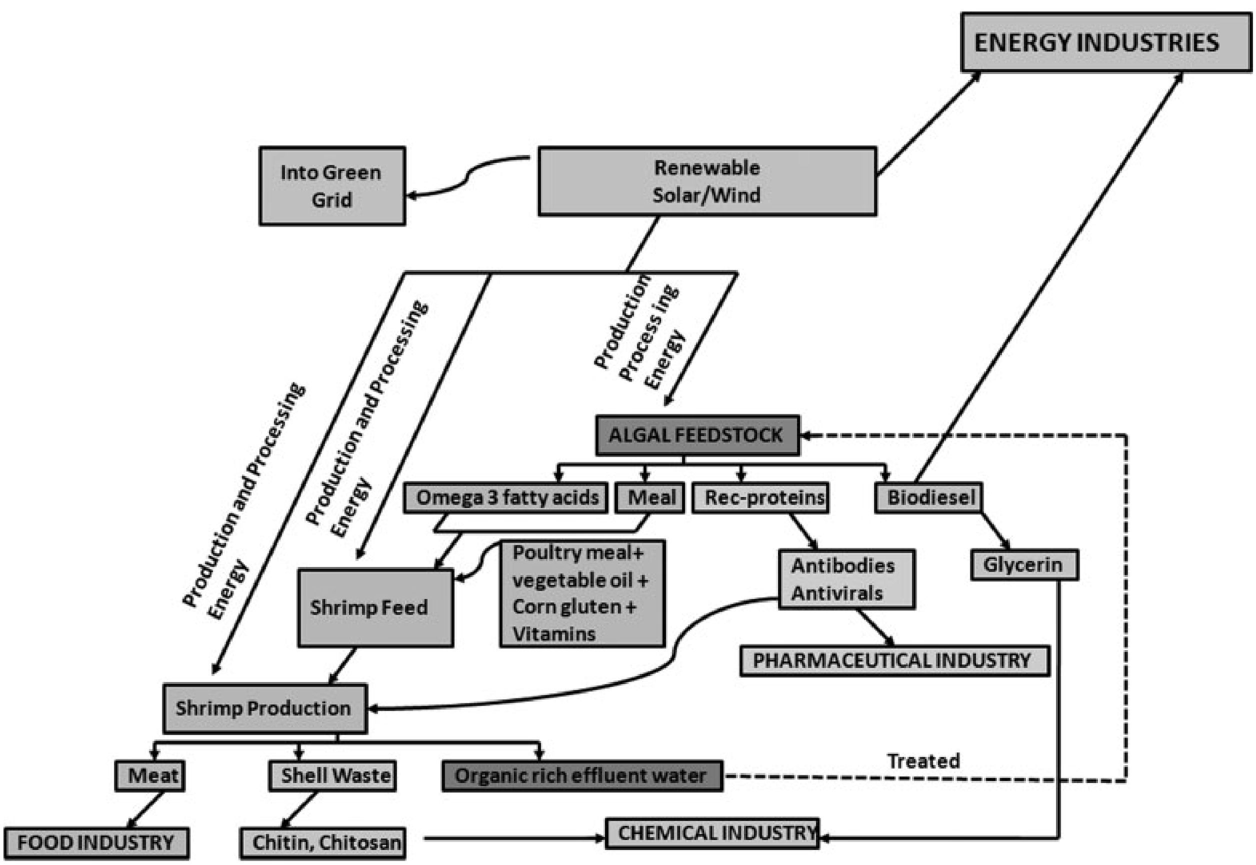

Figure 4. Algal biofuel and shrimp culture: a framework for sustainable food and fuel production.

off infections, thereby increasing global protein food supply (Fig. 4).

Use of nutrient-rich effluents from shrimp production and processing for algal biofuel production

As aquaculture faces continued pressure from the environmental community and increased governmental regulations, efforts are being made to further improve production efficiency and decrease the environmental impacts of the industry. In the USA, perhaps the most important environmental concern facing the aquaculture industry is the disposal of the nutrient-rich effluent water produced during the culture of aquatic animals.[78] Wastewaters from flow-through aquaculture operations are discharged directly into receiving water bodies and are regulated under the Federal Clean Water Act (CWA), 1977. Steps have already been taken towards reducing the impact of these effluent waters by reducing nutrient loading through the manipulation of feeds and feeding practices,[79] improved water treatment enabling water reuse and reducing the volume of water used in animal production.[80] While each of these methods can effectively reduce the impact of aquaculture effluents on the receiving water, they do not eliminate aquaculture effluents entirely and also increase the cost of aquaculture operation. Disposal of wastewater from the production and processing of marine organisms is not so straightforward, as the salinity of the water prohibits its use as a source of irrigation water, except in select cases.

Fertilizer cost is one of the major contributors of energy intensiveness in algal biofuel production[81] and also contributes a key operational cost to algal production. The treated effluents from the shrimp industry contain significant amounts of nitrates and phosphates – two otherwise costly nutrients – required for optimum algal production (Fig. 4). The effluent from shrimp production and processing facilities can be treated and then used for algal farming, which in turn will offset energy and GHG emission in algal production. Less investment is needed for aquaculture sector for wastewater management, while earning an income for effluent by selling treated nutrient-rich water to algal-growing facilities.

Ancillary industries

Many ancillary industries can also be developed along with the algal biofuel aquaculture industry. A fish feed production sector can be developed using locally available ingredients such as poultry and blood meal from southwestern poultry and livestock industries, together with algal meal from the algal biofuel sector. These feed industries based on nonmarine ingredients can support local fish and shellfish producers without the need to transport feed from distant places, which in turn reduces indirect GHG emission or 'feed miles' to reach the production facilities. Glycerin, another byproduct, can be used as a raw material for the bioproduction of chemicals such as propanediol, which in turn can feed into industrial chemical production. Shrimp shell waste from processing facilities can feed into small-scale units producing chitosan, a biodegradable chemical commodity with high market demand.[82]

INTEGRATION OF GREEN ENERGY INTO FOOD AND FUEL PRODUCTION AND PROCESSING

Production and processing of fuel and food require substantial energy input and a way to reduce the negative impact could be to use renewable energy for these processes. A framework called integrated renewable energy park (IREP) is envisioned for amalgamating different renewable energy industries in resource-specific regions for synergistic electricity and liquid biofuel production with zero net carbon emissions.[39,40] IREPs could enable the harvest of multiple sources of renewable energy, which could flow into future 'green grids'. They could also generate substantial amounts of liquid fuel such as biodiesel from algal biomass, using renewable energy sources. The energy input for the production and processing of biofuel and food can be drawn from these renewable sources such as wind/solar electricity. A schematic of integrated algal biofuel and shrimp culture using green energy from wind as a framework for sustainable food and fuel production is illustrated in Fig. 5.

BENEFITS ASSOCIATED WITH INTEGRATION OF INDUSTRIES FOR FOOD AND FUEL PRODUCTION

Algal biofuel can provide a net energy gain, have environmental benefits, be economically competitive and be produced in large quantities without affecting food supplies. Undoubtedly, the benefits associated with integrated algal biofuel biorefineries are an important predictor of the future of this sector[83] and some major ones are listed below.

Resource minimization and effective utilization

Algal biofuel production minimizes water, energy, and land use compared to other terrestrial biofuel production platforms.

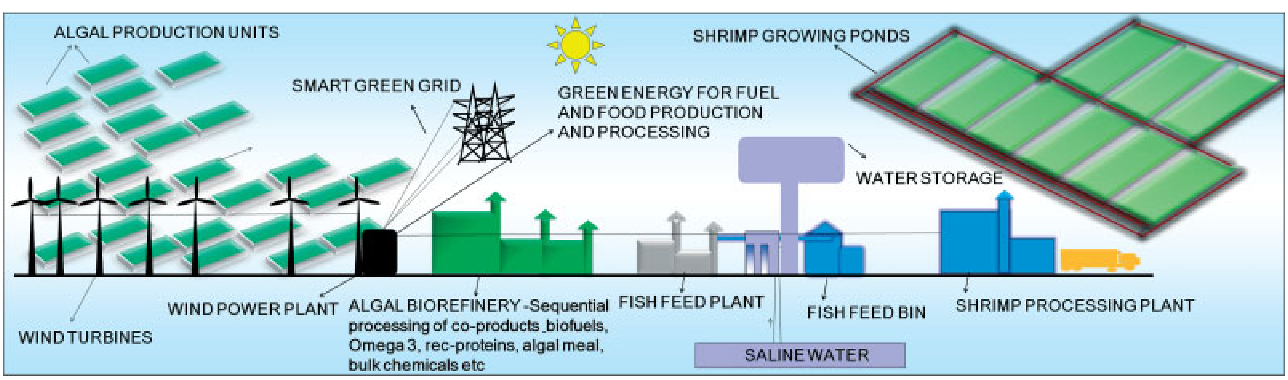

Figure 5. Algal biofuel and shrimp culture integrated with wind energy sector.

Nutrient-rich wastewater from municipal sources, the dairy industry, poultry industry and other agricultural practices, which could otherwise lead to nutrient pollution (i.e., eutrophication) of water resources, can be fed into an algal production system yielding significant pollution control benefits, with no competing land use for food production and sustainable use of underutilized resources for food and fuel production. This new aquaculture production could recirculate up to 99% of treated effluent for algal production. These systems also would have no discharge, use no chemicals or antibiotics, and could be located close to market (lower 'food miles' required), resulting in a fresher product and dramatically lower transportation costs.

Integration of sectors

Integrating algal biofuel production with allied industries by cross-feeding products, coproducts and power among them (i.e., industrial ecology) could improve resource management and minimize the ecological footprint of a production pathway. Integrating algal biofuel production using anthropogenic wastewater addresses sustainability issues of water use for the biofuel sector. Integration of the algal sector with the dairy industry could coproduce nonfossil-based methanol for biodiesel production. Integration with the lignocellulosic industry could produce cellulase/hemicellulase-like enzyme for hydrolysis processes, thereby increasing the commercial viability of both sectors. Integration of the algal fuel sector with aquaculture offers a new inland-based animal production system to meet the world's growing protein demand. Further, the inland-based aquaculture system obviates sustainability issues such as marine resource pollution and use of marine resources for aqua feeds, thereby dramatically minimizing adverse environmental impacts associated with aquaculture. The integrated industrial ecology to incorporate the new clad of emerging industries will definitely lead to infrastructure development and regional economic sustainability of rural communities. The 'spillover effect' of other small-scale industries, services and investments to support these bigger integrated industries will also be substantial from an economic perspective.[39,40]

Carbon efficacy

Undoubtedly, reducing CO_2 emission to the atmosphere is the prime goal in battling with the recent climatic changes. Algae capture 2 pounds of CO_2 for each pound of algae produced. Algal feedstock is one of the few biological platforms that can effectively sequester and convert CO_2 emitted from fossil fuel-driven power plants, creating economically viable products and services.

Sustainability

In the USA, sustainable seafood production can meet the growing future food demand and reduce trade deficits. The use of green energy in food and fuel production will significantly reduce the use of fossil fuel and offset significant indirect GHG emission.

In addition, to satisfy international demand for biofuels, the creation of energy sources for national consumption can offer a number of benefits. Biofuels can offset energy imports, diversify energy sources and create employment. Countries that can produce biofuels without causing scarcity of land, water and food will have a better income and a sustainable future. Opportunities beyond producing raw biomass should also have a share in the value chain.

CONCLUSION

Reducing the carbon intensity of the energy sources used in various industrial sectors by transitioning to alternative fuels and energy efficient machineries could reduce GHG emissions. Food and fuel security, two alarming issues faced by mankind today, are intricately interconnected and an unsustainable way to produce one might affect the other. The complex and interconnected nexus of fuel, food and GHG emission needs a planned, integrated approach. Undoubtedly, all industrial sectors are going to require radical changes in the future to address the massive challenges of emission-related regulatory framework. An important key to limit emissions in all these processes is an integrated industrial framework. For example, traditional animal food production uses a lot of feed-grade grain and other processes requiring substantial fossil fuel input and GHG emission, which can be essentially called a 'red path'. But sustainable food production for the planet's growing population is also a must. Therefore, if nutrient-rich byproducts from biofuel industries can be used as alternatives to animal feed ingredients as illustrated in this paper, it will be a 'green path' offsetting GHG emission and the fossil carbon intensity of animal food production. Following a green path for both fuel and food production will be the key to achieving this by synergistically integrating and developing sectors by cross-feeding products, power and byproducts. A future carbon-smart society will have sustainable ways to produce both food and fuel by integrating biofuel and food production sectors. This could obviate many sustainability issues associated with both sectors. Policy initiatives for synergistic development of algal biorefinery-based industrial ecology can bring many sustainable deliverables to society. In the coming decades governments and nongovernmental institutions will work together to develop a broader green industrial consortium to bring radical changes so that many of the key issues faced by humans can be solved sustainably.

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