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Life cycle assessment of industrial scale production of *spirulina* tablets

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ABSTRACT

Spirulina platensis has been successfully commercialized as functional food ingredients, animal feed and medicine due to its high contents of protein, beta-carotene, vitamins, and minerals. In this study, we investigated the environmental performance (cradle-to-gate) of edible *Spirulina* tablets using Life Cycle Assessment (LCA). A comparative analysis with other three traditional foods or diets was conducted by using various nutrient values as functional units (e.g., protein content and a composite nutrient score) in the analysis. This research showed that *Spirulina* tablets production for protein caused environmental impacts mainly in fossil fuel use, acidification, climate change, smog formation, and eutrophication. The impact of the cultivation stage was the highest environmental impacts among all production stages resulting from the extensive use of chemicals, nutrients, and energy. The impacts of algae food production are around 2–5 times to algae production for biofuels which was also modeled in this study. In terms of protein production, algae tablet cause higher impacts than traditional terrestrial crops but lower impacts than protein from animal products. However, as the algae contain a wide variety of nutrients, especially high micronutrients such as the beta-carotene, the environmental impacts of producing the same nutrient combinations of protein and beta-carotene from carrot + tofu were higher than producing *Spirulina* tablets. The results in this work can be used to assess edible algae production inventories and provide reliable information for development of more sustainable products and processes.

1. Introduction

Microalgae are excellent natural sources of highly valuable bioactive compounds, and have become the most promising and innovative sources of new food and functional products in the 21st century [1]. *Spirulina platensis*, a special microalgae species, is rich in protein, beta-carotene, vitamins, and minerals, which makes it the most ideal natural nutrition supplement that meets requirements set by Food and Agriculture Organization (FAO). It was granted Generally Recognized as Safe (GRAS) status by Food and Drug Administration (FDA) in 2003 [2,3]. Researchers have demonstrated that *Spirulina* can improve the immunity of organism, promote calcium absorption and prevent aging [1,4]. It has been commercialized successfully as a dietary supplement with the forms of tablet, flake and powder, and also as a feed supplement in the aquaculture, aquarium and poultry industries [5,6].

Spirulina platensis was introduced to China in the 1980s as a national strategic program in the 7th Five-Year Plan for the country [7]. By the mid-1990s, China had become the largest *Spirulina* producer in the world. In the last decade, the microalgae industry in China had been developing rapidly and has made remarkable achievements. According to the International Energy Agency (IEA), the total world production of dry algal biomass is estimated at about 10,000 tons per year with half of the yield being produced in mainland China [8]. Currently, there are more than 60 cultivation plants in China, producing around 9600 tons of algae powder, which accounts for 80% of the world's total output and generates $570 million annually [9]. With increasing environmental and health awareness in China over the last decades, researchers, industries and consumers have become more interested in the environmental benefits and nutritional value of the *Spirulina* cultivation and derived products. It is recognized that environmental impact analysis is crucial to the sustainable development of the industry because it can help reduce resource consumption and identify environmental impacts and therefore improve production efficiency and environmental stewardship.

Life Cycle Assessment (LCA), which assesses the entire life cycle of product and provides quantitative and holistic analysis of resource use

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and environmental impacts, has wide applications in various organizations and industries as a popular tool for environmental impacts analysis. LCA has long been used to effectively analyze and evaluate the environmental impacts of traditional food products such as soybean, corn, wheat, and dairy products [10–13] while there are only a few studies on algae food or feed. Taelman et al. found that in terms of resource use, microalgae production for aquaculture purposes is more sustainable than the traditional fish feed in the scaled up scenarios [14]. More recently, same researchers compared the environmental sustainability of protein-rich algal meal and that of soybean meal for livestock feed applications [15]. A life cycle comparative analysis between *Dunaliella salina* microalgae and *Daucus carota* carrots for extracting beta-carotene as food additives revealed that the cultivation and harvesting of *D. salina* exhibited greater environmental impacts [16].

Those existing studies, however, were either on *Spirulina* as animal and aquaculture feeds [14] or on other algae species such as *Dunaliella salina*, *Scenedesmus*, *Chlorella* and *Tetraselmis suecica* [15–17]. There is no study conducted for algae as a supplementary food for human. Furthermore, current research results mainly came from small-scale outdoor cultivation with limited time and without involving all the processes that occur in an industrial setting. Therefore, there is a knowledge gap in life cycle environmental impacts analysis of *Spirulina* as a functional food for human in a large-scale production.

In this study, we quantitatively examined the life cycle (cradle-to-gate) of *Spirulina* production as edible functional food and conducted a comparative analysis with three other traditional foods or diets such as maize grain, milk and tofu. In order to evaluate the environmental and nutritional impacts of *Spirulina* products, several nutrient values (e.g., protein content and a composite nutrient score) were selected as functional units for analysis within LCA. Especially, the composite nutrient score was first applied as a functional unit for the algae LCA study. Another uniqueness of this study is the data used in our LCA analysis were mostly based on the actual data collected from a real *Spirulina* production plant. Therefore, our analysis would be accurate than those using data from the literature. In addition, the analysis was focused on algae nutrient production in China which is a region that had never been included in existing algae LCA studies. The results would generate significant interest in both LCA and algae research areas. Broadly, the project will help to promote application of algae as a food and nutrient source and thus increase diverse nutrients sources for human consumption. Lastly, as the LCA studies on all kinds of nutrients and food supplements are very rare in existing literature, this study were expected to fill the data gap and guide future studies in this area.

2. Methodology

2.1. Goal and scope definition

The LCA was performed according to the ISO standards (ISO 14040, 2006). The main goal of this study was to evaluate algae food production in terms of environmental performance on a life cycle base. The study was also aimed to identify the hotspots that raised the negative environmental impacts and the opportunities for improvement. In this study, the production of the edible *Spirulina* tablets, a commercial functional food, was modeled in an industrial scale. In addition, to explore the nutritional impacts of algae food, some high-protein edible food (e.g. maize grain, tofu and milk) were compared with algae tablets with various functional units (FUs). The results were expected to fill the data gaps in algal food industries.

All information on the cultivation system, harvest, and tablet manufacturing was obtained from an actual plant located in the city of Beihai in the south of China, N21°30′45.47″ E109°13′12.17″ (Fig. 1). The climate there, characterized by high temperature and abundant sunshine throughout the year (2009 h a year), is suitable for *Spirulina platensis* cultivation in the open pond system. During 2015–2016, this plant achieved a monthly production of 20 tons of *Spirulina* products in the forms of a powder tablet as dietary supplement for food or feed. The figures of algae cultivation and tablet manufacturing processes are shown in Fig. 1.

The system boundary for analysis is illustrated by the flow chart in Fig. 2. Cradle-to-gate environmental impacts of eligible *Spirulina* tablets were considered. The life cycle of algal tablets production was broken down into three discrete stages, namely inoculation and cultivation, harvest and dewatering, and tablet manufacturing which are described in the following section.

This study is for audience from the research community, the algae and *Spirulina* production industries and mass consumers of algae food. *Spirulina*, as the most successfully commercialized microalgae, may attract algae researchers for its large-scale production data and environmental impacts. The study outcome can also help edible *Spirulina* producers improve environmental performance by identifying key stage in their production processes, which will allow them to target energy and emissions reductions. In addition, the results may be useful for consumers because of the nutritional values and the safety issues of edible *Spirulina* products, which are still being questioned today in China. This study may give them answers through exploring a case study of whole *Spirulina* cultivation and tablet manufacturing processes.

2.2. Edible spirulina production in south China

2.2.1. Algae cultivation (preparation and cultivation)

Our algae production started with inoculant enrichment, which was accomplished indoor with a small photobioreactor (5 L). Microalgae cultivation, which requires large amount of nutrients (nitrogen and phosphorus), salts, CO_2, light and water, has significant environmental impacts and intensive energy consumption of the whole life cycle [18]. The culture medium was prepared in the medium tank, where different nutrients and salts were mixed and then pumped to each open pond. Sodium bicarbonate was mixed and added every few days as the main inorganic carbon source. The paddlewheel worked about 10 h per day for the suspension of microalgae. The freshwater was pumped from underground and reused after harvest and thus the water consumption was mainly due to evaporation. During cultivation and pre-harvest stage, food grade CO_2 was pumped into medium from CO_2 bottle for the pH regulation of the medium.

2.2.2. Algae powder production (concentration, drying and sieving)

The harvest system, with a series of dewatering and drying steps, is designed to progressively concentrate the algae biomass. The dewatering process, which involves a few stages of filtration, together with the following drying process is energy intensive. At first, fresh water was pumped to wash the algae cells, in order to eliminate their excess of salts and with the required degree of water content. Then, an industrial spray dryer was used for rapid drying. The extremely short drying time minimized the exposure of algal biomass to heat and oxygen which can cause undesirable changes to algal biomass. The loss of water contained in algae liquid during drying process is ignored in this study. Finally, the resultant algae powder with the concentrations of 95% solid content is directly used for tablets production [19]. In order to reduce the greenhouse gas impact, a biomass boiler was used to supply heat and the biofuels are wastes from agriculture such as wood pellet. Water collected in the harvest and dewatering containing many mediums, therefore it was recycled back to open ponds in order to reduce mediums and water use in the algae cultivation stage.

2.2.3. Tablet manufacturing

The harvested dry *Spirulina* powder (5% moisture) was transported to the tablet manufacturing workshop. With a series of tablet manufacturing processes, *Spirulina* tablets were produced as functional food which contains of 80% algae powder. The nutrient parameters of algae tablets are shown in Table 1 (supported by the test report of *Spirulina* tablets and USDA Food Composition Databases).