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Review

Drying Techniques of Microalgal Biomass: A Review

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Abstract

Microalgae are attracting attention as a resource for the production of biofuels, food nutrients, biochemicals, and bioplastics. Among a wide range of sources of the biomass, microalgae have been highlighted due to relatively easy cultivation, ability to eliminate carbon dioxide, and low culturing cost. Despite the great potential of microalgal biomass as a biological material, the complexity and relatively expensive downstream processes have inhibited the commercial use of microalgae. In this study, we reviewed recent techniques for microalgal drying for the production of microalgal based products. As drying processes comprise the largest portion of microalgae processing cost, an efficient drying technique is key to the utilization of microalgal biomass.

***Keywords**: Microalgae, Drying techniques, Downstream process, Biomass, CO_2 conversion*

1. Introduction

Microalgae are photosynthetic microorganisms that are widely distributed throughout Earth due to their strong vitality to survive in a variety of aquatic environments. Microalgae not only have the ability to uptake carbon dioxide, but also serve as a resource to produce foods and biochemicals. Because of the potential of these microalgae, microalgae research is being actively conducted around the world[1].

Microalgae contain the photosynthetic pigment, chlorophyll a, which can convert solar energy to chemical energy through photosynthesis. The chemical energy is used to convert carbon into complex organic carbon compounds[2]. Microalgae, which are abundant in aquatic environments, are expected to be responsible for half of photosynthesis in the planet. The carbon dioxide (CO_2) uptake rate of microalgae is at least 10 times faster than that of terrestrial plants[3,4]. Superiority to exploiting CO_2 from microalgae compared to terrestrial plants results from their simple structures with no vascular system by direct uptake of nutrient components such as nitrogen and phosphorus, so called photoautotroph. Recent findings regarding potential advantages of microalgae have opened new field of applications to carbon neutrality, wastewater treatment and general purpose products[5-7].

The initial application of microalgae was focused on the production of renewable biofuels such as biodiesel and bioethanol. In the biofuel industry, microalgae are emerged as a candidate source for biofuels to overcome existing technical and/or ethical issues associated with the utilization of grains (such as corn and sugar cane) and lignocellulosic biomass[8]. In recent years, microalgae application has been expanded to cosmetics, pharmaceuticals, and nutrient supplements[9,10]. One of the greatest advantages utilizing microalgae in industry lies on economic viability due to their massive and fast growth under harsh conditions in which oxygen and nutrients are insufficient[11,12]. Besides, high added value components from microalgae such as fatty acids and lipids are viable driven by advanced technology regarding extracting components from microalgae[13,14]. This enables to produce massive oil yield, substituting for preexisting crop industry to obtain oil[15]. Despite their expanded application, the size of the commercial market for microalgae has not increased significantly[16].

To obtain the valuable ingredients, which mainly exist intracellularly, complex downstream operations including coagulation, flocculation, solid-liquid separation, thickening, dewatering, drying, cell disruption, extraction, and purification are required after cultivation[17-19]. Among the above downstream operations, the drying consumes the largest energy to evaporate water contents from microalgal biomass[20]. Here we review research on drying techniques for the dehydration of microalgal biomass.

2. Drying techniques for microalgae

Microalgae, which are harvested and dewatered after cultivation, have a water content of roughly 85%. Drying removes water from microalgae to achieve generally a water content of 5%[21]. The process of culturing, harvesting, and drying microalgae is schematically presented in Figure 1. Low water activity by drying is critical to stabilize microalgal biomass by reducing the incidence of microbial and chemical decomposition. Heat transfer and water diffusion are key mechanisms to reduce the water content in microalgae during the drying

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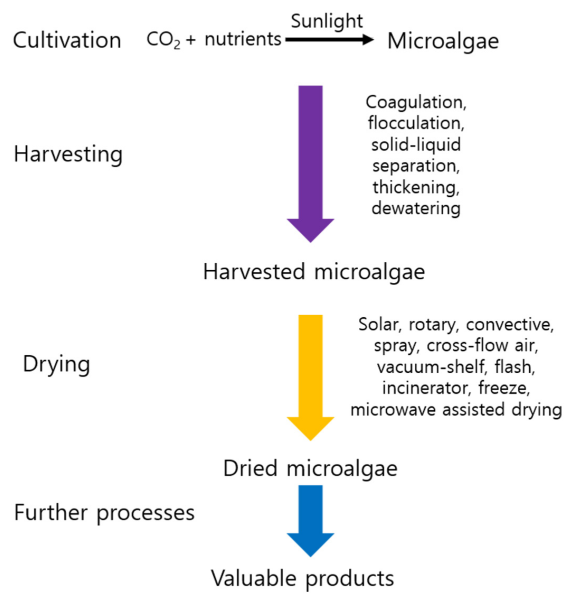

Figure 1. The schematic diagram of culturing, harvesting, and drying processes for microalgae.

process[22].

During drying, heat is necessary for water vaporization, and is provided via the contact of the microalgal biomass with a hot solid surface (conduction), hot gas (convection), or electromagnetic radiation (microwave). A vacuum is sometimes used in the drying processes to enhance the mass transfer of water. Because of the high level of latent heat of water vaporization, drying processes require large amounts of energy, accounting for 75% of the total cost for the downstream process, consisting of condensation, solid-liquid separation, concentration, dehydration, and drying[1,17,23]. It has also been reported that drying processes account for approximately 60% of the total costs of biofuel production from microalgae[24,25]. Additionally, it was reported that the thermal drying of microalgae requires up to an energy of 3556 kJ/kg[26,27]. As a result, the development of a cost-effective and efficient drying process is a prerequisite for the commercialization of microalgae-based products.

Solar drying, rotary drying, spray drying, cross-flow air drying, vacuum-shelf drying, flash drying, incinerator drying, freeze-drying, and convective drying are representative microalgal drying processes. A detailed description of the drying methods is as follows.

2.1. Solar drying

Drying techniques that utilize solar energy are eco-friendly and economical due to their intrinsic renewable properties and abundance. These techniques are typically categorized into direct and solar water heating methods. In direct sun radiation, the denaturation and discoloration of microalgae occur because of the dehydration and decomposition of the chlorophyll in microalgae. Despite its cost-effectiveness, this method mainly relies on weather conditions, and consistent controls are not possible, resulting in overheating, which restricts its industrial use. The solar water heating method has been developed as an alternative to direct sun radiation. This method involves the collection of solar heat energy to increase the temperature of water. The heated water works as an energy source to dry the microalgae. Compared to direct sun radiation, consistent controls are possible through the use of solar water heating, resulting in a high potential for usability. However, high capital costs are an important issue associated with this method [28-31].

In a report by Brink and Marx, an average harvesting yield of 47.3 kg / m^2 y (annualized weight per drying area, y: year) of dry weight microalgal biomass was recorded per square meter of drying area when a new harvesting method was applied by combining sand filtration and solar drying[28].

2.2. Rotary drying

Rotary drying involves the use of a sloped rotating cylinder, wherein heat transfer occurs between the heated cylinder surface and the microalgal biomass, followed by a downward movement due to gravity. Drum drying is a manner similar to rotary drying. Sterilization and cell disruption occur simultaneously in rotary drying, which is time-efficient. However, a major drawback of this method is the high levels of energy consumption required to operate the process[29,32]. Aziz et al. developed a steam tube rotary dryer based on heat circulation technology. Energy consumption was saved up to 90% for drying brown algae using steam recirculation, which is superior to conventional heat recovery drying from an economical perspective[33]. In their work, the principle of energy recovery performed through energy elevation and effective heat pairing for both sensible and latent heat was used to develop a heat circulating rotary dryer. Silva et al. used experimental and numerical analysis to evaluate how the air temperature, feed rate, rotation speed, and filling degree of the inert particles affected the yield of drying *Spirulina platensis* using a rotary dryer with an inert bed. They found that rotation speed and filling degree had a major impact on the performance of the rotary drying process[34].

2.3. Convective drying

Convective drying is a common method used to eliminate water from microalgae. Convective drying is typically performed by spreading the biomass into thin layers and supplying convective hot air in an oven, tray, or tunnel-type drier, leading to dehydration. Although the temperature and time applicable to this process are in the range of 20-60℃ and 18-48 h, a drying time of 24 h is generally used. The optimization of the drying temperature and the thickness of the biomass is important to obtain high-quality dried microalgae[35,36]. Viswanathan et al. conducted thin-layer drying of microalgal biomass consortium (*Chlorella minutissima*, *Chlamydomonas globosa*, and *Scenedesmus bijuga*) ruptured by French press, autoclave, and sonication methods at four drying temperatures (30, 50, 70, and 90°C) to analyze how cell rupture methods affect convective drying properties. In their study, it was confirmed that the drying speed and effective moisture diffusivity strongly depended on the drying temperature and rupture method[37].

2.4. Spray drying

Spray drying process consists of liquid atomization, gas/liquid droplet mixing, and drying operations. Using this method, a liquid droplet is sprayed downward in a perpendicular tower and comes into contact with a hot gas stream, which triggers drying. Advantages of this method include a quick drying time and a high efficiency. However, undesirable decomposition of valuable components can occur due to the disruption of the cell wall at high pressures by atomization. In addition, the operating costs are high, and the digestibility of the resulting dried microalgae is low[23,38-40]. Fasaei et al. reported that the amount of water evaporated by spray drying and drum drying reached 10000 kg water/h and 1000 kg water/h, respectively. Furthermore, drum dryers require more equipment to treat the same amount biomass as spray driers, increasing the capital and maintenance costs[21]. However, total costs, including capital, maintenance, and operating costs, for both processes are almost identical (0.5 €/kg dried algae) because of the relatively lower energy consumption of drum dryers (0.9 kWh/kg evaporated water) compared to spray dryers (1.09 kWh/kg evaporated water)[21,41]. Although spray drying is more cost-inefficient, the structure of dried microalgal biomass obtained using the spray dryer is superior, as it has individual blocs of spheres with thousands of microalgae[42]. The processes of spray drying and oil extraction of microalgae were intensified by vapor recompression, wherein heat integration was developed to reduce the energy cost (52.4%), the capital cost (22.6%), and the operation cost (81.0%)[43].

2.5. Cross-flow air drying

Cross-flow air drying is a method for drying microalgal biomass using the cross-flow of hot air with a compartment dryer. This method has a higher efficiency than solar heat drying, and a higher cost performance compared to drum drying. Despite its relatively low cost and high efficiency, the high energy cost associated with this method hinders its general use[29,44]. According to a study on *Spirulina* algae, dried microalgae with high dispersity and a water content of 4~8% were obtained by drying algae with 55~66% water using hot air at 62°C for 14 h[45].

2.6. Vacuum-shelf drying

Vacuum-shelf drying is a method used to obtain a high drying efficiency at relatively low temperatures. It is widely applied to the drying of algae for food as it prevents the oxidization of sensitive products, which occurs frequently when using other drying processes[46,47]. In a study on *Spirulina* algae, porous-type dried microalgae with a water content of 4% were produced using a vacuum shelf dryer at 50~65℃ under low pressure (0.06 atm)[45]. Vacuum-shelf drying for *Arthrospira spirulina* has the advantage of maintaining high quality in foods by minimizing the oxidization of lipids and the loss of phycocyanin, comparing oven drying[46]. However, drawbacks of this method include high capital and operating costs, in spite of its high drying speed[29].

2.7. Flash drying

Flash drying, initially developed to dry sewage sludge, involves injecting a hot gas stream into a wet and dried algae mixture, thereby converting the water content in algae to a hot gas stream[48]. The economical efficacy of this method depends on how the hot gas is acquired. This method is considered to be the most efficient when waste hot gases are easily obtained as by-products during the production process. The speed of water content removal using this method is faster than that of other drying processes[23,38].

2.8. Incinerator drying

Incinerator drying is a drying method developed based on the application of multiple hearth incinerators, which are circular steel cylinders consisting of multiple hearths that serve to dry or incinerate sewage sludge. By adequately controlling the available heat that enters the incinerator, this method can be exclusively used for the drying of microalgae. Fluidized bed incinerators are a type of incinerator dryer that is used to incinerate sludge. For the uniform drying of algae, a fluidized sand bed should be used in this method. After drying, the algae are separated from sand using a cyclone separator. The processes are complex and require high capital costs, to the detriment of the industrial application of this method[29].

2.9. Freeze-drying

In the food and feed industries, freeze-drying is widely used as a commercially available drying method to preserve high-quality algal biomass. This method consists of two steps: (1) freezing biomass and transportation to the vacuum chamber and (2) sublimation of water by radiative or conductive heating[49]. In freeze-drying, the protein in cells can be extracted by using the freeze-thaw cycles since the expansion of intracellular water by freezing damages the cell wall. As a result, this method can be used to simultaneously induce cell disruption and drying[50,51]. Microalgae that have been dried by freeze-drying typically have a sheet type structure where the biomass is linearly attached[42]. This method is useful in food drying as it preserves bioactive ingredients that are easily decomposed by heat and oxygen. However, its high capital and operating costs, loss of performance in commercial large-scale processes, and the long time required for complete drying are the main drawbacks of this method[49,52].

2.10. Microwave assisted drying

Microwave assisted drying is typically used to dry fruit slices due to its fast drying capacity by an efficient heat distribution[24]. The microwave frequencies that are mainly used to dry agricultural products are 915 MHz and 2.45 GHz. Using this method, water evaporation occurs due to heat induced by the friction between water molecules and microwave energy absorbed by water[53]. One of applications of microwaves to the treatment of microalgae is microwave assistance for oil extraction process from microalgae including *Chlorella vulgaris, Botryococcuc sp., Scenedesmus sp.,* and *Nannochloropsis sp.*[13,53,54]. According to the analysis of the microwave assisted drying experiment by Villagracia et al., who studied the irradiation of *Chlorella vulgaris* using 2.45 GHz of microwave frequencies with different powers, the time required to dry microalgae using this method is shorter than that

Table 1. Summary of Applicable Microalgae Drying Methods

Drying method	Principle	Pros	Cons
Solar drying	Direct solar radiation or solar water heating	Low energy cost	Slow operation, sensitive to weather, texture and color change, overheating
Rotary drying	Rotating hot cylinder surface	Fast operation, sterilization and disruption	High energy cost, biomass degradation
Convective drying	Heating by hot air	Practically useful	Biomass degradation
Spray drying	High pressure automization, Liquid droplet in contact with hot gases	fast and efficient drying, high valuable product	High energy cost, low digestibility
Cross-flow air drying	Contacting wet biomass slurry with cross-flow hot air	superior cost performance, fast drying	High energy cost
Vacuum shelf drying	Heating in vacuum shelf dryer	Fast and efficient	High capital and operating cost
Flash drying	Wet and dried algae mixture injected into hot gas	Fast drying	Sensitive to hot gas source and quality
Incinerator drying	Multiple hearth incinerator, fluidized bed incinerator	Fast, powdered dry mass	Complex process, high capital cost
Freeze drying	Warm surface heat frozen biomass	High quality biomass, simultaneous disruption	Slow, high capital cost, High cost for large scale
Microwave-assisted drying	Electromagnetic radiation	Fast, high controllable	High capital cost, safety concerns

of other drying methods, and a minimum of 20 W/g of power is required to dry *Chlorella vulgaris* with a moisture content of 42.5%[24].

2.11. Summary of drying techniques

The properties, benefits, and drawbacks of the microalgae drying processes mentioned above are summarized in Table 1. Methods belonging to rotary, spray, vacuum shelf, flash and incinerator drying take advantage of time-efficiency, enabling fast process while high capital costs are major concern. On the other hand, economically viable methods such as solar and cross flow air drying are timely inefficient. Despite high potentials of microalgae, coexistence of pros and cons for each drying method is an obstacle to compete with other industries. Uniform and homogeneous products using microwave-based drying method enables homogeneous volumetric heating, increasing drying efficiency[55-57]. However, immature technology owing to short history limits massive amounts of production, making it difficult to be applied in industry. Facing the 4th industrial revolution, fusion of experimental and simulation modelling by analyzing drying kinetics of microalgae has also been conducted recently[58,59]. The combination of modeling and advanced technology might be the breakthrough for high barrier to market entry associated with microalgae drying.

3. Conclusion

A variety of drying techniques, namely solar drying, rotary drying, convective drying, spray drying, cross-flow air drying, vacuum-shelf drying, flash drying, incinerator drying, freeze-drying, and microwave-assisted drying, were reviewed in terms of their advantages and disadvantages for the production of dried microalgal biomass. Drying is an operation that uses the most energy among the downstream processes for the industrial utilization of cultured microalgae, so the technology should be developed considering both drying efficiency and energy consumption. Recently, various utilization methods, such as extracting valuable metabolites from biomass or utilizing the entire dried biomass as a source material for producing biomass-based products, after drying microalgae have been developed. Therefore, we expect that drying techniques should be developed suitable for the purpose of final application of microalgal biomasses.

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