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Challenges for greening Spirulina value chain in terms of freshwater input – a case study

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To promote a shift towards more sustainable food productions greener approaches should be put in place. When it comes to process sustainability, one of the most important elements is water management. Water is surely the key to food security but, concurrently, food productions themselves must try to adopt all tolerable changes to achieve an increasingly positive water balance. The attention was focused on the optimization of Spirulina (*Arthrospira platensis*) production. The case study was BioSpira Srl, a start-up located in Alvignano (Caserta, Italy). An inventory assessment was carried out to take a snapshot of the current situation.

To estimate the freshwater consumption, the chain summation approach was followed. Then, in order to conduct a structured strategic planning targeting process optimisation and environmental sustainability, the SWOT analysis (or SWOT matrix) was applied to identify the Strengths, Weaknesses, Opportunities, and Threats related to the production chain of Spirulina intended for human consumption.

1. Introduction

As a consequence of the increasing world population and, hence, of the increasing food demand, the main objective of food production chains is more than ever obtaining the highest yields with the lowest environmental impact. Alternative and sustainable sources of proteins are, therefore, being investigated.

Spirulina (*Arthrospira platensis*), a blue-green coil shaped cyanobacterium, is known in the food and nutraceutical sectors as an important source of proteins, antioxidants, vitamins and minerals (Grosshagauer et al., 2020). In particular, due to its high protein concentration providing all the essential amino acids, Spirulina has received more and more attention as a ‘superfood’ suitable against protein-energy-malnutrition and protein-energy-wasting (Siva Kiran et al., 2015). Consequently, in the last decades, a number of start-up and small-medium enterprises conducted an investment boom right focusing on microalgae cultivation.

Spirulina requires less land and less water than any other animal or vegetable protein source with a high yield per unit area, it can help cutting greenhouse gas emissions due to its CO_2 fixation capability and, moreover, the entirety of the harvested microalgae biomass can be used as food ingredient or food supplement. These are the reasons why it gained the reputation of a sustainable and eco-friendly microalga.

The prominence of sustainability is already the main distinctive feature of Spirulina value chain, however, there is still space for its greening. Along the entire chain, water is the most abundant natural resource that is consumed (Usher et al., 2014). Indeed, it is the necessary medium for Spirulina to remain in suspension and grow. The microalgae itself, differently from terrestrial crops, do not actively evaporate water through evapotranspiration, and, therefore, water losses are limited to evaporative losses from the open raceway ponds surface, biomass-bound water and water used in biomass processing (Costa et al., 2019).

Worldwide water scarcity, the lack of sufficient available freshwater resources to meet water demand, is affecting billions of people. Water is surely the key to food security but, concurrently, food productions themselves must try to adopt all tolerable changes to achieve a more and more positive water balance.

Indeed, concerning the specific Spirulina production case study, special attention was paid with regards to freshwater consumption along the entire chain. Then, in order to conduct a structured strategic planning targeting environmental sustainability, the SWOT analysis (or SWOT matrix) was applied to identify Strengths, Weaknesses, Opportunities, and Threats related to the entire production chain of Spirulina intended for human consumption. As reported in the present paper, several aspects were carefully accounted and evaluated to put water into judicious use and to help the company increasing its environmental and economic sustainability.

The aim of the paper is to propose a systemic approach to give a full survey over Spirulina production chain, in order to draw up an individual blueprint for sustainable development.

2. Materials and Method

2.1 The case study

The start-up under study, BioSpira Srl, is located in Alvignano (Caserta, Italy). The company focuses on Spirulina cultivation for food and nutraceutical purposes. Through on site visits and interviews to the plant owners, a careful, in-depth study of the Spirulina production chain was the first step of the process analysis. The entire process was subdivided in macro-areas and sub-stages.

2.2 Water consumption analysis

Special attention was paid with regards to freshwater consumption along the entire chain. The chain summation approach was followed (Hoekstra et al., 2011). The freshwater consumption (WC) of the product p (Spirulina) was calculated using the following Eq(1):

$$\mathrm{WC}\ (\mathrm{p}) = \left(\sum_{s=1}^{k} WC(s)\right)/P(p) \qquad [\mathrm{m}^3/\mathrm{KgDM}] \qquad (1)$$

Where WC(s) is the freshwater consumption of production phase s [m^3/y], and P(p) is the Spirulina production quantity on a yearly basis [KgDM/y].

2.3 SWOT analysis

In order to conduct a structured strategic planning, the SWOT analysis (or SWOT matrix) was applied to identify the Strengths, Weaknesses, Opportunities, and Threats related to the production chain of Spirulina intended for human consumption. SWOT allows to identify and categorize in a 2x2 matrix the internal factors (strengths and weaknesses) and the external factors (opportunities and threats) typical of the subject that is analysed (Falcone et al., 2020). The definition of the different points was based on a literature review and on structured interviews to the founders of the start-up. Following the circular economy principles, solutions were suggested in the attempt to optimize the Spirulina production chain within the company. A hypothetical optimisation plan was designed.

3. Results

3.1 Spirulina production chain and water fluxes

The overall process was mapped in detail and divided into four main areas: cultivation, harvesting, drying and packaging; some are characterised by their own sub-phases as schematised in Figure 1.

The company uses 4 raceway ponds sized from 1’500 to 15’000 Litres filled with a modified Zarrouk medium for the commercial cultivation of Spirulina. The water bed is 25 cm high and the overall surface is 120 m^2. All raceway ponds are located within a greenhouse covered with a transparent plastic sheet. Consequently, the light source is solely the direct sunlight in respect of the microalgae biological cycle. In the absence of forced heating and lightning, which may cause an accumulation of sulphur dioxide, the organoleptic properties of Spirulina are preserved.

Harvesting is carried out with a vibrating sieve equipped with a 40 µm filter. The biomass, then, is put within cotton bags and pressed using a steel press for 2 h to eliminate the excess of water. Finally, the biomass is extruded in the shape of sticks. The amount which can not go through the extruder is recovered and spread in thin layers and, together with sticks, is dried at 40°C for 8-10 h. Part of the dry sticks is then grinded into powder.

Spirulina in sticks, chips and powder formats is manually packed and commercialised within paper bags characterised by an aluminium thin inner layer. The company sells part of the Spirulina powder to a local pharmacy that encapsulates it and packs the capsules within plastic bottles.

The quantity of harvested biomass per day is, on average, 0.5 KgDM, considering a maximum yield of 1 KgDM/day during the summer period and a harvesting stop-over between January and February. The typical protein content yield within the harvested biomass is equal to 60%w/w.

Along the entire process, different are the water flows which can be accounted at each stage (Figure 1).

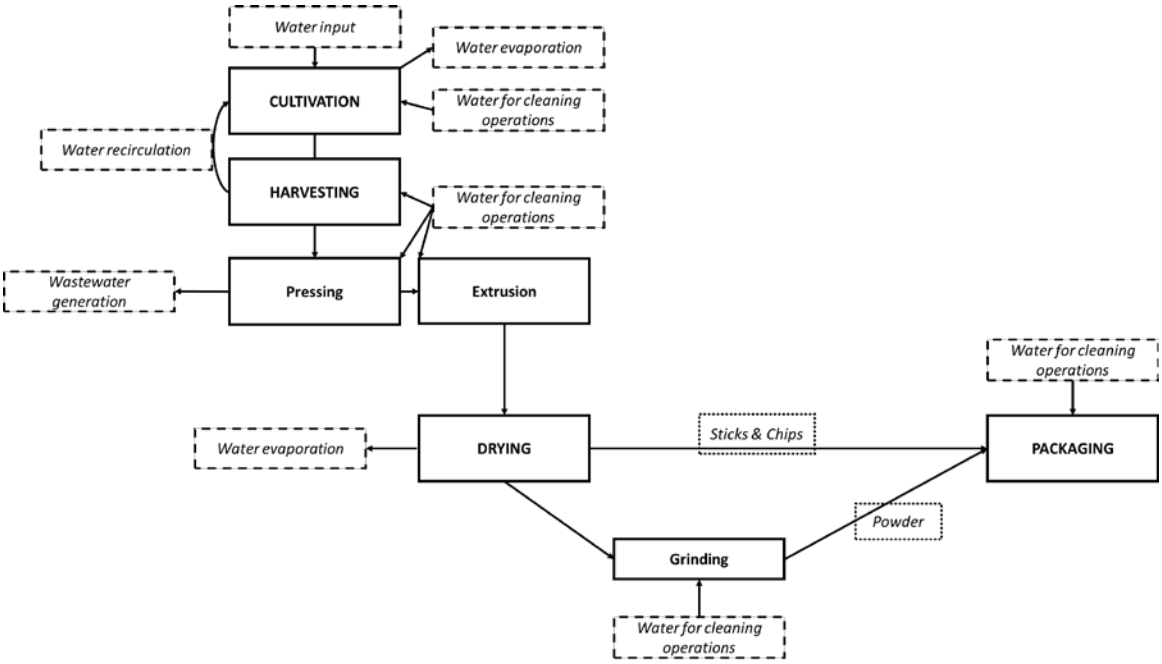

Figure 1: Spirulina production chain diagram: main process areas (capital letters) and sub phases (lowercase). Water fluxes (italics) are also included.

The initial freshwater input at time zero within all ponds is 29 m^3. 2 m^3 of water medium are renewed every month to enable an always sufficient amount of macro and micro nutrients for the Spirulina to grow.

Water evaporation from the ponds highly varies during the year according to the climatic conditions. On average, it can be said that water losses through evaporation ranges between 0.3 m^3 per day during the summer period and 0.1 m^3 per day during winter. This means that, on average, 50 m^3/y of water evaporated from raceway ponds, and therefore replaced within them, can be accounted.

For cleaning and cooling operations on the greenhouse itself 10-15 m^3/y of freshwater are used. Water recirculation to the raceway ponds during the harvesting is essential for saving 225 m^3/y. Indeed, on a yearly basis, harvesting is carried out 250 times. Each of them implies a 0.9 m^3 water removal from the raceway ponds. Harvesting, pressing and extrusion operations imply the use of 2 m^3/y of freshwater for cleaning activities. The resulting wastewater, together with the wastewater generated during pressing operations (20 m^3/y), is not recovered. The harvested, pressed and extruded biomass is wet and during the drying step 3.5 m^3/y of water are removed. Finally, the last water flows within the Spirulina production chain are those related to the cleaning operations at the grinding and packaging steps. The resulting wastewater, equal to 2 m^3/y, is sent to an Imhoff tank (Lgs. D. 152/06) together with the same amount from the cleaning activities during harvesting, pressing and extrusion, with the 20 m^3/y generated during pressing and with the 24 m^3/y of water medium that is renewed. Water flows amounts are summarised in Table 1.

On a yearly basis, approximately 0.8 m^3 of freshwater are used per Kg of dry biomass.

Table 1: Amount of water consumption, losses and saving at each step of the Spirulina production chain. At time zero, the freshwater used to fill all the raceway ponds is 29 m^3

Operation	Water consumption	Water losses	Water saving	m^3/y	$m^3/KgDM$
Cultivation	Medium renewal			24	0.13
		Evaporation		50	0.27
	Cleaning and cooling operations			10-15	0.05-0.08
Harvesting			Recirculation	225	1.23
Harvesting + Pressing + Extrusion	Cleaning operations			2	0.01
Pressing		Wastewater		20	0.11
Drying		Evaporation		3.5	0.02
Grinding + Packaging	Cleaning operations			2	0.01

3.2 SWOT outputs

In order to conduct a structured strategic planning, the SWOT analysis was applied to identify the strengths, weaknesses, opportunities, and threats related to the production chain of Spirulina (Table 2).

Table 2: SWOT analysis outputs presented in consecutive 2x2 matrixes of the internal factors (strengths and weaknesses) and of the external factors (opportunities and threats) characterizing all the macro-areas of the production process of Spirulina intended for food consumption. Underlined points are water-related aspects

Cultivation in raceway ponds	
Strengths	Weaknesses
Low construction and operation costs. Easy cleaning and maintenance. Direct exposure to sunlight. Low accumulation of dissolved oxygen.	Dependence on local climatic conditions. High water evaporation rate. Uncertain optimum of culture depth, rate of mixing, and algal population density. Freshwater water use for cleaning and cooling operations concerning the greenhouse. No replaced water medium recovery (2 m^3/month).
Opportunities	Threats
Rainwater used for cleaning and cooling operations. Use of closed system (photo-bioreactor) to enable: • higher control of the cultivation conditions; • higher photosynthetic efficiency and productivity of the biomass; • lower installation area, water evaporation rate, higher CO_2 fixation rate, and risks of contamination with other microorganisms.	Susceptibility to contamination by other microorganisms. Higher photo-bioreactor construction and operation costs.
Harvesting, Pressing and Extrusion	
Strengths	Weaknesses
Water recirculation. High performance vibrating screen.	Filament breakage during filtration process. No washing water recovery after cleaning operations. Water losses during pressing. Limited steel press capacity.
Opportunities	Threats
BAT to achieve an efficient water-biomass separation and increase water savings. Vibrating, negatively charged, patterned polysulfone membranes (Zhao et al., 2021). Pressing automation. Hydraulic press.	Bacterial contamination. Slower effect of the hydraulic press.
Drying	
Strengths	Weaknesses
It enables to reach a moisture content around 3–6% necessary to extend Spirulina shelf-life. Thin layer drying renders protein loss minimal.	Long drying (8-10 h) could threaten the preservation of heat sensitive nutrients, such as pigments and certain enzymes.
Opportunities	Threats
Vacuum drying. Microwave drying. Vacuum-microwave drying.	High capital cost. High energy demand. The intensive water evaporation might exceed the capacity of the vacuum pump.
Grinding and Packaging	
Strengths	Weaknesses
Paper bags protect Spirulina (in stick, chips and powder formats) from light sources while the aluminium thin inner layer preserves the microalgae nutritional properties. Plastic bottles for the Spirulina in capsules enable to gain more attractiveness towards consumers.	Grinding equipment overheating which can alter Spirulina. Plastic waste generation. Cost. No washing water recovery after cleaning operations.
Opportunities	Threats
Grinding operated at a controlled temperature using an external unit to allow the cooling of the equipment. Eco-friendly packaging (e.g. bio-plastic). Packaging automation.	Oxygen penetration and consequent loss of carotenoids by oxidation. Selling Spirulina in capsules within paper/aluminium bags is not a good market option.

A major challenge lies in the harvesting of the microalgae, which requires the separation of a low amount of biomass consisting of small individual cells from a large volume of culture medium. Techniques include coagulation and flocculation, flotation, centrifugation and filtration or a combination of various techniques (Singh and Patidar, 2018). Flocculation is seen as a promising low-cost harvesting method despite its chemicals requirement, centrifugation is considered as the technique with the highest yield but even the highest cost, while filtration (which can be vacuum, pressure or membrane) is the most common among Italian Spirulina producers (Fasaei et al., 2018). Indeed, the company is currently using a vibrating screen characterised by a 40 µm mesh membrane. The installation of a second membrane with smaller mesh size would allow a greater recovery of fresh biomass during each harvesting operation. Recently, Zhao et al. (2021) published the enhanced harvesting performance using vibrating, negatively charged, patterned polysulfone membranes. In particular, higher membrane clean water permeance, higher critical flux, lower membrane intrinsic resistance and lower foulant resistance than a corresponding flat membrane were recognised (Zhao et al., 2021).

The drying process is another crucial point. Drying can be drum, spray or solar. Drum-drying is more adequate for preparing animal-grade algal biomass, while spray-drying is mostly indicated in those cases in which microalgae are intended for human consumption despite being more costly and more energy demanding. Solar drying is the cheapest but also the slowest and the weakest in terms of microbial contamination (Fasaei et al., 2018). Notwithstanding, spray-drying enables the production of dry powders from a fluid material, therefore, it would not be possible to use the same method for Spirulina sticks and chips. The company is now applying a convective hot air drying within a hot chamber at 40°C for 8-10 h which positive feature is the high capacity. However, other methods can be suggested in accordance with the company needs: vacuum drying and microwave drying. Vacuum drying, due to the low O_2 partial pressure, helps preserving the sample colour values, as well as the total phenolic content and antioxidant capacity; while microwave technology enables the reduction of drying time and the enhancement of the bioactive content (Ozcan-Sinir et al., 2019). An emerging technology is right the combination of the two operational units in a vacuum-microwave drying (Figiel and Michalska, 2017). On this purpose a cost and benefit analysis should be made to understand the operative cost implications of these two novel technologies compared with the conventional hot air-drying and the possible positive implications on the final product quality.

3.3 Optimisation plan

Considering the SWOT outputs and, in particular, the critical issues contained within, possible solutions were suggested by the analysts together with the company owners in order to solve or improve each specific issue as summarized in Table 3. The recommended future actions would enable the whole process to achieve a higher sustainability but also a higher productivity yield.

Table 3: Critical issues in citrus process and operative suggestions for a future improvement

Criticality	Ways to optimize
Dependence on local climatic conditions.	Introduction of an emergency light and heat sources.
High water evaporation rate.	Installation of a water vapour condenser.
Freshwater use for cleaning and cooling operations concerning the external part of the greenhouse.	Rainwater recovery and use for the external cleaning and cooling.
Uncertain optimum of culture depth, rate of mixing, and algal population density within the raceway ponds.	Sensors for on-line, in-situ measurement of both physicochemical and biological process variables.
Filtration process may introduce the risk of filament breakage and loss of biomass.	Addition of a second membrane on the vibrating screen for higher microalgae recovery. Consider the use of a vibrating, negatively charged, patterned polysulfone membrane.
No washing water recovery after in-door cleaning operations and no recovery of the monthly-replaced water medium.	Water use for irrigation.
Long drying could threaten the preservation of heat sensitive nutrients, such as pigments and certain enzymes.	Vacuum-microwave drying.
Plastic waste generation and packaging cost.	Mater-Bi bottles for selling Spirulina in capsules.

The most easily feasible and readily applicable solutions are surely the following:

- Rainwater recovery would enable a freshwater saving of 10-15 m^3/y;
- The highly alkaline water medium replaced every month from the ponds (2 m^3/month) and the wastewater coming from the pressing operations (20 m^3/y) could be diluted with the wastewater from in-door cleaning operations, tested for its chemical components and monitored during a trial irrigation operation. Several are, indeed, the farms and garden centres nearby the company site. It is well known that Spirulina may be an optimal source of bio-stimulants and bio-fertilisers for crops. Therefore, both the replaced water medium and the wastewater originated during pressing operations and after washing the equipment might be an optimal liquid fertiliser besides replacing 48 m^3/y of freshwater for crops irrigation;
- Addition of a second membrane on the vibrating screen for high-yield microalgae harvesting recovery might be an easy and cheap improvement. However, the great innovation that should be kept under control to see its market trends is the one concerning the vibrating, negatively charged, patterned polysulfone membranes.
- Mater-Bi is a biodegradable and compostable plastic. Mater-Bi bottles could be used to sell Spirulina in capsules after specific shelf-life tests to understand kinetics of microalgae deterioration when commercialised within that packaging material.

The overall amount of freshwater used per year along the Spirulina production chain is 145.2 m^3. If the above mentioned expedients in water management are put into place, the freshwater savings, directly or indirectly connected with the microalgae production, would be around 63 m^3/y (the 43% of the total freshwater input).

4. Conclusions

The crucial Spirulina processing steps in terms of equipment optimisation are harvesting and drying, while, when focusing on water savings, attention is drawn to the following issues. Water evaporation from the raceway ponds accounts for the majority of water losses (50 m^3/y). Water recirculation within the ponds enables saving around 225 m^3/y. Wastewater recovery for irrigation and rainwater collection for external cleaning and cooling operations would allow getting additional 63 m^3/y of freshwater saving.

These simple suggestions together with a cost and benefit analysis regarding the use of vibrating, negatively charged, patterned polysulfone membranes during the harvesting, a vacuum-microwave drying unit and the substitution of plastic bottles for Spirulina capsules commercialisation with Mater-Bi bottles might be a good starting point for the company to develop in a sustainable way and to improve its competitiveness. Such recommendations were shared with the company to establish a ranking of intervention priorities.

References

Costa J.A.V., Freitas B.C.B., Rosa G.M., Moraes L., Morais M.G., Mitchell B.G., 2019, Operational and economic aspects of Spirulina-based biorefinery, Bioresource Technology, 292, 121946.

Falcone P.M., Tani A., Tartiu V.E., Imbriani C., 2020, Towards a sustainable forest-based bioeconomy in Italy: Findings from a SWOT analysis, Forest Policy and Economics, 110, 101910.

Fasaei F., Bitter J.H., Slegers P.M., Van Boxtel A.J.B., 2018, Techno-economic evaluation of microalgae harvesting and dewatering systems, Algal Research, 31, 347-362.

Figiel A., Michalska A., 2017, Overall quality of fruits and vegetables products affected by the drying processes with the assistance of vacuum-microwaves, International Journal of Molecular Sciences, 18(1), 71.

Grosshagauer, S., Kraemer K., Somoza V., 2020, The True Value of Spirulina, Journal of Agricultural and Food Chemistry, 68(14), 4109-4115.

Hoekstra A.Y., Chapagain A.K., Aldaya M.M., Mekonnen, M.M., 2011, The water footprint assessment manual - setting the global standard, Earthscan, London - Washington, DC. ISBN: 978-1-84971-279-8.

Ozcan-Sinir G., Ozkan-Karabacak A., Tamer, C. E., Copur O. U., 2019, The effect of hot air, vacuum and microwave drying on drying characteristics, rehydration capacity, color, total phenolic content and antioxidant capacity of Kumquat (Citrus japonica), Food Science and Technology, 39(2), 475-484.

Singh G., Patidar S.K., 2018, Microalgae harvesting techniques: A review, Journal of environmental management, 217, 499-508.

Siva Kiran R.R., Madhu G. M., Satyanarayana S.V., 2015, Spirulina in combating protein energy malnutrition (PEM) and protein energy wasting (PEW)-A review, Journal of Nutrition Research, 3(1), 62-79.

Usher P.K., Ross A. B., Camargo-Valero M.A., Tomlin A.S., Gale W.F., 2014, An overview of the potential environmental impacts of large-scale microalgae cultivation, Biofuels, 5(3), 331-349.

Zhao Z., Liu B., Ilyas A., Vanierschot M., Muylaert K., Vankelecom I.F., 2021, Harvesting microalgae using vibrating, negatively charged, patterned polysulfone membranes, Journal of Membrane Science, 618, 118617.