



M 2022



OPTIMIZATION OF SPIRULINA SOLAR DRYING

COMPARISON WITH SPRAY DRYING

BEATRIZ ALEXANDRINA SIMÕES PEREIRA
MASTER THESIS IN CHEMICAL ENGINEERING
PRESENTED TO THE FACULTY OF ENGINEERING
OF THE UNIVERSITY OF PORTO

Master in Chemical Engineering

OPTIMIZATION OF SPIRULINA SOLAR DRYING

Master dissertation

of

Beatriz Alexandrina Simões Pereira

Developed within the course of dissertation

held in

Allmicroalgae / R&D unit



Supervisor at FEUP: **Manuel José Vieira Simões, PhD**

Supervisor at Allmicroalgae: **Helena Cardoso, PhD**

Specialist supervisor at Allmicroalgae: **Pedro Quelhas**



October 2022

Acknowledgment

I would like to start by thanking Professor Manuel Simões for suggesting Allmicroalgae for my thesis. Thank you for always being available to help and providing the support I needed.

To Quelhas, for being the most spectacular supervisor ever. This work was not easy at all, but you were always there to help me deal with all the problems. You are an inspiration to me and I hope that one day I can be as good an engineer as you are. You are a great leader and I still believe that one day you will be my boss.

To Helena, for the encouraging words, for lifting my spirits, and making sure that I would never give up.

To Eng. Luís Matos, for helping me with the rheological measurements performed at the Department of Chemical Engineering, and to Doctor Anabela Fernandes and Eng. Isabel Oliveira, for helping me with the contact angles measurements performed at the Biofilm Engineering Lab.

To the entire R&D team at Allmicroalgae, for being incredible teachers and always giving me constructive criticism on my work. A special thanks to Cátia for helping me on my assays and for making me feel heard.

A major thanks to my friends at Casa 70: Noémie, Lucas, Jorge, Inês, and Pedro. Noémie, thank you for being the best partner for spontaneous plans and providing emotional support when I needed it the most. Lucas, thank you for your patience, for your honest opinions and most of all thank you for your friendship. Jorge, thank you for always being down for every plan and for being a great example of balance, organization, and efficiency. Inês, I have never met a person as intelligent and kind as you. Thank you for sharing your knowledge and for guiding me in this very difficult work. Pedro, thank you for your stubbornness and your grumpiness. The few moments in which you gave me motivating words were very important to me.

To Magaida, Sofia, Rita, Gil, and Manel, the most extraordinary people in the entire world. I feel so privileged for being your friend. Thank you for always making me smile and making me feel loved. You will always be in my life no matter how far we might be from each other.

To Beatriz and Catarina, for being the best colleagues in the last 5 years. Thank you for not only being the best people to work with, but also for your friendship.

To Leonor, Inês, Cat, Toni, and Tiago, for all the fun moments in Lisbon and Viseu. Growing up with you has been amazing.

To my grandmother, for paying for all my education and helping me to be the first person in my family with a college degree. To Beta and Rogério, for treating me like a daughter and teaching me so much about life. Your unconditional love and support were really important. You will always be family to me. To my father, for giving the best advice and for always being able to comfort me. To my mother, for all the sacrifices she made for me and for encouraging me to do what makes me happy, no matter how crazy it seems.

Abstract

In recent years, the industrial production of microalgae has increased to respond to the expanding market demand in the areas of nutrition, pharmacy, cosmetics, and biofuels. Spirulina, the commercial name of *Arthrospira platensis*, is the dominant species and it is characterized by a high content of protein and phycocyanin. Due to the high perishability of this product after harvesting, an efficient drying process is required for proper preservation. Since drying is often the downstream unit operation that entails the highest cost due to high energy consumption, indirect solar drying has emerged as an alternative to conventional drying strategies, namely spray drying. The present study aimed to optimize the drying process of Spirulina in a solar dryer and compare its performance with spray drying.

The solar dryer included a drying chamber, two solar collectors, inlet and outlet ventilation ducts, temperature and humidity sensors, a heater, a dehumidifier, and a fan. To improve air distribution, an extra fan was placed and it was assessed how the moisture content of the biomass was affected in various places of the drying chamber. The optimum drying time was determined and compared with the drying time before optimization. A study of the impact of load, tray filling, initial moisture content of the paste, and weather conditions on drying time, final moisture content, and specific energy consumption was performed. The optimum drying temperature of Spirulina in the spray dryer was assessed and the performance of both dryers was compared in terms of specific energy consumption, production capacity, protein and phycocyanin contents.

Before optimization, drying cycles had a duration of approximately 17 hours, which was decreased to 7.9 ± 2.9 hours. Air homogenization in the drying chamber was also improved by the second fan. Drying performance was optimal for medium and high loads (76-99 and 105-125 kg of wet biomass, respectively), for an amount of wet biomass per m^2 of tray between 0.64 and 0.92 kg m^{-2} and with a moisture content below $82 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$. Outdoor temperature, humidity, and solar irradiance did not influence specific energy consumption. The ideal drying temperature of Spirulina in the spray dryer was 80°C . Spray drying involved a specific energy consumption 5.5 times higher and a production capacity 4.4 times higher than solar drying. Solar drying led to a lower protein loss (16 % in comparison to 35 %) and a lower phycocyanin loss (11 % in comparison to 37 %). The estimated payback time was 2 years for the solar dryer and 5 years for the spray dryer. Solar drying was considered a more suitable strategy to dry Spirulina on an industrial scale.

Keywords: solar drying, spray drying, Spirulina, protein, phycocyanin, energy consumption

Resumo

Nos últimos anos, a produção industrial de microalgas tem aumentado para responder à crescente procura nos mercados de nutrição, farmacêutica, cosméticos e biocombustíveis. A Spirulina, nome comercial de *Arthrospira platensis*, é a espécie dominante e é caracterizada por um alto teor em proteína e ficocianina. Devido à alta perecibilidade deste produto após a colheita, é necessário um processo de secagem eficiente para a sua conservação adequada. Uma vez que a secagem é frequentemente a operação unitária de processamento que acarreta o maior custo devido ao elevado consumo de energia, a secagem solar indireta tem surgido como uma alternativa às estratégias de secagem convencionais, nomeadamente à secagem por atomização. O presente estudo teve como objetivo otimizar o processo de secagem da Spirulina num secador solar e comparar o seu desempenho com um secador por atomização.

O secador solar incluiu a câmara de secagem, dois coletores solares, dutos de ventilação de entrada e saída, sensores de temperatura e humidade, um aquecedor, um desumidificador e um ventilador. Para melhorar a distribuição do ar, um ventilador adicional foi colocado e avaliou-se a forma como o teor de humidade da biomassa foi afetado em vários locais da câmara de secagem. O tempo de secagem ótimo foi determinado e comparado com o tempo de secagem antes da otimização. Estudou-se o impacto da carga, enchimento de tabuleiros, teor de humidade inicial da pasta e condições climáticas no tempo de secagem, teor de humidade final e consumo energético específico. A temperatura ótima de secagem da Spirulina no secador por atomização foi avaliada e o desempenho de ambos os secadores foi comparado em termos de consumo energético específico, capacidade de produção, teor de proteína e ficocianina.

Antes da otimização, os ciclos de secagem tinham uma duração de aproximadamente 17 horas, que foi reduzida para $7,9 \pm 2,9$ horas. A homogeneização do ar na câmara de secagem também foi melhorada pelo segundo ventilador. O desempenho de secagem foi ótimo para cargas médias e altas (76-99 e 105-125 kg de biomassa húmida, respetivamente), para uma quantidade de biomassa húmida por m² de tabuleiro entre 0,64 e 0,92 kg m⁻² e com teor de humidade abaixo de $82 \frac{\text{g}_{\text{água}}}{100 \text{ g}_{\text{amostra}}}$. A temperatura ambiente, humidade e radiação solar não influenciaram o consumo energético específico. A temperatura ideal de secagem da Spirulina no secador por atomização foi de 80 °C. A secagem por atomização envolveu um consumo energético específico 5,5 vezes superior e uma capacidade de produção 4,4 vezes superior à secagem solar. A secagem solar levou a uma menor perda de proteína (16 % em comparação a 35 %) e a uma menor perda de ficocianina (11 % em comparação a 37 %). O tempo de retorno estimado foi de 2 anos para o secador solar e 5 anos para o secador por atomização. A secagem solar foi considerada a estratégia mais adequada para secar a Spirulina à escala industrial.

Palavras-chave: secagem solar, secagem por atomização, Spirulina, proteína, ficocianina, consumo energético

Declaration

I hereby declare, under the word of honor, that this work is original and that all non-original contributions are indicated and due reference is given to the author and source

Beatriz A.S. Pereira

26/09/2022

Index

1	Introduction.....	1
1.1	Framing and presentation of the work	1
1.2	Presentation of the company	1
1.3	Contribution of the author to the work	2
1.4	Organization of the dissertation	2
2	Context and State of the art.....	3
2.1	Importance of microalgae and global market.....	3
2.2	Cultivation and harvesting of microalgae	4
2.2.1	Coagulation and flocculation	5
2.2.2	Sedimentation	6
2.2.3	Centrifugation	6
2.2.4	Filtration and sieving	6
2.2.5	Pressing.....	7
2.3	Drying process and different drying technologies	7
2.3.1	Spray drying	8
2.3.2	Freeze-drying.....	9
2.3.3	Rotary drum drying	9
2.3.4	Convective drying, sun drying, and solar drying.....	9
2.4	Factors that influence the drying process	10
3	Materials and Methods	13
3.1	Spirulina cultivation, harvesting and processing.....	13
3.2	Solar drying	13
3.3	Placement of a second fan	14
3.4	Influence of operation variables on response variables	14
3.5	Influence of weather conditions on energy consumption.....	15
3.6	Assessment of optimum drying time	15
3.7	Spray drying optimization assay	15

3.8	Quantification of moisture content	16
3.9	Quantification of phycocyanin content	16
3.10	Quantification of protein content	16
3.11	Energy consumption	17
3.12	Payback time	18
3.13	Statistical analyses.....	19
4	Results and Discussion	21
4.1	Spirulina harvesting and processing	21
4.2	Optimization of solar drying	21
4.2.1	Placement of a second fan	22
4.2.2	Influence of operation variables on response variables	24
4.2.3	Influence of weather conditions on energy consumption	30
4.2.4	Assessment of optimum drying time	33
4.3	Optimization of spray drying	35
4.4	Comparison between solar drying and spray drying.....	37
5	Conclusions	43
6	Assessment of the work done	45
6.1	Objectives achieved and future perspectives	45
6.2	Final assessment	46
7	References	47
Appendix A. Behavior of the organic biomass.....		I
A.1	Problem Presentation	I
A.2	Materials and Methods	II
A.2.1	Microscopic observations of exopolysaccharides	II
A.2.2	Enzymatic and alkaline treatments	II
A.2.3	Adhesive interactions	II
A.2.4	Rheology	III
A.3	Results and Discussion	IV
A.3.1	Microscopic observations of exopolysaccharides	IV

A.3.2	Enzymatic and alkaline treatments	V
A.3.3	Adhesive interactions	VII
A.3.4	Rheology	VIII
Appendix B. Mass and energy balances.....		XIII
B.1.	Drying time.....	XIII
B.2.	Efficiencies.....	XIV
Appendix C. Weather conditions		XV

List of Figures

Figure 1 Typical drying curve (adapted from Babu et al. 2018).	8
Figure 2 BLACK BLOCK solar dryer (Block, 2020).	13
Figure 3 Solar dryer drawing in Ansys DesignModeler: a) back view with identification of equipment (dehumidifier, heater, and fan 1); b) isometric view with trolley numbering and identification of fan 2.	22
Figure 4 Color maps of the variation of moisture content, ΔMC , on top, middle and bottom trays on 9 trolleys: a) trolleys 1-3; b) trolleys 4-6; c) trolleys 7-9.	23
Figure 5 Influence of load (total mass of wet biomass in the dryer), W (kg), on drying time, t_{drying} (h); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).	24
Figure 6 Influence of load (total mass of wet biomass in the dryer), W (kg), on final moisture content, MC_{final} ($g_{water} 100 g_{sample}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).	25
Figure 7 Influence of load (total mass of wet biomass in the dryer), W (kg), on specific energy consumption, $E_{consumption}$ ($kWh kg_{dry microalgae}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$).	26
Figure 8 Influence of tray filling (mass of wet biomass per m^2 of tray), F ($kg m^{-2}$), on drying time, t_{drying} (h); values are given as mean $\pm$ standard deviation; *: significant difference between the groups ($0.01 < p < 0.05$).	27
Figure 9 Influence of tray filling (mass of wet biomass per m^2 of tray), F ($kg m^{-2}$), on final moisture content, MC_{final} ($g_{water} 100 g_{sample}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).	27
Figure 10 Influence of tray filling (mass of wet biomass per m^2 of tray), F ($kg m^{-2}$), on specific energy consumption, $E_{consumption}$ ($kWh kg_{dry microalgae}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).	28
Figure 11 Influence of initial moisture content, $MC_{initial}$ ($g_{water} 100 g_{sample}^{-1}$), on drying time, t_{drying} (h); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$).	29
Figure 12 Influence of initial moisture content, $MC_{initial}$ ($g_{water} 100 g_{sample}^{-1}$), on specific energy consumption, $E_{consumption}$ ($kWh kg_{dry microalgae}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); ***: extremely significant differences between the groups ($0.0001 < p < 0.001$).	29

Figure 13 Linear relationship between initial moisture content, $MC_{initial}$ ($g_{water} 100 g_{sample}^{-1}$), and final moisture content, MC_{final} ($g_{water} 100 g_{sample}^{-1}$).....	30
Figure 14 Influence of outdoor temperature, T_{out} ($^{\circ}C$), on specific energy consumption $E_{consumption}$ ($kWh kg_{dry microalgae}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).....	31
Figure 15 Influence of outdoor relative humidity, RH_{out} (%), on specific energy consumption $E_{consumption}$ ($kWh kg_{dry microalgae}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).	31
Figure 16 Influence of solar irradiance, I_{out} ($W m^{-2}$), on specific energy consumption $E_{consumption}$ ($kWh kg_{dry microalgae}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).....	32
Figure 17 Representation of moisture content, MC (purple), protein content, [Protein] (orange), and phycocyanin content, [Phycocyanin] (blue), along time, during the 1 st (●), 11 th (■), 12 th (▲) and 13 th (▼) of July of 2022. The purple continuous line marks the maximum moisture content the final product can have ($7 g_{water} 100 g_{sample}^{-1}$).	33
Figure 18 Protein content, [Protein] ($g_{protein} 100 g_{dry microalgae}^{-1}$), of spray dried Spirulina at drying temperatures, T_{drying} ($^{\circ}C$), of 60, 70, 80 and 90 $^{\circ}C$; values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); **: very significant differences between the groups ($0.001 < p < 0.01$); ***: extremely significant differences between the groups ($0.0001 < p < 0.001$).	35
Figure 19 Phycocyanin content, [Phycocyanin] ($g_{phycocyanin} 100 g_{dry microalgae}^{-1}$), of spray dried Spirulina at drying temperatures, T_{drying} ($^{\circ}C$), of 60, 70, 80 and 90 $^{\circ}C$; values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$); **: very significant differences between the groups ($0.001 < p < 0.01$).	36
Figure 20 Final moisture content, MC_{final} ($g_{water} 100 g_{sample}^{-1}$), of spray dried Spirulina at drying temperatures, T_{drying} ($^{\circ}C$), of 60, 70, 80 and 90 $^{\circ}C$; values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$); **: very significant differences between the groups ($0.001 < p < 0.01$).	36
Figure 21 Comparison of specific energy consumption, $E_{consumption}$ ($kWh kg_{dry microalgae}^{-1}$), in the solar dryer and in the spray dryer; values are given as mean $\pm$ standard deviation; ****: extremely significant differences between the groups ($p < 0.0001$).	37
Figure 22 Comparison of production capacity, PC ($kg_{dry microalgae} h^{-1}$), in the solar dryer and in the spray dryer; values are given as mean $\pm$ standard deviation; ****: extremely significant differences between the groups ($p < 0.0001$).	38
Figure 23 Comparison of protein content, [Protein] ($g_{protein} 100 g_{dry microalgae}^{-1}$), in the solar dryer and in the spray dryer; values are given as mean $\pm$ standard deviation; ****: extremely significant differences between the groups ($p < 0.0001$).....	39

Figure 24 Comparison of phycocyanin content, [Phycocyanin] ($\text{g}_{\text{phycocyanin}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$), in the solar dryer and in the spray dryer; values are given as mean $\pm$ standard deviation; ****: extremely significant differences between the groups ($p < 0.0001$).	39
Figure 25 Description of total product cost associated with solar drying.	40
Figure 26 Description of total product cost associated with spray drying.	40
Figure 27 Accumulated cash flow in 10 years considering the use of the solar dryer (left) and spray dryer (right).	41
Figure A1 Spirulina biomass displays different behaviors upon extrusion onto a stainless steel tray: a) organic biomass; b) non-organic biomass.	I
Figure A2 Microscopic observations of a) organic concentrate, b) organic filtrate, c) non-organic concentrate, and d) non-organic filtrate of Spirulina cells stained with Alcian blue.	V
Figure A3 Microscope observations of Spirulina paste after treatment with a) Glucan, b) Prozym, c) Vintage, and d) NaOH.	VI
Figure A4 Flow curves for organic biomass, before (Org1) and after pressing (Org2), and non-organic biomass, before (NOrg1) and after pressing (NOrg2). Both axes are presented in logarithmic scale and curves are accompanied by error bars ($n=3$).	IX
Figure A5 Viscosity curves of organic biomass, before (Org1) and after pressing (Org2), and non-organic biomass, before (NOrg1) and after pressing (NOrg2). Both axes are presented in logarithmic scale and curves are accompanied by error bars ($n=3$).	IX
Figure A6 Amplitude sweep test results illustrating the variation of the storage modulus (G') and loss modulus (G'') with shear stress (τ) for the organic (Org) and non-organic (NOrg) biomass and identification of the yield points (τ_y) and crossover points (τ_f). Both axes are presented in logarithmic scale and curves are accompanied by error bars ($n=2$).	X
Figure C1 Solar irradiance (orange), air humidity (blue) and air temperature (red) measured by the Watchdog Weather Station at Allmicroalgae's premises, during a drying cycle from 30 th June to 1 st July.	XV

List of Tables

<i>Table 1 Classes of operation variables.</i>	<i>14</i>
<i>Table 2 Classes of weather variables.</i>	<i>15</i>
<i>Table A1 Surface energy components of water, bromonaphtalene, formamide, and 316 stainless steel (Jańczuk et al., 1993).</i>	<i>III</i>
<i>Table A2 Surface energy components of the organic and non-organic biomass.</i>	<i>VII</i>
<i>Table A3 Lifshitz-van der Waals (^{LW}) components, Lewis acid-base (^{AB}) components, respective interfacial free energies (^{Tot}) of paste-steel (_{sb}), steel-water (_{bw}), and paste-water (_{sw}) of organic and non-organic biomass.</i>	<i>VII</i>
<i>Table A4 Power law parameters of the flow curves for organic biomass, before (Org1) and after pressing (Org2), and non-organic biomass, before (NOrg1) and after pressing (NOrg2).</i>	<i>X</i>

Notation and Glossary

Nomenclature

A	area of the product exposed to heated air	m^2
A_c	collector area	m^2
c_p	air specific heat	$J\ kg^{-1}\ ^\circ C^{-1}$
C_{drying}	electricity cost of drying cycle	$\text{€}\ cycle^{-1}$
$C_{capital}$	cost of capital	€
CF	cash flow	€
$CF_{accumulated}$	updated cash flow	€
$CF_{updated}$	accumulated cash flow	€
d_c	characteristic dimension	m
D	effective mass diffusivity	$m^2\ s^{-1}$
$E_{consumption}$	specific energy consumption	$kWh\ kg_{dry\ microalgae}^{-1}$
F	tray filling	$kg\ m^{-2}$
G_{profit}	gross profit	€
h	convective heat transfer coefficient	$W\ m^{-2}\ ^\circ C^{-1}$
I_{out}	solar irradiance	$W\ m^{-2}$
L_w	latent heat of water	$J\ kg_{water}^{-1}$
$\dot{m}_a$	air flow rate	$kg\ s^{-1}$
m_p	mass of dry biomass	$kg_{dry\ solids}$
$\dot{m}_w$	rate of water evaporation	$kg_{water}\ s^{-1}$
MC	moisture content	$g_{water}\ 100\ g_{sample}^{-1}$
$MC_{initial}$	initial moisture content	$g_{water}\ 100\ g_{sample}^{-1}$
MC_{final}	final moisture content	$g_{water}\ 100\ g_{sample}^{-1}$
$MC_{critical}$	critical moisture content	$g_{water}\ 100\ g_{sample}^{-1}$
$MC_{equilibrium}$	equilibrium moisture content	$g_{water}\ 100\ g_{sample}^{-1}$
$M_{dry\ biomass}$	total mass of dry biomass obtained after drying	kg
N_{profit}	net profit	€
PC	production capacity	$kg_{dry\ microalgae}\ h^{-1}$
$P_{dehumidifier}$	dehumidifier power	kW
P_{fan}	fan power	kW
P_{heater}	heater power	kW
$[Phycocanin]$	phycocanin content	$g_{phycocyanin}\ 100\ g_{dry\ microalgae}^{-1}$
$[Protein]$	protein content	$g_{protein}\ 100\ g_{dry\ microalgae}^{-1}$
q	rate of heat transfer	W
RH_{out}	average outdoor relative humidity	$\%$
t_{drying}	drying time	h
$t_{constant-rate}$	duration of constant-rate period	h
$t_{falling-rate}$	duration of falling-rate period	h
T_a	heated air temperature	$^\circ C$
T_i	collector inlet air temperature	$^\circ C$
T_o	collector outlet air temperature	$^\circ C$
T_{out}	average outdoor temperature	$^\circ C$
TR	tax rate	$\%$
T_s	biomass surface temperature	$^\circ C$
W	load	kg

Greek Letters

η_c	thermal efficiency of the solar collector
η_d	thermal efficiency of the drying chamber

List of Acronyms

CAGR	compound annual growth rate
EPS	exopolysaccharides
PBR	photobioreactor

1 Introduction

1.1 Framing and presentation of the work

Over the years, industrial production of microalgae has increased to respond to the rising market demand for this product in several sectors such as food, feed, cosmetics, pharmaceutical, and biofuels (Nitsos et al., 2020). Spirulina, the commercial name of *Arthrospira platensis*, is the dominant species in the microalgae market (Cuellar-Bermudez et al., 2020).

Spirulina is commercialized in the form of fresh paste, powder, or nibs, which consist of small pieces of dried biomass. After culture and harvesting, the biomass paste needs to be dried to obtain the last two products. Drying is a crucial step as it increases the product's durability and final stability and facilitates transportation and storage (Singh & Heldman, 2014). However, unlike other products sold in the same sectors, microalgae have a high moisture content, which makes the drying process more challenging (Neves et al., 2019). Longer drying periods decrease nutritional content, especially in terms of pigments and proteins (Silva et al., 2021). For that reason, a compromise needs to be made between reaching the lowest moisture content and assuring the highest quality of the product (Neves et al., 2019).

It is crucial to study the influence of several factors on the quality of the final product. The goal is to assure a high content of protein and phycocyanin, the two main quality parameters of interest in the commercialization of Spirulina. Following the optimization of the drying process in the solar dryer, a comparison needs to be made with the performance of the spray dryer used by the company.

1.2 Presentation of the company

Allmicroalgae is a company whose mission is to produce high nutritional value microalgae, in a sustainable way, with the goal of making affordable and accessible products (Allmicroalgae, 2022). Nowadays, Allmicroalgae has an industrial unit located in Leiria, Portugal, dedicated to the production of microalgae with a volumetric capacity greater than 1800 m³ and a production capacity of 100 tons per year.

Some species cultivated include *Chlorella vulgaris*, *Nannochloropsis* sp., *Phaeodactylum tricornutum*, and *Chlorococcum amblystomatis*. Last year, the company started the production of Spirulina.

1.3 Contribution of the author to the work

Spirulina cultivation, harvesting and processing was performed by the company's operators. Besides this, all the work presented in this manuscript was performed by the author, including literature research, sampling, and all analyses (of moisture, phycocyanin, protein, energy consumption, payback time).

1.4 Organization of the dissertation

The focus of the present dissertation was to optimize the drying process of Spirulina in the solar dryer. To achieve such optimization, an extra fan was placed inside the solar dryer, and the variation of the moisture content of the biomass in different places of the drying chamber was evaluated. Moreover, optimum drying time was determined by analyzing how moisture, phycocyanin, and protein contents varied along a drying cycle. A study of the impact of load, tray filling, initial moisture content of Spirulina paste, and weather conditions on drying time, final moisture content, and energy consumption was also performed. Regarding the drying process in the spray dryer, the temperature that optimized phycocyanin and protein contents was established. Finally, the performance of both dryers was compared in terms of energy consumption, production capacity, phycocyanin and protein contents.

The present dissertation is divided as follows: Section 2 includes the context and state of the art, Section 3 the materials and methods used throughout the work, Section 4 the results and discussion, Section 5 the conclusions, and Section 6 the assessment of the work done. Section 4 is divided into 4 subsections: Spirulina harvesting and processing, optimization of solar drying, optimization of spray drying and comparison between both drying strategies. Appendix A presents a complementary study on the behavior of the organic Spirulina biomass. Although this work was developed within the scope of this thesis, it was not considered essential for the global theme under discussion. Appendix B presents equations based on mass and energy balances useful for the discussion of results and Appendix C shows an example of data collected by the weather station and used to analyze the impact of weather conditions on specific energy consumption.

2 Context and State of the art

2.1 Importance of microalgae and global market

Microalgae are unicellular photosynthetic microorganisms that convert carbon dioxide and water into biomass and oxygen (Nitsos et al., 2020). They are mostly present in both freshwater and saltwater ecosystems, and it is estimated that there are 300 000 species of microalgae around the globe (Neves et al., 2019). They can be divided into blue-green prokaryotic cyanobacteria and eukaryotic microalgae and the main groups of microalgae are Cyanophyta, Chlorophyta, Ochrophyta, Dinophyta, Rhodophyta, Euglenophyta, Haptophyta, and Prymnesiophyta (Neves et al., 2019). Due to their metabolism, microalgae play a key role in the food chain, acting as primary producers and converting inorganic matter into organic matter (Neves et al., 2019). They can also be applied in wastewater treatment and atmospheric CO₂ mitigation (Khan et al., 2018).

Microalgae are responsible for producing several bioproducts, including polysaccharides, lipids, pigments, proteins, vitamins, and antioxidants (Delattre et al., 2016). For that reason, they have been used in different industries for decades: in the food industry as food supplements, in the pharmaceutical and cosmetic industry as a raw material to extract specific molecules, in aquaculture as feed supplements, in agriculture as biofertilizers, and as a producer of biofuels (Neves et al., 2019). Despite the great diversity of species and applications, the majority of microalgae production on an industrial scale is destined for the food industry, with emphasis on the production of *Chlorella*, *Spirulina*, *Dunaliella*, and *Haemaotococcus* (Cuellar-Bermudez et al., 2020).

The global microalgae market was evaluated at 889.8 M€ in 2020 and is projected to reach 1 352.1 M€ by 2028, with a CAGR of 5.4%. North America is the dominant market, and the key companies involved in microalgae production are Algenol Biotech, Cellana Inc., Cyanotech Corporation, DIC Corporation, E.I.D Parry Ltd., Fuqing King Dnarmsa Spirulina Co. Ltd., Kent BioEnergy Corporation, Taau Australia Pty Ltd. (Kumar & Deshmukh, 2021).

The species cultivated at the largest scale are *Arthrospira* spp., with a global production of 12 000 tons per year (Cuellar-Bermudez et al., 2020). *Arthrospira platensis* is generally marketed as *Spirulina*, a blue-green filamentous photosynthetic cyanobacterium. It grows relatively quickly in aquatic environments with regular sunlight (Silva et al., 2021). The optimal growth yield of *Spirulina* is obtained at pH levels of 8.5-10.5, temperature regimes of 25-30 °C, and light intensities of 1500-3500 lux (Soni et al., 2019).

A significant advantage that allows Spirulina to dominate the microalgae industry is the fact that it is an extremophile that grows in a highly alkaline medium, which inhibits the growth of possible contaminants (Cuellar-Bermudez et al., 2020).

Spirulina is characterized by a high content of protein and phycocyanin. Phycocyanin is the predominant pigment, and it is an intense blue dye that has recently been valued by medicine, pharmaceutical, and cosmetic industries (Silva et al., 2021). Besides phycocyanin ($\lambda_{\max} = 610\text{-}625\text{ nm}$), there are three other groups of phycobiliproteins: phycoerythrin ($\lambda_{\max} = 490\text{-}570\text{ nm}$), phycoerythrocyanin ($\lambda_{\max} = 560\text{-}600\text{ nm}$), and allophycocyanin ($\lambda_{\max} = 650\text{-}660\text{ nm}$). Phycobiliproteins are accessory photosynthetic pigments present in red algae and cyanobacteria, which increase the performance of photosynthesis by absorbing light at wavelengths that chlorophyll, the main photosynthetic pigment, is incapable of (Limrujiwat et al., 2022).

Spirulina has significant levels of phenols, bioactive antioxidants that are beneficial to human health by scavenging free radicals. Due to its chemical composition, several authors emphasize its nutritional and pharmacological properties (Silva et al., 2021).

2.2 Cultivation and harvesting of microalgae

Microalgae cultivation can be performed in either open or closed systems (Narala et al., 2016). Open systems consist of paddle wheel raceways or open cascade systems, which have simple design and construction, low capital cost, daylight and temperature control, and easy maintenance (Nitsos et al., 2020). Despite these advantages, open systems are highly susceptible to contamination, require a large building area, depend on environmental conditions, and are characterized by insufficient heat and mass transfer (Narala et al., 2016). On the other hand, closed systems such as tubular photobioreactors (PBRs) require less space, allow greater control of operational parameters, and better mixing, but require higher construction and operating costs (Nitsos et al., 2020).

Cultivation is followed by a series of downstream steps that start with harvesting, the solid-liquid separation of cells from the culture medium. The culture medium is a valuable water resource that can be recycled back to the bioreactor or supplemented with more nutrients before this step (Nitsos et al., 2020). Harvesting involves the highest costs in microalgae processing, since cultures are kept at low concentrations. This happens to avoid self-shading, which restrains access to light in autotrophic cultures, and to avoid deposition of biomass when high densities are reached (González-Camejo et al., 2019). Some of the process units involved in harvesting include centrifugation, coagulation-flocculation, membrane filtration, gravity sedimentation, and flotation, among others (Nitsos et al., 2020). These dewatering processes can be classified as primary or secondary, meaning that the amount of water removed during

the primary processes is much higher than during the secondary ones. Also, the energy required during the second stage is much higher (Jeevanandam & Danquah, 2020).

It should be noted that there is no universally applied method for the culture and processing of microalgae, as this depends on the species, condition of the culture medium, concentration of biomass, environmental conditions, and the final product desired (Khanra et al., 2018). In the case of Spirulina, its structure is characterized by relatively large trichomes reaching up to 100 μm , which facilitates the harvesting process (Jeevanandam & Danquah, 2020). Other microalgae are two orders of magnitude smaller in size, making them more difficult to harvest (Cuellar-Bermudez et al., 2020).

2.2.1 Coagulation and flocculation

Coagulation and flocculation are primary dewatering techniques that involve the addition of compounds (coagulants and flocculants) which cause the agglomeration of small particles into large flocs. These flocs either settle by gravity sedimentation or are aerated and moved to the surface (Jeevanandam & Danquah, 2020).

Coagulation is a chemical method where the neutralization of the charges on the cells' surface promotes their aggregation. Flocculation is a physical method that does not involve surface charge neutralization but brings cells to clump together (Nitsos et al., 2020).

Coagulation can occur by adding aluminum sulfate, ferric, calcium, and magnesium chlorides. When multivalent cations are used, the coagulation can be improved by pH adjustment, which affects the cell's zeta potential. One of the major disadvantages of this process is the fact that coagulants act as contaminants and can interfere with the following downstream steps. In addition, the use of coagulants is restricted to a few applications and market segments. This can be overcome by resuspending the coagulation reagent after harvesting by doing mild acidification, for example (Nitsos et al., 2020).

Inorganic reagents are less efficient for marine microalgae due to the shielding of cells by ions in the medium, inhibiting floc formation. Organic polymers with a positive charge are more efficient since they neutralize the negative surface charge of several cells simultaneously, leading to a bridging effect and floc formation. It should be noted that the concentration of such polymers should not be substantial as the surface charge of the cells can be reversed, and repulsive forces from the cationic polymers can inhibit floc formation (Nitsos et al., 2020). In the microalgae industry, bioflocculants are seen as the most attractive option, namely chitosan and Tanfloc - a tannin natural polymer (Nitsos et al., 2020). The price of coagulants and flocculants is high, and they should only be considered when the size of microalgae cells justifies the need for increasing sedimentation velocity. In the case of Spirulina, the

sedimentation velocity is high, meaning that this technique is not appropriate (Zhu et al., 2018).

2.2.2 Sedimentation

Sedimentation is a simple and inexpensive method which is also included in the primary dewatering techniques. It consists of separating suspended solid particles from a liquid via gravitational settling. Sedimentation can be induced by increasing the pH of the culture (e.g. sodium hydroxide) or by adding coagulants (Jeevanandam & Danquah, 2020). Even though it is characterized by low energy consumption, it is not economically viable, since it involves high time consumption (Jeevanandam & Danquah, 2020; Khanra et al., 2018).

2.2.3 Centrifugation

Centrifugation consists of the separation of solids from liquids using centrifugal forces based on the particle size of the solid and the density of the liquid. It is considered a secondary dewatering method, where strain morphology plays a major role in efficiency (Nitsos et al., 2020). According to studies performed by Cuellar-Bermudez et al. (2020), centrifugation allows the harvesting of linear *Spirulina* filaments with high efficiency. In contrast, helical filaments, which are the most common, are harvested with a low yield.

Some disadvantages of centrifugation include high energy requirements, maintenance, and operating costs, and possible disruption of the cells (Jeevanandam & Danquah, 2020).

2.2.4 Filtration and sieving

Filtration is a separation method where the liquid phase of a suspension passes through a permeable medium and the cells are retained. The filtering medium is often referred to as a membrane, the liquid phase is called permeate, and the retained phase is called concentrate. A pressure drop is applied to force the liquid through the membrane (Jeevanandam & Danquah, 2020). Compared to centrifugation, filtration is simpler for large-scale dewatering but is associated with low separation rates. It also involves high operating and capital costs and membrane fouling is a frequent phenomenon, which requires pausing a continuous process for washing or, in some cases, replacing the membrane (Jeevanandam & Danquah, 2020).

Sieving is a similar process to filtration, where a particle is denied access through a pore or passageway that is smaller than the particle itself (Sandle, 2013). The most recent sieving technology is vibrating sieving, in which the vibration agglomerates the particles, ensuring the product's quality, and facilitating the dewatering process. This technology overcomes the fouling problems often seen in filtration and is used in most large-scale production facilities as a primary method for harvesting *Spirulina*. This is achieved by using simple nylon membranes with a pore size of 25-40 μm (Cuellar-Bermudez et al., 2020).

2.2.5 Pressing

Pressing is a secondary dewatering method that can be performed using either a hydraulic press or a vacuum press. A hydraulic press is a system that generates a compressive force, where one of the parts is a piston acting as a pump, with a mechanical force acting on a small cross-sectional area; the other part is a piston with a larger area, which generates a corresponding large mechanical force (Phelan, 2019). A vacuum press is a device that applies an equal amount of clamping pressure over a large area using a pneumatic or electric pump (English, 2017). For efficient dewatering, the pump must remove both the air and water from the paste. Cell rupture is one of the biggest concerns when using pressing as a downstream step. This is only a disadvantage when the goal is to keep the integrity of the cells. When a large pressure is applied, it leads to a high release of intracellular products such as lipids, an advantage for instance for the extraction needed for biodiesel production (Abbassi et al., 2014).

2.3 Drying process and different drying technologies

Biomass can be sold as fresh paste or as a dry product according to the species and its application. Dry biomass is obtained by reducing the content of water in paste, after culture and harvesting. The main goal is to minimize the biochemical changes and microbiological activity, to increase durability and stability of the final product (Silva et al., 2021). The biomass compounds are highly sensitive to temperature, light, enzymatic activity, and oxidation in the presence of air, so they can degrade during the drying process (Silva et al., 2021). In addition to preservation, dehydration reduces product mass and volume by significant amounts (4 times the volume occupied by paste), and it improves the efficiency of transportation and storage (Singh & Heldman, 2014).

After harvesting, microalgae have an average moisture content of 80% (wet basis) which must be reduced below 10% (Hosseinizand et al., 2018). Such reduction of moisture content is often seen in food products such as pineapples, mangos, onions, and berries (Lingayat et al., 2020).

According to Figure 1, the drying process starts with a preheating period (I), followed by a constant rate evaporation period (II). During the constant rate period, unbound moisture (free water) is removed by evaporation from the product's surface. The constant rate drying period ends when critical moisture content is reached. Constant-rate drying time is directly proportional to the difference between the initial moisture content and the critical moisture content and inversely proportional to the surface area of product exposed to heated air. During falling-rate drying period(s) (III and IV), the drying rate decreases because the moisture inside the material is slowly transported to the surface and then evaporated. This period ends when equilibrium moisture content is reached. Although the water removed during the falling-rate period is small, the time taken is considerably high (Babu et al., 2018). The falling-rate drying

period is highly dependent on the effective mass diffusivity for moisture movement within the product structure. The magnitude of this property is influenced by the product's structure (Singh & Heldman, 2014).

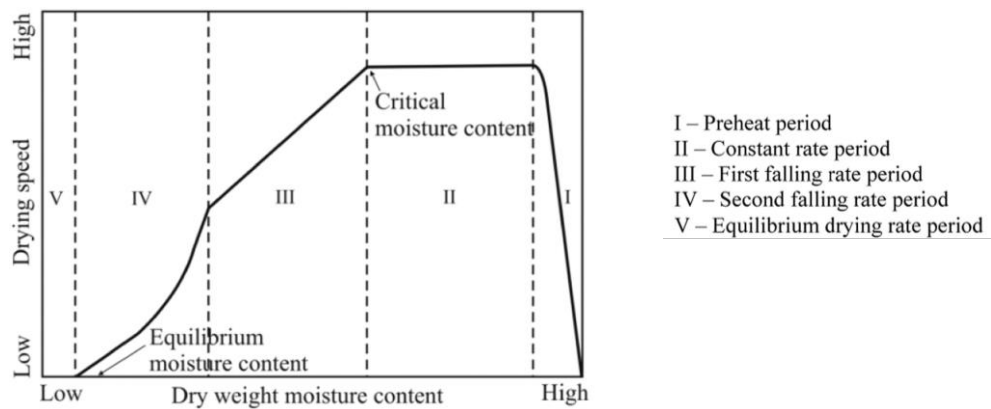


Figure 1 Typical drying curve (adapted from Babu et al. 2018).

Different technologies are used for drying, and the most efficient systems can maintain the maximum vapor pressure gradient and temperature gradient between the air and the inside of the product (Singh & Heldman, 2014). The different drying techniques differ in cost, energy, duration, shape of the final product, and preservation of the nutritional content (ProFuture, 2020). Since one of the main applications of microalgae is in the food industry, the latter factor is extremely important. During the drying process, the nutritional quality decreases as proteins, lipids, pigments, and other nutrients are lost due to time, temperature, and oxygen exposure (Neves et al., 2019).

Even though the main dryer used in the microalgae industry is the spray dryer, in small Spirulina productions, it is very common to use ovens with forced ventilation. Other technologies used are solar drying, freeze-drying, and drum drying (Neves et al., 2019).

2.3.1 Spray drying

In spray drying, microalgae slurry is atomized into heated air within a drying chamber, forming a dry powder (Nitsos et al., 2020). While the product droplets are moving with the heated air, the water evaporates and is carried away by air. After the dry particles leave the drying chamber, the product is separated from the air in a cyclone separator (Singh & Heldman, 2014). The main factors that influence the quality of the dried product are the size of the droplets, air temperature (inlet and outlet), and liquid flow. Other factors are related to the biomass characteristics and include the surface tension, density, viscosity, and composition (Neves et al., 2019).

Drying of single droplets provides a large surface area per unit volume of liquid, which favors rapid drying. Since biomass is exposed to high temperatures for a short period, only moderate degradation of product quality occurs (Neves et al., 2019). Besides these advantages, spray

drying has high versatility, provides easy control, allows a constant quality of the product, and enables powder production without any milling process (Neves et al., 2019).

The disadvantages of spray drying include high capital investment and operation costs, loss of volatile compounds, and possible rupture of the cells due to the high temperature and pressure applied during atomization. The latter promotes oxidation and decrease of phycocyanin content in the case of Spirulina (Neves et al., 2019).

2.3.2 Freeze-drying

Freeze-drying is characterized by three stages: freezing stage, first drying (sublimation) stage, and second drying stage. During the freezing stage, the product is frozen, achieving a solid structure. In the first drying stage, the product is transferred to a vacuum chamber where the decrease of pressure allows sublimation to occur at a constant temperature. During the second drying stage, unfrozen water (bound water molecules) is removed by evaporation to obtain a low water content. Cells can collapse if incorrect drying parameters are used (Reyes et al., 2010).

Freeze-drying is particularly useful when the product is sensitive to high temperatures and oxidation. It does not compromise the nutritional content of microalgae and decreases the water activity to extremely low values (Neves et al., 2019). Due to the application of vacuum and the need for negative temperatures, this is the most expensive method. Since it involves high energy and time consumption, as well as high investment and operating costs, it should only be considered for sensitive and value-added products (Nitsos et al., 2020).

2.3.3 Rotary drum drying

Drum dryers consist of a metallic cylinder rotating at a variable speed. A thin layer of paste forms on the heated surface of the cylinder, which enables drying. The apparatus includes a blade that removes the dry layer formed on the surface and after that, the material is milled to produce a powder (Neves et al., 2019).

Although this technology has lower costs than the spray dryer and can be easily managed by small producers, it has a much lower capacity (Nitsos et al., 2020). It also requires a long contact time with the high-temperature surface of the dryer. Since this leads to significant nutritional degradation, it is not appropriate to obtain biomass for food supplements. Instead, it is more suitable to produce raw materials for the biofuel industry (Neves et al., 2019).

2.3.4 Convective drying, sun drying, and solar drying

Convective drying includes both oven and microwave drying. Over the years, small-scale producers have been drying microalgae by oven drying thin layers of spread biomass or extruded

biomass cylinders. Some examples of oven drying are convective tunnel drying, continuous conveyor belt drying, and convective tray drying (Neves et al., 2019).

One of the disadvantages of convective drying is overheating of the microalgae biomass if the temperature is not properly controlled. Another disadvantage often associated with drying is heating the air, which is usually achieved using fossil fuels or electricity (Silva et al., 2021).

The most traditional and most straightforward drying technique is sun drying, in which the product to be dried is directly exposed to sunlight. Solar drying is a drying method where the air is preheated by sunlight in collectors before coming into contact with the moisture in the product (Silva et al., 2021).

Although it involves low capital and operating costs, solar drying requires long drying times which can lead to microbial contamination. Besides these problems, solar drying cannot be used in all regions of the globe, since it is highly dependent on weather conditions, namely temperature of the air, relative humidity, and solar irradiance (Nitsos et al., 2020).

2.4 Factors that influence the drying process

One of the major factors that influence the drying process is the rheology of the paste. Since the most common geometry used for drying Spirulina are thin cylinders (commonly referred to as “spaghetti”), a previous extrusion step is needed. The extrusion is highly influenced by the rheology of the material, which itself has consequences on drying.

Rheology is the study of the deformation and flow of matter or the response of materials to stress (Bourne & Szczesniak, 2003). Although rheological measurements are commonly performed on polymers to assess their behavior during processing, they can also have other applications, namely in food products. The science of rheology aims to study complex materials, such as Spirulina paste, that are partly solid and partly liquid (Taguet, 2020).

As stated by Bourne and Szczesniak (2003), from a rheological point of view, flow may be divided into the following classes:

1. Newtonian flow, where the shear rate is directly proportional to the shear stress. Viscosity is independent of shear rate.
2. Plastic or Bingham flow, in which a minimum shear stress, known as the yield stress, must be exceeded before flow begins.
3. Pseudoplastic flow, in which an increasing shear force gives a more than proportionate increase in shear rate. Apparent viscosity decreases with increasing shear rate.
4. Pseudoplastic with yield point flow, which exhibits the same behavior as the pseudoplastic, but requires a yield stress to begin the flow.

5. Dilatant flow, in which equal increments in shear stress give less than equal increments in shear rate. Apparent viscosity increases with increasing shear rate.

To better understand the rheology of the Spirulina paste, it is essential to understand the composition and structure of this microalga. The cell wall of Spirulina is composed of four layers, one of which is a robust layer of peptidoglycans. Although the cell wall is less rigid than other species (due to the low amount of carbohydrates), it has extracellular components called exopolysaccharides (EPS) (Nitsos et al., 2020).

EPS produced by microalgae can remain associated with the cell surface and/or be released into the extracellular medium (Delattre et al., 2016). So far, studies have shown that in some species of microalgae, namely *Nostoc* sp., *Spirulina* sp., and *Porphyridium* sp., the EPS surrounding the cells form a polymeric matrix that acts as a protective layer against the environmental stress (Khanra et al., 2018).

Spirulan is a rhamnose-containing exopolysaccharide present in Spirulina, which has a high molecular weight and a pseudoplastic and polyelectronic behavior. Although spirulan exists in small amounts, it is believed to contribute to the rheological properties of Spirulina suspensions. Since EPS promote cell-cell interactions, low concentration suspensions have a shear thinning behavior that impacts the downstream steps (Martínez-Sanz et al., 2020).

Other factors influence the rheology of a suspension, such as particle size distribution and viscosity of the continuous liquid phase. Despite several studies developed over the years, there are still many uncertainties regarding the rheological properties of concentrated microalgae suspensions. This results from high particle heterogeneity, the softness of particles, the presence of crystalline and amorphous states, and highly non-spherical particle shape (Martínez-Sanz et al., 2020).

Besides the rheology of the paste, the drying process is highly influenced by the amount of water that needs to be removed to reach the final moisture content required by the market for Spirulina sale ($7 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$). The amount of water to be removed depends on the initial moisture content of the paste and the total mass of wet biomass to be dried (loading of the dryer). Additionally, as drying rate is highly influenced by the area of biomass exposed to the heated air, the amount of biomass per m^2 of tray (tray filling) is also an important factor. When tray filling is too high, the thin cylinders of biomass can overlap, reducing the area exposed to the air (Silva et al., 2021).

3 Materials and Methods

3.1 Spirulina cultivation, harvesting and processing

Spirulina cultivation was performed through gradual scale up, from laboratory scale autotrophic reactors to pilot raceways (5 m³) where the inoculum was produced. The large scale was finally achieved in 200 m³ raceways. Spirulina was harvested from the raceways and concentrated in a vibrating sieve (Vibrowet, Solaro, Italy). Following this step, biomass took one of two paths: either it was directly dried in the spray dryer (final product was in powder form) or it was further concentrated with a hydraulic press (Black Widow, Wisconsin, USA) by applying pressure to the filter cake. In the case of the latter, it proceeded to be extruded into long 4 mm diameter cylinders (“spaghetti”) in a plunger-type extruder (Linkrich, Guangzhou, China). Spirulina spaghetti was placed on stainless steel trays (area of approximately 0.5 m²) which were then moved to tray rack trolleys. The trolleys were placed inside the solar dryer (final product was in the form of nibs).

3.2 Solar drying

The solar dryer used by Allmicroalgae is the BLACK BLOCK (BBKW Drying Solutions, Lisbon, Portugal) hybrid solar dryer (internal dimensions of 5.80 × 2.20 × 2.30 m) shown in Figure 2.



Figure 2 BLACK BLOCK solar dryer (Block, 2020).

This dryer is powered by solar energy during the day and by auxiliary energy at night or in adverse weather conditions. It is equipped with sensors that register the temperature and the relative humidity of the air inside the dryer. The data is analyzed in real-time by an automatic program that controls all the equipment, assuring that the drying environment allows a high-quality drying process with maximum energy saving (Block, 2020).

The dryer has two modules: a computer module (or controller) with different drying programs that require little intervention from the user; a physical module that consists of a drying chamber, two solar collectors (one on the south wall and another at the top), inlet and outlet ventilation ducts, and temperature, and relative humidity sensors. The collectors capture and transform the solar energy into thermal energy and store the hot air. The inlet ventilation duct forces the hot and dry air from the collectors to the inside of the drying chamber. The ventilation outlet allows the natural circulation of saturated air from inside to outside the dryer (Block, 2020). Besides this equipment, there is a heater (B15 EPB, Master Climate Solutions Pastrengo, Italy) that turns on when the temperature inside the dryer is below the setpoint and turns off when the temperature is above 45 °C. A dehumidifier (TTK 655 S, TROTEC, Marchtrenk, Austria) removes excess moisture from the air and a fan (SFDC3-600CT0, EQUATION, Ronchin, France) allows a more efficient air distribution. A second fan was placed inside the dryer to optimize the drying process. The dryer was operated in manual mode: the inlet ventilation duct was kept open, while the outlet ventilation duct was opened at 8 AM and closed at 7 PM, approximately.

3.3 Placement of a second fan

Spirulina spaghetti was placed on top, middle, and bottom stainless-steel trays in 9 tray rack trolleys (total of 27 trays). Variation of moisture content before drying and after 17 hours of drying was determined. It was also assessed the position of the drying chamber in which biomass had the highest moisture content after drying. To facilitate results interpretation, a drawing of the drying chamber with the 9 tray rack trolleys, the heater, the dehumidifier and the two fans was created on Ansys DesignModeler.

3.4 Influence of operation variables on response variables

Operation variables were defined: load of the dryer (total mass of wet biomass loaded in the dryer), W (kg), tray filling (mass of wet biomass per m^2 of tray), F (kg m^{-2}), and initial moisture content, MC_{initial} ($\text{g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$). Due to the impossibility of controlling any variable, a total of 16 drying cycles were followed and variables were grouped by classes according to Table 1.

Table 1 Classes of operation variables.

Operation variable	Classes
W (kg)	[44;62]; [76;99]; [105;124]
F (kg m^{-2})	[0.64;0.92]; [1.10;1.30]
MC_{initial} ($\text{g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$)	[75;80[; [80;82[; [82;85[

The response variables were the drying time, t_{drying} (h), final moisture content, MC_{final} ($\text{g}_{\text{water}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$), and specific energy consumption, $E_{consumption}$ ($\text{kWh kg}_{\text{dry microalgae}}^{-1}$).

3.5 Influence of weather conditions on energy consumption

Outdoor temperature, relative humidity and solar irradiance were monitored by a weather station (Watchdog Weather Station WD-2000 series, Spectrum Technologies Inc., Aurora, IL, USA). Data was plotted against time and the area under each curve was determined by the trapezoidal rule. The weighted averages of outdoor temperature (T_{out}), relative humidity (RH_{out}) and solar irradiance (I_{out}) were calculated dividing the area under the curve by the duration of the drying cycle. A calculation example can be found in Appendix C. As in section 3.4, weather variables were grouped into classes according to Table 2.

Table 2 Classes of weather variables.

Weather variables	Classes
T_{out} ($^{\circ}\text{C}$)	[16;18[; [18;20[
RH_{out} (%)	[30;35[; [35;40[
I_{out} (W m^{-2})	[100;200[; [200;300[

Specific energy consumption was calculated for each set of conditions, in order to evaluate the influence of weather conditions.

3.6 Assessment of optimum drying time

Optimum drying time was obtained by plotting drying curves of 4 drying cycles with a duration of 17 hours and determining the time at which moisture content reached $7 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$. Samples were taken from the position of the drying chamber in which biomass had the highest moisture content after drying (section 3.3). During this assay, both fans were switched on. Phycocyanin and protein content was also quantified in order to assess the influence of drying time on biochemical composition.

3.7 Spray drying optimization assay

Spirulina paste was diluted to a moisture content of approximately $90 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$ to be atomized in the Allmicroalgae's spray dryer (Wuxi Modern, Wuxi, China). According to the manufacturer, the evaporation capacity is $0.2 \text{ m}^3 \text{ h}^{-1}$ and the volume of the drying chamber is 79 m^3 . The air inlet temperature was set at 220°C by the operation of 240 kW electric heating resistor modules. The influence of temperature on final moisture, protein and phycocyanin content was evaluated by testing 4 values of biomass temperature: 60, 70, 80 and 90°C .

Following temperature optimization, a series of drying cycles at a temperature of 80 °C were monitored and specific energy consumption, production capacity, protein and phycocyanin content were determined.

3.8 Quantification of moisture content

Moisture content, MC ($\text{g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$), was determined using a moisture analyzer (MA 50.R Moisture Analyzer, Radwag, Radom, Poland). Approximately 1 g of sample was weighted and dried at a constant temperature of 120 °C, until the mass was unchanged over time.

3.9 Quantification of phycocyanin content

Quantification of phycocyanin content of Spirulina paste, nibs and powder was carried out according to Allmicroalgae's protocol. Nibs were grinded in a coffee grinder until reaching powder form. Moisture content of the product was determined according to section 3.8.

Approximately 5 mg of dry biomass were weighed in a tube and 6 mL of phosphate buffer were added. The mass of paste, nibs and powder needed to obtain 5 mg dry biomass, $m_{\text{phycocyanin}}$ (mg), was calculated using Equation (1).

$$m_{\text{phycocyanin}} = \frac{5}{\frac{(100 - MC)}{100}} \quad (1)$$

The solutions were frozen and then thawed on the day of the analysis. A volume of 750 μL of glass beads were added to each tube. The tubes were vortexed for 15 minutes protected from light and centrifuged at $4250 \times g$ for 10 minutes. The supernatant (with extracted phycocyanin) was stored in flasks and the pellet was resuspended in new aliquots. The process was repeated until the extraction was completed (pellet or supernatant uncolored).

The extracts stored in the flaks were analyzed using the spectrophotometer. Absorbances were measured at 615 and 652 nm, and the concentration of pure phycocyanin, $[\text{Phycocyanin}]$ ($\text{g}_{\text{protein}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$), was calculated using Equation (2), according to the Bennett and Bogorad (1973) method. $V_{\text{phosphate buffer}}$ (mL) was the total volume of phosphate buffer used for the extraction and m_{sample} (mg) was the actual mass of dry biomass weighed.

$$[\text{Phycocyanin}] = 100 \left(\frac{V_{\text{phosphate buffer}}}{m_{\text{sample}}} \right) \left[\frac{OD_{615} - (0.474 \times OD_{652})}{5.34} \right] \quad (2)$$

3.10 Quantification of protein content

Quantification of protein content was carried out using the Lowry method (Lowry et al., 1951). Solutions of 1 g L^{-1} were prepared by suspending 10 mg of dry biomass in 10 mL of water in a 15 mL Falcon tube. After determining the moisture content, the mass of paste, nibs (previously

grinded) or powder needed to obtain 10 mg dry biomass, $m_{protein}$ (mg), was calculated using Equation (3).

$$m_{protein} = \frac{10}{\frac{(100 - MC)}{100}} \quad (3)$$

Solutions were frozen and then thawed on the day of the analysis. A volume of 750 μ L of glass beads were added to each tube and vortexed for 15 minutes. These steps were performed before the Lowry method to ensure complete cell lyses.

A volume of 2 mL of each 1 g L⁻¹ solution and 2 mL of a 2M sodium hydroxide solution were added to glass tubes. The blank was prepared using demineralized water instead of the sample. The glass tubes were placed on a metal tube rack and moved to a bain-marie at 99 °C for 6 minutes. The tubes were cooled until reaching room temperature and were centrifuged at 4250 $\times$ g for 10 minutes. 1 mL of the supernatant was taken to another tube and 5 mL of the reagent I were added. The solutions were left 10 minutes in the dark and after that 1 mL of the reagent II was added. The solutions were vortexed immediately for 20 seconds and kept in the dark for 30 minutes. The absorbances were read at a wavelength of 750 nm. Protein concentration was determined using a calibration curve plotted by the company.

Notes: Reagent I was prepared by mixing 48 mL of a sodium carbonate solution (5% m/v), 1 mL of a sodium-potassium tartrate solution (2% m/v) and 1 mL of a copper sulphate solution (1% m/v). Reagent II was prepared by diluting the Folin-Ciocalteu with demineralized water in a proportion of 1:2.

3.11 Energy consumption

The power of the heater (P_{heater}), the dehumidifier ($P_{dehumidifier}$) and each fan (P_{fan}) were 15 kW, 1.9 kW and 0.33 kW, respectively. Due to a connection failure between the physical and the computer modules, caused by the malfunction of the sensors placed inside the dryer, it was not possible to know the operating time of each equipment. For calculation purposes, it was considered that the dehumidifier and both fans were always on. However, due to a thermostat connected to the heater, this equipment switched off when the temperature inside was above 45 °C. As an approximation, it was considered that this only happened during daytime. For that reason, the operating time of the heater was calculated by subtracting 9 hours to the drying time, t_{drying} (h), as the most common drying cycles started at 3 PM and finished at 8 AM of the next day.

The specific energy consumed during a drying cycle, $E_{consumption}$ (kWh kg_{dry biomass}⁻¹) was calculated by Equation (4), where $M_{dry biomass}$ (kg) is the total mass of dry biomass obtained after drying.

$$E_{consumption} = \frac{P_{dehumidifier} t_{drying} + 2 P_{fan} t_{drying} + P_{heater} (t_{drying} - 9)}{M_{dry\ biomass}} \quad (4)$$

The cost of each drying cycle, C_{drying} (€ cycle⁻¹) was calculated by Equation (5), considering that the cost of electricity was 0.08 € kWh⁻¹.

$$C_{drying} = 0.08 P_{dehumidifier} t_{drying} + 2 P_{fan} t_{drying} + P_{heater} (t_{drying} - 9) \quad (5)$$

3.12 Payback time

Payback time was determined according to Peters et al. (2002). To simplify calculations, it was considered that costs, revenues, and amortizations remained constant over the years. A tax rate of 25% and a cost of capital of 12% were considered.

For the estimation of payback time, it was considered that the spray dryer operated for 1750 hours to produce 7000 kg_{dry biomass}, while the solar dryer operated for 5400 hours to produce 4875 kg_{dry biomass}. Revenue was calculated considering the annual production of dry biomass in each dryer. Capital investment was calculated as a sum of the fixed capital investment and working-capital investment.

Total product cost was divided into production costs and general expenses. Production costs included variable production costs (labour, raw materials, utilities, and maintenance and repair), fixed expenses (amortization, taxes, and insurance), and overheads. General expenses included administrative expenses, distribution and marketing expenses, and research and development (Peters et al., 2002). It was estimated that 4 operators were needed for the operation of the solar dryer, while 1 operator was needed for the spray dryer. The only utility taken to account was electricity, and maintenance and repair costs were approximately 5% of the cost of each equipment. Amortization was calculated considering a 10-year period and taxes and insurance were estimated as 2% and 1% of the capital investment, respectively. Overheads were 50% of the total expenses for operating labor, maintenance and repair. Administrative expenses were 25% of operating labor, distribution and marketing expenses were 4% of the total product cost, and research and development were 2% of revenue (Peters et al., 2002).

Gross profit, G_{profit} (€), was calculated as a difference between revenue and total product cost.

Net profit, N_{profit} (€), was calculated by Equation (6), where TR is the tax rate.

$$N_{profit} = G_{profit} (1 - TR) \quad (6)$$

Cash flow, CF (€), was calculated as a sum of net profit and amortization. Cash flow was updated to year 0, $CF_{updated}$ (€), considering the cost of capital, $C_{capital}$ (€), through Equation (7), where i is the year number.

$$CF_{updated} = CF (1 + C_{capital})^{-i} \quad (7)$$

The accumulated cash flow, $CF_{accumulated}$ (€), was determined by Equation (8).

$$CF_{accumulated_i} = CF_{accumulated_{i-1}} + CF_{updated_i} \quad (8)$$

Payback time was determined as the first year where accumulated cash flow was positive.

3.13 Statistical analyses

The Shapiro-Wilk test was used to test normality of data sets. For data sets that followed a normal distribution, ANOVA with Tukey's post hoc test was used to detect significant effects on response variables (drying time, final moisture content, energy consumption, capacity of production, protein content, and phycocyanin content). For data sets that did not follow a normal distribution, Mann-Whitney test was used. A significance level (p) of 0.05 was used for all performed tests. Statistical categories were represented in graphs as follows: ns ($p \geq 0.05$); *** ($0.0001 < p < 0.001$); ** ($0.001 < p < 0.01$); * ($0.01 < p < 0.05$). Results were reported as means $\pm$ standard deviations. All graphs were plotted in GraphPad Prism9.

4 Results and Discussion

4.1 Spirulina harvesting and processing

Although the focus of the present work was the drying process of Spirulina biomass, a brief analysis of the antecedent downstream steps was made. The motivation for this analysis was the fact that operation variables such as tray filling and initial moisture content were closely associated with the concentration steps.

As described in section 3.1, downstream started with culture concentration in the vibrating sieve until reaching a moisture content of approximately $90 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$. During the months of July and August (maximum production capacity), the sieve was working approximately 14 hours a day. It was observed a degradation of the filtration medium along time, which forced operators to lower the harvest flow. As a result, harvesting time increased at least 1 hour. Due to the increase of time consumption, the filtration medium should be frequently replaced.

After sieving, biomass was further concentrated in the hydraulic press until reaching a moisture content between 75 and $85 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$. Considering maximum production capacity, pressing took between 4 to 6 hours. Pressure was applied with the aid of a foot pedal pressed by an operator. This apparatus made it difficult to apply constant conditions, which explained the high variability of moisture content. The manometer of the apparatus was designed for higher pressures than the ones that the cells can withstand. During pressing, it was often observed the release of phycocyanin, which is undesirable for commercial purposes. Since it is important to standardize process conditions, a possible solution would be replacing the manometer with one that measures lower pressures. The operator would be able to accurately read the applied pressure and maintain it below cell rupture.

After pressing, the paste was extruded into thin cylinders. Considering maximum production capacity, extrusion took approximately 4 hours. It was observed that the pedal used to control biomass extrusion was not sensitive and kicked when the movement started, causing the spaghetti to become tangled. The sensitivity of this pedal could be adjusted to avoid this problem. In addition, due to pressure drop along the extrusion tube, spaghetti did not come out with a constant velocity from all the orifices. For that reason, new geometries of the tube could be tested to overcome this issue.

4.2 Optimization of solar drying

Due to the malfunction in the sensors placed inside the dryer, the communication between the physical module and the computer module was interrupted. For that reason, it was impossible

to observe how different parameters were varying inside the dryer. Besides, it was not possible to follow the original plan of manipulating variables such as the setpoint temperature at which the heater switches on, the humidity below which the dehumidifier turns off or the air recycling time. This malfunction happened before the beginning of the assays performed in the dryer and was not fixed until the end of the work.

Optimization possibilities were also limited in terms of adding or replacing equipment, so the only equipment that was added was a second fan. In addition, since the present work was carried out at the same time as the daily industrial production, it was not possible to interfere with the operation variables: load of the dryer, tray filling, and initial moisture content. As a result of these limitations, the drying process was optimized by assessing the influence of operation and weather variables on response variables. More specifically, it was analyzed if loading the dryer to the maximum would significantly impact the drying time or if using lower loads would increase specific energy consumption in such a way that drying was no longer economically viable. A similar analysis was made regarding tray filling and initial moisture content. Finally, the minimum drying time needed to meet the maximum moisture content of biomass, $7 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$, was determined and variation of protein and phycocyanin contents was evaluated.

4.2.1 Placement of a second fan

Figure 3 shows a drawing of the solar dryer in Ansys DesignModeler with the identification of equipment and numbering of the 9 trolleys. Despite not being represented in Figure 3, the air inlet duct is located next to the dehumidifier, while the outlet is located near trolley 9.

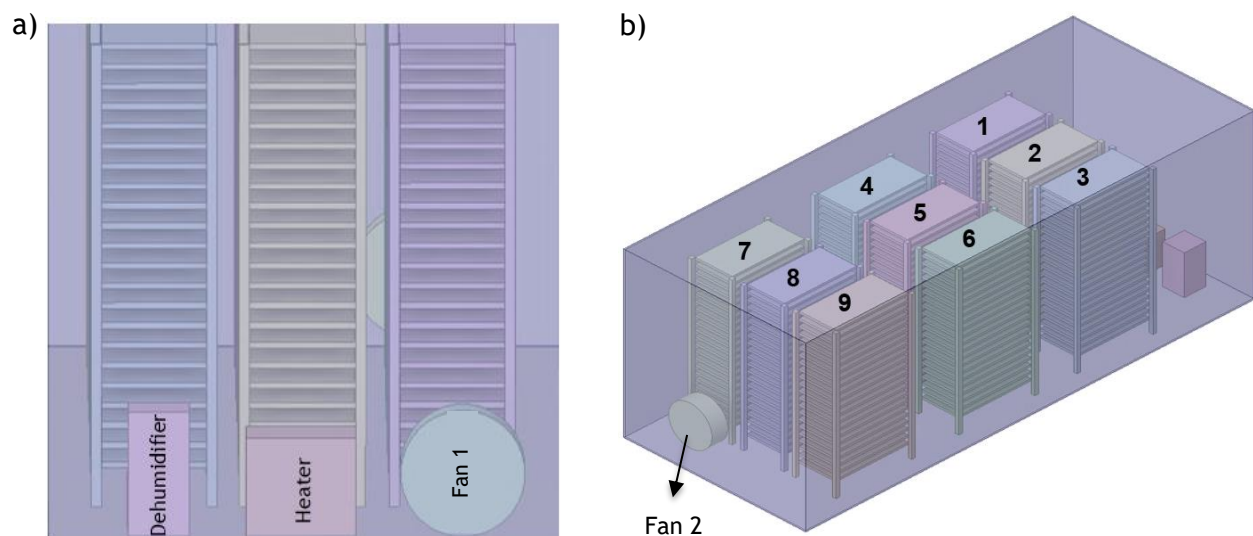


Figure 3 Solar dryer drawing in Ansys DesignModeler: a) back view with identification of equipment (dehumidifier, heater, and fan 1); b) isometric view with trolley numbering and identification of fan 2.

Figure 4 shows three color maps of the variation of moisture content, ΔMC ($\text{g}_{\text{water}} / 100 \text{ g}_{\text{sample}}^{-1}$), compared to drying with only one fan, on top, middle and bottom trays on the 9 trolleys numbered in Figure 3. In each map, the number of the trolley is displayed on top, and the tray position is displayed on the left. Map a) represents trolleys 1-3, map b) represents trolleys 4-6 and map c) represents trolleys 7-9. The rectangles are colored according to the scale under each map. Since the scale only has negative values (decrease of MC), grey rectangles represent the trays in which MC increased.

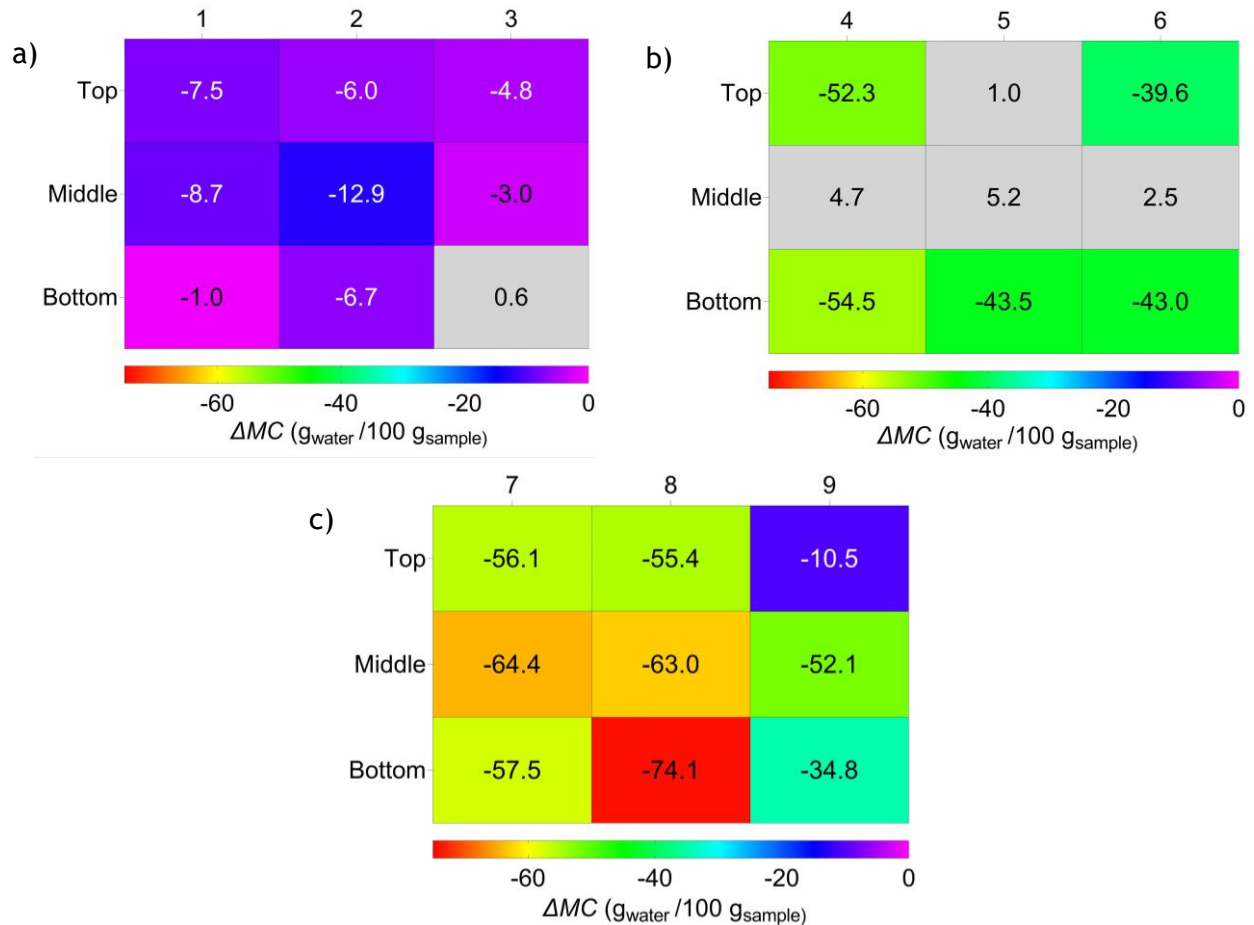


Figure 4 Color maps of the variation of moisture content, ΔMC , on top, middle and bottom trays on 9 trolleys: a) trolleys 1-3; b) trolleys 4-6; c) trolleys 7-9.

Biomass in trolleys 1, 2 and 3, which were placed closer to the dehumidifier, heater, and fan 1, suffered a decrease of MC by a small extent. There was an increase of MC on the biomass placed on trays located in the middle of trolleys 4, 5 and 6 and on top of the trolley 5. However, not only was this increase very small, but also the rest of the trays had significantly high decreases of MC. Biomass present in trolleys 7, 8 and 9 suffered a drastic reduction in MC.

These results suggest that the air homogenization close to fan 1 was already efficient, since placing the second fan only led to a slight decrease of MC in this region. However, one fan did not allow sufficient air homogenization in all the drying chamber. This problem was overcome

by the placement of fan 2 since it led to a drastic decrease of MC in the region furthest from fan 1.

After placing fan 2, it was identified that the biomass on the top tray of trolley 9 had the highest MC . For that reason, it would be advised to measure MC of the biomass placed in this tray and end the drying cycle if the value is below $7 \text{ g}_{\text{water}} \text{ 100 g}_{\text{sample}}^{-1}$. Considering a drying cycle of 17 hours, using two fans increases electricity consumption by 5.3 kWh, which corresponds to 0.42 €.

Kong et al. (2020) studied two modes of indirect solar drying of turnips: in mode 1, only one group of fans placed at the air entrance of the drying chamber were turned on; in mode 2, two groups of fans placed on both sides of the drying chamber were additionally turned on. It was observed that after 8 hours of drying, moisture content was reduced from $24 \text{ kg}_{\text{water}} \text{ kg}_{\text{dry matter}}^{-1}$ to $9 \text{ kg}_{\text{water}} \text{ kg}_{\text{dry matter}}^{-1}$ in mode 1 and to $1 \text{ kg}_{\text{water}} \text{ kg}_{\text{dry matter}}^{-1}$ in mode 2. According to Kong et al. (2020), the additional set of fans eliminated the hot airflow dead zone and enhanced hot air convection in the drying chamber, improving drying efficiency.

4.2.2 Influence of operation variables on response variables

The influence of load (total mass of wet biomass in the dryer), W (kg), tray filling (mass of wet biomass per m^2 of tray), F (kg m^{-2}), and initial moisture content, MC_{initial} ($\text{g}_{\text{water}} \text{ 100 g}_{\text{sample}}^{-1}$), on drying time, t_{drying} (h), final moisture content, MC_{final} ($\text{g}_{\text{water}} \text{ 100 g}_{\text{sample}}^{-1}$), and specific energy consumption, $E_{\text{consumption}}$ ($\text{kWh kg}_{\text{dry microalgae}}^{-1}$), was studied.

Figure 5 shows the effect of different loads on drying time.

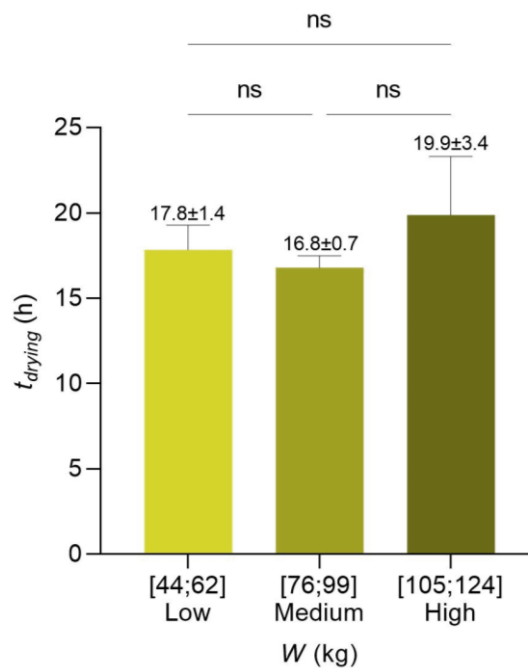


Figure 5 Influence of load (total mass of wet biomass in the dryer), W (kg), on drying time, t_{drying} (h); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).

Figure 5 exhibits no significant difference on drying time for different loads, which was a result of the incorrect definition of the end of the drying cycles. Due to company's operational ease, drying cycles were ended at approximately 8 AM (start of the day shift), despite the biomass already being dry during the night shift.

Figure 6 displays the influence of different loads on final moisture content of the biomass.

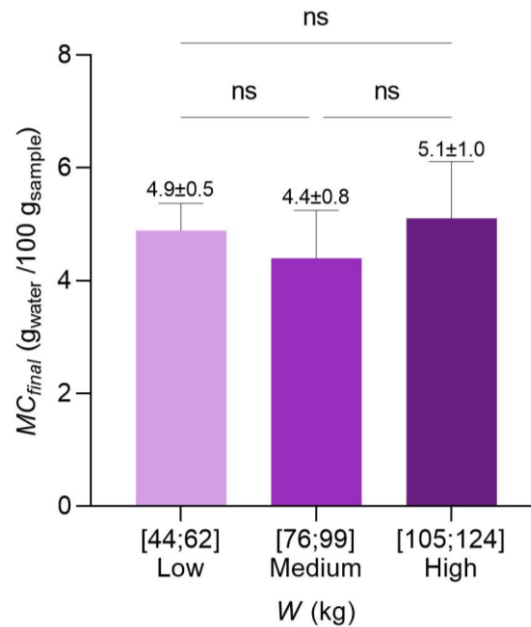


Figure 6 Influence of load (total mass of wet biomass in the dryer), W (kg), on final moisture content, MC_{final} (g_{water} 100 g_{sample}⁻¹); values are given as mean ± standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).

Figure 6 displays no significant difference on final moisture content for different loads, which could be explained by the fact that equilibrium moisture content, $MC_{equilibrium}$, was reached. As explained in section 2.3, MC does not drop below $MC_{equilibrium}$, regardless of increasing drying time.

The effect of different loads on specific energy consumption is presented in Figure 7.

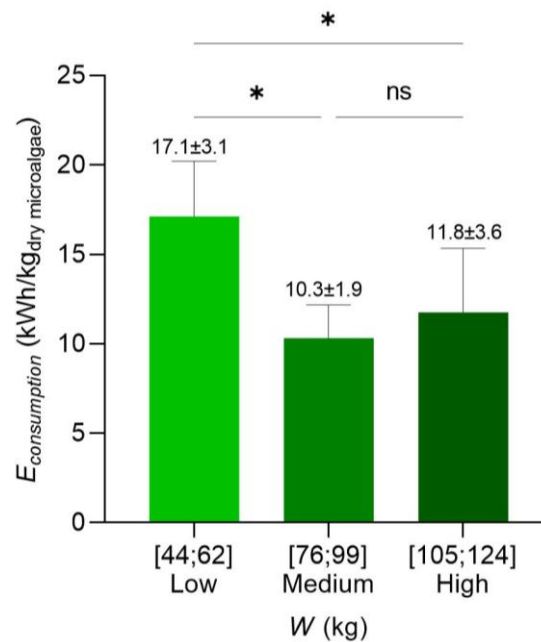


Figure 7 Influence of load (total mass of wet biomass in the dryer), W (kg), on specific energy consumption, $E_{consumption}$ (kWh kg_{dry microalgae}⁻¹); values are given as mean ± standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$).

Figure 7 indicates that loading the dryer with a load between 44 and 62 kg of wet biomass required between 5.3 and 6.8 kWh kg_{dry microalgae}⁻¹ more energy than the other two classes. Specific energy consumption was calculated by Equation (4) assuming that the dehumidifier and both fans were always on, and that the heater was only switched off for 9 hours of the drying cycle. Although this was the closest approximation that could be made according to data from previous months, specific energy consumption could only be accurately estimated if the sensors were working properly and if there was communication between the physical and computer modules. This would allow knowing how long each equipment was actually switched on.

After analyzing the results presented in Figure 5, Figure 6 and Figure 7, it was observed that loading the dryer with either medium or high loads led to a similar drying performance.

To the author's knowledge, no studies have been performed so far to assess the influence of different loads on the drying performance of microalgae on an industrial scale. Chan et al. (2015) studied indirect solar drying of two different loads of rough rice. Considering an initial moisture content between 27.6-28.4 g_{water} 100 g_{sample}⁻¹ and a final moisture content of 14.3 g_{water} 100 g_{sample}⁻¹, the drying time of 104 kg of rough rice was 5 hours, while the drying time of 200 kg of rough rice was 8 hours. These results showed that approximately doubling the load increased drying time by 3 hours. Hii et al. (2006) analyzed the influence of different loads of cocoa beans on the drying performance of a pilot scale direct solar dryer. The initial moisture content was in the region of 39.5-41.6 g_{water} 100 g_{sample}⁻¹ and the desired final moisture content

was $7.5 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$. For loads of 20, 30, and 60 kg of cocoa beans, the duration of the drying cycle was 5.0, 7.5 and 9.5 hours, respectively. Similarly to the study carried out by Chan et al. (2015), this study showed that increasing the load increased drying time.

Figure 8, Figure 9 and Figure 10 show the impact of low and high tray filling on the response variables.

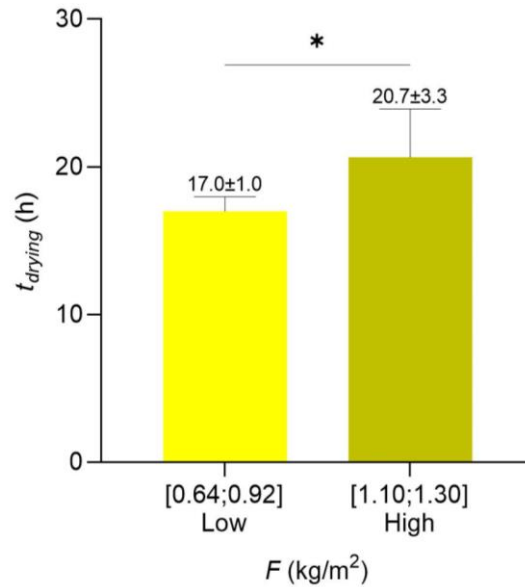


Figure 8 Influence of tray filling (mass of wet biomass per m^2 of tray), F (kg m^{-2}), on drying time, t_{drying} (h); values are given as mean $\pm$ standard deviation; *: significant difference between the groups ($0.01 < p < 0.05$).

Figure 8 displays a significant difference on drying time between low and high tray filling. This shows that higher tray filling led to higher drying times.

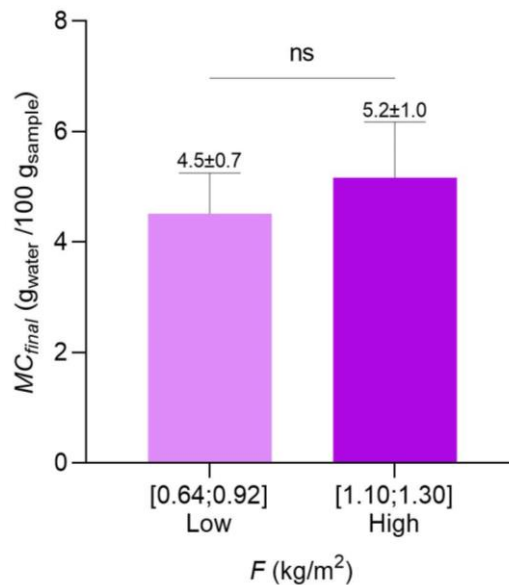


Figure 9 Influence of tray filling (mass of wet biomass per m^2 of tray), F (kg m^{-2}), on final moisture content, MC_{final} ($\text{g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).

Figure 9 shows no significant difference on final moisture content for low and high tray filling.

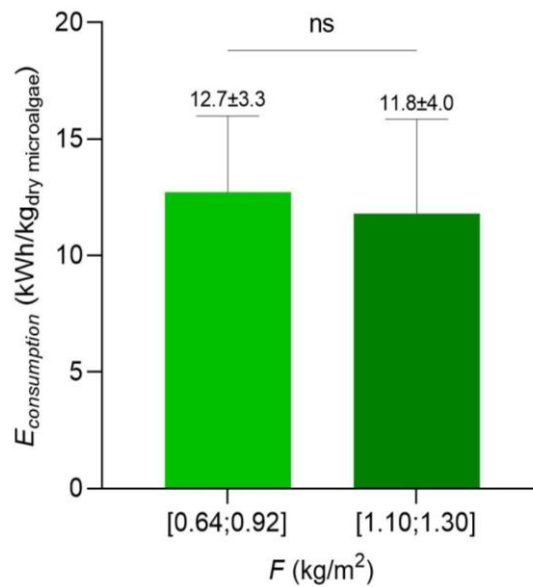


Figure 10 Influence of tray filling (mass of wet biomass per m² of tray), F (kg m⁻²), on specific energy consumption, $E_{consumption}$ (kWh kg_{dry microalgae}⁻¹); values are given as mean ± standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).

Figure 10 suggests that tray filling did not affect specific energy consumption.

Silva et al. (2021) studied Spirulina drying on a solar dryer with smaller dimensions (0.6 m × 0.6 m × 0.65 m) in which there were 3 trays with a working area of 0.3364 m². In this work, different volumetric air flow rates were combined with different tray fillings to evaluate the influence on the drying time. Increasingly higher values of F led to increasingly higher drying times, for all volumetric air flow rates. For example, for a drying temperature of 41.6 °C and a volumetric air flow rate of 0.038 m³ s⁻¹, t_{drying} was 120, 148, and 163 min for F values of 0.3079, 0.4618 and 0.6158 kg m⁻², respectively. The values of t_{drying} were significantly lower than the ones obtained in the present work, not only due to the fact that lower values of F were studied, but also due to the incorrect definition of the end of the drying cycles.

Figure 11 and Figure 12 show the impact of initial moisture content on drying time and specific energy consumption, respectively.

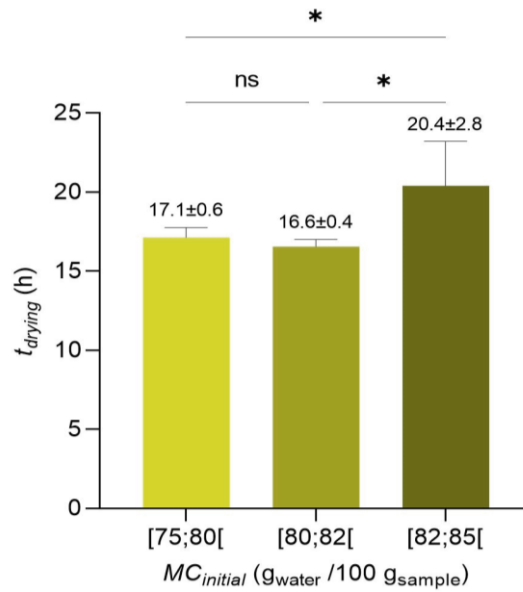


Figure 11 Influence of initial moisture content, $MC_{initial}$ ($g_{water} 100 g_{sample}^{-1}$), on drying time, t_{drying} (h); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$).

Figure 11 displays no significant difference on drying time when initial moisture content was between 75 and 82 $g_{water} 100 g_{sample}^{-1}$. However, for values above 82 $g_{water} 100 g_{sample}^{-1}$, longer drying times were registered. According to Equation (VII) in Appendix B.1, t_{drying} is a sum of $t_{constant-rate}$ and $t_{falling-rate}$. As shown in Equation (XV) in Appendix B.1, $MC_{initial}$ only influences $t_{constant-rate}$. Considering that all other parameters are constant, the higher the value of $MC_{initial}$, the longer the drying time. Due to the impossibility of performing controlled experiments, the results obtained deviate from what would be expected from the theoretical equations.

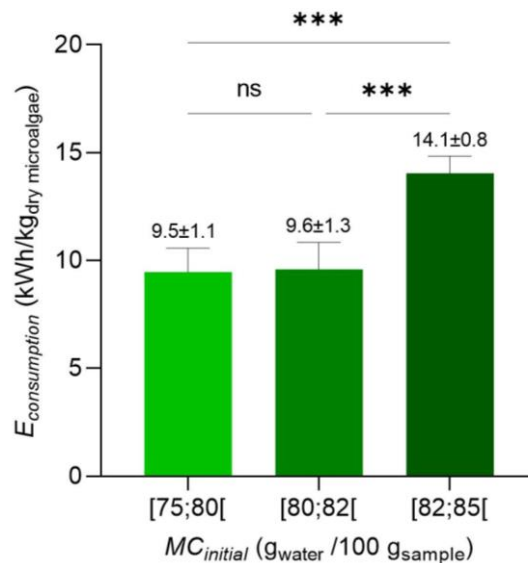


Figure 12 Influence of initial moisture content, $MC_{initial}$ ($g_{water} 100 g_{sample}^{-1}$), on specific energy consumption, $E_{consumption}$ (kWh $kg_{dry} microalgae^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); ***: extremely significant differences between the groups ($0.0001 < p < 0.001$).

Figure 12 exhibits no significant difference on specific energy consumption for an initial moisture content between 75 and 82 $\text{g}_{\text{water}} \text{100 g}_{\text{sample}}^{-1}$. For values above 82 $\text{g}_{\text{water}} \text{100 g}_{\text{sample}}^{-1}$, a significantly higher specific energy consumption was observed.

During data analysis, it was observed that for 8 drying cycles with a duration of approximately 17h, MC_{initial} and MC_{final} had a linear relationship with a statistical significance ($R^2 = 0.9526$), as shown in Figure 13.

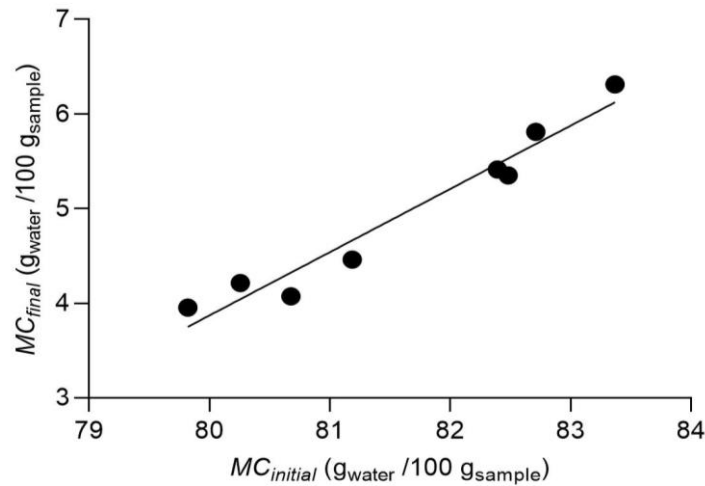


Figure 13 Linear relationship between initial moisture content, $MC_{\text{initial}} (\text{g}_{\text{water}} \text{100 g}_{\text{sample}}^{-1})$, and final moisture content, $MC_{\text{final}} (\text{g}_{\text{water}} \text{100 g}_{\text{sample}}^{-1})$.

The linear relationship between MC_{initial} and MC_{final} was described by Equation (9).

$$MC_{\text{final}} = 0.67MC_{\text{initial}} - 49.61 \quad (9)$$

This result shows that MC_{final} could be predicted for a drying cycle of 17 hours, considering that MC_{initial} is in the range of 79.8-83.4 $\text{g}_{\text{water}} \text{100 g}_{\text{sample}}^{-1}$.

4.2.3 Influence of weather conditions on energy consumption

Weather conditions were monitored as mentioned in Section 3.5 and grouped by classes according to Table 2. Figure 14, Figure 15 and Figure 16 represent the effect of outdoor temperature, outdoor relative humidity, and solar irradiance on specific energy consumption, respectively.

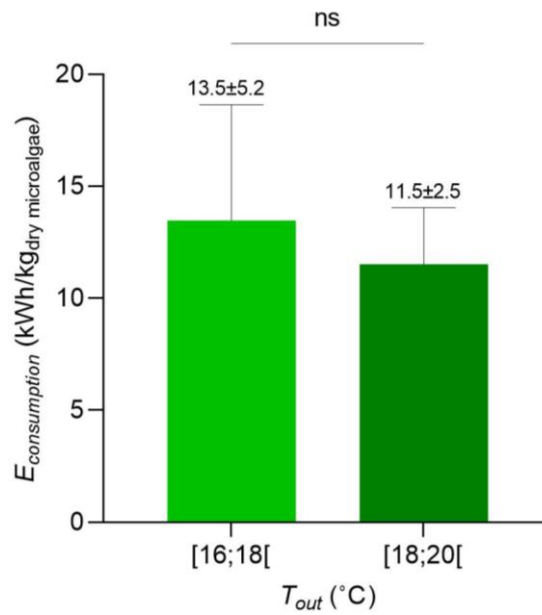


Figure 14 Influence of outdoor temperature, T_{out} (°C), on specific energy consumption $E_{consumption}$ (kWh kg_{dry microalgae}⁻¹); values are given as mean ± standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).

Figure 14 shows no significant difference on specific energy consumption for the two classes of outdoor temperature.

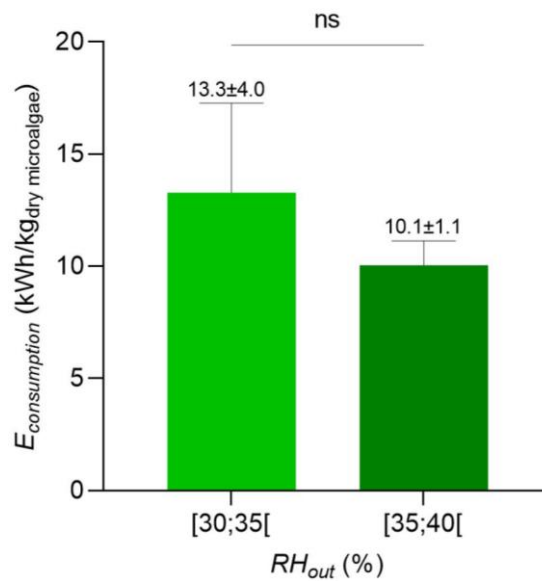


Figure 15 Influence of outdoor relative humidity, RH_{out} (%), on specific energy consumption $E_{consumption}$ (kWh kg_{dry microalgae}⁻¹); values are given as mean ± standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).

Similar to what was observed above, Figure 15 shows a lack of significant difference on specific energy consumption for the two classes of outdoor relative humidity.

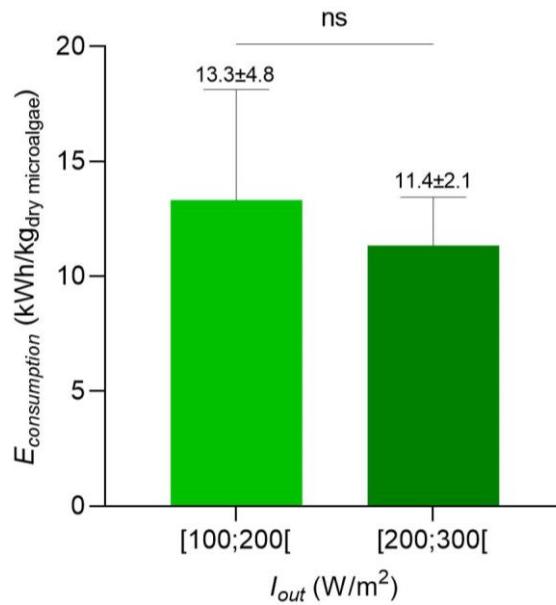


Figure 16 Influence of solar irradiance, I_{out} ($W\ m^{-2}$), on specific energy consumption $E_{consumption}$ ($kWh\ kg_{dry\ microalgae}^{-1}$); values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$).

Figure 16 also suggests that there was no significant difference on specific energy consumption for the two classes of solar irradiance. Values of T_{out} , RH_{out} and I_{out} were reduced, since Allmicroalgae is located in a geographic location with mild weather in July, period during which this study took place. The results suggest that, for the range of T_{out} , RH_{out} and I_{out} studied, the hybrid system worked efficiently to compensate variable weather conditions.

If the connection between the physical and the computer modules had not been interrupted, the system would provide a low consumption of energy by only switching on equipment when temperature and humidity parameters were outside the setpoint band (Block, 2020). This suggests that the results obtained for $E_{consumption}$ based on the assumptions made were higher than what the system needs.

Equation (XVI) in Appendix B.2 shows that the higher the temperature of the air entering the collector (T_{out}), the higher the temperature of the air leaving the collector, that is, the temperature of the air entering the drying chamber. As a result, the heater would not have to be on for so many hours and $E_{consumption}$ would be smaller. It would also be expected that the lower H_{out} , the higher the amount of water that the air can remove from the product. Consequently, it would take a longer time to reach the humidity at which the dehumidifier switches on, which means that $E_{consumption}$ would be smaller. Equation (XVII) in Appendix B.2 indicates that t_{drying} is inversely proportional to I_{out} . Therefore, higher values of I_{out} would lead to lower values of $E_{consumption}$.

It should be mentioned that the results were obtained during the month of July. To properly assess how weather conditions influence energy consumption, it would be necessary to perform

this study during other seasons. To the best of the author's knowledge, no previous studies have been performed to assess the influence of weather conditions on energy consumption of indirect solar dryers to dry microalgae.

Lamrani et al. (2019) developed a numerical model for investigating the performance of an indirect hybrid solar dryer. The model was validated for wood drying under the meteorological conditions of Tangier city, where average solar irradiance during daytime was approximately 850 W/m^2 . It was determined that throughout the year, additional heat delivered by the auxiliary heater decreased as the useful heat gained by the solar collector increased. During December, the heat rate provided by the auxiliary heater system reached the maximum value of 239 kWh. In September, energy consumption reached the minimum value of 137.5 kWh, while in July it was approximately 170 kWh. In the present work, the heat rate provided by the auxiliary heater system in July was between 105 and 210 kWh (considering that the heater was only switched off during nighttime). Although the average solar irradiance registered during the development of the present work was significantly lower than the one registered in Tangier city, energy consumption of both auxiliary heater systems was close.

4.2.4 Assessment of optimum drying time

Optimum drying time was determined by analyzing how moisture, phycocyanin, and protein contents varied along the drying process. The curves were plotted during 4 drying cycles on the 1st, 11th, 12th and 13th July. The results obtained are presented in Figure 17.

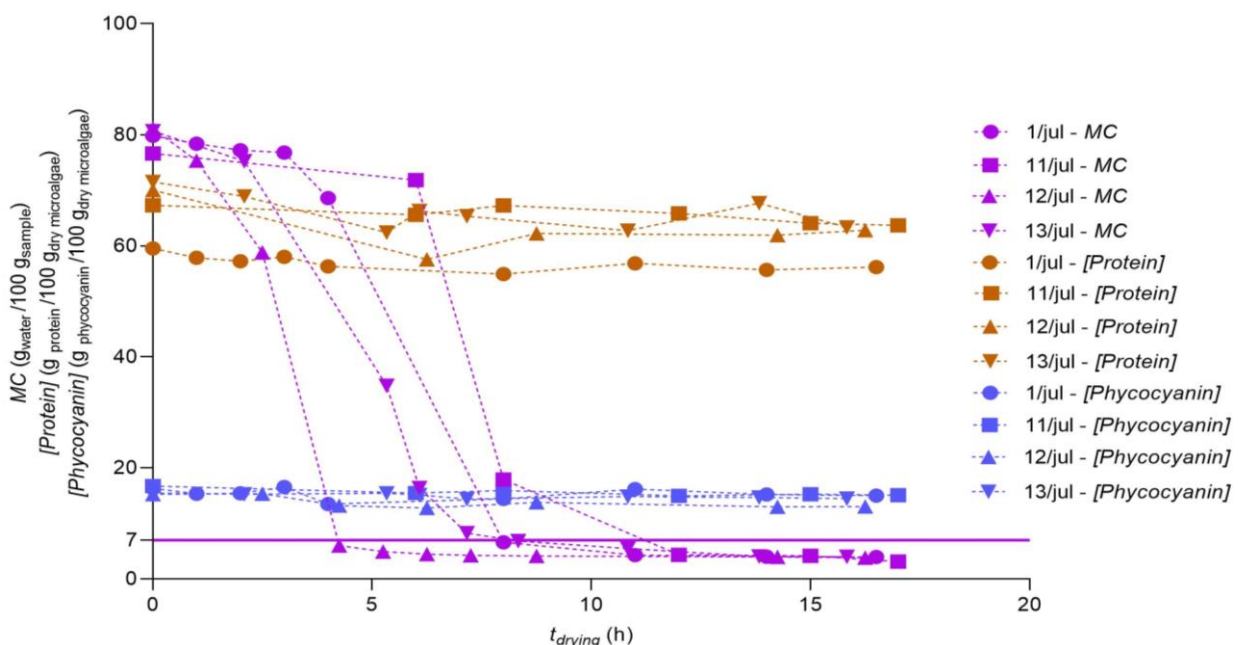


Figure 17 Representation of moisture content, MC (purple), protein content, [Protein] (orange), and phycocyanin content, [Phycocyanin] (blue), along time, during the 1st (●), 11th (■), 12th (▲) and 13th (▼) of July of 2022. The purple continuous line marks the maximum moisture content the final product can have ($7 \text{ g}_{\text{water}} \text{ } 100 \text{ g}_{\text{sample}}^{-1}$).

Although the conditions during the 4 drying cycles were similar, *MC* curves were out of phase. The average estimated time at which the biomass reached a *MC* equal to $7 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$ was $7.9 \pm 2.9 \text{ h}$. This result shows that t_{drying} had a high variability, since a drying cycle lasted from 5 hours to approximately 11 hours. Before placing the second fan, drying cycles had a duration of approximately 17 hours (the reason why this assay was carried out during that period), meaning that drying time was reduced by 6 to 12 hours. Kong et al. (2020) determined that switching on two groups of fans placed on both sides of the drying chamber reduced drying time by 45.4%, in comparison to only switching on one group of fans placed at the air entrance of the drying chamber. In the present work, the placement of the second fan reduced drying time by $53.5 \pm 17.1\%$. Drying curves also confirmed that it is possible to have at least 2 drying cycles per day, which was the company's goal.

When comparing the drying curves of the present work with the ones obtained by Silva et al. (2021) and Schmid et al. (2022) - assays in Olhão, Portugal, with the same dryer model but with other species shaped into plates - the major difference occurs at the beginning of the drying cycle. Figure 17 shows that in the first hours *MC* decreases slightly until approximately $75 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$. The existence of this level on the curves suggests that biomass needs a minimum amount of energy so that evaporation of water on the surface can start (which will be influenced by the spaghetti diameter and the initial moisture content). After this, the drying process proceeds as observed in the drying curves presented in the literature (Schmid et al., 2022; Silva et al., 2021). *MC* decreases abruptly at an approximately constant drying rate. Then *MC* decreases at a drying rate progressively smaller during the falling-rate period.

[Protein] and *[Phycocyanin]* curves did not show significant fluctuations. The estimated decrease of *[Protein]* was $5.0 \pm 3.2 \text{ g}_{\text{protein}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$ and the estimated decrease of *[Phycocyanin]* was $1.6 \pm 0.5 \text{ g}_{\text{phycocyanin}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$.

Oliveira et al. (2009) assessed the performance of Spirulina drying on a tray dryer with perpendicular air flow at a temperature between 50 and 60 °C. Fresh Spirulina had a protein content of $74 \text{ g}_{\text{protein}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$ and it was observed a loss of 17% in protein content, which was higher than the loss of approximately 7.5% in protein content reported in the present work.

Stramarkou et al. (2021) studied Spirulina drying in a laboratory-scale accelerated artificial solar dryer of 1000 W m^{-2} total light source. Drying was performed at 60 °C for a period of 180 min and *[Phycocyanin]* decreased from $10.57 \pm 0.28 \text{ g}_{\text{phycocyanin}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$ to $3.32 \pm 0.10 \text{ g}_{\text{phycocyanin}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$. The results obtained by Stramarkou et al. (2021) show a decrease of phycocyanin content approximately 4.5 times higher than the present work.

Silva et al. (2021) observed that phycocyanin levels either increased or decreased depending on the drying conditions. Fresh microalgae had $8.75 \pm 0.51 \text{ g}_{\text{phycocyanin}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$ and

phycocyanin content after drying was between 6.31 and 12.91 $\text{g}_{\text{phycocyanin}} \text{100 g}_{\text{dry microalgae}}^{-1}$. These results confirm the possibility that phycocyanin content can increase during the drying cycle, as observed in some points of the *[Phycocyanin]* curves in Figure 17. According to Stramarkou et al. (2021), phycocyanin levels increased by an average of 44% when drying was carried out at the highest temperature (41.6 °C) combined with the lowest airflow (0.0378 $\text{m}^3 \text{s}^{-1}$). On the other hand, phycocyanin levels decreased by an average of 25% when drying was carried out at the lowest temperature (34.5 °C) combined with the highest air flow (0.0841 $\text{m}^3 \text{s}^{-1}$). The authors stated that the higher temperature could have inactivated the harmful activity of some enzymes and favored the release of this compound by the rupture of some cellular structures during drying.

4.3 Optimization of spray drying

Figure 18, Figure 19 and Figure 20 show the influence of different drying temperatures on protein, phycocyanin, and final moisture content of spray dried Spirulina. Fresh Spirulina had an initial protein content of $67.1 \pm 5.3 \text{ g}_{\text{protein}} \text{100 g}_{\text{dry microalgae}}^{-1}$ and an initial phycocyanin content of $16.0 \pm 0.6 \text{ g}_{\text{phycocyanin}} \text{100 g}_{\text{dry microalgae}}^{-1}$. Moisture content of atomized Spirulina was approximately 90 $\text{g}_{\text{water}} \text{100 g}_{\text{sample}}^{-1}$.

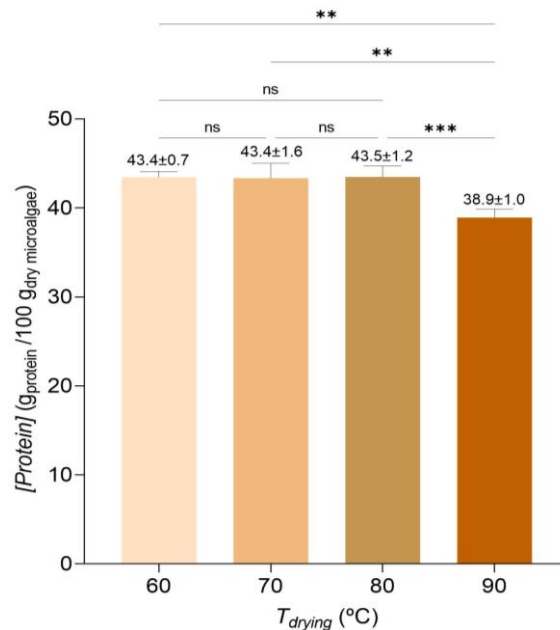


Figure 18 Protein content, $[\text{Protein}] (\text{g}_{\text{protein}} \text{100 g}_{\text{dry microalgae}}^{-1})$, of spray dried Spirulina at drying temperatures, $T_{\text{drying}} (^{\circ}\text{C})$, of 60, 70, 80 and 90 °C; values are given as mean $\pm$ standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); **: very significant differences between the groups ($0.001 < p < 0.01$); ***: extremely significant differences between the groups ($0.0001 < p < 0.001$).

Figure 18 indicates that protein content was similar for drying temperatures of 60, 70, and 80°C. However, protein content was significantly lower at 90 °C.

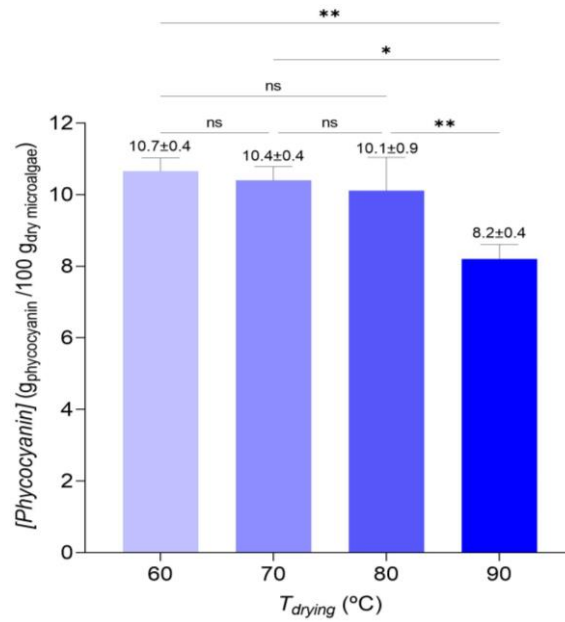


Figure 19 Phycocyanin content, $[Phycocyanin]$ (g_{phycocyanin} 100 g_{dry microalgae}⁻¹), of spray dried Spirulina at drying temperatures, T_{drying} (°C), of 60, 70, 80 and 90 °C; values are given as mean ± standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$); **: very significant differences between the groups ($0.001 < p < 0.01$).

Figure 19 shows that phycocyanin content was similar for drying temperatures of 60, 70, and 80 °C. However, drying at 90 °C led to a significant decrease in phycocyanin content.

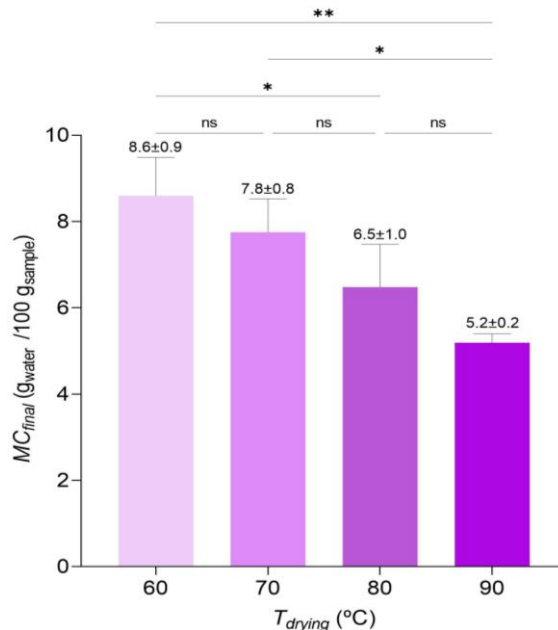


Figure 20 Final moisture content, MC_{final} (g_{water} 100 g_{sample}⁻¹), of spray dried Spirulina at drying temperatures, T_{drying} (°C), of 60, 70, 80 and 90 °C; values are given as mean ± standard deviation; ns: no significant differences between the groups ($p \geq 0.05$); *: significant differences between the groups ($0.01 < p < 0.05$); **: very significant differences between the groups ($0.001 < p < 0.01$).

Since final product specification demands a moisture content below $7 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$, drying must be performed at either 80 or 90 °C. Therefore, the most suitable temperature for drying Spirulina in the spray dryer was 80 °C.

Desmorieux and Hernandez (2004) compared the protein losses of Spirulina using different drying technologies. Spray drying was performed using inlet air temperatures of 130 and 150 °C which led to a loss of protein content between 10 to 15%, while freeze-drying showed the lowest protein loss below 10%. The protein loss of the present work was between 35 to 42%, which was approximately 3 times higher than the results obtained by Desmorieux and Hernandez (2004). It is believed that the discrepancy in the results was due to the quantification method that was used. Recently, the company detected that the Lowry's method often indicated an amount of protein below that reported by external analyses. To confirm these results, a different analytical method, e.g. CHN analysis, should be used.

Zhang et al. (2022) studied the influence of different inlet temperatures (120, 170 and 220 °C) and initial solid contents (8, 12 and 16%) during the spray drying of *Scenedesmus acuminatus* biomass. The results indicated that spray drying did not change the protein content, contrary to what was observed in the present work. Moreover, higher temperatures led to lower values of moisture content, a tendency that was also observed in the present work. No studies were found regarding the influence of temperature on phycocyanin content in spray dried Spirulina.

4.4 Comparison between solar drying and spray drying

Data from dryings performed at 80 °C in the spray dryer was used to compare the performance of this dryer with the solar dryer. Figure 21 shows the comparison of specific energy consumption in both dryers and Figure 22 shows the comparison of production capacity.

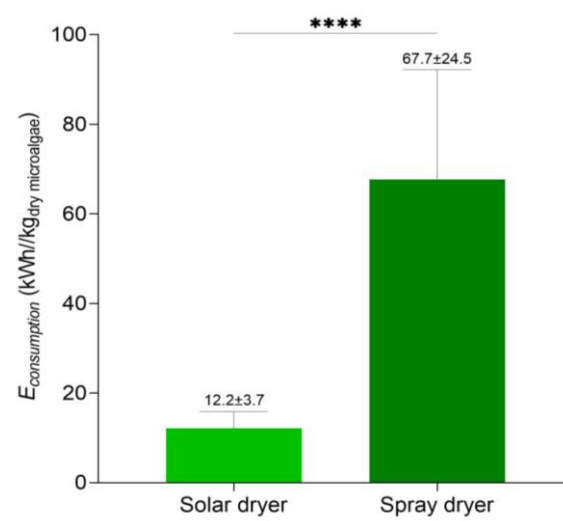


Figure 21 Comparison of specific energy consumption, $E_{\text{consumption}}$ (kWh kg_{dry microalgae}⁻¹), in the solar dryer and in the spray dryer; values are given as mean ± standard deviation; ****: extremely significant differences between the groups ($p < 0.0001$).

Figure 21 indicates that solar drying consumed around 5.5 times less energy than spray drying.

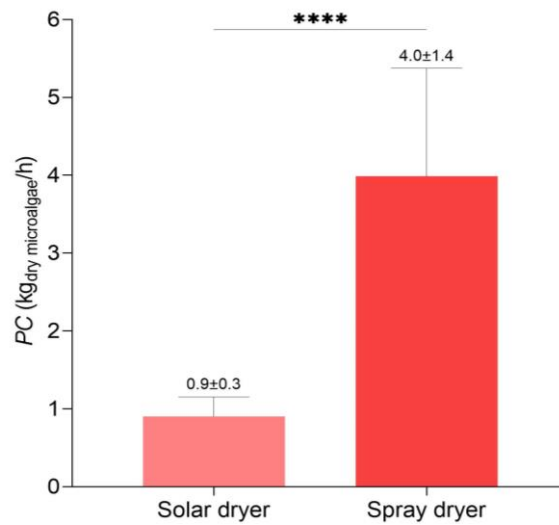


*Figure 22 Comparison of production capacity, PC (kg_{dry microalgae} h⁻¹), in the solar dryer and in the spray dryer; values are given as mean ± standard deviation; ****: extremely significant differences between the groups (p<0.0001).*

Figure 22 shows that spray drying had a production capacity around 4.4 times higher than solar drying.

Vázquez-Romero et al. (2022) performed a techno-economic analysis of microalgae production, harvesting and drying and assessed that spray drying consumed 36.45 kWh kg_{dry microalgae}⁻¹. This value was lower than the specific energy consumption of spray drying obtained in the present work. Vázquez-Romero et al. (2022) also determined that freeze-drying required 22.29 kWh kg_{dry microalgae}⁻¹, which was approximately 10 kWh kg_{dry microalgae}⁻¹ more energy than the solar drying system studied in the present work.

Figure 23 and Figure 24 present the comparison of protein and phycocyanin content in Spirulina after drying in both dryers. Since it was not possible to dry the same batch in both dryers, it was considered the same initial protein content and phycocyanin content of the assays in section 4.3 (67.1±5.3 g_{protein} 100 g_{dry microalgae}⁻¹ and 16.0±0.6 g_{phycocyanin} 100 g_{dry microalgae}⁻¹, respectively).

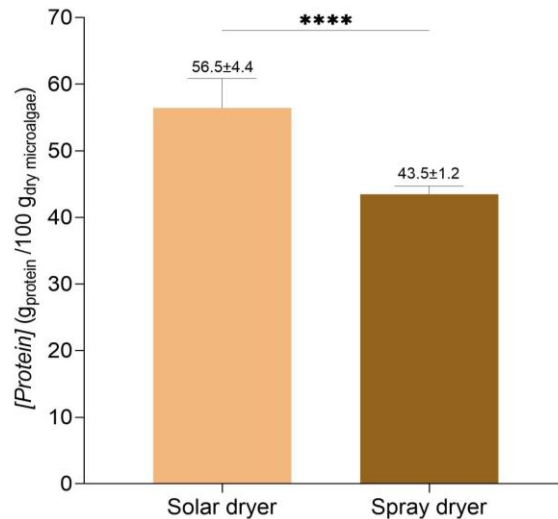


*Figure 23 Comparison of protein content, [Protein] (g_{protein} 100 g_{dry microalgae}⁻¹), in the solar dryer and in the spray dryer; values are given as mean ± standard deviation; ****: extremely significant differences between the groups (p<0.0001).*

The results displayed in Figure 23 show that samples dried in the solar dryer had a significantly higher protein content than the samples dried in the spray dryer. More specifically, solar drying led to an average protein loss of approximately 16%, while spray drying led to an average protein loss of 35%, in comparison to the initial protein content in the fresh paste.

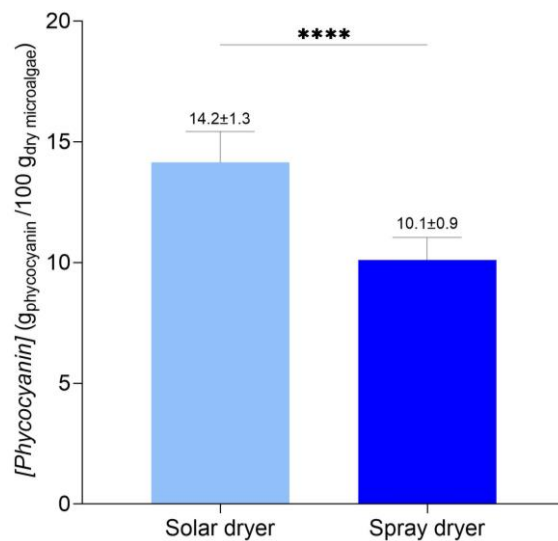


*Figure 24 Comparison of phycocyanin content, [Phycocyanin] (g_{phycocyanin} 100 g_{dry microalgae}⁻¹), in the solar dryer and in the spray dryer; values are given as mean ± standard deviation; ****: extremely significant differences between the groups (p<0.0001).*

Similar to what was noted above, Figure 24 shows that samples dried in the solar dryer had a significantly higher phycocyanin content than the samples dried in the spray dryer. In fact, solar drying decreased phycocyanin content by approximately 11%, while spray drying led to a

decrease of approximately 37%, in comparison to the initial phycocyanin content in the fresh paste.

A techno-economic assessment was performed to evaluate economic feasibility of drying Spirulina in both dryers. It was in the company's interest not to disclose the values associated with total product cost, revenues, and capital investment. For this reason, total product cost was described in percentages as observed in Figure 25 for the solar drying and Figure 26 for spray drying.

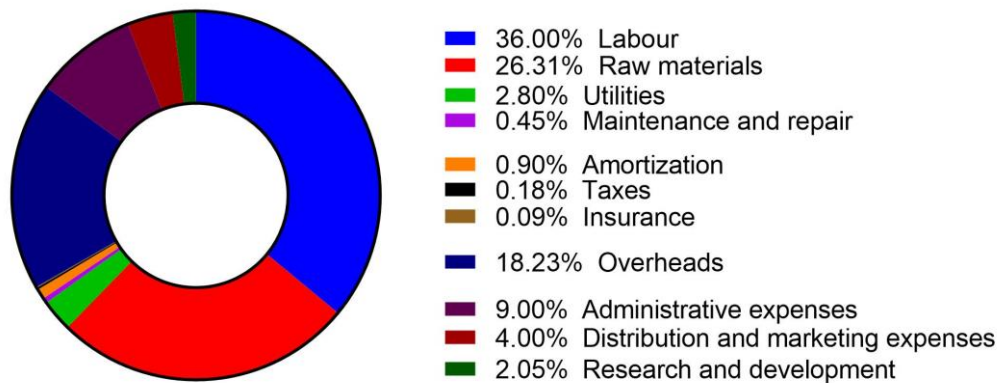


Figure 25 Description of total product cost associated with solar drying.

It should be noted that labour accounts for the largest percentage of the total cost of drying Spirulina in the solar dryer. Labour demand is a result of the pressing and extrusion steps needed to obtain Spirulina in thin cylinders before drying.

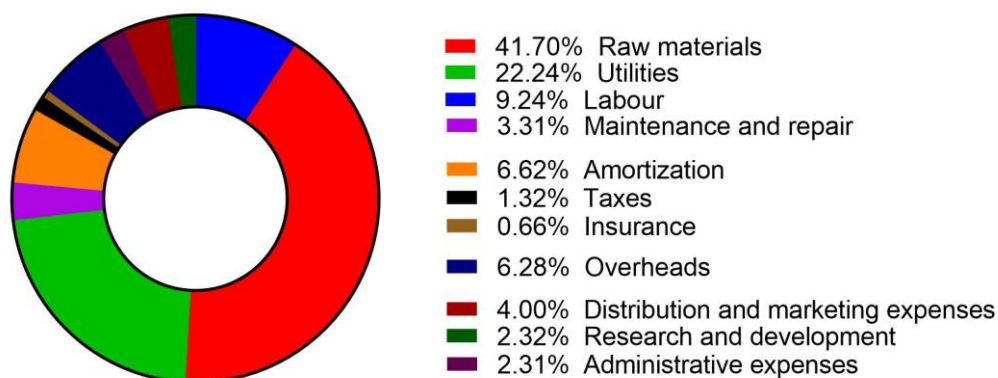


Figure 26 Description of total product cost associated with spray drying.

As observed in Figure 26, raw materials had the highest impact on the total product cost associated with spray drying. Even though the cost of raw materials per kg of dry biomass produced is equal, the solar dryer has a lower production capacity than the spray dryer. This is a result of the fact that it can only be used for a shorter period during the year due to weather conditions. It should also be noted the impact of utilities on total product cost associated with spray drying in comparison to solar drying.

Payback time was determined by calculating the accumulated cash flows in 10 years considering the use of the solar dryer and spray dryer to dry Spirulina, as presented in Figure 27. Due to business secrecy, the y-axis values were omitted.

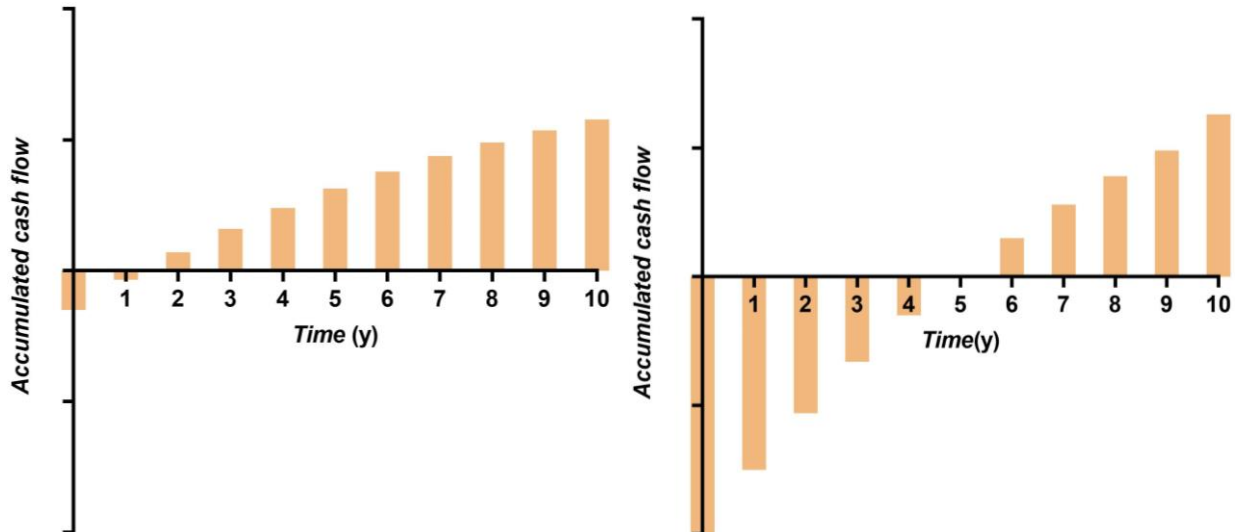


Figure 27 Accumulated cash flow in 10 years considering the use of the solar dryer (left) and spray dryer (right).

Figure 27 shows that the payback time of the solar dryer was 2 years, while the payback time of the spray dryer was 5 years. El Hage et al. (2018) investigated the influence of different loads, operating times, and types of products to be dried in a solar dryer with a purchase cost 8000\$. Considering that the dryer operated during approximately 60% of the year (close to the estimation done in the present work) and with a drying load of 120 kg (in the range of the maximum load studied in this work), the payback times were 5, 7, and 10 months for drying apples, bananas, and carrots, respectively. When the operating time increased to all year (maintaining the load), payback times decreased to 2.8, 4 and 6 months, respectively. When the load increased to 600 kg (maintaining operating time), payback times decreased to 0.9, 1.3 and 2.1 months, respectively. These results show that not only is payback time highly dependent on load and operating time, but also on the type of product, which explains the discrepancy between the values obtained by El Hage et al. (2018) and the payback time of 2 years determined in the present work.

After analyzing the results obtained for the comparison of both dryers, solar drying was considered a more suitable strategy to dry Spirulina on an industrial scale.

5 Conclusions

The present work studied the optimization of the drying process of Spirulina on a hybrid solar dryer. The placement of a second fan inside the drying chamber increased air homogenization. Before optimization, drying cycles had a duration of approximately 17 hours in the solar dryer. After placing the second fan, the estimated drying time of Spirulina biomass in the hybrid solar dryer was 7.9 ± 2.9 hours, which shows that drying time was reduced by 6 to 12 hours. The estimated decrease of protein content for a drying cycle of 17 hours in the solar dryer was $5.0 \pm 3.2 \text{ g}_{\text{protein}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$, while the estimated decrease of phycocyanin content was $1.6 \pm 0.5 \text{ g}_{\text{phycocyanin}} 100 \text{ g}_{\text{dry microalgae}}^{-1}$.

Loading the dryer with either medium loads (76 to 99 kg of wet biomass) or high loads (105 to 125 kg of wet biomass) led to a similar drying performance. However, drying time was minimized for cycles in which the amount of wet biomass per m^2 of tray was between 1.10 and 1.30 kg m^{-2} . Moreover, wet biomass with an initial moisture content above $82 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$ led to longer drying times and higher specific energy consumption. Outdoor temperature, humidity and solar irradiance did not influence specific energy consumption, which indicated that the hybrid system worked efficiently to compensate variable weather conditions.

A further study was made regarding temperature optimization of Spirulina drying on an industrial scale spray dryer. It was determined that Spirulina dried at a temperature below 80°C did not meet the final moisture content specification ($7 \text{ g}_{\text{water}} 100 \text{ g}_{\text{sample}}^{-1}$). However, drying at 90°C led to a significant decrease in phycocyanin content in comparison to the other temperatures. Hence, it was concluded that the most suitable temperature to spray dry Spirulina was 80°C .

The drying performance of both strategies was compared. Although solar drying consumed around 5.5 times less energy than spray drying, it had a production capacity around 4.4 times lower. Solar drying led to a protein loss of 16% and a phycocyanin loss of 11%, while spray drying led to a protein loss of 35% and a phycocyanin loss of 37%. In addition, the estimated payback time was 2 years for the solar dryer and 5 years for the spray dryer. After comparing the performance of both dryers, solar drying was considered a more suitable strategy to dry Spirulina on an industrial scale.

6 Assessment of the work done

6.1 Objectives achieved and future perspectives

The main goal of the present dissertation was to optimize the drying process of Spirulina in the solar dryer, which was achieved by the placement of the second fan. The moisture content of biomass placed in different positions in the drying chamber decreased and drying time was significantly reduced. However, the estimated optimum drying time had a high variability. More drying curves should be obtained to experimentally predict drying time with greater statistical confidence. In addition, a study of the impact of load, tray filling, initial moisture content of Spirulina paste, and weather conditions on drying time, final moisture content, and energy consumption was conducted. Since this study was based on 16 drying cycles, variables had to be grouped in classes and each one of them was tested at a time. This means that a combination of different variables was not tested to assess the best drying performance. Consequently, more drying cycles should be analyzed in the future to draw more widely applied conclusions. As optimization was carried out at the same time as daily industrial production, it was not possible to interfere with the operation variables. If that had been possible, the present work could have been conducted according to the design of experiments methodology, which would have allowed the achievement of more robust conclusions. Due to the malfunction of the sensors placed inside the dryer, it was not possible to manipulate variables such as the setpoint temperature at which the heater switches on, the humidity below which the dehumidifier turns off or the recycling time of air. In the future, these variables could be tested with the sensors in operation for a better understanding of the hybrid drying process. Since this malfunction interrupted the communication between the physical and the computer modules, it was not possible to determine the real operation time of each auxiliary equipment. As a result, specific energy consumption should be recalculated to accurately assess the best drying conditions. Although it was concluded that the most suitable temperature for spray drying was 80 °C, protein content should be confirmed by another analytical method (for example, by CHN analysis) as it was found to be too low in comparison to literature values. Finally, the performance of both dryers was compared in terms of specific energy consumption, production capacity, phycocyanin and protein contents. Although solar drying was considered a better strategy to dry Spirulina, real values of specific energy consumption should be obtained, and protein content quantification should be repeated. Besides the improvements previously mentioned, it would also be interesting to test different air inlet velocities and solar collector angles, since many studies suggest that these variables have a great impact on the drying performance. A theoretical approach could also be adopted using the mathematical models

based on heat and mass transfer to predict drying times. Another suggestion would be using the Ansys Fluent software to determine the best placement position of both fans and observe air distribution to detect dead zones in the drying chamber of the solar dryer.

6.2 Final assessment

The development of the present work was conditioned by challenges that included the malfunction of the sensors and the impossibility to manipulate operation variables, which were crucial in a project where the main goal was optimization. Despite these limitations, the author managed to adapt its work and optimization of Spirulina drying was achieved.

7 References

- Abbassi, A., Ali, M., & Watson, I. A. (2014). Temperature dependency of cell wall destruction of microalgae with liquid nitrogen pretreatment and hydraulic pressing. *Algal Research*, 5, 190-194. doi:<https://doi.org/10.1016/j.algal.2013.12.008>
- Allmicroalgae. (2022). About Us. Retrieved from <https://www.allmicroalgae.com/en/about-us/>
- Babu, A. K., Kumaresan, G., Raj, V. A. A., & Velraj, R. (2018). Review of leaf drying: Mechanism and influencing parameters, drying methods, nutrient preservation, and mathematical models. *Renewable and Sustainable Energy Reviews*, 90, 536-556. doi:<https://doi.org/10.1016/j.rser.2018.04.002>
- Benelhadj, S., Gharsallaoui, A., Degraeve, P., Attia, H., & Ghorbel, D. (2016). Effect of pH on the functional properties of *Arthrospira* (Spirulina) platensis protein isolate. *Food Chemistry*, 194, 1056-1063. doi:<https://doi.org/10.1016/j.foodchem.2015.08.133>
- Bennett, A., & Bogorad, L. (1973). Complementary chromatic adaptation in a filamentous blue-green alga. *The Journal of cell biology*, 58(2), 419-435. doi:<https://doi.org/10.1083/jcb.58.2.419>
- Block, B. (2020). *Manual de Instruções - Secadores BLACK BLOCK*. Retrieved from https://fialhostore.com/storage/media/store/656_20200504014654_pdf_products.pdf
- Bos, R., van der Mei, H. C., & Busscher, H. J. (1999). Physico-chemistry of initial microbial adhesive interactions - its mechanisms and methods for study. *FEMS Microbiology Reviews*, 23(2), 179-230. doi:<https://doi.org/10.1111/j.1574-6976.1999.tb00396.x>
- Bourne, M. C., & Szczesniak, A. S. (2003). SENSORY EVALUATION | Texture. In B. Caballero (Ed.), *Encyclopedia of Food Sciences and Nutrition (Second Edition)* (pp. 5167-5174). Oxford: Academic Press doi:<https://doi.org/10.1016/B0-12-227055-X/01067-1>.
- Chan, Y., Dyah, N., & Abdullah, K. (2015). Performance of a Recirculation Type Integrated Collector Drying Chamber (ICDC) Solar Dryer. *Energy Procedia*, 68, 53-59. doi:<https://doi.org/10.1016/j.egypro.2015.03.232>
- Cuellar-Bermudez, S. P., Kilimtzidi, E., Devaere, J., Goiris, K., Gonzalez-Fernandez, C., Wattiez, R., & Muylaert, K. (2020). Harvesting of *Arthrospira platensis* with helicoidal and straight trichomes using filtration and centrifugation. *Separation Science and Technology*, 55(13), 2381-2390. doi:<https://doi.org/10.1080/01496395.2019.1624573>
- Delattre, C., Pierre, G., Laroche, C., & Michaud, P. (2016). Production, extraction and characterization of microalgal and cyanobacterial exopolysaccharides. *Biotechnology Advances*, 34(7), 1159-1179. doi:<https://doi.org/10.1016/j.biotechadv.2016.08.001>
- Desmorieux, H., & Hernandez, F. (2004). *Biochemical and physical criteria of Spirulina after different drying processes*, São Paulo.
- El Hage, H., Herez, A., Ramadan, M., Bazzi, H., & Khaled, M. (2018). An investigation on solar drying: A review with economic and environmental assessment. *Energy*, 157, 815-829. doi:<https://doi.org/10.1016/j.energy.2018.05.197>
- English, J. (2017). Vacuum presses: Commercial and shop-built solutions. Retrieved from <https://www.woodshopnews.com/tools-machines/vacuum-presses-commercial-and-shop-built-solutions>
- Gilbertson, J. A. (2019). 15 - Amyloid. In S. K. Suvarna, C. Layton, & J. D. Bancroft (Eds.), *Bancroft's Theory and Practice of Histological Techniques (Eighth Edition)* (pp. 231-253): Elsevier doi:<https://doi.org/10.1016/B978-0-7020-6864-5.00015-3>.

- González-Camejo, J., Viruela, A., Ruano, V., Barat, R., Seco, A., & Ferrer, J. (2019). Dataset to assess the shadow effect of an outdoor microalgae culture. *Data in Brief*, 25, 104-143. doi:<https://doi.org/10.1016/j.dib.2019.104143>
- Hii, C. L., Abdul Rahman, R., Jinap, S., & Che Man, Y. B. (2006). Quality of cocoa beans dried using a direct solar dryer at different loadings. *Journal of the Science of Food and Agriculture*, 86(8), 1237-1243. doi:<https://doi.org/10.1002/jsfa.2475>
- Hosseinizand, H., Sokhansanj, S., & Lim, C. J. (2018). Studying the drying mechanism of microalgae *Chlorella vulgaris* and the optimum drying temperature to preserve quality characteristics. *Drying Technology*, 36(9), 1049-1060. doi:<https://doi.org/10.1080/07373937.2017.1369986>
- Jańczuk, B., Chibowski, E., Bruque, J. M., Kerkeb, M. L., & Caballero, F. (1993). On the Consistency of Surface Free Energy Components as Calculated from Contact Angles of Different Liquids: An Application to the Cholesterol Surface. *Journal of Colloid and Interface Science*, 159, 421-428. doi:<https://doi.org/10.1006/jcis.1993.1342>
- Jeevanandam, J., & Danquah, M. K. (2020). Chapter 9 - Dewatering and drying of algal cultures. In E. Jacob-Lopes, M. M. Maroneze, M. I. Queiroz, & L. Q. Zepka (Eds.), *Handbook of Microalgae-Based Processes and Products* (pp. 207-224): Academic Press doi:<https://doi.org/10.1016/B978-0-12-818536-0.00009-9>.
- Khan, M. I., Shin, J. H., & Kim, J. D. (2018). The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microbial Cell Factories*, 17(1), 36. doi:<https://doi.org/10.1186/s12934-018-0879-x>
- Khanra, S., Mondal, M., Halder, G., Tiwari, O. N., Gayen, K., & Bhowmick, T. K. (2018). Downstream processing of microalgae for pigments, protein and carbohydrate in industrial application: A review. *Food and Bioproducts Processing*, 110, 60-84. doi:<https://doi.org/10.1016/j.fbp.2018.02.002>
- Kong, D., Wang, Y., Li, M., Keovisar, V., Huang, M., & Yu, Q. (2020). Experimental study of solar photovoltaic/thermal (PV/T) air collector drying performance. *Solar Energy*, 208, 978-989. doi:<https://doi.org/10.1016/j.solener.2020.08.067>
- Kumar, S., & Deshmukh, R. (2021). Microalgae Market by Type (Spirulina, Chlorella, Dunaliella Salina, and Aphanizomenon Flos-Aquae), Application (Dietary Supplements, Food/Feed, Pharmaceutical, Cosmetic, and Others): Global Opportunity Analysis and Industry Forecast 2021-2028. Retrieved from <https://www.alliedmarketresearch.com/microalgae-market-A13419>
- Lamrani, B., Khouya, A., & Draoui, A. (2019). Energy and environmental analysis of an indirect hybrid solar dryer of wood using TRNSYS software. *Solar Energy*, 183, 132-145. doi:<https://doi.org/10.1016/j.solener.2019.03.014>
- Limrujiwat, K., Supan, S., & Khetkorn, W. (2022). Cyanobacterial biodiversity from Thai karstic caves as a potential source for phycobiliprotein production. *Algal Research*, 64, 102666. doi:<https://doi.org/10.1016/j.algal.2022.102666>
- Lingayat, A. B., Chandramohan, V. P., Raju, V. R. K., & Meda, V. (2020). A review on indirect type solar dryers for agricultural crops - Dryer setup, its performance, energy storage and important highlights. *Applied Energy*, 258, 114005. doi:<https://doi.org/10.1016/j.apenergy.2019.114005>
- Lowry, O. H., Rosebrough, N. J., Farr, A. L., & Randall, R. J. (1951). Protein measurement with the Folin phenol reagent. *Journal of Biological Chemistry*, 193(1), 265-275. doi:[https://doi.org/10.1016/S0021-9258\(19\)52451-6](https://doi.org/10.1016/S0021-9258(19)52451-6)
- Lv, J., Zhao, F., Feng, J., Liu, Q., Nan, F., & Xie, S. (2019). Extraction of extracellular polymeric substances (EPS) from a newly isolated self-flocculating microalga *Neocystis*

- mucosa* SX with different methods. *Algal Research*, 40, 101479. doi:<https://doi.org/10.1016/j.algal.2019.101479>
- Martínez-Sanz, M., Garrido-Fernández, A., Mijlkovic, A., Krona, A., Martínez-Abad, A., Coll-Marqués, J. M., . . . Lopez-Sanchez, P. (2020). Composition and rheological properties of microalgae suspensions: Impact of ultrasound processing. *Algal Research*, 49, 101960. doi:<https://doi.org/10.1016/j.algal.2020.101960>
- Molobela, I., Cloete, T., & Beukes, M. (2010). Protease and amylase enzymes for biofilm removal and degradation of extracellular polymeric substances (EPS) produced by *Pseudomonas fluorescens* bacteria. *African Journal of Microbiology Research*, 4. doi:<https://doi.org/10.5897/AJMR>
- Narala, R. R., Garg, S., Sharma, K. K., Thomas-Hall, S. R., Deme, M., Li, Y., & Schenk, P. M. (2016). Comparison of Microalgae Cultivation in Photobioreactor, Open Raceway Pond, and a Two-Stage Hybrid System. *Frontiers in Energy Research*, 4. doi:<https://doi.org/10.3389/fenrg.2016.00029>
- Neves, F., Demarco, M., & Tribuzi, G. (2019). Drying and Quality of Microalgal Powders for Human Alimentation *Microalgae - From Physiology to Application*. IntechOpen doi:<https://doi.org/10.5772/intechopen.89324>.
- Nitsos, C., Filali, R., Taidi, B., & Lemaire, J. (2020). Current and novel approaches to downstream processing of microalgae: A review. *Biotechnology Advances*, 45, 107650. doi:<https://doi.org/10.1016/j.biotechadv.2020.107650>
- Oliveira, E. G., Rosa, G. S., Moraes, M. A., & Pinto, L. A. A. (2009). Characterization of thin layer drying of *Spirulina platensis* utilizing perpendicular air flow. *Bioresource Technology*, 100(3), 1297-1303. doi:<https://doi.org/10.1016/j.biortech.2008.05.052>
- Paar, A. (2022). Amplitude sweeps. Retrieved from <https://wiki.anton-paar.com/en/amplitude-sweeps/>
- Peters, M. S., Timmerhaus, K. D., & West, R. E. (2002). Analysis of Cost Estimation. In McGraw-Hill (Ed.), *Plant Design and Economics for Chemical Engineers* (Fifth edition ed.). New York: McGraw-Hill Education
- Phelan, R. M. (2019). Hydraulic press. doi:<https://doi.org/10.1036/1097-8542.327000>
- Proenol. (2019). *Glucan*. Retrieved from https://www.proenol.com/web/files/fichas/FT1027-01_Lallzyme_Process_Glucan_PT.pdf?PDF
- Proenol. (2020a). *Lallzyme EX-V*. Retrieved from https://www.proenol.com/web/files/fichas/FT0053-09_Lallzyme_EX_V_PT.pdf?PDF
- Proenol. (2020b). *Prozym*. Retrieved from https://www.proenol.com/web/files/fichas/FT0622-03_Prozym_Flot_PT.pdf?PDF
- ProFuture. (2020). Could solar drying make the drying of microalgae proteins more sustainable and affordable? Retrieved from <https://www.pro-future.eu/blog/solar-drying-microalgae>
- Reyes, A., Bubnovich, V., Bustos, R., Vásquez, M., Vega, R., & Scheuermann, E. (2010). Comparative Study of Different Process Conditions of Freeze Drying of 'Murtilla' Berry. *Drying Technology*, 28, 1416-1425. doi:<https://doi.org/10.1080/07373937.2010.482687>
- Sandle, T. (2013). 10 - Sterilisation by filtration. In T. Sandle (Ed.), *Sterility, Sterilisation and Sterility Assurance for Pharmaceuticals* (pp. 143-155): Woodhead Publishing doi:<https://doi.org/10.1533/9781908818638.143>.
- Schmid, B., Navalho, S., Schulze, P. S. C., Van De Walle, S., Van Royen, G., Schüler, L. M., . . . Cavaco Rodrigues, A. M. (2022). Drying Microalgae Using an Industrial Solar Dryer: A Biomass Quality Assessment. *Foods*, 11(13). doi:<https://doi.org/10.3390/foods11131873>

- Silva, J. P. S., Veloso, C. R. R., de Souza Barrozo, M. A., & Vieira, L. G. M. (2021). Indirect solar drying of *Spirulina platensis* and the effect of operating conditions on product quality. *Algal Research*, 60, 102521. doi:<https://doi.org/10.1016/j.algal.2021.102521>
- Singh, R. P., & Heldman, D. R. (2014). Chapter 12 - Dehydration. In R. P. Singh & D. R. Heldman (Eds.), *Introduction to Food Engineering (Fifth Edition)* (pp. 675-710). San Diego: Academic Press doi:<https://doi.org/10.1016/B978-0-12-398530-9.00012-7>.
- Soni, R. A., Sudhakar, K., & Rana, R. S. (2019). Comparative study on the growth performance of *Spirulina platensis* on modifying culture media. *Energy Reports*, 5, 327-336. doi:<https://doi.org/10.1016/j.egy.2019.02.009>
- Stramarkou, M., Papadaki, S., Kyriakopoulou, K., Tzovenis, I., Chronis, M., & Krokida, M. (2021). Comparative Analysis of Different Drying Techniques Based on the Qualitative Characteristics of *Spirulina platensis* Biomass. *Journal of Aquatic Food Product Technology*, 30(5), 498-516. doi:<https://doi.org/10.1080/10498850.2021.1900969>
- Taguet, A. (2020). Chapter 16 - Rheological characterization of compatibilized polymer blends. In A. A.R & S. Thomas (Eds.), *Compatibilization of Polymer Blends* (pp. 453-487): Elsevier doi:<https://doi.org/10.1016/B978-0-12-816006-0.00016-5>.
- van Oss, C. J. (1994). *Interfacial Forces in Aqueous Media*: Taylor & Francis
- Varun, Sunil, Sharma, A., & Sharma, N. (2012). Construction and Performance Analysis of an Indirect Solar Dryer Integrated with Solar Air Heater. *Procedia Engineering*, 38, 3260-3269. doi:<https://doi.org/10.1016/j.proeng.2012.06.377>
- Vázquez-Romero, B., Perales, J. A., Pereira, H., Barbosa, M., & Ruiz, J. (2022). Techno-economic assessment of microalgae production, harvesting and drying for food, feed, cosmetics, and agriculture. *Science of The Total Environment*, 837, 155742. doi:<https://doi.org/10.1016/j.scitotenv.2022.155742>
- Zhang, H., Gong, T., Li, J., Pan, B., Hu, Q., Duan, M., & Zhang, X. (2022). Study on the Effect of Spray Drying Process on the Quality of Microalgal Biomass: a Comprehensive Biocomposition Analysis of Spray-Dried *S. acuminatus* Biomass. *BioEnergy Research*, 15. doi:<https://doi.org/10.1007/s12155-021-10343-8>
- Zhu, L., Li, Z., & Hiltunen, E. (2018). Microalgae *Chlorella vulgaris* biomass harvesting by natural flocculant: effects on biomass sedimentation, spent medium recycling and lipid extraction. *Biotechnology for Biofuels*, 11(1), 183. doi:<https://doi.org/10.1186/s13068-018-1183-z>

Appendix A. Behavior of the organic biomass

The present section concerns a complementary study on the behavior of the organic biomass at the beginning of the dissertation, in the months of March and April of 2022. This section is divided into 3 subsections: problem presentation, materials and methods, and results and discussion.

A.1 Problem Presentation

Since the optimal temperature range for the growth of Spirulina is between 25-30 °C, the industrial production and processing started in May 2022. During the months of March and April, the focus of the company was to solve the problem that persisted in 2021. Spirulina grown in organic and non-organic medium (grown in pre-production reactors) exhibited different behaviors during extrusion, which can be observed in Figure A1.

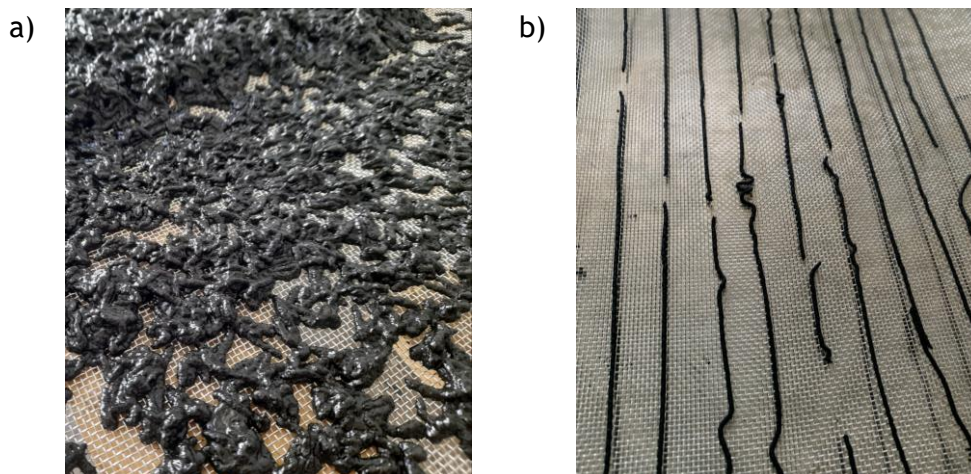


Figure A1 Spirulina biomass displays different behaviors upon extrusion onto a stainless steel tray: a) organic biomass; b) non-organic biomass.

To address the different behaviors of organic and non-organic biomass, four main studies were performed: microscopic observations of exopolysaccharides (EPS), enzymatic and alkaline treatments, determination of adhesive interactions, and rheological analysis. The goal was to identify what factor was influencing the behavior of the organic biomass. However, the company decided to change the composition of the organic culture medium and this problem was overcome.

A.2 Materials and Methods

A.2.1 Microscopic observations of exopolysaccharides

Microscope observations of EPS in Spirulina cultures were performed in the fermentation lab of the R&D unit of Allmicroalgae's facilities. Samples were stained with Alcian blue at a ratio of 1:1 and examined by optical microscopy (Axio Scope A1, ZEISS, Oberkochen, Germany) at 10× magnification.

A.2.2 Enzymatic and alkaline treatments

Enzymatic treatments were carried out using three mixtures of enzymes: Glucan (Proenol), Vintage (Proenol), and Prozym (Proenol). Spirulina paste was diluted in a proportion of 1:10 with distilled water to the final concentration of 20 g L⁻¹. 0.1 g_{enzymatic mix} mL⁻¹ of distilled water was prepared at room temperature. The diluted biomass was mixed with the enzymatic solution at the proportion 1:1 and mixed for 2 minutes. Alkaline treatment was carried out using 1M NaOH solution and following the procedure of Lv et al. (2019). The alkaline solution was added to the diluted biomass solution, until reaching 12.5 pH.

A.2.3 Adhesive interactions

To address adhesion of the pastes to the stainless steel, the free energy of adhesion ($\Delta G^{adhesion}$) was calculated. According to Bos et al. (1999), the adhesion of the paste to the working material is favorable to occur from a free energy point of view, when is negative, but energetically unfavorable when is positive.

$\Delta G^{adhesion}$ (mJ m⁻²) was determined using Equation (I), where γ_{sb}^{Tot} (mJ m⁻²), γ_{bw}^{Tot} (mJ m⁻²), and γ_{sw}^{Tot} (mJ m⁻²) are the paste-steel, steel-water, and paste-water interfacial free energies, respectively (Bos et al., 1999).

$$\Delta G^{adhesion} = \gamma_{sb}^{Tot} - \gamma_{bw}^{Tot} - \gamma_{sw}^{Tot} \quad (I)$$

The interfacial free energy was calculated with the Lifshitz-van der Waals acid-base approach. According to this model, γ^{Tot} (mJ m⁻²) is the sum of the Lifshitz-van der Waals, γ^{LW} (mJ m⁻²), and Lewis acid-base components, γ^{AB} (mJ m⁻²), as presented in Equation (II) (van Oss, 1994).

$$\gamma^{Tot} = \gamma^{LW} + \gamma^{AB} \quad (II)$$

The Lifshitz-van der Waals and Lewis acid-base components were calculated with Equations (III) and (IV), taking the paste-steel interaction as example. The other two were calculated by replacing with the respective variables. The acid-base interaction component incorporates the electron acceptor, γ^+ (mJ m⁻²), and electron donor, γ^- (mJ m⁻²), parameters of the substances involved (Bos et al., 1999).

$$\gamma_{sb}^{LW} = \left(\sqrt{\gamma_b^{LW}} - \sqrt{\gamma_s^{LW}} \right)^2 \quad (\text{III})$$

$$\gamma_{sb}^{AB} = 2 \left(\sqrt{\gamma_s^+ \gamma_s^-} + \sqrt{\gamma_b^+ \gamma_b^-} - \sqrt{\gamma_s^+ \gamma_b^-} - \sqrt{\gamma_b^+ \gamma_s^-} \right) \quad (\text{IV})$$

The surface energy components of the two solid pastes (s) were obtained by measuring the contact angles, θ ($^\circ$), with three reference liquids (l): water, formamide, and α -bromonaphtalene (Sigma). Contact angles measurements were carried out at the Biofilm Engineering Lab at the Faculty of Engineering of the University of Porto. The contact angles were determined automatically by the sessile drop method in a contact angle meter (OCA 15 Plus, Dataphysics, Filderstadt, Germany). Contact angles were measured at room temperature and evaluated with the software SCA20-F.

After measuring the contact angles, γ_s^{LW} , γ_s^+ , and γ_s^- were calculated by the simultaneous resolution of three equations of the type of Equation (V).

$$(1 + \cos \theta) \gamma_l = 2 \left(\sqrt{\gamma_s^{LW} \gamma_l^{LW}} + \sqrt{\gamma_s^+ \gamma_l^-} + \sqrt{\gamma_s^- \gamma_l^+} \right) \quad (\text{V})$$

Surface energy components of water, bromonaphtalene, formamide, and 316 stainless steel were taken from literature and are shown in Table A1.

Table A1 Surface energy components of water, bromonaphtalene, formamide, and 316 stainless steel (Jańczuk et al., 1993).

	γ_l^{LW} (mJ m ⁻²)	γ_l^+ (mJ m ⁻²)	γ_l^- (mJ m ⁻²)	γ_l^{AB} (mJ m ⁻²)	γ_l^{Tot} (mJ m ⁻²)
Water	21.8	25.5	25.5	51.0	72.8
Bromonaphtalene	44.4	0.0	0.0	0.0	44.4
Formamide	39.00	2.28	39.60	19.00	58.00
316 stainless steel	40.87	0.00	0.95	0.00	40.87

A.2.4 Rheology

Rheological studies were carried out at the Department of Chemical Engineering at the Faculty of Engineering of the University of Porto. The measurements were performed at a constant temperature of 20 °C using the Anton-Paar MCR 92 plate-plate rheometer (Anton-Paar Germany GmbH, Ostfildern, Germany) controlled by the RheoCompass™ software. The equipment was set in controlled shear rate (CSR) mode.

To obtain flow and viscosity curves, 18 points were collected in the shear rate range of 0.01-100 s⁻¹. In flow curves, the shear rate, $\dot{\gamma}$ (s⁻¹), is plotted on the x-axis and the shear stress,

τ (Pa), is plotted on the y-axis. In viscosity curves, $\dot{\gamma}$ is plotted on the x-axis and the dynamic viscosity, η (Pa s) is plotted on the y-axis. In these plots, both axes are presented on a logarithmic scale.

After obtaining the graphs, each one of the flow curves was adjusted to a power law function, according to Equation (VI), in which K (Pa s ^{$m-1$}) is the flow consistency index and m is the flow behavior index.

$$\tau = K\dot{\gamma}^m \quad (\text{VI})$$

The rheological stability of the biomass was evaluated by amplitude sweep tests. 25 points were collected at a constant angular frequency, ω , of 10 s⁻¹. Storage modulus, G' (Pa), and loss modulus, G'' (Pa), were plotted on the y-axis and shear stress, τ (Pa), on the x-axis. The yield points, τ_y , and crossover points, τ_f , were identified. τ_y is the shear stress which marks the end of the plateau of the G' function. For τ values under τ_y , the paste has more stiffness, while for τ values above τ_y , the paste starts to soften. τ_f is the shear stress at which G' and G'' curves crossover. For τ values between τ_y and τ_f , micro cracks start to develop, and the deformation energy is lost. The broken fragments around the cracks start to show internal viscous friction leading to the conversion of deformation energy into friction heat. For τ values above τ_f , micro cracks form macro cracks that contribute to the dominance of the viscous response over the elastic response, which initiates the flow of the paste (Paar, 2022).

A.3 Results and Discussion

A.3.1 Microscopic observations of exopolysaccharides

Microscopic observations (MOs) of organic and non-organic Spirulina biomass stained by Alcian blue are shown in Figure A2. MOs were performed on concentrate and filtrate samples obtained after sieving.

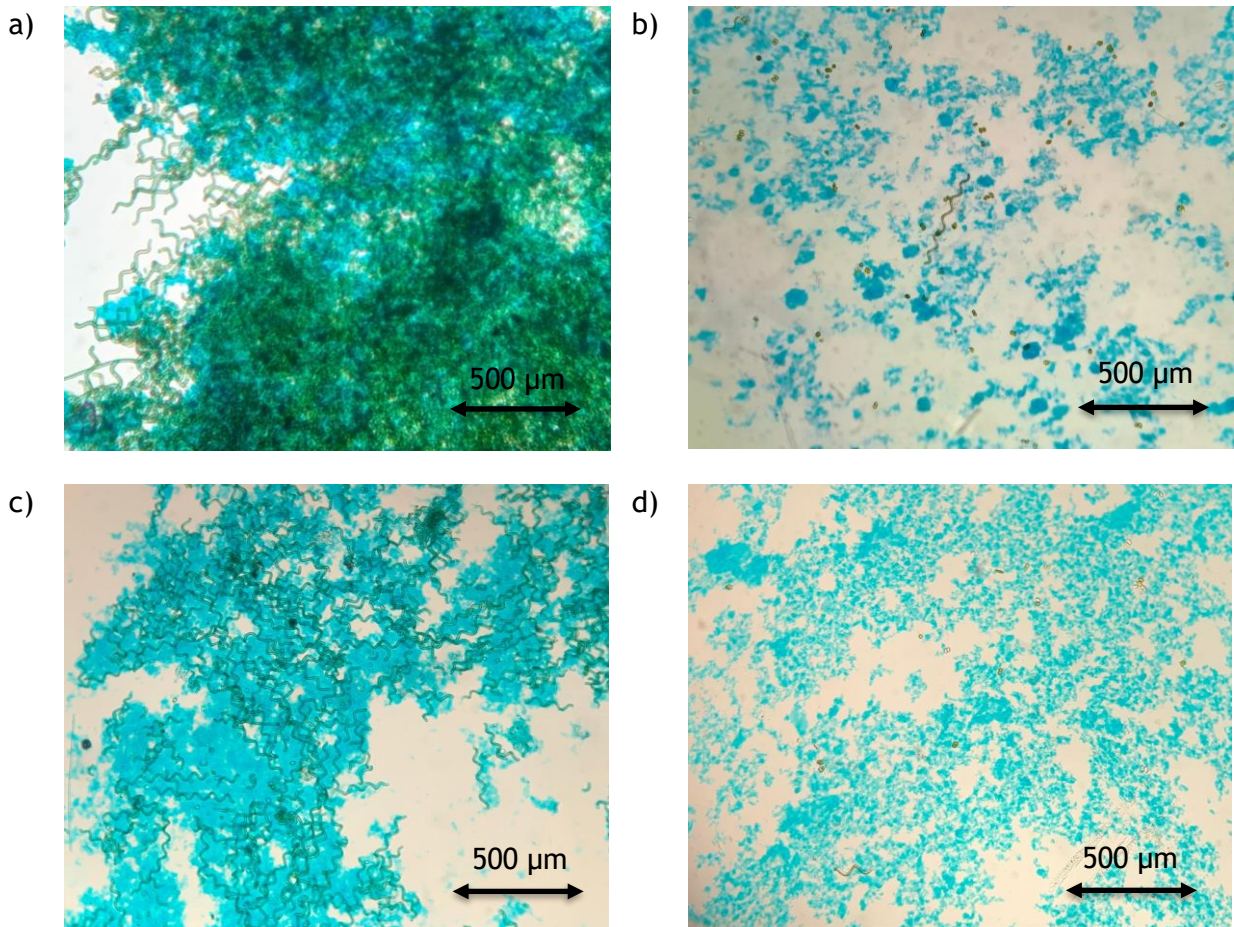


Figure A2 Microscopic observations of a) organic concentrate, b) organic filtrate, c) non-organic concentrate, and d) non-organic filtrate of Spirulina cells stained with Alcian blue.

Both organic and non-organic concentrates showed EPS associated with the surface of Spirulina cells, while filtrates showed EPS released into the extracellular medium. These observations were in agreement with the studies of Delattre et al. (2016).

As the filtrate was recycled back to the raceway, the focus was on the concentrate. MOs suggest that the organic concentrate had more EPS, which would explain the more accentuated shear-thinning behavior; still, no definite conclusions could be drawn by these observations since Alcian blue is not specific for spirulan, Spirulina's EPS, but rather it identifies the entire class of acid mucopolysaccharides (Gilbertson, 2019).

A.3.2 Enzymatic and alkaline treatments

Attempts to remove EPS from the matrix were made, without compromising cellular integrity, as described in section A.2.2. MOs of Spirulina paste after treatments with Glucan, Prozym, Vintage, and NaOH are presented in Figure A3.

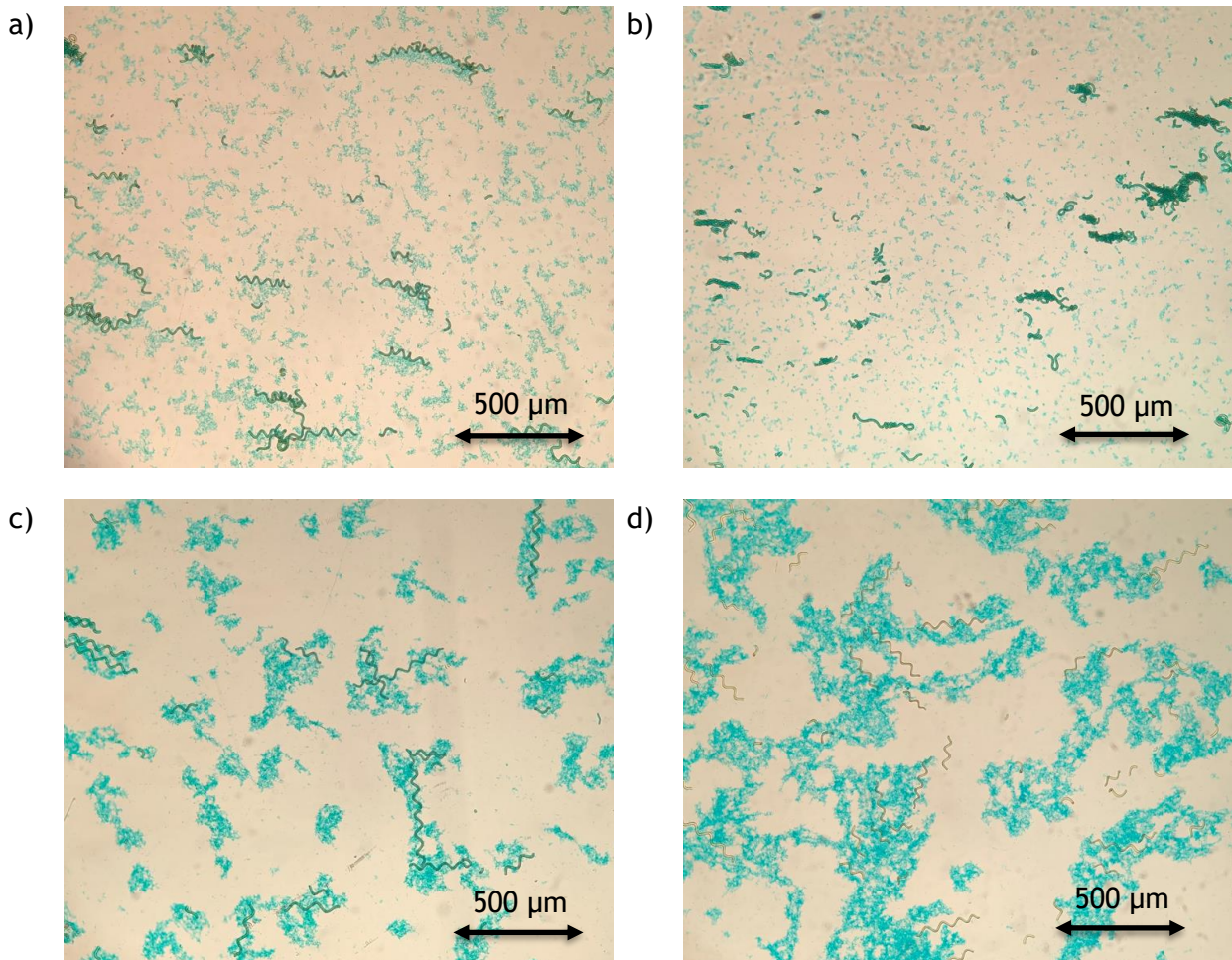


Figure A3 Microscope observations of *Spirulina* paste after treatment with a) Glucan, b) Prozym, c) Vintage, and d) NaOH.

Literature suggests that mixtures of enzymes are often used to degrade EPS in biofilms. For example, protease and amylase enzymes efficiently degrade EPS produced by *Pseudomonas fluorescens* bacteria (Molobela et al., 2010). Since there is a lack of literature regarding which enzymes are the most suitable for removing EPS associated with *Spirulina*, biomass was treated with different mixtures of enzymes. Glucan, Prozym, and Vintage are enzyme cocktails commonly used in the wine industry and are safe for human consumption. Starting with the composition of Glucan, it consists of β -glucanases (Proenol, 2019). Prozym is a mixture of polygalacturonases and pectinesterases (Proenol, 2020b). Vintage is a mixture of cellulases, hemicellulases and pectolytic enzymes, namely pectin lyases, polygalacturonases, and pectinesterases (Proenol, 2020a).

Besides enzymatic treatments, other procedures were considered. Lv et al. (2019) performed different treatments to extract EPS from a new strain of *Neocystis mucosa*: cation exchange resin, EDTA, heating, acidic treatment, and alkaline treatment. On an industrial scale, cation exchange is not a viable solution due to its high cost. EDTA is not considered a bio reagent, which is one of the commercial demands of the product. Introducing a heating step in the

downstream would require additional equipment and labor. Although an acidic treatment is easy to implement as it only requires the addition of a reagent to the paste, it would cause cell lysis. An alkaline treatment would be more adequate as the optimal pH for Spirulina ranges between 8.5 and 11 (Benelhadj et al., 2016). For this reason, the alkaline treatment with NaOH was chosen.

MOs in Figure A3 suggest that all treatments caused cell rupture, especially using Glucan and Prozym mixtures. Despite damaging the cellular integrity, Glucan and Prozym caused the detachment of EPS from the surface of the cells, while Vintage and NaOH did not. When comparing the composition of each cocktail, it would be expected that the Vintage mixture had a similar effect as Prozym, since not only has the same pectolytic enzymes, but also additional ones. On a macroscopic level, all treatments caused changes in the color of the solution, which suggests the extraction of other components besides EPS.

These results suggest that none of these strategies is suitable to be implemented on an industrial scale to remove EPS from Spirulina since they all compromised cell integrity, and as a consequence reduced the commercial value of the biomass.

A.3.3 Adhesive interactions

Adhesive interactions between the biomass and the working surface, in this case the stainless-steel trays, were studied. Contact angles formed between the biomass and the reference liquids were determined as described in section A.2.3. The contact angles formed using water and formamide were considered null, as the drops were immediately absorbed by the paste. This demonstrates the highly hydrophilic behavior of both pastes. The contact angles formed using bromonaphtalene were $(34.55 \pm 2.68)^\circ$ and $(31.71 \pm 5.65)^\circ$ ($n=10$) for organic and non-organic biomass, respectively. Surface energy components of the organic and non-organic biomass were calculated using the contact angles and results are shown in Table A2.

Table A2 Surface energy components of the organic and non-organic biomass.

	$\gamma_s^{LW} (\text{mJ m}^{-2})$	$\gamma_s^+ (\text{mJ m}^{-2})$	$\gamma_s^- (\text{mJ m}^{-2})$	$\gamma_s^{AB} (\text{mJ m}^{-2})$	$\gamma_s^{Tot} (\text{mJ m}^{-2})$
Organic	36.9	2.0	54.6	20.9	57.8
Non-organic	38.0	1.8	54.7	19.6	57.6

These values show that both pastes had a similar total surface energy, γ_s^{Tot} .

Intermediate values for the determination of the free energy of adhesion were calculated and are shown in Table A3.

Table A3 Lifshitz-van der Waals (^{LW}) components, Lewis acid-base (^{AB}) components, respective interfacial free energies (^{Tot}) of paste-steel ($_{sb}$), steel-water ($_{bw}$), and paste-water ($_{sw}$) of organic and non-organic biomass.

	Organic	Non-organic
γ_{sb}^{LW} (mJ m $^{-2}$)	0.1	0.1
γ_{sb}^{AB} (mJ m $^{-2}$)	18.2	17.0
γ_{sb}^{Tot} (mJ m $^{-2}$)	18.3	17.1
γ_{bw}^{LW} (mJ m $^{-2}$)	2.0	2.2
γ_{bw}^{AB} (mJ m $^{-2}$)	-17.0	-17.5
γ_{bw}^{Tot} (mJ m $^{-2}$)	-15.0	-15.3
γ_{sw}^{LW} (mJ m $^{-2}$)	3.0	3.0
γ_{sw}^{AB} (mJ m $^{-2}$)	41.1	41.2
γ_{sw}^{Tot} (mJ m $^{-2}$)	44.1	44.2

The free energy of adhesion of both pastes was calculated using Equation (I). Organic paste had a value of $\Delta G^{adhesion}$ of -10.9 mJ m $^{-2}$, while non-organic paste had a value of -11.8 mJ m $^{-2}$. This result was not in agreement with what was observed regarding the behavior of both pastes. Visually, the organic biomass adhered more to stainless steel than the non-organic one. For this reason, it was expected that the organic biomass had a substantially more negative value of $\Delta G^{adhesion}$. These results could be explained by the fact that the contact angles registered for the non-organic biomass were more dispersed than those of the organic biomass. The method used to measure the contact angles is highly sensitive and strongly dependent on the operator, which reflects on its low precision.

A.3.4 Rheology

Since the rheological behavior of a material is highly affected by the quantity of water, it is important to present the moisture content associated with each paste. It should also be mentioned that the moisture content reached after each downstream step is not always constant. In the present work, organic biomass had a moisture content of $(91.60 \pm 0.64)\%$ before pressing, while non-organic biomass had a moisture content of $(91.26 \pm 0.38)\%$; the values were statistically equal ($p \leq 0.05$). After pressing, organic biomass had a moisture content of $(78.07 \pm 2.16)\%$, while the non-organic biomass had a moisture content of $(79.80 \pm 3.05)\%$; the values were statistically equal ($p \leq 0.05$). Figure A4 and Figure A5 show the flow and viscosity

curves, respectively, of the organic and non-organic biomass in different stages of the downstream process: before (Org1 and NOrg1) and after (Org2 and NOrg2) pressing.

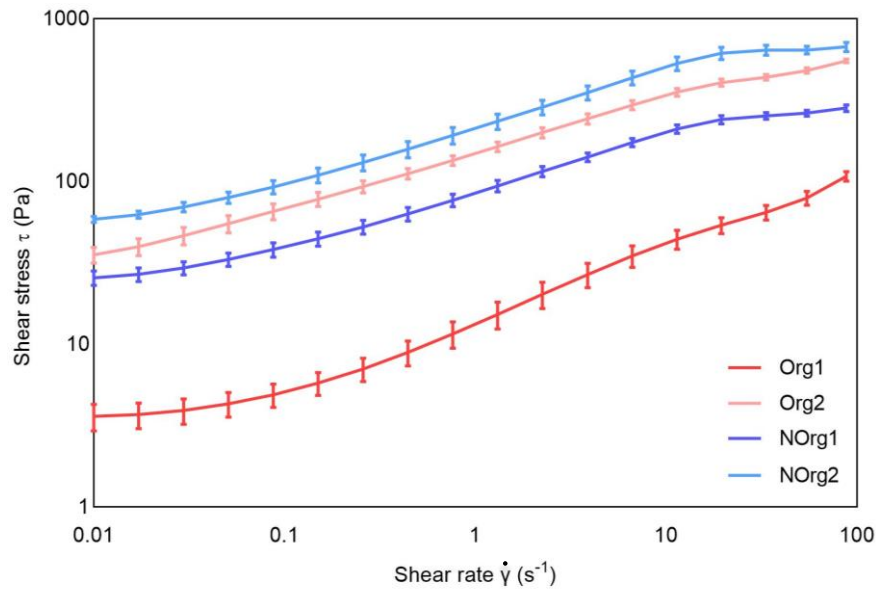


Figure A4 Flow curves for organic biomass, before (Org1) and after pressing (Org2), and non-organic biomass, before (NOrg1) and after pressing (NOrg2). Both axes are presented in logarithmic scale and curves are accompanied by error bars ($n=3$).

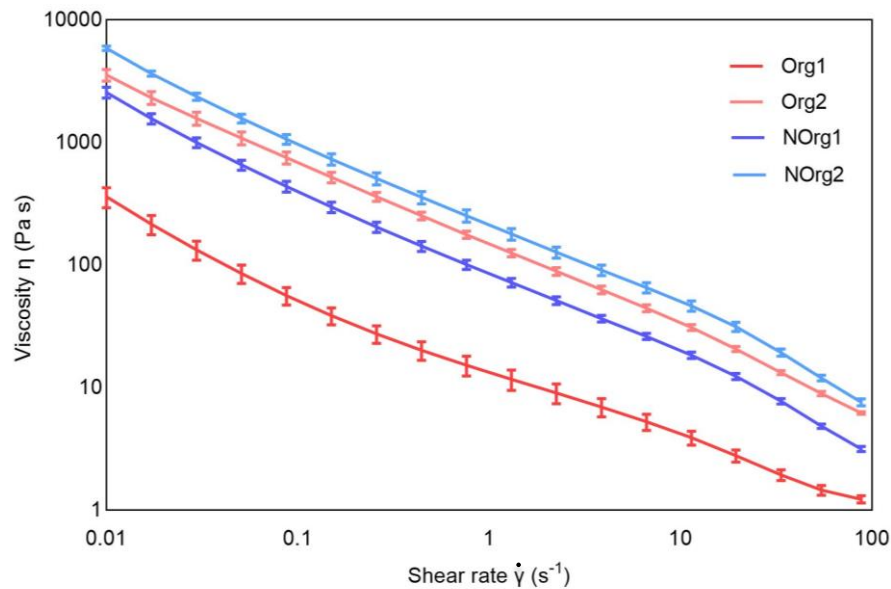


Figure A5 Viscosity curves of organic biomass, before (Org1) and after pressing (Org2), and non-organic biomass, before (NOrg1) and after pressing (NOrg2). Both axes are presented in logarithmic scale and curves are accompanied by error bars ($n=3$).

Figure A4 and Figure A5 suggest that all pastes displayed a behavior similar to that of a pseudoplastic with yield point, as viscosity decreased with increasing shear rate. Figure A5 shows that the viscosity of the organic biomass was highly affected by the amount of water. As

expected, the higher moisture content paste had a lower viscosity. The non-organic biomass with higher moisture content had a higher viscosity for smaller shear rates, but a lower viscosity for higher shear rates, in comparison to the organic biomass.

Flow curves were adjusted to the power law function described by Equation (VI) and the respective parameters and R^2 value are presented in Table A4.

Table A4 Power law parameters of the flow curves for organic biomass, before (Org1) and after pressing (Org2), and non-organic biomass, before (NOrg1) and after pressing (NOrg2).

	Org1	NOrg1	Org2	NOrg2
K	15.2	86.8	147	213
m	0.402	0.300	0.319	0.307
R^2	0.980	0.987	0.996	0.986

According to the values of R^2 , the power law function provided a good fitting to the flow curves of Spirulina paste.

The amplitude sweep tests were performed as described in section A.2.4. Results are shown in Figure A6.

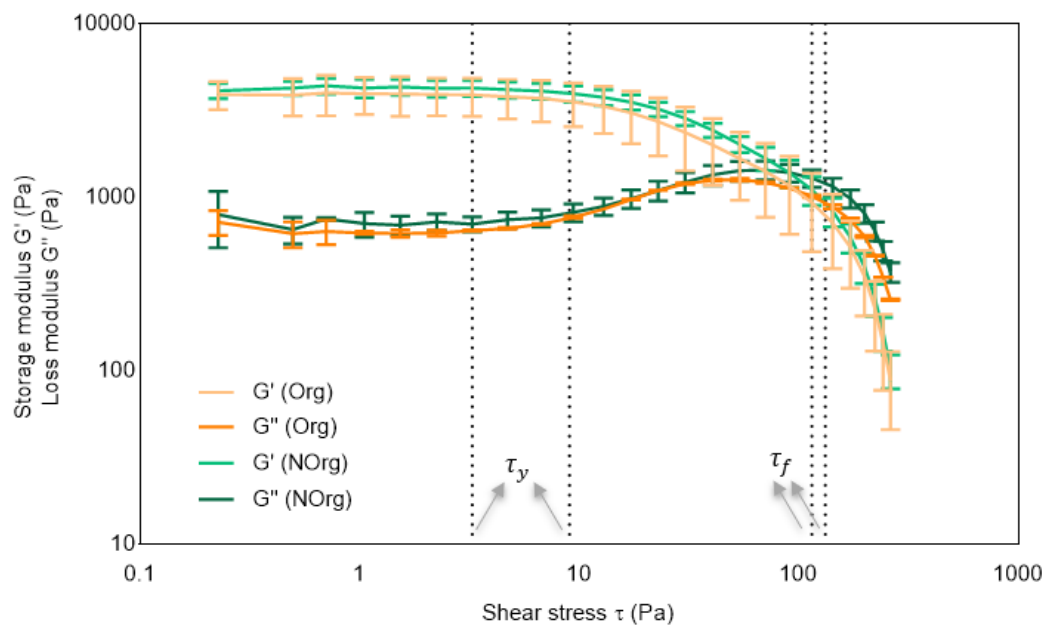


Figure A6 Amplitude sweep test results illustrating the variation of the storage modulus (G') and loss modulus (G'') with shear stress (τ) for the organic (Org) and non-organic (NOrg) biomass and identification of the yield points (τ_y) and crossover points (τ_f). Both axes are presented in logarithmic scale and curves are accompanied by error bars ($n=2$).

The τ_y value for the organic paste was 3.3 Pa, while for the non-organic paste was 9.0 Pa. This suggests that a higher shear stress needs to be applied to the non-organic paste to break its

stiffness and make it softer. The τ_f value for the organic paste was 114.6 Pa, while for the non-organic paste was 132.0 Pa. These results show that both pastes required approximately the same shear stress to flow, which suggests that the major difference in behavior was not a consequence of these properties.

Appendix B. Mass and energy balances

B.1. Drying time

The present subsection is based on Singh and Heldman (2014). According to section 2.3, the total drying time corresponds to the sum of the constant-rate period and the falling-rate period, as described by Equation (VII).

$$t_{drying} = t_{constant-rate} + t_{falling-rate} \quad (VII)$$

During the constant-rate drying period, thermal energy is used to cause phase change of water at the biomass surface. The rate of heat transfer, q (W), is given by Equation (VIII), where $\dot{m}_w$ ($\text{kg}_{\text{water}} \text{ s}^{-1}$) is rate of water evaporation and L_w is the latent heat of water ($\text{J kg}_{\text{water}}^{-1}$).

$$q = \dot{m}_w L_w \quad (VIII)$$

$\dot{m}_w$ is given by Equation (IX), where m_w ($\text{kg}_{\text{water}} \text{ kg}_{\text{dry solids}}^{-1}$) is the total amount of water evaporated during the constant-rate period.

$$\dot{m}_w = \frac{m_w}{t_{constant-rate}} \quad (IX)$$

m_w can be calculated by Equation (X), where m_p ($\text{kg}_{\text{dry solids}}$) is the mass of dry biomass, $MC_{initial}$ ($\text{kg}_{\text{water}} \text{ kg}_{\text{sample}}^{-1}$) and $MC_{critical}$ ($\text{kg}_{\text{water}} \text{ kg}_{\text{sample}}^{-1}$) are the initial and critical moisture content of the biomass on a wet basis, respectively.

$$m_w = \frac{m_p(MC_{initial} - MC_{critical})}{100 - MC_{critical}} \quad (X)$$

Combining Equations (VIII), (IX) and (X), the rate of heat transfer can be calculated by Equation (XI).

$$q = \frac{L_w}{t_{constant-rate}} \left[\frac{m_p(MC_{initial} - MC_{critical})}{100 - MC_{critical}} \right] \quad (XI)$$

During the constant-rate drying period, thermal energy is transported from the hot air to the surface of the biomass, while water vapor is transferred from the surface to the heated air. The rate of heat transfer, q (W), is given by Equation (XII), where h ($\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$) is the convective heat transfer coefficient, A (m^2) is the area of the product exposed to heated air, T_a ($^{\circ}\text{C}$) is the heated air temperature and T_s ($^{\circ}\text{C}$) is the biomass surface temperature. In the constant-rate drying period, this temperature is equal to the wet-bulb temperature of the heated air.

$$q = hA(T_a - T_s) \quad (XII)$$

By combining Equations (XI) and (XII), and solving for $t_{constant-rate}$, Equation (XIII) is obtained.

$$t_{constant-rate} = \frac{L_w}{hA(T_a - T_s)} \left[\frac{m_p(MC_{initial} - MC_{critical})}{100 - MC_{critical}} \right] \quad (XIII)$$

As observed by Equation (XIII), the time for constant-rate drying is proportional to the difference between the initial and critical moisture contents and is inversely proportional to the temperature gradient between the biomass surface and the air.

During the falling-rate period, moisture content decreases from the critical value to the equilibrium. The diffusion of moisture inside the biomass, the rate-controlling factor, is dependent on the product shape. Since biomass is extruded into long thin cylinders, its geometry can be approximated to that of an infinite cylinder. Equation (XIV) describes the time for falling-rate drying considering an infinite cylinder, where d_c (m) is the radius of the cylinder, β is first root of the zero-order Bessel function equation, with a value of 2.4048 and D ($m^2 s^{-1}$) is the effective mass diffusivity.

$$t_{falling-rate} = \frac{d_c^2}{\beta^2 D} \left[\frac{4}{\beta^2} \left(\frac{MC_{critical} - MC_{equilibrium}}{MC_{final} - MC_{equilibrium}} \right) \left(\frac{100 - MC_{final}}{100 - MC_{critical}} \right) \right] \quad (XIV)$$

By combining Equations (VII), (XIII) and (XIV), t_{drying} can be calculated according to Equation (XV).

The critical parameters in the calculation of drying time are h and D .

$$t_{drying} = \frac{L_w}{hA(T_a - T_s)} \left[\frac{m_p(MC_{initial} - MC_{critical})}{100 - MC_{critical}} \right] + \frac{d_c^2}{\beta^2 D} \left[\frac{4}{\beta^2} \left(\frac{MC_{critical} - MC_{equilibrium}}{MC_{final} - MC_{equilibrium}} \right) \left(\frac{100 - MC_{final}}{100 - MC_{critical}} \right) \right] \quad (XV)$$

B.2. Efficiencies

In indirect solar drying, only a part of the solar radiation incident on the solar collector is effectively used to heat the air (Silva et al., 2021). The thermal efficiency of the solar collector, η_c , can be calculated by Equation (XVI), where $\dot{m}_a$ is the air flow rate ($kg s^{-1}$), c_p is the air specific heat ($J kg^{-1} ^\circ C^{-1}$), T_i and T_o are the collector inlet and outlet air temperature ($^\circ C$), A_c is the collector area (m^2) and I_{out} is the solar irradiance ($W m^{-2}$) (Varun et al., 2012).

$$\eta_c = \frac{\dot{m}_a c_p (T_i - T_o)}{A_c I_{out}} \quad (XVI)$$

Considering that water evaporation occurs solely due to the incident solar radiation and the power of the heater, the efficiency of the drying chamber, η_d , can be calculated by Equation (XVII).

$$\eta_d = \frac{m_w L_w}{A_c I_{out} t_{drying}} \quad (XVII)$$

Appendix C. Weather conditions

Figure C1 is an example of the data collected by the Watchdog Weather Station at Allmicroalgae's premises, during a drying cycle from 30th June to 1st July. Solar irradiance, I_{out} (W m^{-2}), was plotted on the left y-axis, while outdoor air humidity, H_{out} (%), and outdoor air temperature, T_{out} ($^{\circ}\text{C}$), were plotted on the right y-axis.

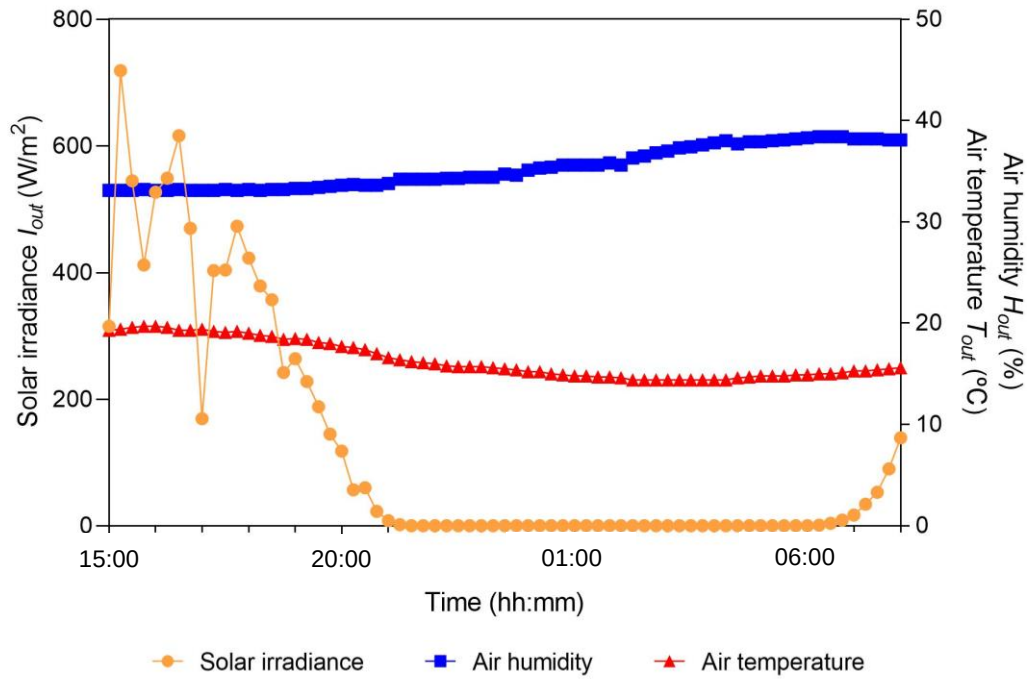


Figure C1 Solar irradiance (orange), air humidity (blue) and air temperature (red) measured by the Watchdog Weather Station at Allmicroalgae's premises, during a drying cycle from 30th June to 1st July.

The area under each curve was calculated by the trapezoidal rule. For this specific drying cycle, the integral of I_{out} was $2054 \text{ W}\cdot\text{h m}^{-2}$, the integral of H_{out} was $600 \text{ \%}\cdot\text{h}$, and the integral of T_{out} was $278 \text{ }^{\circ}\text{C}\cdot\text{h}$. The weighted averages of the outdoor air humidity and temperature were calculated by dividing the integrals by the total drying time (in this case, 17 hours). The weighted average of the solar irradiance was calculated by dividing the integral by the total daytime, which was obtained by subtracting 9 hours (nighttime) to the total drying time. For this specific drying cycle, the weighted averages of I_{out} , H_{out} and T_{out} were 257 W m^{-2} , 35.3% and $16.4 \text{ }^{\circ}\text{C}$. The same procedure was applied to the rest of the analyzed drying cycles.

