23th May 2024

Food and Feed for the future:

the role of microalgae as a sustainable ingredient

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Linking Landscape, Environment, Agriculture and Food (LEAF)
School of Agriculture - University of Lisbon

Summary

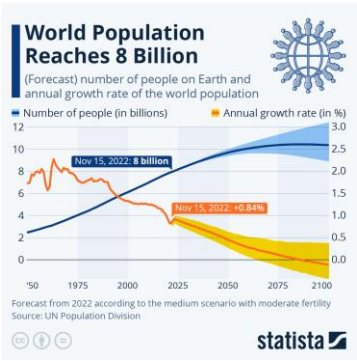
Sharp population growth: scarcity of water resources and arable land; Climate change; Protein shortage
Importance of finding **alternative food sources** - microalgae play a decisive role!

Moving from a domestic scale to a large-scale consumption?
3 strategies: low incorporation rates, Chemical and biochemical processes for deodorization and decolorization and Gastronomic science/ Disruptive Experiences

Case studies from the 3 different strategies
The impact of adding microalgae on the nutritional profile, texture characteristics, and final appearance of foods.

The importance of food-paring
Chromatographic and empirical approach

Avoid consumers having bad experiences with microalgae-based food



ALTERNATIVE FOOD SOURCES

2050 there will be 9 billion people on the planet!

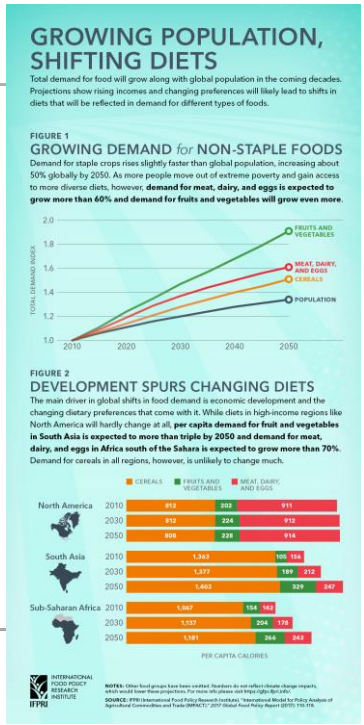
FAO estimates the production will have to rise by up to 70%, in order to have food available for all…

In the XXI century, food production is scarce and food prices assume significant increases

Sharp population growth → Resource scarcity

Thomas Malthus (1798) - At that time he realized that the supply of food did not keep pace with population growth.

Efficiency of agricultural production systems
Scarcity of water resources and arable land
Climate change
Protein shortage



It's already possible to find on the market...

marine protection | novel ingredients | plant-based

Trend 8. Oceans of Possibilities

The seas are developing into the farms of the future, providing inspiration alongside new, environmentally positive ingredient sources

drink blue.
act green.
feel renewed.
Harnessing nature's delicious blue spirulina to DETOX your body and the planet.

PLANET DETOX & RENEWAL
- FUL® Spirulina captures 2X its weight in CO2
- No arable land, fertilizers or pesticides required

Breathing life into our planet

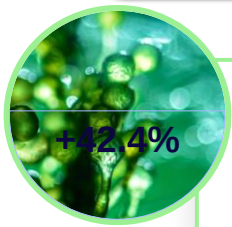
Refreshing our world

Resource Efficient

food ingredients 1st
31 Mar 2023

"Diving into untapped benefits of microalgae"

Plant-based *Natural* *Sustainable* *Highly nutritious*

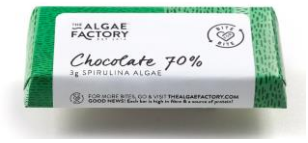


New food and beverage launches containing **microalgae** as an ingredient

(Global, CAGR 2020H2-2023H1)

Sources: Innova Database, Ful, Food Ingredients First

It's already possible to find on the market...



Moving from a domestic scale to a large-scale consumption?

Take into account food trends
Understand that microalgae have aromas and flavors that are not easy to accept
Avoid bad experiences with microalgae

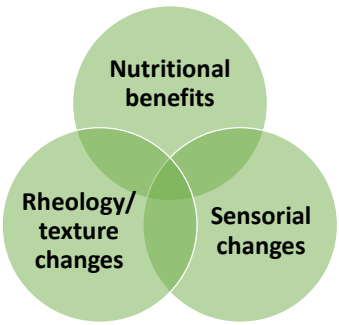
Consumers are not willing to pay for foods that are beneficial to health, are nutritionally rich, but are sensorial unpleasant!

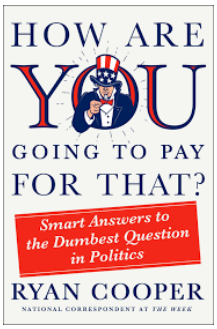
There are some examples of microalgae-containing foods produced at industrial scale, and even from scientific publications the solution to overcome sensory issues is often the inclusion of algae **at low concentrations**.

Moving from a domestic scale to a large-scale consumption?

Are the consumers prepared?

Sharp increase in microalgae consumption from domestic scale to industrial food production?...



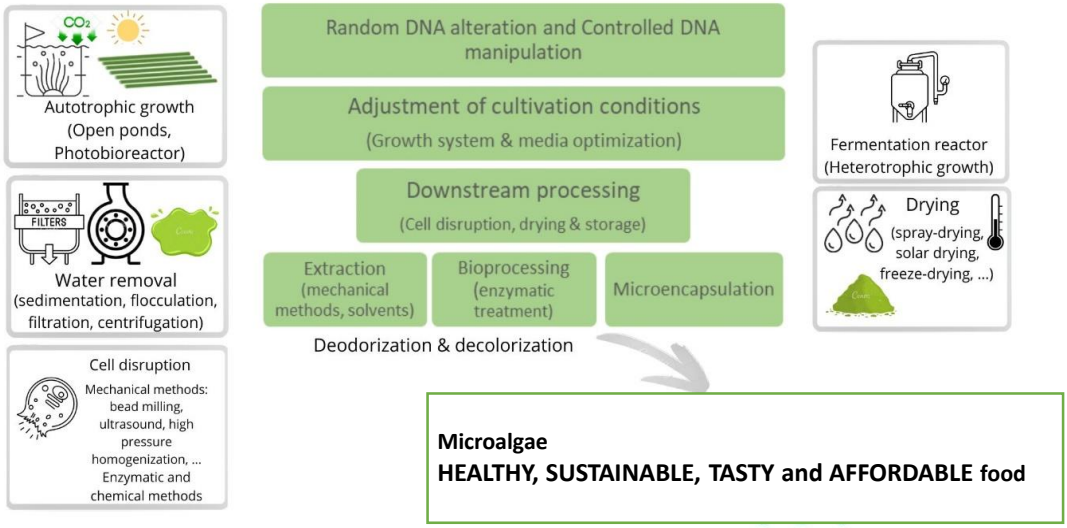


TASTE, FLAVOUR, COLOUR?

Strategies to engage the consumers?

CHALLENGE: NUTRITIONAL VALUE & SENSORY PROFIILE

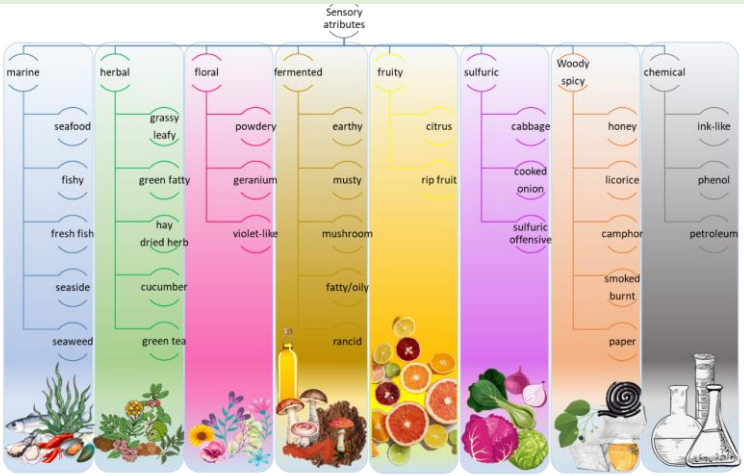
Technological developments impacting the sensory traits of microalgae



M.C. Nunes, J. Ferreira, A. Raymundo (2023). Volatile fingerprint impact on the sensory properties of microalgae and development of mitigation strategies. Current Opinion in Food Science. 101040, ISSN 2214-7993.https://doi.org/10.1016/j.cofs.2023.101040.

CHALLENGE: NUTRITIONAL VALUE & SENSORY PROFIILE

Typical odors and flavors of microalgae include:
marine, herbaceous, floral, fermented, fruity, sulfuric, woody-spicy and chemical notes



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CHALLENGE: NUTRITIONAL VALUE & SENSORY PROFIILE

Technological developments impacting the sensory traits of microalgae…

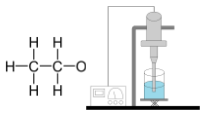
Low inclusion rates
Encapsulation of the biomass

1

Chemical and biochemical processes for deodorization and decolorization:
Heterotrophic production & Chemical random mutagenesis

Ethanolic extraction
Ultra-sound extraction + PEF treatment
Enzymatic treatment

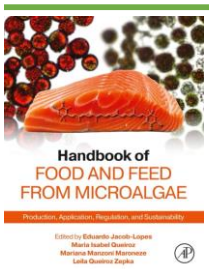
2



Gastronomic science/ Disruptive Experiences

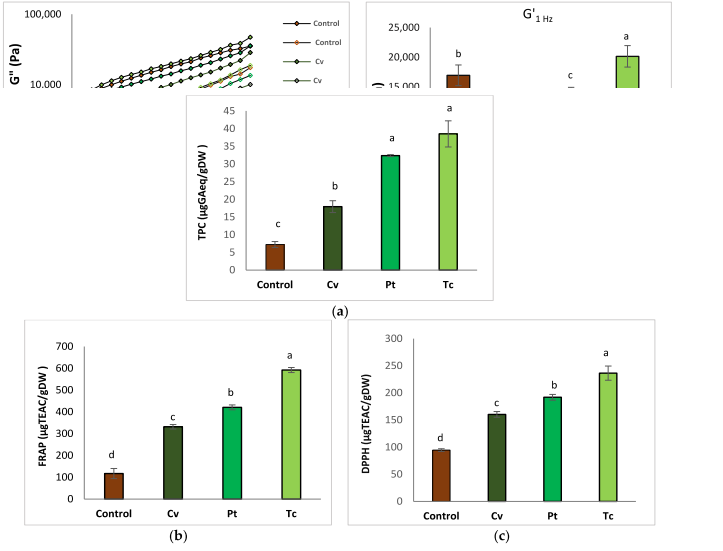
3

Examples in conventional foods



26. Application of microalgae in baked goods and pasta

Anabela Raymundo, Patrícia Fradinho, and Maria Cristiana Nunes



Low inclusion rates

BREAD

1

Examples in conventional foods

Low inclusion rates

1

Boisen & Fernández. Anim. Feed Sci. Technol. 68 (1997)

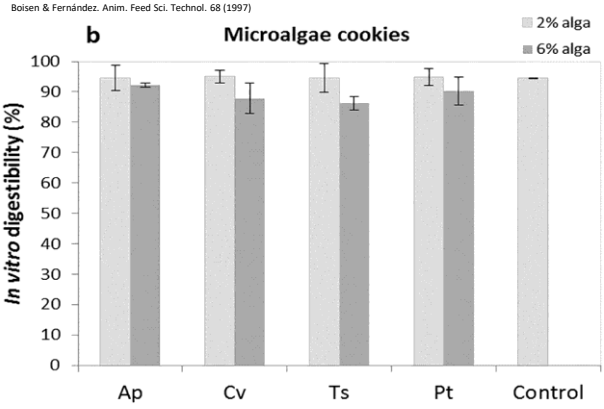


Fig. 7. *In vitro* digestibility (%) of four microalgae strains (a) and in cookies enriched with different levels of microalgae (b) (Ap – *A. platensis*, Cv – *C. vulgaris*, Ts – *T. suecica*, Pt – *P. tricornutum*). Results are expressed as average ± standard deviation (n = 3).

No significant difference in IVD between microalgae cookies and the control (IVD 87–95%) were found.

High thermal resistance

COUSCOUS

foods MDPI

	Semolina	White *Chlorella*	Honey *Chlorella*	Smooth *Chlorella*	Organic *Chlorella*	Algaessence®
Protein% DW *	12	**40.9**	31.6	26.3	**56.6**	29.5
Carbohydrate% DW *	69	40.1	54.1	**58.1**	6.3	8.6
Lipid% DW *	2.4	**9.3**	7.2	7	8.5	4.4
Ash% DW *	0.9	5	4.1	4	10.2	18.3
Fiber% DW *	nd	nd	nd	nd	12.9	**33.4**
Chlorophyll mg/100 g **	0.2	**5.8**	8.9	89	**322**	123
Minerals mg/100 g **						
K	nd	376 ± 7.1	545 ± 13.5	700 ± 17.5	943 ± 23.5	1978 ± 30.8
P	nd	1191 ± 17.8	736 ± 13.0	1054 ± 30.0	2202 ± 42.6	886 ± 12.4
Mg	nd	61.9 ± 1.0	74.7 ± 2.2	109 ± 2.7	**229 ± 4.3**	**1366 ± 18.8**
Ca	nd	493 ± 3.3	210 ± 8.1	257 ± 6.5	**1119 ± 25.8**	**947 ± 9.0**
Fe	nd	7.1 ± 0.1	6.8 ± 0.5	10.2 ± 0.9	**167 ± 3.2**	**177 ± 4.1**
Cu	nd	0.6 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	2.6 ± 0.0	1.6 ± 0.0
Mn	nd	4.8 ± 0.1	3.85 ± 0.0	4.03 ± 0.0	**11.74 ± 0.1**	**15.32 ± 0.1**
Zn	nd	14.5 ± 0.2	11.1 ± 0.2	16.2 ± 0.4	34.8 ± 0.5	19 ± 0.2

* Label information; ** determined in the current study; nd: not determined. Bold highlights the main differences in composition. DW: Dry weight.

***In vitro* starch digestibility and estimation of glycemic index in algae-based couscous**

Improved nutritional profile (4% incorporation): protein, mineral and antioxidant content
Possibility of **nutritional claims**

Examples in conventional foods

Low inclusion rates

1

PORK FRANKFURTERS

Meat Science 198 (2023) 109123

Contents lists available at ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

White and honey *Chlorella vulgaris*: Sustainable ingredients with the potential to improve nutritional value of pork frankfurters without compromising quality

Marija Bošković Cabrol [a,1,2,*], Milica Glišić [a,1], Milan Baltić [a], Dragoljub Jovanović [b], Čaba Šiladi [c], Stefan Simunović [c], Igor Tomašević [d], Anabela Raymundo [e]

Incorporation of Chlorella induced the **increase of various essential amino acids.**
3% white and honey **C. vulgaris** modifies frankfurter fatty acid composition; **increased PUFA, more beneficial n-6/n-3 PUFA and PUFA/SFA ratios.**
Antibacterial effect of *C. vulgaris* microalgae could be a means to prolong product shelf life during chilled storage.

FEED

foods MDPI

Article

Digestibility of Meat Mineral and Proteins from Broilers Fed with Graded Levels of *Chlorella vulgaris*

Marija Boskovic Cabrol [1,2,*], Joana C. Martins [3], Leonardo P. Malhão [1], Cristina M. Alfaia [3], José A. M. Prates [3], André M. Almeida [1], Madalena Lordelo [1] and Anabela Raymundo [1]

Amino Acids (% of Total Amino Acids)	Dietary Treatment			SEM	*p* Value
	C	CV10%	CV15%	CV20%		
Essential amino acids:						
Histidine	4.30	4.26	4.15	4.22	0.241	0.8294
Isoleucine	2.95	2.84	3.12	3.16	0.412	0.6654
Leucine	6.10	5.86	5.94	6.04	0.318	0.7388
Lysine	14.69 ^{a}	14.14 ^{ab}	13.58 ^{bc}	13.11 ^{c}	0.516	0.0021
Methionine	2.69	2.82	2.97	2.88	0.161	0.1209
Phenylalanine	3.51	3.56	3.47	3.53	0.052	0.1279
Threonine	4.71 ^{a}	5.10 ^{b}	5.27 ^{bc}	5.54 ^{c}	0.143	<0.0001
Valine	3.43	3.42	3.69	3.64	0.433	0.7438
Nonessential amino acids:						
Alanine	6.28	6.73	6.60	6.94	0.372	0.1165
Arginine	11.40 ^{a}	12.13 ^{b}	12.19 ^{b}	12.33 ^{b}	0.273	0.0005
Aspartic acid	8.26	8.32	8.25	8.22	0.140	0.8188
Cysteine	2.75 ^{a}	2.19 ^{ab}	2.30 ^{ab}	1.81 ^{b}	0.442	0.0499
Glutamic acid	13.18	13.20	12.99	12.68	0.746	0.1561
Glycine	4.00	4.14	4.06	4.31	0.212	0.2206
Proline	5.10	4.89	4.76	5.06	0.268	0.2796
Serine	3.18	3.19	3.26	3.19	0.146	0.8728
Tyrosine	3.49	3.22	3.42	3.36	0.263	0.5333

^{a,b,c} Different superscripts within a row indicate a significant difference ($p < 0.05$).

Heterotrophic production & Chemical random mutagenesis

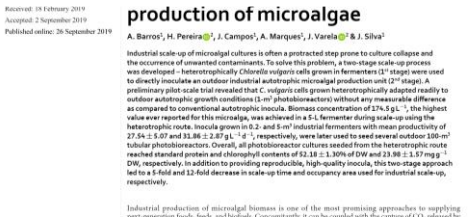
Chemical and biochemical processes for deodorization and decolorization

2

Chlorella vulgaris biomass with different pigmentation: chemically random mutagenesis (ethyl methane sulfonate – EMS) was induced in order to develop chlorophyll-deficient

Autotrophic organic *Chlorella vulgaris*

Heterotrophic *Chlorella vulgaris:* Smooth Chlorella, Honey Chlorella and White Chlorella.



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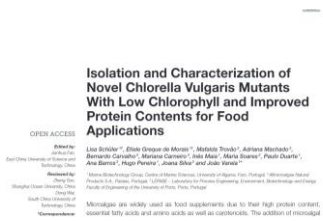
Accepted: 2 September 2019
Published online: 26 September 2019

production of microalgae

A. Barros[1], H. Pereira[1], J. Campos[1], A. Marques[1], J. Varela[1]* & J. Silva[1]

Industrial scale-up of microalgal cultures is often a protracted step prone to culture collapse and the occurrence of unwanted contaminants. To solve this problem, a two-stage scale-up process was developed – heterotrophically *Chlorella vulgaris* cells grown in fermenters (1st stage) were used to directly inoculate an outdoor industrial autotrophic microalgal production unit (2nd stage). A preliminary pilot-scale trial revealed that *C. vulgaris* cells grown heterotrophically adapted readily to outdoor autotrophic growth conditions (1-m² photobioreactors) without any measurable difference as compared to conventional autotrophic inocula. Biomass concentration of 174.5 g L^{-1}, the highest value ever reported for this microalga, was achieved in a 5-L fermenter during scale-up using the heterotrophic route. Inocula grown in 0.2- and 5-m² industrial fermenters with mean productivity of 27.54 ± 5.07 and 31.86 ± 2.87 g L^{-1} d^{-1}, respectively, were later used to seed several outdoor 100-m² tubular photobioreactors. Overall, all photobioreactor cultures seeded from the heterotrophic route reached standard protein and chlorophyll contents of 52.18 ± 1.30% of DW and 23.90 ± 1.57 mg g^{-1} DW, respectively. In addition to providing reproducible, high-quality inocula, this two-stage approach led to a 5-fold and 12-fold decrease in scale-up time and occupancy area used for industrial scale-up, respectively.

Industrial production of microalgal biomass is one of the most promising approaches to supplying



OPEN ACCESS

Isolation and Characterization of Novel Chlorella Vulgaris Mutants With Low Chlorophyll and Improved Protein Contents for Food Applications

Microalgae are widely used as food supplements due to their high protein content, essential fatty acids and amino acids as well as carotenoids. The addition of microalgal

Examples in nonconventional foods

Heterotrophic Chlorella: inhibition of chlorophyl production

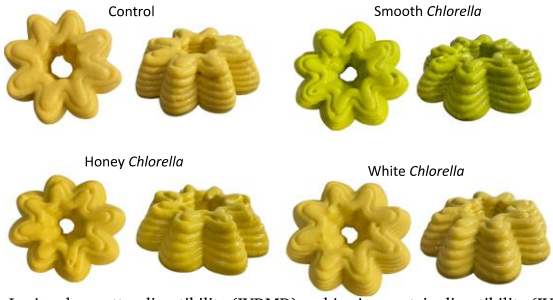
2

Algal Research 79 (2024) 103447

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal



Control

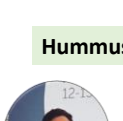
Smooth *Chlorella*

Honey *Chlorella*

White *Chlorella*

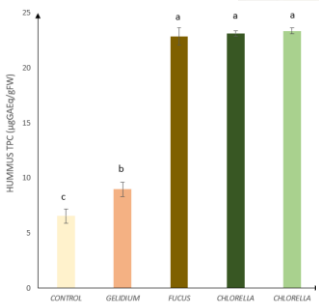
In vitro dry matter digestibility (IVDMD) and *in vitro* protein digestibility (IVPD) of the control puree and purees with 3 % of smooth, honey and white *Chlorella*.

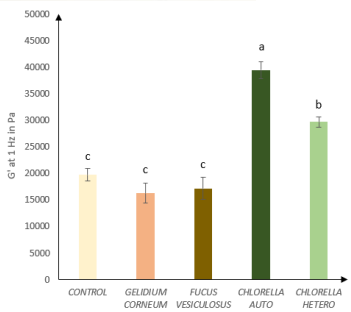
Samples	IVDMD (%)	IVPD (%)
Control	90.9 ± 0.9^{A}	37.9 ± 4.5^{B}
SC	92.6 ± 1.4^{A}	45.7 ± 0.9^{C}
HC	91.8 ± 0.9^{A}	34.4 ± 1.6^{A}
WC	91.6 ± 0.5^{A}	38.3 ± 7.2^{B}



Hummus from with seaweeds and microalgae

Mathues Silva





Examples in unconventional foods

Heterotrophic Chlorella and extracts

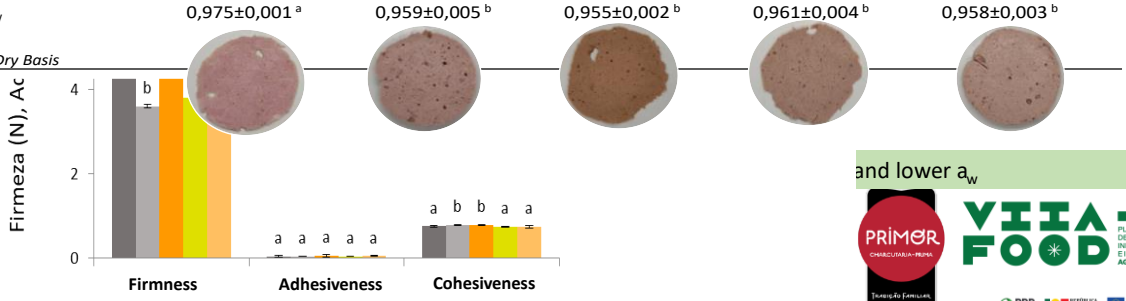
2

Hybrid meat products are a trend – reduction of meat in ham (4% wt of algae/extract)

Alternative microalgae proteins

(%)	Control (100% meat)	0% Microalgae	*Parachlorella kessleri* (extract)	Honey *vulgaris*	*Chlorella*	White *vulgaris*	*Chlorella*
							lgaris
Protein*	64,8±1,18[a]	31,4±0,30[b]	36,9±0,89[c]	32,43±0,84[b]		31,55±1,05[b]	
Ash=	13,4±0,02[a]	9,6±0,09[b]	9,8±0,07[c]	9,6±0,04[b]		10,11±0,10[e]	
Humidity	78,0±0,19[a]	63,1±0,30[b]	61,0±0,17[c]	61,7±0,10[c]		61,1±0,66[c]	
a_w	0,975±0,001[a]	0,959±0,005[b]	0,955±0,002[b]	0,961±0,004[b]		0,958±0,003[b]	

** Dry Basis*



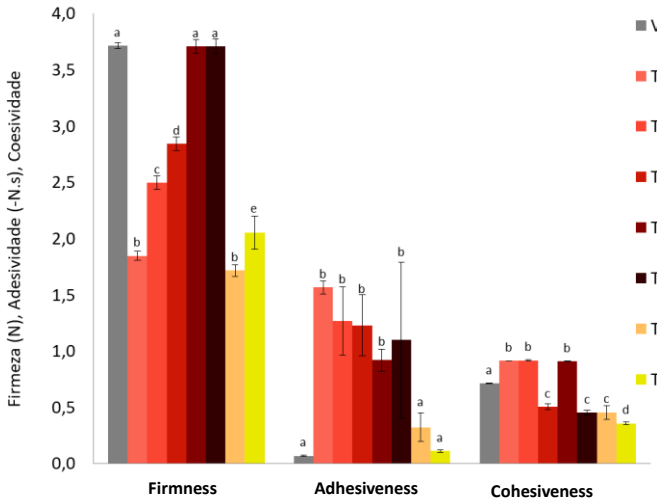
and lower a_w

Examples in unconventional foods

Egg replacers

2

Meat analogues - vegan



Ethanolic extraction

Chemical deodorization and decolorization

2

ALGAE TO FUTURE

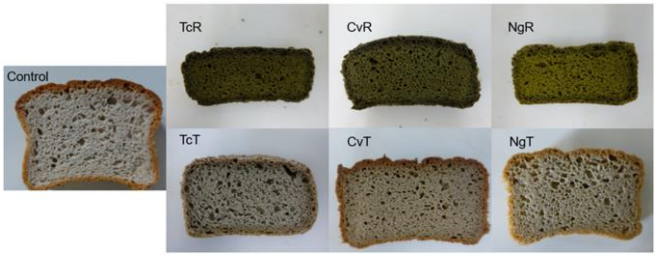
foods

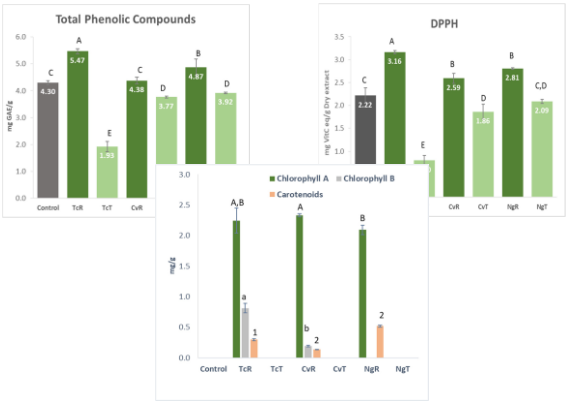
MDPI

Article

Improving the Nutritional, Structural, and Sensory Properties of Gluten-Free Bread with Different Species of Microalgae

Muhammad Waqas Qazi [1,*], Inês Gonçalves de Sousa [2], Maria Cristiana Nunes [2] and Anabela Raymundo [2]





***Chlorella vulgaris* ethanol treated**: improves the sensory properties to a large extent, dough rheology - softer texture breads with higher volume.

The ethanol treatment intended to eliminate pigment inevitably removed the bioactive compounds from the breads which is a drawback.

Iceland Liechtenstein Norway grants

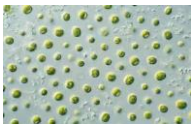
DoMAR - Development of Microalgae Advanced Resources

PT-INNOVATION-0013

US assisted extraction

2

Optimisation of Ultrasound assisted extraction - controlled cell disruption + improvement of the microalgal sensory profile with a reduced loss of antioxidant components.



Nannochloropsis oceanica

Dunaliella salina

Promote the full recovery of the two fractions (circular economy)

solid protein-rich fraction

liquid bioactive-rich fraction

US - **efficient, easy to implement and reproducible.**
Extraction conditions: microalgal concentration (1%/5% w/v), ethanol/water proportion (96%/60%) and temperature (room temperature/50°C).
US extraction conditions fixed: acoustic
and
. The

marine drugs

MDPI

Article

Tuning the Bioactive Properties of *Dunaliella salina* Water Extracts by Ultrasound-Assisted Extraction

Joana P. A. Ferreira [1,*], Madalena Grácio [1], Isabel Sousa [1], António Pagarete [2], M. Cristiana Nunes [1] and Anabela Raymundo [1]

Mar. Drugs **2023**, *21*, 472. https://doi.org/10.3390/md21090472

Partner:

YUM ALGAE – Let's make algae yummy!

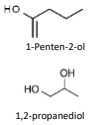
Project supported by **EEA.BG.CALL4.006.2020**

Enzymatic treatment

2

Results from ATI1 - ISA

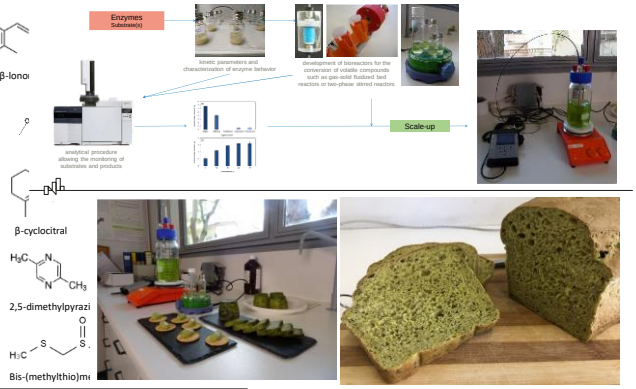
ATI3: Chemical Trait Analysis



Chemical Compounds	*C. vulgaris*	*T. chuii*	*P. tricornutum*	*N. oceanica*	*N. gaditana*	
					freeze dried	spray dried
Alcohols	7.20	6.53	7.56	7.90	15.60	45.57
Aldehydes	6.79	14.19	2.31	14.21	2.73	39.38
Ketones	2.65	7.93	2.62	1.05	4.26	0.22
Carboxylic Acids	12.83	2.25	0.32	2.67	0.27	0.07
Alkanes/Alkenes/Alkynes	10.95	1.21	2.37	1.61	16.83	0.64
Terpenes	0.53	0.57	0.81	1.45	0.19	0.07
N-compounds	3.23	11.55	21.68	20.28	0.31	0.20
O-heterocyclic compounds	55.65	11.57	62.31	50.79	59.81	13.85
S-compounds	0.19	44.20	0.02	0.04	0.02	0.00

ATI2: SENSORY ENZYME DISCOVERY PIPELINE (IST - 15%)

T2.5. Enzyme profiling and characterization under application conditions
Assessment of enzyme robustness in aqueous solution (T and pH profile) and under desiccation conditions (i.e. low water activity).
T2.6. Pilot fermentation and purification of top sensory enzymes for application test
The purified enzymes will be delivered to IST for biokinetic studies (T3.2) and application of the microalgae as substrate (T4.1).



Future perspectives

Programme operator: REPÚBLICA PORTUGUESA ECONOMIA E MAR · Política do Mar

Project promoter: U LISBOA · INSTITUTO SUPERIOR DE AGRONOMIA

Partners: NORCE · Microalgae · TÉCNICO LISBOA

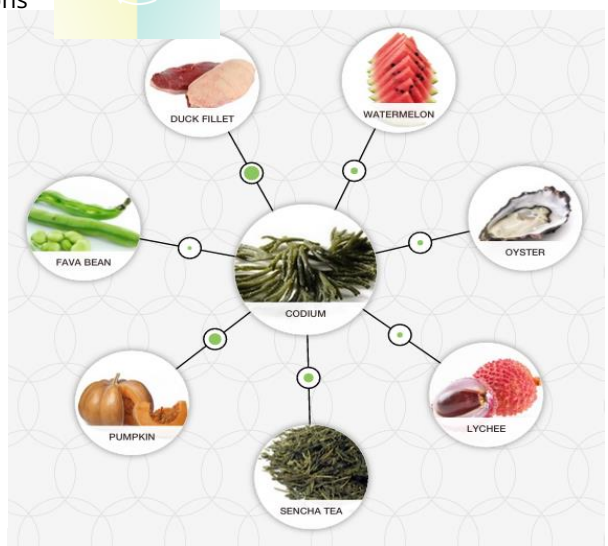
Gastronomic science/ Disruptive Experiences

Surprinsing food

3

FOOD PAIRING

Pairings for strawberry based on aromatic connections



https://www.foodpairing.com/how-does-the-foodpairing-tool-work/

Mixture of carefully selected ingredients to mitigate or to assume the taste of the microalga

Gastronomic science/ Disruptive Experiences

Surprinsing food 3

Innovative experiences with microalgae-cheese

Air [Fresh cheese spread with Chlorella, cream, oyster essence]

Mousse [fresh cheese with Chlorella, cream, sugar, cinnamon, orange flavor]

Spherification [whey cheese with Chlorella, herbs from Provence]

Spiral [whey cheese with Chlorella, cream, garam masala spices]

Spaghetti [cream cheese spread with Chlorella, cream, pumpkin powder]

Different pairing solutions for Chlorella cheese...

Let's make the Algae Yummy! Revelando o potencial culinário das microalgas

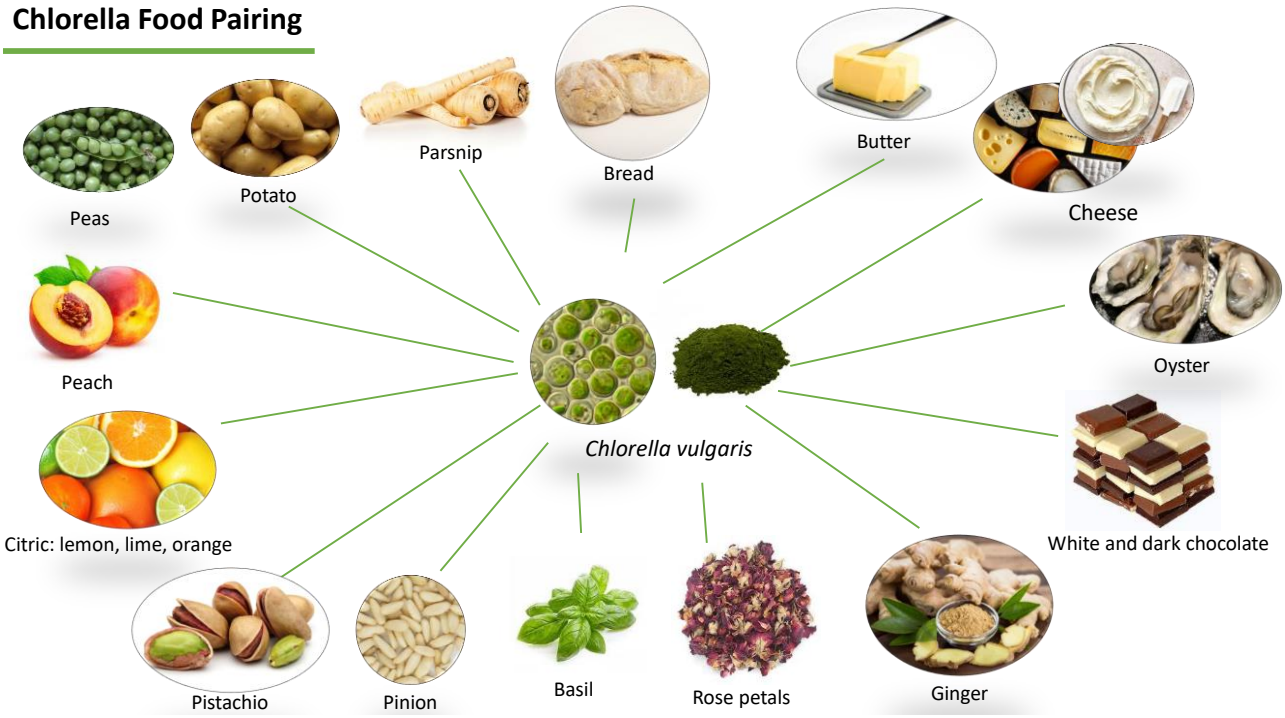
Algae Crispy

Algae crispy is an ode to the vibrant green color of seaweed. Inspired by this tone, the developed dish explores monochrome and all its richness of flavor with the texture that seaweed can offer.

Bread with Spirulina and mushroom steam with banana chips

Creamy Cheese Pie

Chlorella Food Pairing

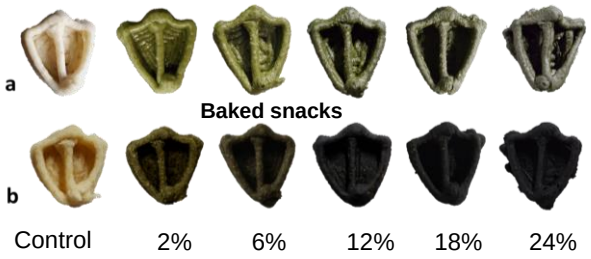


Gastronomic science/ Disruptive Experiences

Surprising foods 3

3D printing - texture creation tool

Printed doughs



Baked snacks

2% Cv snack presented the **highest global appreciation** scores, were the **most preferred** snack (53%) and **highest purchase intention** value (5.4)

frontiers | Frontiers in Food Science and Technology

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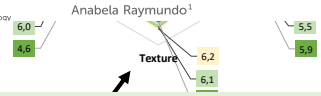
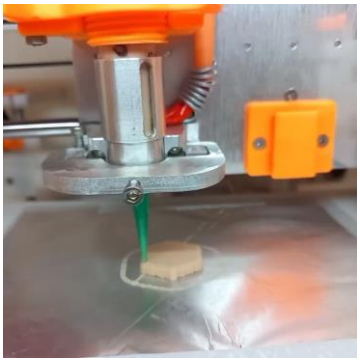
3D-printed *Chlorella vulgaris* snacks: a contribution to a healthy diet

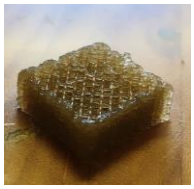
Sónia Oliveira[1]*, María Dolores Torres Pérez[2], Isabel Sousa[1] and Anabela Raymundo[1]



Hedonic analysis (7-point Likert scale)

Other ways of printing!





gels 2024, 10, 166. https://doi.org/10.3390/gels10030166 MDPI

Article

Three-Dimensional Printing of Red Algae Biopolymers: Effect of Locust Bean Gum on Rheology and Processability

Sónia Oliveira [1], Isabel Sousa [1], Anabela Raymundo [1] and Carlos Bengoechea [2,*]

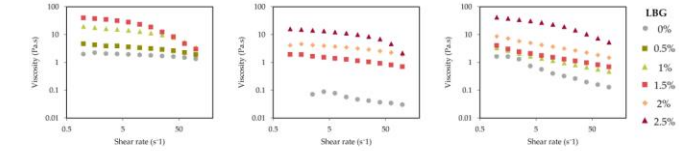


Figure 4. Flow curves of *C. crispus* (**a**), *G. gracilis* (**b**), and *G. corneum* (**c**), at 80 °C (1–100 s^{-1}).

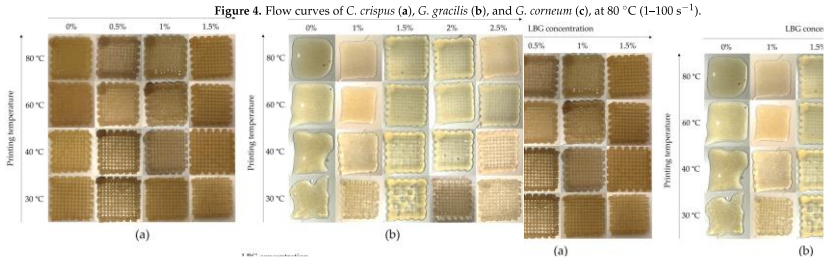


Figure 5. Visual effect of LBG additions (0–2.5% *w*/*w*) and printing temperature (80–30 °C) on gel's structure of *C. crispus* (**a**), *G. gracilis* (**b**), and *G. corneum* (**c**).

Messages to take home…

Microalgae as a food ingrediente – good sensory experiences are crutial

Microalgae are an important source of bioactive compounds and macromolecules (proteins).
But…
if microalgae foods are not tasty, nutritional factors and health benefits lose relevance!!!

PROTECT CONSUMER TO BAD EXPERIENCES WITH MICROALGAE

Applications in conventional foods have associated acceptance issues in terms of aroma, color and flavour – **FOOD PAIRING**

It is important to develop strategies to reduce the fishy flavor to increase consumer acceptance, to make the production of microalgae-foods on a large scale viable.

INTERDISCIPLINARY WORK IS ESSENTIAL!

Algae@ISA