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Assessing the Environmental and Economic Sustainability of Functional Food Ingredient Production Process

Anushree Priyadarshini [1,2], **Brijesh K. Tiwari** [3] **and Gaurav Rajauria** [4,*]

1 College of Business, Technological University Dublin, City Campus, Aungier Street, D02 HW71 Dublin, Ireland; anushree.priyadarshini@tudublin.ie
2 Environmental Sustainability and Health Institute, Technological University Dublin, Grangegorman, D07 H6K8 Dublin, Ireland
3 Department of Food Chemistry and Technology, Teagasc Food Research Centre, Ashtown, D15 KN3K Dublin, Ireland; brijesh.tiwari@teagasc.ie
4 Department of Biological & Pharmaceutical Sciences, Munster Technological University, Clash, V92 CX88 Tralee, Ireland
* Correspondence: gaurav.rajauria@mtu.ie

Abstract: Development and application of novel technologies in food processing is vital for ensuring the availability of adequate, safe, and convenient food with the desired quality and functional properties. Environmental and economic sustainability of technologies is essential prior to their application in the food processing sector. The objective of this research is to determine the environmental and economic feasibility of ultrasound-assisted extraction (UAE) for recovering functional food ingredients from seaweed. Experimental data is used to conduct a life cycle assessment (LCA) to investigate the environmental performance with a functional unit (FU) of obtaining 1 g of extracted polyphenols, measured as gallic acid equivalents (mg GAE)/g seaweed. A life cycle impact assessment is performed with ReCiPe 2016 at midpoint. The cost of manufacturing (COM) of phenolic-rich extracts (as functional ingredient, bioactive, or nutraceutical) is estimated using time-driven activity-based costing (TDABC). The environmental profile findings show that across all categories, the UAE has considerably lower impacts than the conventional method, with electricity as the most important impact contributor, followed by solvent production. An economic assessment estimates the COM over a one-year period at a large scale using the UAE to be EUR 1,200,304, EUR 2,368,440, and EUR 4,623,290 for extraction vessel capacities of 0.05, 0.1, and 0.15 m^3, respectively. Raw materials (including the type of raw material) and operational labour costs are the primary contributors to the COM. The findings thus present evidence to support the adoption of an environmentally and economically viable technology for functional ingredient production.

Keywords: bioactive; ultrasound-assisted extraction; cost of manufacturing; TDABC; nutraceutical; emerging technology; food processing; production process

1. Introduction

Nutraceuticals, or functional foods, are foods that not only provide essential nutrition but are also beneficial to health by reducing the risk of diseases [1]. These benefits of nutraceuticals are largely associated with the functional ingredients or bioactive (phytochemicals), especially to polyphenols, they contain. Polyphenols exert a wide range of biological activities that can protect the body against external factors. They can rinse the body of the reactive oxygen species formed in the case of some diseases, while in others they can stop the disease progression [2]. The importance of these bioactive polyphenols has been linked with many degenerative diseases and disorders, some of the prominent ones being cancer, metabolic problems, coronary heart disease, cold and cough, depression, and delayed gastrointestinal emptying. Research into these functional ingredients highlights their potential as constituents to be used in food products, thus creating added value for

producers and benefits for consumer health [3]. Moreover, nutraceuticals are contributing towards the solution to the United Nations Sustainable Development Goals (SDGs) goals of sustainability, food security, and health [4].

Primarily, nutraceuticals are recovered from terrestrial plants, fruits, and vegetables, while attempts to find new sources to extract them are part of ongoing research on bioactives. In this vein, marine sources are extensively being explored for bioactive components as the marine environment contains enormous amounts of biodiversity with potential functional and nutraceutical capabilities [5,6]. The biodiversity of marine microflora is overwhelming owing to the secondary metabolites synthesized by the marine microflora and fauna and thus can be used as potential biotherapeutic agents [7]. Macroalgae (or seaweed), a renewable marine resource, is a commercially valuable source of bioactive compounds with therapeutic and preventative effects [8]. These are therefore increasingly used for manufacturing nutraceuticals or dietary supplements and are being exploited for the development of drugs for diabetes, microbial infections, and inflammation [9]. Exploring marine sources is in line with the EU's bioeconomy strategy and global systems-level policy agendas of sustainable food production and processing and foods for health [10]. The importance and market potential of this emerging area have been recognised globally and by the EU under initiatives such as blue bioeconomy and integrated marine plans such as harnessing our ocean wealth [11]. Ireland is among the top three seaweed biomass producing nations in Europe and produces approximately 40,000 tonnes per annum of seaweed.

With these initiatives, together with the advancements in qualitative and quantitative procedures, the extraction of bioactive compounds has also been greatly augmented. While conventional solvent extraction (CSE) involves maceration (or solvent extraction), Soxhlet or steam distillation advanced techniques such as ultrasound-assisted extraction (UAE), which is a non-thermal extraction technique that utilizes sound waves to induce pressure variations and cavitation as it migrates through a medium. As the sound waves are converted into mechanical energy, they disrupt the cell walls, decrease the particle size and increase the contact between the solvents and the targeted compounds [12]. It has been employed for extracting a number of functional ingredients from a range of plant sources as well as from micro and macroalgae [13]. As extraction yield and functionality of bioactive compounds is influenced by extraction techniques (e.g., heat or solvent use), increasingly advanced technologies are being used for extracting these beneficial compounds from marine sources such as seaweed. Moreover, conventional techniques/processes are more time-consuming and energy-intensive; therefore, the focus is on developing novel techniques that are more efficient in terms of yield, time, and are environmentally friendly [14–16]. The development and application of novel technologies in food processing is particularly relevant to the objective of ensuring the availability of sufficient, safe, and convenient food with the desired quality and functional properties. Novel extraction technologies demonstrated potential for food and pharmaceutical applications for the extraction of bioactive compounds include enzyme-assisted extraction, microwave-assisted extraction, ultrasound-assisted extraction, and supercritical fluid extraction [13,17]. These technologies, commonly referred to as green extraction technologies, offer key advantages for advancing the extraction and processing of foods and for combatting the growing sustainability challenges of rising food demand [18]. However, a major challenge for the process industry in adopting these is to assess the environmental and economic sustainability of the processes involved [16,19,20]. A few life cycle assessment (LCA) studies have been conducted that have focused on evaluating design approaches [21–23] or full-scale production processes in the case of bioenergy production [24–27]. While these novel techniques are being utilized to identify and develop new and efficient extraction processes to valorise marine algal biomass, limited work has been performed to evaluate the environmental and economic sustainability of these processes [28,29].

In catering to the challenges in the coming decades of the rapidly expanding and more affluent population, the application of these technologies is essential; however, for assessing the practicality of any specific process, it is critical to conduct its environmental

and economic evaluation [30,31]. Therefore, this study aims to conduct an environmental and economic evaluation of the novel technology, ultrasound-assisted extraction (UAE), for recovering bioactive (high-value-added phenolic-rich extracts) from seaweed. A few LCA studies focusing on UAE have highlighted the significance of exploring its environmental performance [32–34]. Due to UAE owing to advantages such as high extraction yield, less solvent consumption, low temperature usage, and greater efficiency in terms of energy consumption, UAE is increasingly being employed for extracting valuable compounds from different matrices [35–37]. Thus, to establish the potential of the novel technology UAE for producing a high-value-added bioactive from seaweed, this research aims to assess the environmental and economic sustainability of extraction processes.

2. Materials and Methods

2.1. Recovery of Phenolic-Rich Extract from Seaweed

Phenolic-rich extract from dried and milled brown seaweed was recovered by using conventional solvent extraction (CSE) and ultrasound assisted extraction (UAE) techniques outlined by Ummat et al. [38]. Conventional solvent extraction was carried out to compare the efficiency of the optimised UAE method. Figure 1 (below) presents a diagrammatic description of the process of extracting phenolic-rich extract from seaweed using UAE.
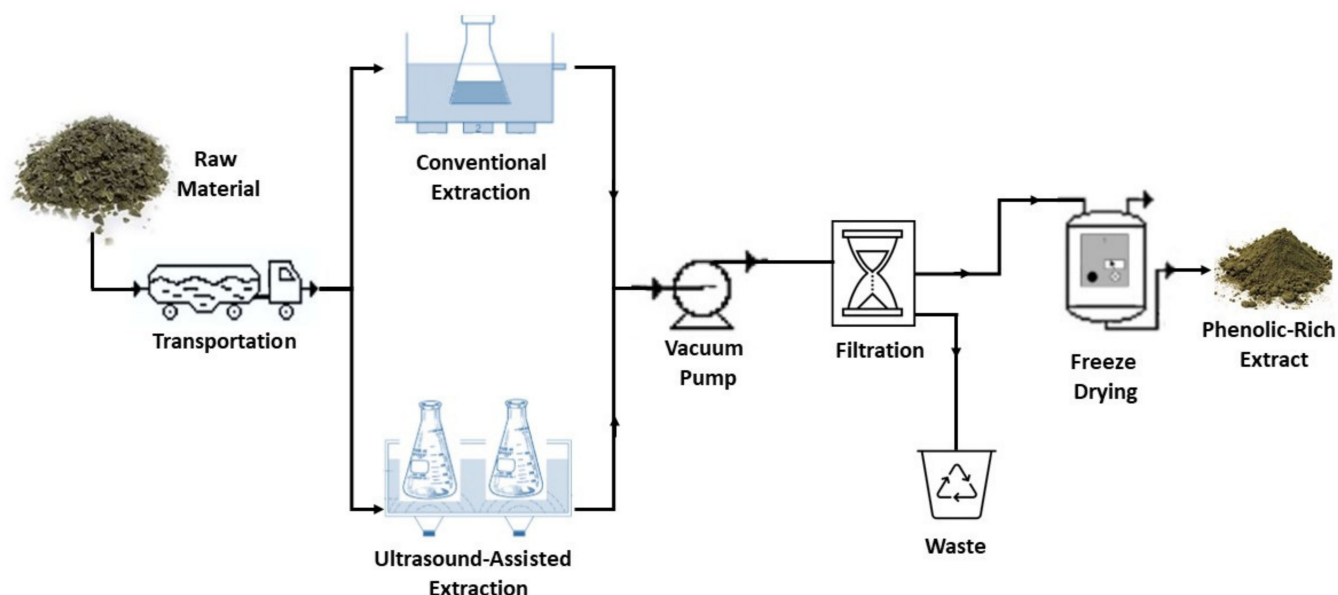

Figure 1. Schematic representation of the extraction process for the recovery of phenolic-rich extract from seaweed.

2.2. Environmental Assessment

The mandatory principles as per ISO standards (ISO 14040) [39] were followed in this study, and the included steps were the following: goal and scope definition, life cycle inventory, and life cycle impact assessment and interpretation.

2.2.1. Goal and Scope Definition

The goal of this study was to evaluate and compare the environmental impacts of a lab-scale CSE and UAE of polyphenols from seaweed. A gate-to-gate LCA was performed considering the system boundaries as described in Figure 2. No infrastructure-related processes, such as the production of lab-scale equipment, as well as no transportation of any of the materials involved, were included.
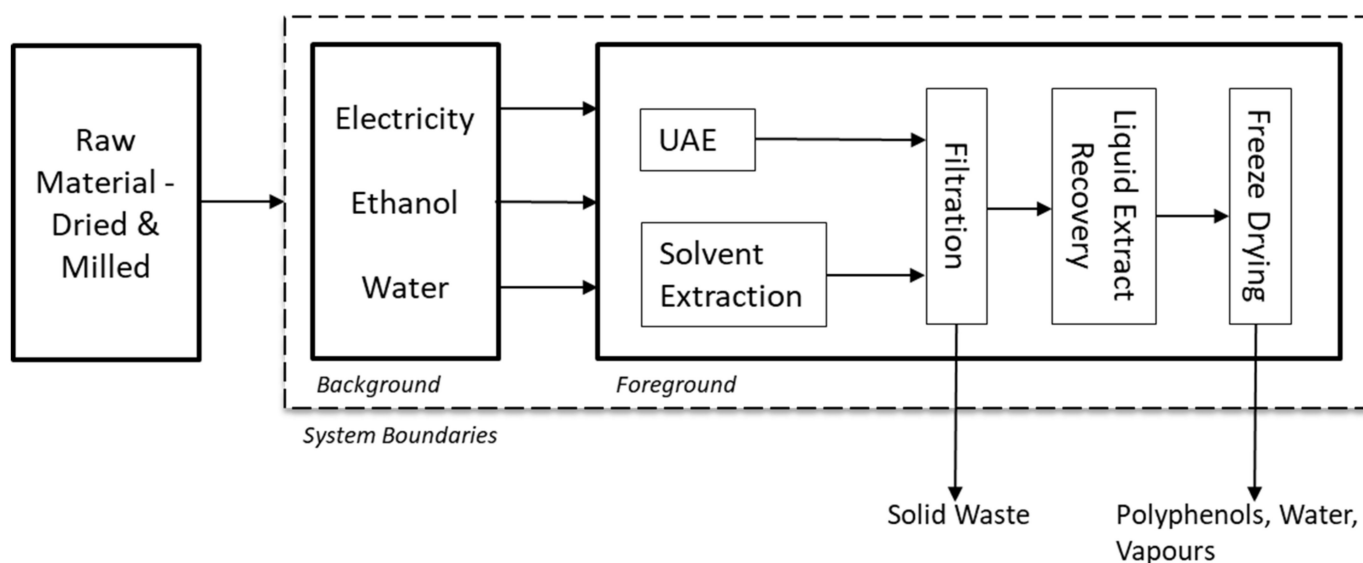
Figure 2. Schematic representation of the studied system boundary (dashed line).

The functional unit (FU) was defined as obtaining 1 g of extracted polyphenols, measured as gallic acid equivalents (mg GAE)/g seaweed. An effective comparison of the extraction methods could be carried out using this FU by considering their technical efficiency expressed as extraction yields. All entries in the inventory were stated to this FU.

2.2.2. Life Cycle Inventory

The life cycle inventory was modelled using generic data from databases and experimental data as presented in Table 1. Generic data, as well as associated impacts, were sourced from the Environment Footprint (EF) database (version 3) using the openLCA 1.10.3 software (GreenDelta GmbH, Berlin, Germany). Experimental data was used for raw material and solvent inventories. Moreover, electricity consumption of all equipment was ascertained by recording their operation time and power ratings.

Table 1. Life cycle inventory data for extraction processes (per g polyphenols).

Inventory	Unit	CSE	UAE	Data Source/Remark
Inputs				
Seaweed	gm	28.79	4.98	Measured
Ethanol	gm	115.17	19.91	Measured
Water	L	0.14	0.02	Measured
Electricity for extraction	kWh	2.76	0.01	Measured
Electricity for filtration	kWh	0.02	0.002	Measured
Electricity for freeze drying	kWh	138.89	24.01	Measured
Outputs				
Polyphenols	g	1	1	
Evaporated ethanol	g	11.52	1.99	Calculated for experiments from mass balance. Assuming 10% loss
Recovered ethanol	g	103.65	17.92	Considers a 90% ethanol recovery rate
Solid waste	g	25.57	3.23	Calculated from mass balance
Wastewater	L	0.14	0.02	Assuming all water used was finally considered as wastewater

CSE: Conventional solvent extraction; UAE: Ultrasound assisted extraction.

2.2.3. Life Cycle Impact Assessment

The life cycle impact assessment was performed using ReCiPe 2016 method at midpoint level. The impact categories evaluated were the following: Fine particulate matter formation; Freshwater ecotoxicity; Human carcinogenic toxicity; Human non-carcinogenic

toxicity; Marine ecotoxicity; Marine eutrophication; Mineral resource scarcity; Ozone formation, Human health; Ozone formation, Terrestrial ecosystems; Terrestrial acidification; Terrestrial ecotoxicity and Water consumption.

2.3. Economic Assessment

Experimental data from Ummat et al. [38] was used to estimate the cost of manufacturing (COM) of phenolic-rich extracts by using time-driven activity-based costing (TDABC) methodology. TDABC is a bottom-up costing methodology presented by Kaplan and Anderson [40] that identifies the cost drivers in processes and has been demonstrated to have utility in production and service industries [41]. Activities are the fundamental cost objects in this process [42] and these costs are combined with any additional occurring costs. This method has been described as providing a more accurate and transparent means of calculating costs than a top-down approach [43]. The COM, covering the different activities during the extraction process as outlined in Figure 3, was determined by using the following equations below:

$$\text{COM} = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 \tag{1}$$

where:

COM = Cost of manufacturing
X_1 = Operational cost of workers
X_2 = Raw material cost
X_3 = Extraction cost
X_4 = Filtration cost
X_5 = Extract drying cost
X_6 = Waste treatment cost

$$X_1 = \sum_{k=1}^{n} W \times (R_h \times H_W) \tag{2}$$

where:

W= Number of workers
R_h = Hourly rate of workers (EUR/h)
H_W = Number of hours worked

$$X_2 = \sum_{k=1}^{n} RM \times R_{RM} + \sum_{k=1}^{n} C_{DO} + (W_{DO} \times RT \times R_E) + \sum_{k=1}^{n} C_{MM} + (W_{MM} \times RT \times R_E) \tag{3}$$

where:

RM = Raw material quantity k (kg)
R_{RM} = Rate of raw material (EUR/kg)
C_{DO} = Cost of dryer oven of size k (EUR)
W_{DO} = Wattage of dryer oven (kW)
RT = Runtime (h)
R_E = Electricity rate (EUR/kWh)
C_{MM} = Cost of milling machine of size k (EUR)
W_{MM} = Wattage of milling machine (kW)

$$X_3 = \sum_{k=1}^{n} S_1 \times R_{S1} + \sum_{k=1}^{n} S_2 \times R_{S2} + \sum_{k=1}^{n} C_V + (W_V \times RT \times R_E) \tag{4}$$

where:

S_1 = Solvent 1 volume k (kg)
R_{S1} = Rate of Solvent 1 volume k (EUR/kg)
S_2 = Solvent 2 (kg)
R_{S2} = Rate of Solvent 2 (EUR/kg)
C_V = Cost of vessel of size k (EUR)
W_V = Wattage of vessel (kW)
RT = Runtime (h)
R_E = Electricity rate (EUR/kWh)

$$X_4 = \sum_{k=1}^{n} CC \times R_{CC} + \sum_{k=1}^{n} C_{VP} + (W_{VP} \times RT \times R_E) \tag{5}$$

where:

CC = Cheesecloth of length k (m)
R_{CC} = Rate of cheesecloth (EUR/m)
C_{VP} = Cost of vacuum pump of size k (EUR)
W_{VP} = Wattage of vacuum pump (kW)
RT = Runtime (h)
R_E = Electricity rate (EUR/kWh)

$$X_5 = \sum_{k=1}^{n} C_{FD} + (W_{FD} \times RT \times R_E) + \sum_{k=1}^{n} C_{VP} + (W_{VP} \times RT \times R_E) \tag{6}$$

where:

C_{FD} = Cost of freeze dryer of size k (EUR)
W_{FD} = Wattage of freeze dryer (kW)
C_{VP} = Cost of vacuum pump of size k (EUR)
W_{VP} = Wattage of vacuum pump (kW)
RT = Runtime (h)
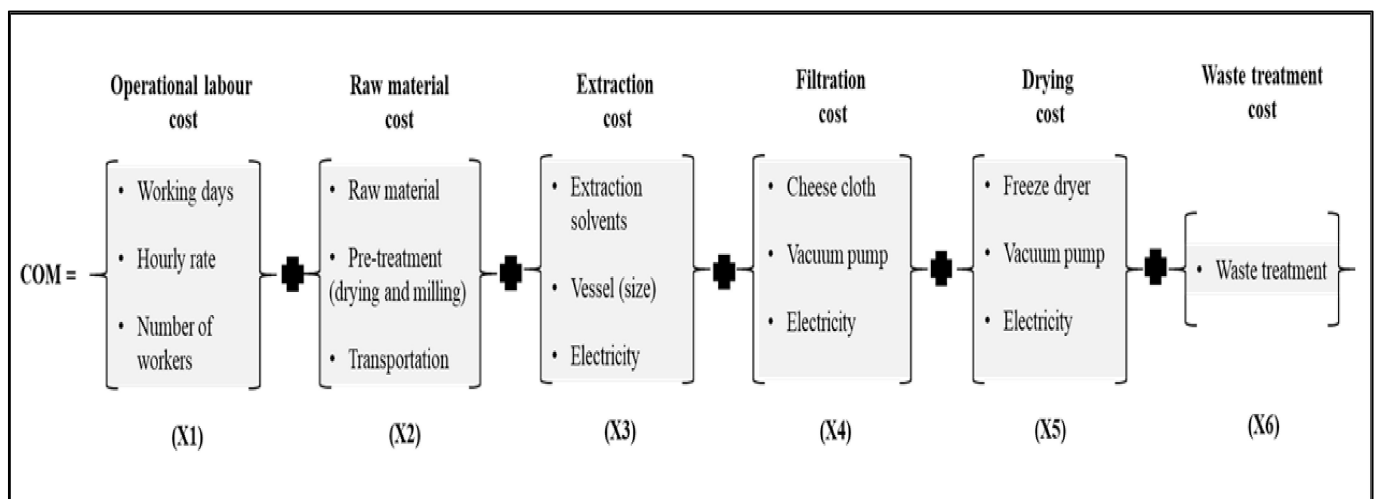R_E = Electricity rate (EUR/kWh)

Figure 3. Schematic representation of various activities during the extraction process.

2.3.1. Lab Scale

The economic parameters used for assessing the cost of manufacturing phenolic-rich extracts are outlined in Table 2. The COM of phenolic-rich extracts on lab scale using both CSE and UAE was determined. A vessel size of $0.01 m^3$ for both shaking water bath and ultrasonic bath was used. The costs of vessels as provided by Fisher Scientific (Ballycoolen, Dublin, Ireland) and Elma Schmidbauer GmbH (Gottlieb-Daimler-Straße, Singen, Germany) were EUR 1980 and EUR 2440, respectively. At lab scale the run time for conventional solvent extraction is 24 h (1 cycle per day), while for UAE, given its run time of 30 min it was estimated that instrument could run for 4 cycles/day (8 working hours). The total operational time at lab scale would involve 1 shift for 253 working days/year (for Ireland), requiring one person for each technology.

Table 2. Economic parameters used for cost of manufacturing (COM) estimation.

Parameters	Rate (Ex VAT)
Pre-treated raw material (dried, milled and transportation) [a]	EUR 27.72/kg
Industrial ultrasound units/vessels [a]	
50 L (0.05 m^3)	EUR 12,360
100 L (0.10 m^3)	EUR 15,175
150 L (0.15 m^3)	EUR 16,975
Labour [b]	EUR 9.80/h
For 50 L	1 operator
For 100 L	2 operators
For 150 L	3 operators
Extraction solvents [a]	
Ethanol	EUR 15.10/kg
Water [c]	EUR 1.21/kg
Electricity cost [d]	EUR 0.2122/kWh
Filtration cost (including cheese cloth, vacuum pump, and electricity cost) [a]	
Cheese cloth	EUR 2.5/metre
Vacuum pump	EUR 1893
Freeze drying cost (including 6L freeze dryer, vacuum pump, and electricity cost)	
Freeze dryer (6L, fully assembled unit)	EUR 18,495
Vacuum pump	EUR 2206
Waste treatment cost [e]	Nil

[a] Direct quotation; [b] National Minimum Wage, Government of Ireland; [c] Irish Water; [d] Electricity Supply Board, Ireland; [e] [44,45].

The cost of raw materials including pre-treatment (drying and milling) as well as transportation to the site was EUR 27.72/kg (Quality Sea Veg., Co. Donegal, Ireland). The cost of the extraction solvent ethanol was EUR 15.10/kg (Fisher Scientific, Dublin, Ireland) and cost of water for commercial usage was EUR 1.21/kg (Irish Water). The capital costs of the filtration vacuum pump (Fisher Scientific, Ireland) and the freeze dryer (Mason Technologies, Ireland) were EUR 1893 and EUR 20,701, respectively. The cost of the cheese cloth used for filtration was EUR 2.5/metre. An electricity cost of 0.2122/kWh was considered based on the current electricity costs in Ireland. The residual waste contains nutrients that are beneficial for crop growth, improving soil tilth, increasing aeration, water holding capacity, soil biological activity, and reducing erosion by wind and water. Therefore, cost of discarding organic residue in the soil was neglected as this cost is considered negligible in comparison to other disposal methods [44,45].

2.3.2. Large Scale

Three UAE extraction vessels with different volumes (0.05, 0.10, and 0.15 m^3) were also evaluated to produce polyphenol-rich extract on a large scale. The individual costs of these vessels as provided by Elma Schmidbauer GmbH (Hohentwiel, Germany), were EUR 12,360, EUR 15,175, and EUR 16,974, respectively. Time of extraction and the solvent to raw material ratio are the two process parameters that must remain constant in order to satisfy the assumption that the industrial-scale process produces the same yield as the laboratory scale [46]. The scale-up from the laboratory to the industrial-scale under the same conditions often increases the extraction yield, but in this study, it was assumed that the yield was identical at both the laboratory and industrial scales [47,48]; therefore, the industrial-scale processes were assumed to have the same yield and extraction time as the laboratory-scale process. Given the run time of 30 min followed by filtration and vessel preparation for next run, it was estimated that the process could run for 12 cycles/day and the total operational time would involve three daily shifts for 330 days, or 7920 h per year [46]. The number of operators required per shift would vary according to the capacity of the plant, with 1 person per shift needed (assuming working at full-time capacity) for 0.05 m^3 vessel capacity, 2 persons per shift for 0.10 m^3, and 3 persons per shift for 0.15 m^3

vessel capacity. All other parameters for calculating the COM on a large scale were as described above for lab scale.

3. Results and Discussion

3.1. Environmental Assessment of the Extraction Processes

The environmental profiles for the extraction processes presented in Table 3 highlight that across all categories, a higher impact is generated by CSE against the UAE technique. This shows that, for the experimental conditions utilized in this study, UAE has considerably lower impacts than the conventional method. For instance, fine particulate matter formation is 8 times more in the case of CSE than of UAE. Similarly, ozone formation adversely impacting both human health and terrestrial ecosystems is about 6 times more in the case of CSE than in UAE. Moreover, CSE causes six times the terrestrial acidification and consumes seven times more water than UAE uses when extracting polyphenols from seaweed using the outlined experimental conditions. Given the use of marine biomass for extracting polyphenols, no land use impact was observed in the case of either CSE or UAE. It is also noteworthy that no global warming impact was observed. Modahl et al. [26] also reported 1 kg CO_2 eq. in the extraction of vanillin when considering weight as a functional unit. As outlined in Figure 4, it was observed that in the case of both CSE and UAE, electricity was the most important impact contributor in all categories, followed by solvent production. This was due to electricity being used to operate a range of equipment in the extraction process, and solvent being the only waste generated in both cases.

Table 3. Environmental profiles for the extraction processes (per functional unit of 1 g polyphenols).

| Impact Category	Unit	CSE	UAE
Fine particulate matter formation (FPMF)	kg PM2.5 eq	7.55×10^{-5}	1.28×10^{-5}
Freshwater ecotoxicity (FE)	kg 1,4-DCB	2.94×10^{-7}	4.98×10^{-8}
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	2.07×10^{-6}	3.52×10^{-7}
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB	1.75×10^{-4}	2.97×10^{-5}
Marine ecotoxicity (MECo)	kg 1,4-DCB	9.72×10^{-4}	1.65×10^{-4}
Marine eutrophication (MEut)	kg N eq	6.66×10^{-9}	1.13×10^{-9}
Mineral resource scarcity (MRS)	kg Cu eq	2.31×10^{-3}	3.92×10^{-4}
Ozone formation, Human health (OFHH)	kg NOx eq	6.80×10^{-4}	1.15×10^{-4}
Ozone formation, Terrestrial ecosystems (OFTE)	kg NOx eq	6.80×10^{-4}	1.15×10^{-4}
Terrestrial acidification (TA)	kg SO2 eq	2.45×10^{-4}	4.16×10^{-5}
Terrestrial ecotoxicity (TECo)	kg 1,4-DCB	1.44×10^{-4}	2.45×10^{-5}
Water consumption (WC)	m^3	1.44×10^{-4}	2.49×10^{-5}

CSE: conventional solvent extraction; UAE: ultrasound-assisted extraction.

3.2. Economic Assessment of the Extraction Processes using Extraction Yield

The COM of phenolic-rich extracts obtained using CSE and UAE techniques was estimated by including costs of inputs (pre-treated raw material, transportation, extraction solvent, vessel cost, filtration, freeze-drying) and operational costs (electricity, labour). Operational site/building costs were not included. Using time-driven activity-based costing (TDABC), the cost was estimated over a one-year operational period. This included listing the various activities involved in the extraction process and their costs were accessed for the duration of the activity.

The costs for manufacturing over a one-year period at laboratory scale were estimated (using Equation (1)) to be EUR 65,513 for UAE based on an extraction vessel capacity of 0.01 m^3. This cost comprises the pre-treated raw material cost (EUR 5611), the cost of extraction (EUR 15,752), the cost of filtration (EUR 3182), the cost of freeze drying (EUR 21,133), and the cost of operational labour (EUR 19,835) using Equations (2)–(6). While using the CSE technique, the extraction cost for a year at lab scale for the same vessel capacity was estimated at EUR 50,897. This cost comprises the pre-treated raw material cost (EUR 1402), the cost of extraction (EUR 6312), the cost of filtration (EUR 2215), the

cost of freeze drying (EUR 21,133), and the cost of operational labour (EUR 19,835) using Equations (2)–(6). The overall COM per year at lab scale is higher in the case of UAE because of the four extraction cycles per day as against one cycle per day in the case of the conventional method. However, owing to the higher extraction yield in UAE (35.1%) compared to the conventional method (11.2%), the COM EUR/kg extract is lower for UAE at EUR 922/kg than for CSE at EUR 8981/kg. The COM per kg of phenolic-rich extracts at the lab scale for both CSE and UAE are summarized in Table 4.
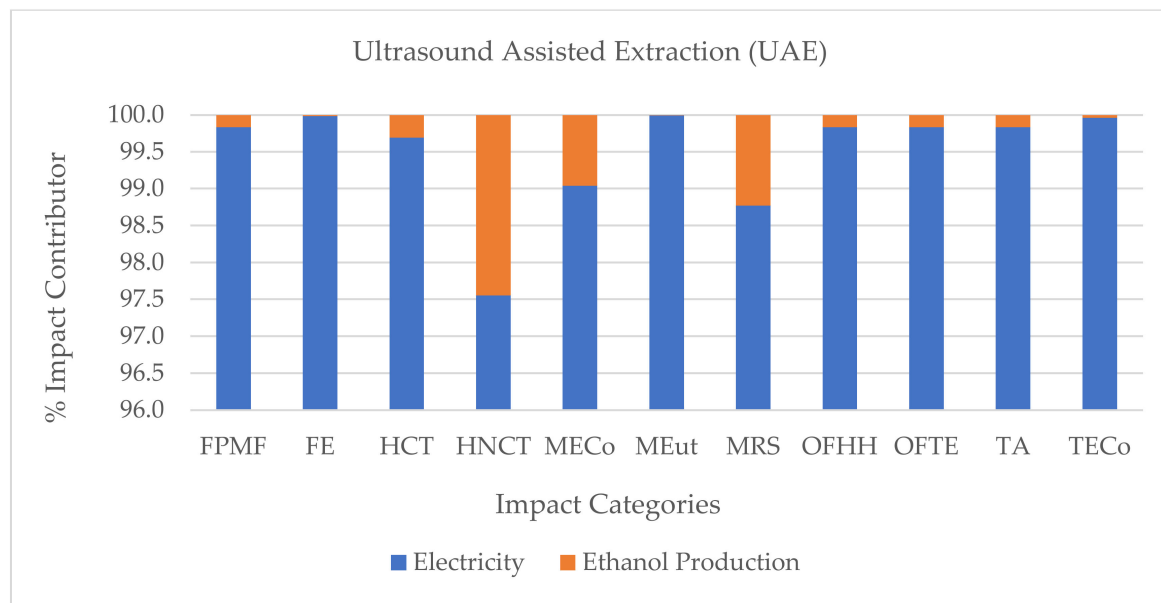
(**a**)
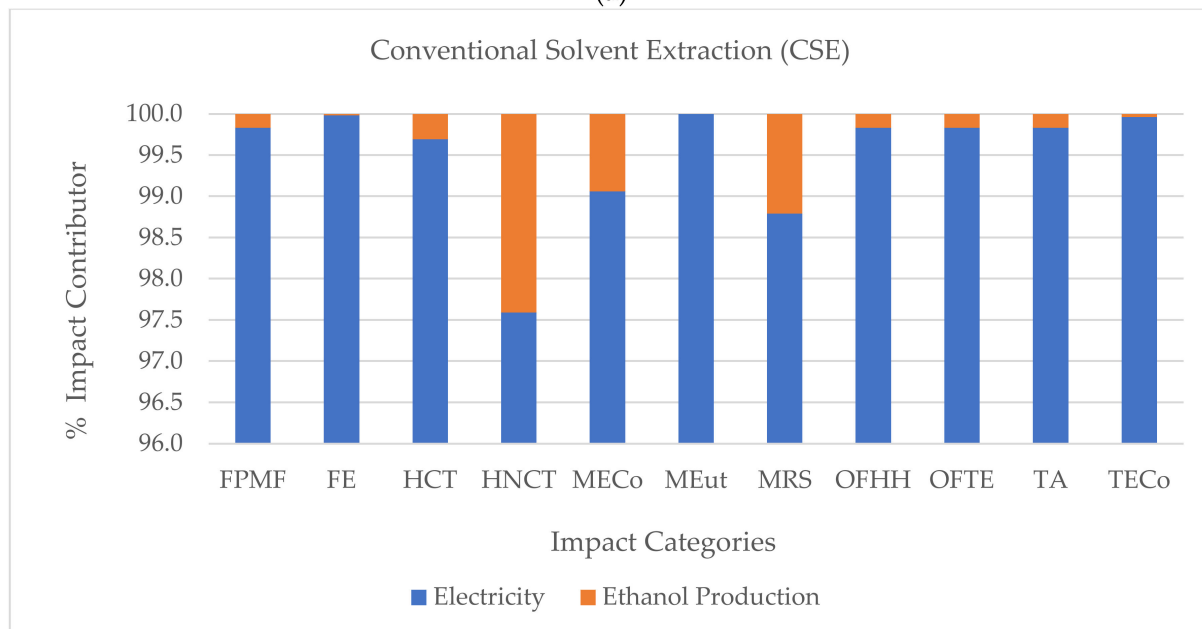
(**b**)

Figure 4. The environmental profile of (**a**) ultrasound-assisted extraction (UAE) and (**b**) conventional solvent extraction (CSE) processes. Abbreviation of impact categories are as follows: FPMF (Fine particulate matter formation), FE (Freshwater ecotoxicity), HCT (Human carcinogenic toxicity), HNCT (Human non-carcinogenic toxicity), MECo (Marine ecotoxicity), MEut (Marine eutrophication), MRS (Mineral resource scarcity), OFHH (Ozone formation, Human health), OFTE (Ozone formation, Terrestrial ecosystems), TA (Terrestrial acidification), and TECo (Terrestrial ecotoxicity).

Table 4. COM of extract and TPC using CSE and UAE at lab and large scale.

	Extraction Yield (%)	TPC (mg/g)	Vessel Capacity (m^3)	COM of Extract (EUR/kg)	COM of Total Polyphenols (EUR/kg)
			Lab Scale		
CSE	11.2	310.11	0.01	8981	28,961
UAE	35.1	572.33	0.01	922	1611
			Large Scale		
UAE	–	–	0.05	345	603
UAE	–	–	0.10	340	595
UAE	–	–	0.15	443	774

CSE: Conventional solvent extraction; UAE: Ultrasound assisted extraction; TPC: Total phenolic content; COM: Cost of manufacturing.

The COM over a one-year period at large scale using UAE was estimated (using Equation (1)) to be EUR 1,200,304 for the extraction vessel capacities of 0.05 m^3, this cost included the pre-treated raw material cost (EUR 274,428), the cost of extraction (EUR 659,875), the cost of filtration (EUR 11,889), the cost of freeze drying (EUR 21,264), and the cost of operational labour (EUR 232,848). The COM for the extraction vessel capacity 0.1 m^3 was EUR 2,368,440, and this included the pre-treated raw material cost (EUR 548,856), the cost of extraction (EUR 1,310,835), the cost of filtration (EUR 21,789), the cost of freeze drying (EUR 21,264), and the cost of operational labour (EUR 465,696). For the 0.15 m^3 extraction vessel capacity the COM was EUR 4,623,290, comprising the pre-treated raw material cost (EUR 823,284), the cost of extraction (EUR 3,048,509), the cost of filtration (EUR 31,689), the cost of freeze drying (EUR 21,264), and the cost of operational labour (EUR 698,544). At the large scale, using extraction yield, the COM per kg of phenolic-rich extract was also calculated, and it was observed that the COM was the lowest for the 0.10 m^3 vessel capacity, at EUR 340/kg, followed by the COM for a vessel capacity of 0.05 m^3 at EUR 345/kg, while the highest COM was observed for a processing capacity of 0.15 m^3, at EUR 443/kg. The COM per kg of phenolic-rich extracts on a large scale for both CSE and UAE are summarized in Table 4.

3.3. Economic Assessment of the Extraction Processes Using Total Phenolic Content

The health benefits derived from the extract are mainly attributed to the amount of total phenolic content of the extract [49–51]. The concentration of TPC in the extract helps to determine the dosage of extract required in the development of nutraceutical or functional foods. Therefore, the COM of the extract based upon the total phenolic content in the extract was also calculated. At lab scale (0.01 m^3 vessel capacity), the COM for UAE was estimated at EUR 1611/kg using TPC (572 mg/g of extract) and the COM for conventional extraction was EUR 28,961/kg using TPC (310 mg/g of extract). While on a large scale, the COM for the UAE was a minimum of EUR 595/kg for a 0.10 m^3 vessel capacity and a maximum of EUR 774 for a 0.15 m^3 vessel capacity. The COM of the extract based upon the total phenolic content in the extract at lab scale as well as at large scale using both CSE and UAE are summarized in Table 4. Compared to lab scale, while it is observed that the COM was lower at large scale vessel capacities, it is noteworthy that the COM did not reduce with the increasing vessel size.

The economic evaluation demonstrated that the cost of raw materials and operational labour costs have a significant impact on the COM to produce extracts using different vessel sizes. Saravacos and Maroulis [52] also highlight that in food production processes, the key cost items are raw materials and labour costs. Similar observations with regard to raw materials being the major component of the cost of manufacturing were made in the case of volatile oil extracted from *Aquilaria sinensis* using supercritical carbon dioxide [53]. Although extraction yield had a large influence on the COM, the phenolic concentration in the extract was identified as a key parameter in the economic evaluation carried out. The estimated COM was a minimum of using a 0.1 m^3 UAE vessel capacity. Prior research

also highlights that in the case of producing extracts, COM is impacted by the extraction vessel capacity [54–56]. Overall, it is economically feasible to operate an industrial scale ultrasound extraction plant to recover phenolic compounds from seaweed, even at a small scale of production. Similar results confirming the feasibility of industrial usage of novel technology, supercritical fluid extraction, for producing extracts from grape bagasse were outlined by Farias-Campomanes et al. [46]. However, it is recommended that a full profiling of phenolic compounds in the extract should be carried out prior to its utilization for commercial applications. Prior research also indicates that COM is strongly influenced by raw material [57,58], hence it can be anticipated that seaweed species (as their phenolic content varies) may have an impact on the COM.

4. Conclusions

Nutraceuticals are being widely used for promoting health, and the potential of marine algae as a valuable source of these bioactive compounds with therapeutic effects is being increasingly recognized. While the natural renewable resource seaweed (marine algae) is a rich source of dietary fibres, polyunsaturated fatty acids, polysaccharides, and vitamins, to better exploit their potential, novel extraction technologies are being utilized. This study evaluated the environmental and economic viability of using the novel extraction technology UAE for extracting bioactives from seaweed. UAE offers benefits such as increased yield and decreased extraction time, it was better than the conventional extraction techniques in terms of a reduction in one-fourth the extraction time (based on per extraction cycle) and providing almost 1.8 times higher yield. With raw materials and operational labour costs being the primary contributors to the COM, it has considerably lower environmental impacts than the conventional extraction method, with electricity being the most important impact contributor.

Advancements in extraction technologies have burgeoned in every aspect of food processing and have led to progress in their scientific applications, but they call for environmental and economic assessment and policy development for widespread uptake. With a range of novel techniques increasingly being used for efficient extraction processes to valorise marine algal biomass, the approach adopted in this study can be employed for other innovative technologies and approaches to determine their suitability prior to commercial exploitation. This study demonstrates the importance of a sustainable extraction technological approach that can aid policy development in an environmentally, economic evidenced, and health-benefit-based manner. The joint approach to economically viable and sustainable technology usage can help policymakers to encourage industrial adoption of technologies for sustainable production for a healthy lifestyle. However, this study is not without its limitations. It considers lab processes and equipment designed for research purposes, which, unlike the industrial-scale systems, do not reach ideal conditions for energy and chemical consumption that can maximize polyphenols extraction. In addition, affordability and challenges of implementation on an industrial scale are not taken into account. Therefore, the scale-up scenarios can only demonstrate an early-stage comparison of the process steps and variables. Moreover, in terms of execution of the study, no infrastructure-related processes such as the production of lab-scale equipment as well as no transportation of any of the materials involved were included, further limiting the findings. Further investigations are thus called for to incorporate facets related to the environmental and economic impacts into the evaluation of extraction processes using novel technologies.

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