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Multi-Criteria Decision-Making Approach for Nutraceuticals Greener Applications: The *Cynara cardunculus* Case Study

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Abstract: Nutraceuticals are an ever-expanding market worldwide, facing the unstoppable transition towards a green economy. Developing economically feasible and sustainable alternatives to current raw materials for the extraction of nutraceuticals is, therefore, essential to reach these goals and, at the same time, achieve social and economic competitiveness. This paper intends to propose an economical and environmentally sustainable feedstock for chlorogenic acid (CGA) and inulin, whose current extraction from green coffee and chicory, respectively, is unsustainable. Our approach is based on the multi-criteria decision-making approach (MCDA), supported by the analytical hierarchy process (AHP), ranking the performance of competitor biomasses according to economic, social, and technological criteria. The results of this study highlight cardoon (*Cynara cardunculus*) as a promising raw material for the extraction of CGA and inulin in virtue of the high concentration, low-input growth regime, and the possibility of being grown on marginal lands. Nevertheless, cardoon biomass availability is currently scarce, extraction methods are underdeveloped, and consequently, the obtained product's price is higher than the benchmark competitors. Policies and investments favoring sustainable cultivations could stimulate cardoon employment, linking economic advantages and land requalification while limiting phenomena such as desertification and food competition in the Mediterranean basin.

Keywords: nutraceuticals; MCDA; cardoon; chlorogenic acid; inulin

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1. Introduction

Nutraceuticals, sometimes referred to as functional foods or food supplements, are a wide range of bioactive compounds belonging to families of secondary metabolites generally extracted from plants or microbes [1]. Widely recognized as products with a beneficial interaction with human metabolism, they have antioxidant and chronic disease-prevention functions. Nutraceuticals show a positive consumption trend, as demonstrated by the increased food-supplement market value, which rose from USD 32 billion (in 2009) to 45 billion (in 2016) [2]. With a wholesome 2019 market value of USD 424 billion, Daliri and Lee estimated that the nutraceutical market will grow annually by an average of 6.5% in 2021–2027 [3].

The green transition of nutraceuticals, functional food, and the cosmetics industry is steadily proceeding [4], pushed by the consumer's demand for environmentally friendly products, policy tools, and investments to reduce the harmful impact of production on the climate and the environment [5]. In this context, the integrated biomass–biorefinery approach is one of the most promising production models for recovering raw materials and obtaining energy, food, feed, and polymers with high added value [6]. However, its feasibility and economic sustainability are limited by the availability of biomass, its quality, the procurement costs, and the conversion yield [7]. Obtaining chemicals capable of replacing their fossil-based counterparts is the crucial point of biomass-based businesses' technological and profitability analysis, which must consider additional factors affecting the supply chain efficiency. Land use, the impact on biodiversity and ecosystems, water consumption, GHG emissions, and food competition are just some of the evaluation criteria to consider in the economic decision-making process and industrial feasibility study.

Our study focuses on two important nutraceuticals: chlorogenic acid (CGA) and inulin, which have a compound annual growth rate (CAGR) of current and projected (until 2027) demand of 3.44% and 4%, respectively [3,8].

CGA is a polyphenolic molecule belonging to the caffeoylquinic acid family, consisting of a quinic acid bonded at C-5 to a caffeic acid molecule [9], biosynthesized by the plant in response to stresses caused by bacteria [10] fungi [11], insects [12], wound damage [13,14], and ultraviolet exposition [15,16]. The growing interest in CGA is due to its beneficial interactions with human metabolisms, such as antioxidant, antimicrobial, hepatoprotective, and anti-obesity activity [9,17]. Green coffee (*Coffea spp. L.*) is the primary source of CGA [18], although it is facing a recent market contraction [8]. Green coffee is cultivated mainly in Brazil and Vietnam [18] where the most cultivated species are *Coffea canephora* and *Coffea arabica* [19]. The *arabica* species is more agronomically demanding than *canephora*, but its yield and quality are superior [20].

Although the CGA extraction processes are industrially diversified [21–24], the Soxhlet method is widely employed [24], followed by the more cost-effective, efficient, and scalable microwave-assisted extraction (MAE) [25–28]. CGA is commercialized mostly as phyto complex formulations (pills or capsules) [29], with a diversified pricing policy according to the concentration, branding, and application [3]. The most expensive formulation is used in the pharmaceutical sector (USD 30/kg), followed by cosmetic (USD 22/kg) and nutraceuticals (USD 14/kg) [3]. The microencapsulation prevents CGA degradation from digestive oxireductive stress [29]. Yearly, more than half of the CGA extracted (6437 tons) is consumed as food supplements, followed by 21% used by the pharmaceutical sector (1444 tons/year), and approx. 20% used in cosmetics [3].

Inulin belongs to the fructans family, consisting of linear (2→1)-linked -d-fructosyl units linked to the fructosyl moiety. Biosynthesized in plant roots, where it exerts an energy reservoir function [30], inulin's structure varies from 2 to 60 fructosyl units [31], according to the vegetative stage, the species, and the environmental conditions [31]. Inulin has low caloric intake values, making inulin-based products recommended for low-glycemic diets [32] and in many food preparations (baby foods, bakery, ice creams) [33]. Furthermore, many studies underline inulin's ability to reach the gut and act as a prebiotic [34]. Chicory (*Chichorium intybus*), the primary inulin source [8], is an overwintering herb endemic of the Mediterranean basin, North America, and Africa [35], whose cultivars are widely employed as food and feed products [36,37]. Environmental conditions play a significant role in plant development, as a temperature above 14 °C is required for consistent production [37]. Chicory needs great cultivation inputs (for example, 750 m^3/year of water), thus causing a high environmental impact (3.75 kg CO_2 eq/kg of biomass) [18,38].

Jerusalem artichoke (*Helianthus tuberosus* L.), also known as topinambur, is an additional source of inulin. Native to North America (36th parallel), the Jerusalem artichoke is a short-day perennial plant. Its adaptability to varying climatic and soil conditions makes it amenable to worldwide cultivation as a warm-season crop with an annual cycle [39]. The species is also used in the exploitation of marginal lands [40,41], albeit harvesting and cultivating practices are yet to be optimized [42]. The traditional inefficient inulin extraction methods have been substituted by MAE [43].

Native to the Mediterranean basin, cardoon (*Cynara cardunculus* L.) is a perennial herb belonging to the *Asteraceae* family [44]. Minorly cultivated as a vegetable, cardoon is attracting interest thanks to its high concentration of bioactive compounds [44,45], biomass yield [46], and ability to grow on marginal lands under low-input agronomical regimes [44]. Cardoon favors carbon sequestration, arable crop-system integration [41], and producing bio-based products, which avoids food competition phenomena [40,41]. Another Asteracea, artichoke (*Cynara scolymus*), is used for CGA extraction.

The growing demand for CGA and inulin is calling for developing and adopting greener business models along the entire supply chain [47].

With the goal of identifying the most efficient biomass for CGA and inulin extraction, this study compares the strategic factors affecting profitability and environmental impact by applying a multi-criteria decision analysis (MCDA) methodology. Conventional biomasses used to extract the two compounds of interest—green coffee, chicory, and Jerusalem artichoke—are compared with cardoon. Comparative methods (MCDA based) for biomass performance evaluation and subsequent choice are present in the literature concerning ethanol production [48], sugarcane varieties [49], and gasification processes [50]. Published studies consider only one component (i.e., technical improvements of the biomass or their processing technologies, and sustainability) [51]. Conversely, this study embraces various methods to optimize the choice among different options and conflicting criteria [52].

Extensively employed in policy-making decisions [53], MCDA proved to be suitable even in technical and scientific domains (reviewed in [54]). MCDA for biomass selection is applied in renewable energy source (RES) analyses [55] using the analytical hierarchical process (AHP), as described in [56]. For example, Chatzimouratidis and Pilavachi [57] used AHP to evaluate power plants' impact on living standards, whereas Amer and Daimon [58] evaluated the efficiency of renewable biomasses for energy production. Concerning nutraceuticals and functional foods, a novel MCDA model was proposed to assess the toxicological risks of botanical extracts [59]. Similarly, an MCDA-based experiment to find the correlation between military multi-nutrient food supplements and chronic disease incidence was recently conducted [60].

Considering the examples reported above, our novel approach considers technical–economic data from the literature and market reports about inulin and CGA production from renewable biomasses and innovatively applies MCDA to the nutraceuticals and food supplement sector, taking into account the environmental, economic, and social dimensions of CGA and inulin extraction. We aim at providing evidence for the validity of our model in providing an efficient decisional mechanism to promote alternative sustainable solutions for the nutraceutical industry.

Our approach is based on a customized MCDA methodology, which will be further described in the Materials and Methods section, applying an innovative computational model developed by Gatto et al. [61] to rank and select biomasses for the sustainable extraction of CGA and inulin. This innovative approach is based on quantitative and qualitative data present in the literature, therefore favoring the procedure's standardization, even in case of niche issues such as the subject of our study. The screened and analyzed literature data considers ultimately only the information useful for CGA and inulin. Based on eight criteria, a set of parameters describing the biomasses' performance, this approach takes into consideration experts' judgements in defining their importance by applying, as a part of MCDA, the AHP method, a general theory of measurement to derive ratio scales from paired comparisons that reflects the relative strength of preferences and feelings [62]. Further details on the AHP model are provided in the Materials and Methods section.

2. Materials and Methods

We developed a two-step method: Firstly, a bibliometric search for the data inventory of the most relevant biomasses for CGA and inulin extraction was conducted; secondly, biomasses were ranked using the MCDA based on economic, environmental, and social criteria. The MCDA calculations, as detailed in paragraph 2.2., were performed in R Studio© version 1.4.11.03 and followed the protocol defined by Gatto et al. [61].

2.1. Bibliometric Analysis

We conducted a bibliometric analysis based on the Web of Science, screening for publications from 1975 to 2021, including articles, proceeding articles, reviews, and book chapters. The two search queries for CGA and inulin are reported below:

- CGA search queries: (caffeoylquinic acid or chlorogenic acid or hydroxycinnamic acid) AND (market or anal * or applic * or employ * or review or extraction * or utilization * or exploit *) AND (biomass or artichoke or green coffee or *Cynara cardunculus* or synthesis) AND (nutraceuticals or cosmetic or pharmaceutical or pills or capsules or yield or efficiency or content or percentage).
- Inulin search queries: (inulin or fructan * or fructooligosaccharde) AND (market or anal * or applic * or employ * or review or extraction * or utilization * or exploit *) AND (biomass or feedstock or chicory or Jerusalem artichoke or artichoke or *Cynara cardunculus* or synthesis) AND (production or nutraceuticals or cosmetic or pharmaceutical or powder or capsules or yield or efficiency or content or percentage or cost * or prebiotic).

These outcomes were then screened and manually selected according to the following eligibility criterion: publications focusing on the linkage between biomass and bioactive compounds. Consequently, publications evaluating the following were discarded:

1. Bioactive compounds or biomasses other than the ones selected for the study;
2. Structure, metabolic behavior, and pharmacokinetics of the compounds;
3. Characterization of methodologies and processes relative to the bioactive compounds;
4. Energy valorization and uses other than nutraceuticals or cosmetics;
5. Clinical trials for medical applications of the bioactive compounds.

The results of the bibliometric search were categorized into economic, environmental, and social macro-areas, as shown in Figure 1.

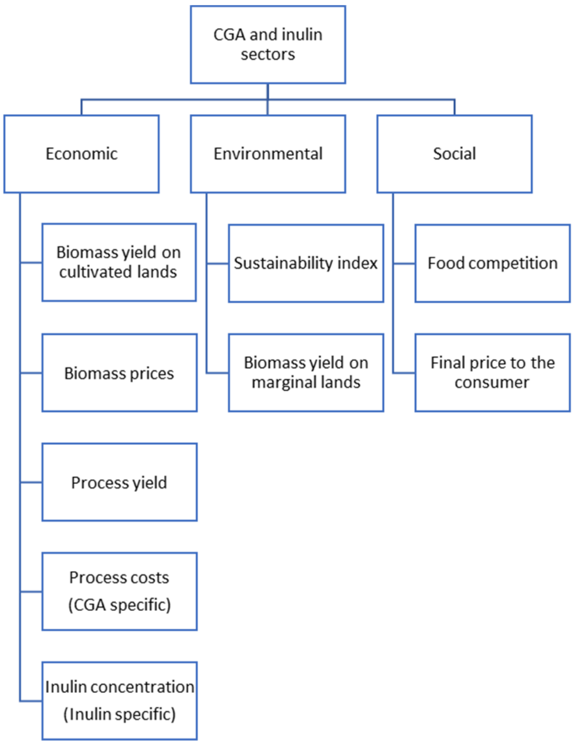


Figure 1. Schematic representation of the criteria selected for the bibliometric analysis for inulin and CGA.

2.2. Multi-Criteria Decision Analysis

The first step in MCDA is a context analysis of the supply chain, technologies for the extraction of bioactive compounds, economic players, policy pricing, and marketing strategies. A political, economic, social, technological, environmental, and legal (PESTEL) analysis enabled assessment of the macro-conditions of CGA and inulin production, from biomass cultivation to compound commercialization [63–65]. Current and future market values for CGA and inulin production were obtained by combining the PESTEL results and the bibliometric analysis with the market studies of absolute reports, Maia research analysis, and Mordor intelligence agencies. The criteria selection, the second step in MCDA, is based on quantitative parameters describing the supply chains according to the literature. We considered Cobuloglu's work [51] to select economic, environmental, and social criteria, as shown in Figure 1. CGA and inulin common and exclusive criteria are shown in Table 1.

Table 1. List of criteria used for MCDA for CGA and inulin. An identifier (C1–C8) was assigned to each criterion based on its position in the MCDA performance table.

Criterium	Criterium Title	Measurement Unit	Description	Evaluation Type
C1	Biomass yield on cultivated lands	Mg/ha	The amount of biomass obtained from each crop in optimal cultivation conditions.	Maximization
C2	Biomass yield on marginal lands	Mg/ha	The amount of biomass obtained in harsh soil unsuitable for conventional cultivation, capturing the added value of promoting rural and social development.	Maximization
C3	Biomass prices	EUR/kg	Calculated on 1 kg of biomass. This value is subject to environmental, social, and economic fluctuations (e.g., pandemic crisis, climate change, regulatory provisions).	Minimization
C4	Sustainability index	kg CO_2 eq/kg	The carbon footprint of each biomass.	Minimization
C5	Food competition	Present/absent	The capacity of the species to spare arable lands otherwise intended for edible crops or exploitation of edible crops (as in the case of coffee or artichoke).	Maximization
C6	Extraction yield	%	The efficiency of the extraction processes for each biomass.	Maximization
C8	Final sale price	EUR/kg	The final price to the consumer of the bioactive compounds.	Minimization
CGA-Specific Criterium				
C7	Extraction costs	EUR/cycle	The extraction costs from a 75 L pilot plant for one work cycle, referring to extraction conditions, electricity, heating, and raw material requirements.	Minimization
Inulin-Specific Criterium				
C7	Inulin concentration	mg/g	The availability of the bioactive compound in fresh biomass, before extraction.	Maximization

The third step in MCDA implies the creation of a performance table, where the rows are the plant species and the columns the criteria. The values obtained were reported for each of the criteria as an arithmetic mean and then normalized in a 0–1 interval, according to the linear Function (1),

$$y = (x - WC)/(BC - WC) \quad (1)$$

where WC is the worst result, BC is the best result, x represents the absolute performance value, and y is the normalized score. In the case of maximized criteria, the best-case scenario corresponds to the highest absolute value and the worst-case scenario to the lowest. Conversely, in the minimized criteria, the best scenario corresponds to the lowest absolute value and the worst one to the highest absolute value. The evaluation type (minimized or maximized) for each criterion is described in Table 1.

The fourth step in MCDA is the weighting of each criterion. The AHP model described by Saaty et al. [56] is based on a pairwise comparison among the selected criteria. From this cross-checking, it is possible to set a weighting rank among the criteria. The weighting process is supported by engaging a pool of seven independent experts (researchers, entrepreneurs, and expert consultants). As required by the AHP methodology, the survey is based on paired comparisons of the criteria. The evaluations reported by the experts are then transformed into effective weights per each criterion using the ahpsurvey R package as the eigenvector of the resulting matrix and, subsequently, the arithmetic average of the individual weights resulted in the final weights for each criterion. The consistency of each of the matrices obtained from the surveys was checked by calculating the consistency ratio (CR). In this study, the CR threshold was set at 0.2 because the high number of choices implied a significant variability of the matrices.

In the overall biomass score calculation, which is the final step in MCDA, each criterion weight is multiplied by the criterion value of each biomass, as expressed in Equation (2), where S_{ij} is the biomass-specific score (i) for the criterion (j), and w_j is the criterion's weight.

$$s_{ij} \times w_j \tag{2}$$

Subsequently, each of the obtained values for the same biomass are summed to obtain an overall score. This latter is expressed in Equation (3) and is the final value.

$$\sum_{k=1}^{n} s_{ij} \times w_j \tag{3}$$

Biomasses are finally classified according to the overall score, combining the performance values (Tables 3 and 5) and each weight (Figures 4 and 7). The sensitivity analysis allows for the evaluation of how much the model outputs (i.e., biomasses' ranking) are affected by the uncertainty of the model input (i.e., the criteria weights). The sensitivity analysis protocol by Gatto et al. [61] proposed a ±25% simulated fluctuation of one criterion at a time to evaluate possible changes in the relative biomass ranking. Calculations were performed with R software, designed to increase the specific weights while keeping their sum equal to 1.

2.3. Study Limitations

Data inventory, an essential phase of MCDA, suffered from a lack of systematic and comprehensive sources. Obsolete and discordant data on yields and extraction costs forced us to insert estimations and mean values, a bias partially mitigated by normalizing the values. Subjectivity biases in the weighting of the criteria are minimized by using expert surveys.

Although a more significant number of experts would have stabilized the results and reduced the aggregate standard deviation (SD), in the MCDA methodology, the number of external respondents is not required to be statistically significant and is sometimes absent. Moreover, in this study, MCDA aims to pay a premium on sustainability-related criteria over others, reducing the attention to the possible economic margins obtained from the conventional supply chain.

3. Results

3.1. Bibliometric Analysis

With over 1500 articles published from 1975 to 2021 devoted to CGA (787 = 51.3%) and inulin (747 = 48.7%), the bibliometric analysis showed a growing interest in these bioactive compounds, as reported in Figure 2.

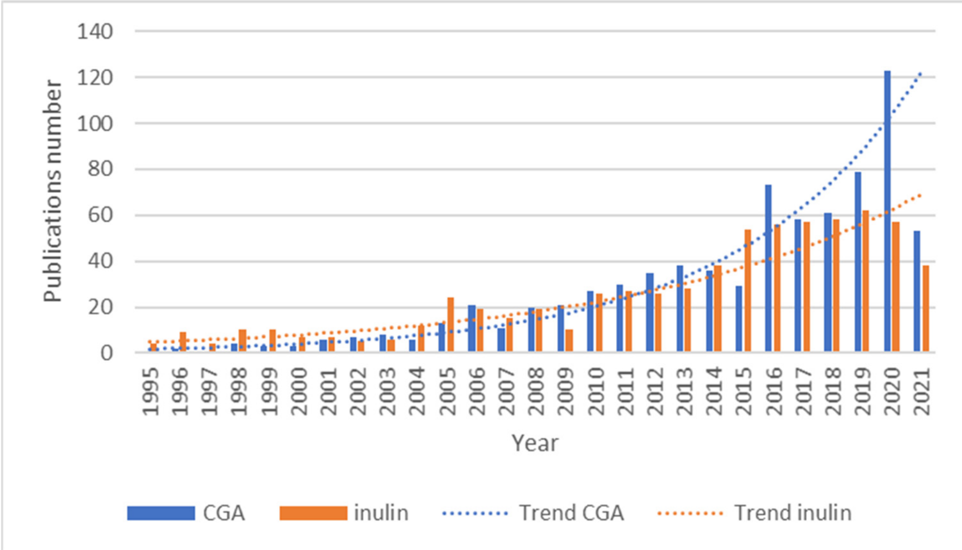
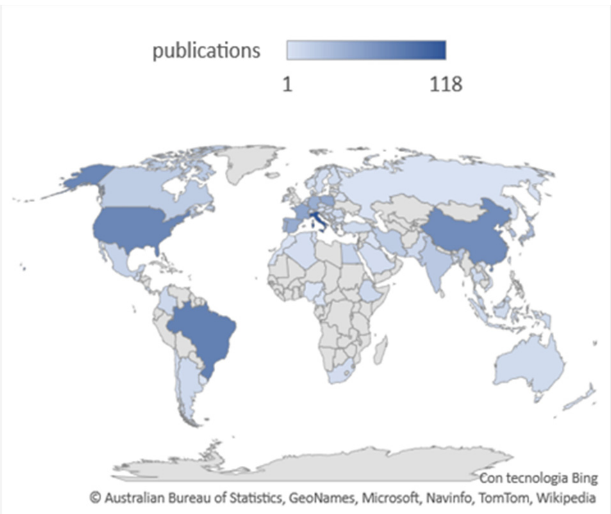


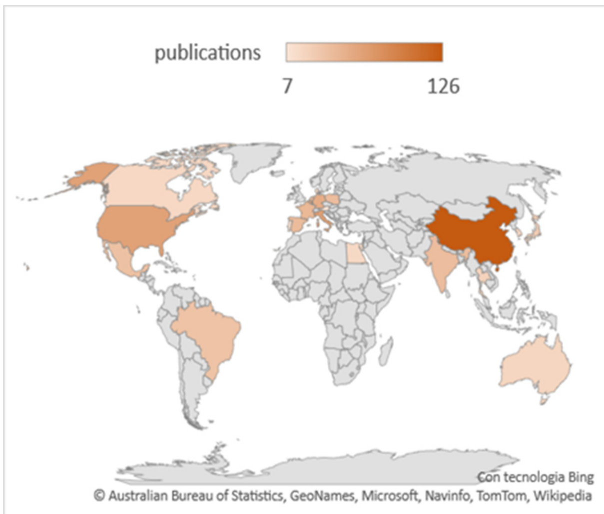
Figure 2. Total number of publications and relative trend for CGA and inulin by year.

A large number of publications (731 and 704) were not further considered in our study as they did not fit the selection criteria. Among these discarded publications, a notable interest was detected in the following areas: (1) studies concerning bioactive compounds (other phenols or saccharides contained in the selected biomasses) or biomasses (still containing CGA or inulin) not included in this study (60% and 55% of all the CGA and inulin publications, respectively); (2) studies considering structure, metabolic behavior, and pharmacokinetics of the compounds (16% and 12% of all the publications, respectively); (3) characterization of methodologies and processes of the bioactive compounds (12.45% and 8.70% of all the publications, respectively); (4) energy valorization and other uses of nutraceuticals and cosmetics (2.67% and 12.58% of all the publications, respectively); and (5) clinical trials for medical applications of the bioactive compounds (1.52% and 4.55% of all the publications, respectively) (Figure 2).

Italy ranked first for the number of publications on CGA research (118), followed by Brazil and the USA, and second for publications on inulin (67) after China (126) (Figure 3).



(**a**)



(**b**)

Figure 3. Publication distribution by country for (**a**) CGA and (**b**) inulin, according to the first author's nationality.

For CGA and inulin, 56 (7.12%) and 43 (5.76%) publications were selected in this study, respectively. The quantitative data used to create the performance matrices (Tables 5 and 6) were eight (CGA) and 11 (inulin) scientific publications, together with dedicated websites (four concerning CGA and two concerning inulin) and market reports (one per bioactive compound).

Considering our aim to identify the most sustainable biomass for CGA and inulin extraction, the biomasses resulting from the bibliometric search are reported in Table 2.

Table 2. List of the biomasses selected in this study for CGA and inulin extraction.

Chlorogenic Acid Source	Inulin Source
Cardoon (*Cynara cardunculus*) Green coffee beans (*Coffea canephora*) Green coffee beans (*Coffea arabica*) Artichoke (*Cynara scolymus*)	Cardoon (*Cynara cardunculus*) Chicory (*Chicorium intybus*) Jerusalem artichoke (*Heliantus tuberosus*)

3.2. MCDA Results for CGA Extraction

The CGA performance matrix reports the competing biomasses in the rows, whereas the descriptive criteria of the supply chain are in the columns, from the biomass yield to the work processes up to the final price of the compound, as shown in Table 3. Four criteria out of eight (C5, C6, C7, and C8) were obtained consulting a single source because of the lack of reliable and specific quantitative data about the biomasses. Concerning the four missing criteria (C1, C2, C3, and C4), the values reported in the performance table are the mean of the gathered data.

Table 3. CGA performance table.

Biomass	Biomass Yield on Cultivated Lands (Mg/ha)	Biomass Yield on Marginal Lands (Mg/ha)	Biomass Prices (EUR/kg)	Sustainability Index ($kgCO_2eq/kg$)	Food Competition	Process Yield (%)	Process Costs (EUR/kg)	Final Price to the Consumer (EUR/kg)
Artichoke (*Cynara scolymus*)	9 [44,66]	Not suitable	1 [67]	0.3 [68]	Yes	22.5 [69]	18.88 [69]	55 [3]
Green coffee (*Coffea canephora*)	3.1 [70]	Not suitable	5 [70]	6.85 [71]	Yes	7.4 [27]	8.51 [27]	23.9 [3]
Green coffee (*Coffea arabica*)	2.3 [70]	Not suitable	5 [70]	6.84 [18]	Yes	7.4 [27]	8.51 [27]	23.9 [3]
Cardoon (*Cynara cardunculus*)	17 [44,73]	7.95 [44]	0.098 [67]	0.2 [72]	No [44]	22.5 [69]	18.88 [69]	55 [3]

Cardoon (*Cynara cardunculus*) had the best biomass yield (17 Mg/ha, ranging from 10 to 25 Mg/ha) under optimal conditions and was the only crop for the production of CGA that had a relevant yield even in marginal lands (7.5 Mg/ha, with a reported low peak of 1.4 to a top value of 14.4 Mg/ha). It had the best biomass price (EUR 0.098/kg, ranging from EUR 0.018 to 0.17/kg), sustainability index (0.2 kg CO_2 eq/kg, ranging from 0.116 to 0.29 kg CO_2 eq/kg), and process yield (22.5%). Although artichoke (*Cynara scolymus*) had only slightly lower performance than cardoon, it cannot be grown on marginal lands, and its potential use as a CGA raw material competes with the food supply chain. On the contrary, green coffee (*Coffea canephora* and *Coffea arabica*) had the best values in process costs (EUR 8.51/kg) and final price (EUR 23.90). However, green coffee shows high variability in the sustainability index (ranging from 0.86 to 13.2 kg CO_2 eq/kg for *arabica* species, and 1.1 to 12.6 kg CO_2 eq/kg for *canephora*), depending on both cultivation methodologies and logistics dynamics.

Normalized values related to CGA performance values are shown in Table 4.

Table 4. CGA scoring table after normalization of the performances reported in Table 3.

Biomass	Biomass Yield on Cultivated Lands	Biomass Yield on Marginal Lands	Biomass Prices	Sustainability Index	Food Competition	Process Yield	Process Costs	Final Price to the Consumer
Artichoke (*Cynara scolymus*)	0.456	0	0.816	0.980	0	1	0	0
Green coffee (*Coffea canephora*)	0.055	0	0	0	0	0	1	1
Green coffee (*Coffea arabica*)	0	0	0	0	0	0	1	1
Cardoon (*Cynara cardunculus*)	1	1	1	1	1	1	0	0

A qualitative evaluation of the criteria led to the criteria ranking to identify the optimal biomass for CGA. The most significant criterion was the final price to the consumer (0.269, s.d. ±0.136), followed by the process costs (0.167, s.d. ±0.083), the sustainability index, food competition (0.112, s.d. ±0.096 and ±0.142 respectively), and biomass yield on marginal lands (0.105, s.d. ±0.069). Lower interest was observed for process yields (0.088, s.d. ±0.043), biomass prices (0.074, s.d. ±0.036), and biomass yield on cultivated lands (0.039, s.d. ±0.017). All criteria showed a high standard deviation. Notably, food competition and the sustainability index showed a high s.d., quantifying 126% and 88% of their weight value, respectively. Such a trend was a consequence of the variability between the different opinions of the experts interviewed. Weights and standard deviations are shown in Figure 4.

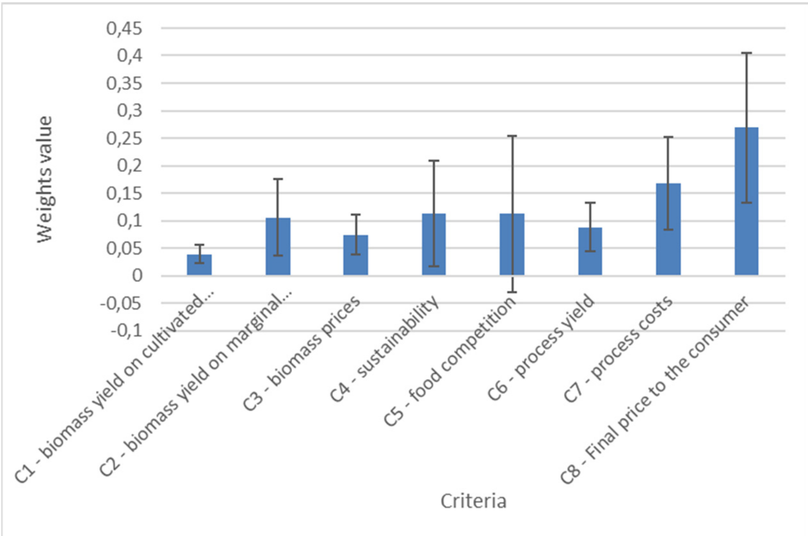


Figure 4. CGA weight representation and their standard deviation.

Cynara cardunculus ranked first (0.534) as the most sustainable source of CGA, followed by green coffee (*canephora* and *arabica*, 0.438 and 0.436, respectively), and artichoke (0.278), as shown in Figure 5, where the impact of each criterion on the overall score is also reported. For example, 38% of the final green coffee score was attributable to process costs, whereas the final price contributed 62%. In *Cynara cardunculus*, 25% of the final score was due to food competition, whereas the sustainability index and the yield on marginal lands represented 19.9% and 18.7%, respectively. Lower percentages were reported for process yields (15.6%), biomass prices (13.2%), and biomass yield on arable lands (6.9%).

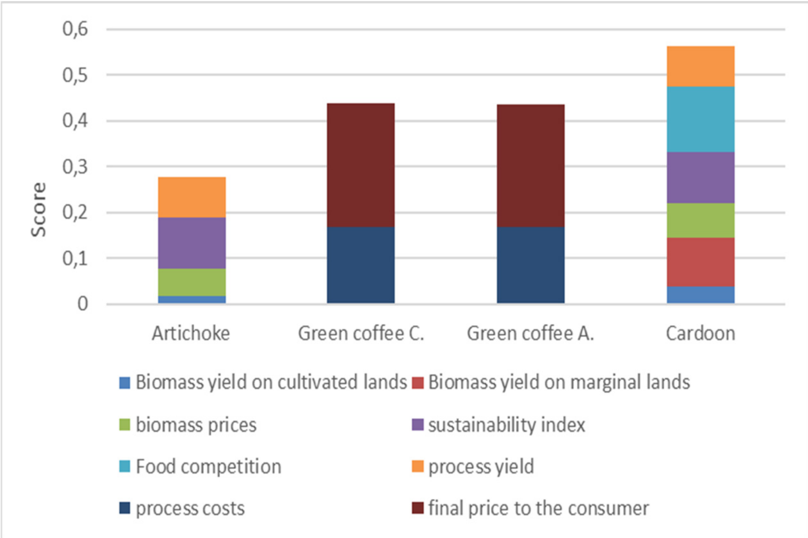


Figure 5. Scores of CGA biomass and contribution of each criterion. Green coffee C. refers to the *canephora* species, and green coffee A. to the *arabica*.

The sensitivity analysis considers changes in biomass performance in the presence of simulated fluctuations of ±25% for each of the criteria weights, as shown in Figure 6. The goal is to model the biomass performances with different weights attributed to each criterium and rank the changes due to the modeled fluctuations. A 25% increase in the "final price" criterion led to a better performance of green coffee, accompanied by reduced performance of cardoon (Figure 7). Specifically, under this scenario, green coffee and cardoon marked an equal performance value of 0.5, whereas the performance value of the artichoke dropped to 0.2. On the contrary, considering a decrease of 25%, the green coffee score was lowered to 0.4, whereas cardoon reached a maximum of 0.6. A similar trend was observed for the positive fluctuations of "process costs", showing an improved performance value of both species of green coffee up to 0.475. Nevertheless, the final biomass ranking did not change, with cardoon scoring the highest performance value (0.55).

3.3. MCDA Results for Inulin Extraction

Concerning inulin production, the C4, C6, and C8 criteria were derived from a single source, whereas C1, C2, C3, C5, and C7 were derived from the average of the gathered data (Table 5) from different sources considering different geographical areas, environmental conditions, or prior works. As for the sustainable biomasses for the extraction of inulin, cardoon showed an excellent value concerning the concentration of the compound (278 mg/g, ranging from 169 to 387 mg/g) compared to that of chicory (155 mg/g, ranging from 110 to 200 mg/g) and Jerusalem artichoke (155 mg/g, ranging from 120 to 190). Cardoon also had a low cost of biomass production (EUR 0.098/kg, compared to EUR 0.9/kg—ranging from EUR 0.7 to 1.1/kg—of chicory and EUR 1.70/kg—ranging from EUR 1.60 to 1.80—of Jerusalem artichoke), as shown in Table 5. Jerusalem artichoke proved to be a valid competitor in terms of biomass yield on marginal lands (12.4 Mg/ha—ranging from 7.1 to 17.8—versus the 8 Mg/ha of cardoon) and the sustainability index (0.06 kg CO_2 eq/kg versus 0.2 kg CO_2 eq/kg for cardoon). Chicory had the best biomass yield on arable crops (51.5 Mg/ha—ranging from 38 to 65 Mg/ha—versus 9.8 Mg/ha and 43.5 Mg/ha for cardoon and Jerusalem artichoke, respectively) and the highest process yield, reaching 63%, whereas cardoon had 57.5% and Jerusalem artichoke 40%. The final price to the consumer (EUR 3/kg) was equal for all the biomasses. Normalized values related to CGA performance values are shown in Table 6.

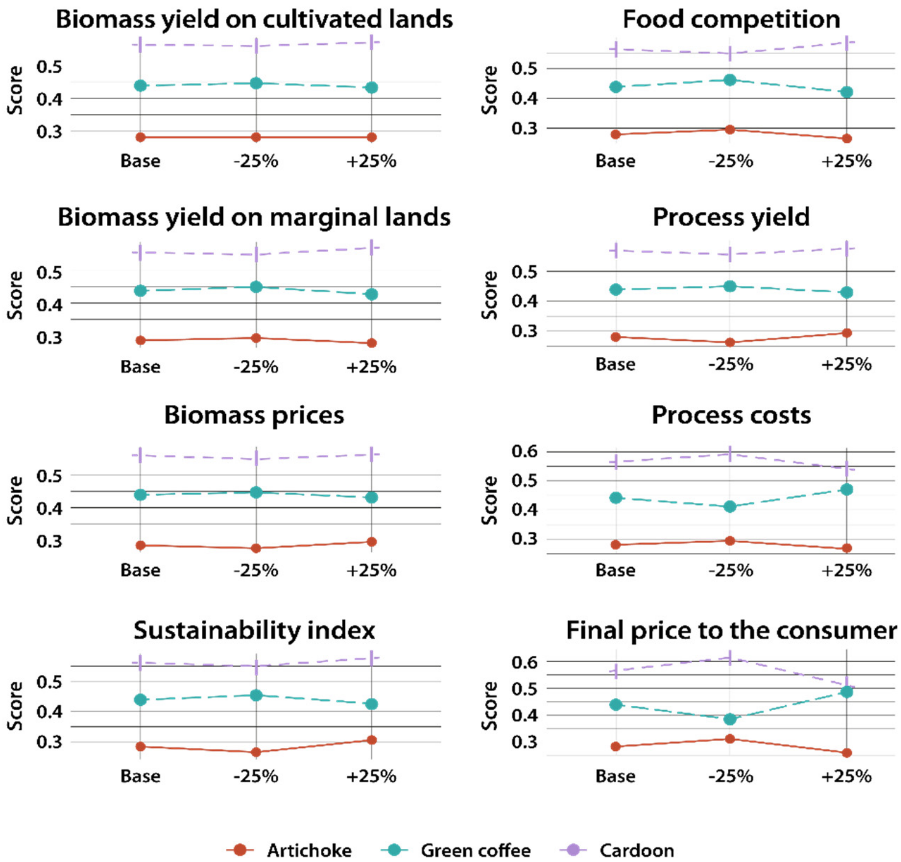


Figure 6. Results of CGA sensitivity analysis. The graphs express the estimated biomass performance under a ±25% fluctuation for each criterion. The performances of the *arabica* and *canephora* species overlap due to their identical behavior.

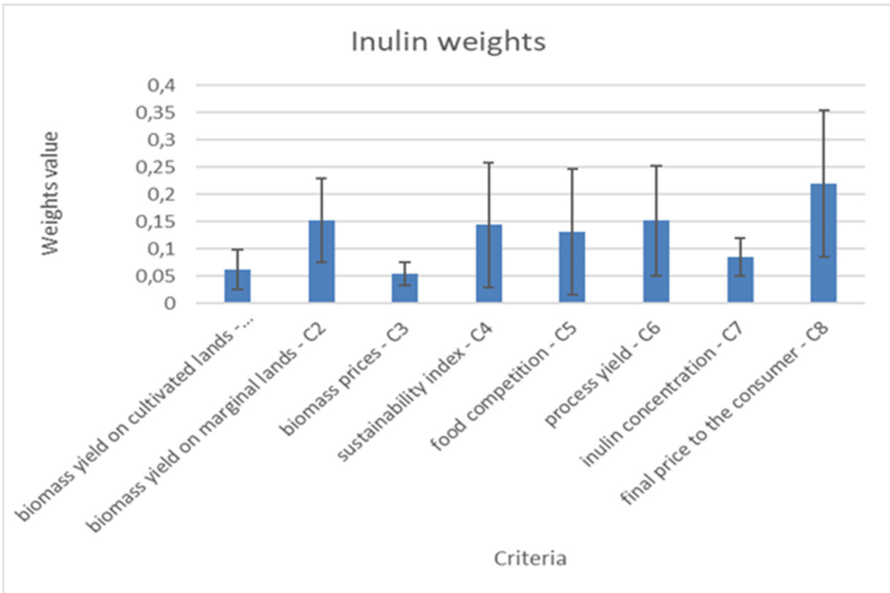


Figure 7. Inulin weight representation and standard deviations.

Table 5. Inulin performances.

Biomass	Inulin Concentration (mg/g)	Biomass Yield on Cultivated Lands (Mg/ha)	Biomass Yield on Marginal Lands (Mg/ha)	Biomass Prices (EUR)	Sustainability Index (kgCO_2eq/kg)	Food Competition	Process Yield (%)	Final Price to the Consumer (EUR)
Cardoon (*Cynara cardunculus*)	278 [45]	9.8 [45]	8 [44]	0.098 [67]	0.2 [72]	No [44]	57.5 [73,74]	3 [8]
Chicory (*Chicorium intybus*)	155 [75]	51.5 [38]	Not suitable	0.9 [76]	0.327 [77]	Yes	63 [43]	3 [8]
Jerusalem artichoke (*Heliantus tuberosus*)	155 [75]	43.5 [38]	12.4 [42]	1.7 [76]	0.06 [42]	No [42]	40 [78]	3 [8]

Table 6. Inulin scoring. Values are the normalization of CGA performances reported in Table 5.

Biomass	Inulin Concentration	Biomass Yield on Cultivated Lands	Biomass Yield on Marginal Lands	Biomass Prices	Sustainability Index	Food Competition	Process Yield	Final Price to the Consumer
Cardoon (*Cynara cardunculus*)	1	0	0.64	1	0.46	1	0.76	0.5
Chicory (*Chicorium intybus*)	0	1	0	0.50	0	0	1	0.5
Jerusalem artichoke (*Heliantus tuberosus*)	0	0.81	1	0	1	1	0	0.5

Regarding the relevance of the criteria (weights), similarly to the CGA, the final price to the consumer was the most important (0.22, s.d. ±0.133), followed by the biomass yield on marginal lands and process yields (0.152, s.d. ±0.071 and 0.151, s.d. ±0.1, respectively). The list of criteria with decreasing importance includes the sustainability index (0.144, s.d. ±0.114), food competition (0.13, s.d. ±0.115), inulin concentration (0.08, s.d. ±0.034), biomass yield on arable lands (0.06, s.d. ±0.036), and biomass prices (0.05, s.d. ±0.021), as reported in Figure 8. High standard deviations were reported for all the criteria. Among these, food competition and sustainability index showed the highest s.d. percentage, at 88.64% and 79.32% of the weight value, respectively.

Cynara cardunculus ranked first for inulin extraction (score 0.66), closely followed by Jerusalem artichoke (0.587) and chicory (0.35), as shown in Figure 8. The best performance of cardoon is due to the fact that all criteria were represented in the final overall score, except for biomass yield on arable lands. The highest contributions came from food competition (19.75%), process yield (17.40%) and biomass yield on marginal lands (14.8%). As for Jerusalem artichoke, the most relevant contributions were biomass yield on marginal lands (25.89%), the sustainability index (24.58%), and food competition (22.23%), whereas the contribution of the biomass yield in arable lands was negligible (8.59%). Despite the excellent performance in the "extraction yield" (43.1%) and "biomass yield in arable lands" (17.8%) criteria, chicory was a low performer under the criteria assessed as very important by the experts, i.e., the index of sustainability, food competition, and yield from biomass on marginal lands.

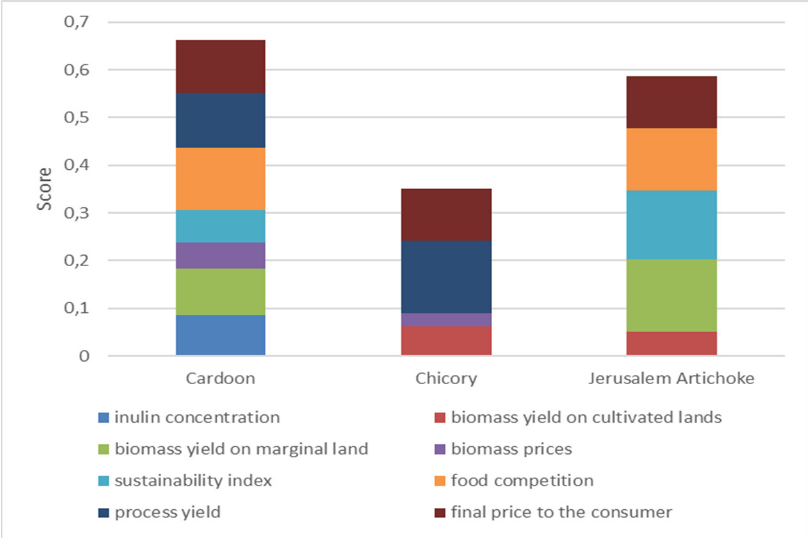


Figure 8. Inulin's overall score and contribution of each criterion.

The results of the modeled ±25% fluctuations of inulin criteria are shown in Figure 9, pointing to no relevant changes in the biomass classification model, the main interest of this evaluation. Cardoon was the best performer in each simulation. Interestingly, the species most affected by the fluctuations was Jerusalem artichoke, whose performance increased with the increase in the weight of the following criteria: (1) yield on marginal lands (from 0.56 in −25% to 0.61), (2) sustainability index (from 0.56 in −25% to 0.61), and (3) food competition (from 0.57 to 0.60).

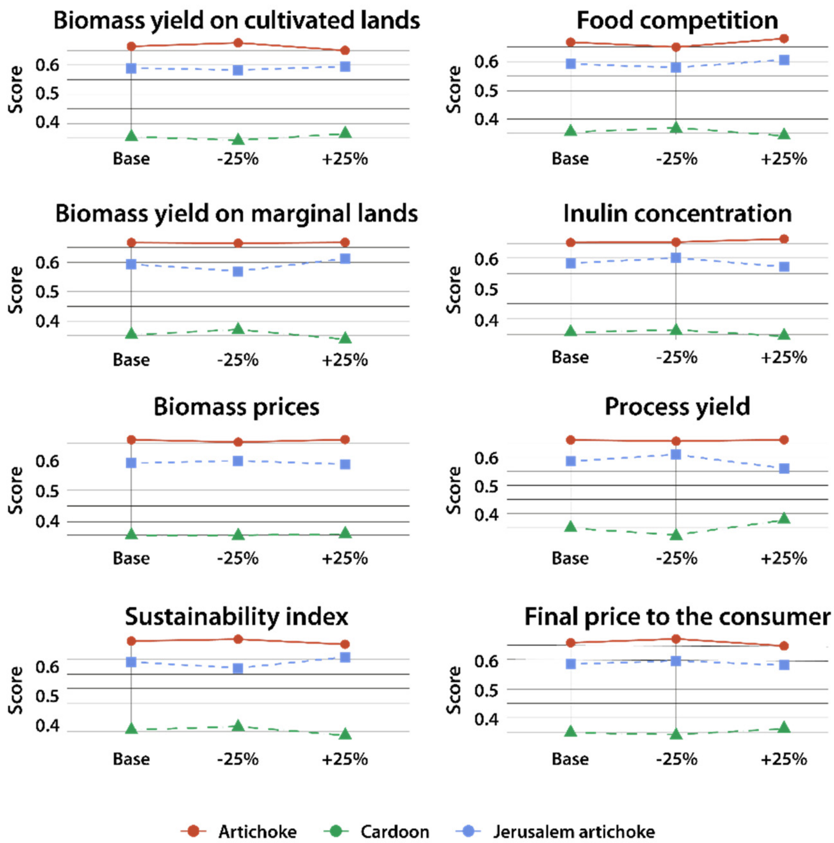


Figure 9. Inulin sensitivity analysis results. The graphs express the simulated biomass performances in case of a ±25% fluctuation for each criterion.

4. Discussion

Global warming, the depletion of natural resources, and a growing environmental awareness are driving the green transition of the manufacturing sector towards sustainable growth, guaranteeing adequate resources and living conditions for future generations. In this context, the European Commission has designed strategies to replace fossil materials with bio-based solutions, reduce environmental pressures, and strengthen green innovation, research, and employment in the EU. Through specific investment measures and strategic plans, such as the New Green Deal and the Next Generation EU, Europe aims to reduce net greenhouse gas emissions by at least 55% by 2030 [79] and make Europe the first climate-neutral continent by 2050 [80].

The transition to a greener economy also involves the nutraceutical sector. Innovation and a growing focus on health care and disease prevention, medical advances, and increasing life expectancy define this market's steady and tangible upward trend [1]. However, CGA and inulin are currently extracted from unsustainable biomasses due to food competition, high cultivation requirements, and logistical costs.

We aimed to identify alternatives to current raw materials for the extraction of CGA and inulin as an essential step to achieving social, economic, and environmental sustainability.

The MCDA approach employed in this study provides recommendations on which sources of CGA and inulin are more sustainable, based on economic, social, and technological criteria. This study paves the way for using the MCDA methodology in the nutraceutical industry.

The "process costs" and "inulin concentration" criteria were considered exclusively for CGA and inulin, respectively. In the case of inulin, process evaluation was unnecessary since competitor biomasses are morphologically similar, and the same can thus be assumed for process settings and costs. CGA concentration was not included because of contradictory data reported in the literature. The inclusion of this criterion would have risked biasing the study.

This study identified *Cynara cardunculus* as the most promising biomass for the extraction of CGA and inulin, qualifying it as an eco-sustainable, low-input alternative in marginal lands at risk of desertification in the Mediterranean basin. Desertification affects about 75% of the world's soil, and in Europe, the problem affects 13 countries for a total of 645,000 km^2 [81]. Cultivation in marginal and abandoned lands is environmentally efficient, and it favors the economic and social growth of these regions. Furthermore, cardoon is not an edible crop and does not compete with the food industry, thus supporting the growing demand for food and the global demand for bio-based products.

However, the current extraction of CGA and inulin from *Cynara cardunculus* is not economically nor technically competitive with the traditional, industrial biomasses, mainly green coffee and chicory. In the selection phase, expert heterogeneity was purposedly sought to include the broadest overview possible. Therefore, due to their different backgrounds and specific interests, the variability in expert judgments was relevant. Nevertheless, an agreement was recorded about the importance of the final price to consumers in evaluating the ranking of the biomasses for nutraceutical extraction.

CGA from cardoon is sold at almost double the price of green coffee. The reasons behind the expensiveness of CGA cardoon are biomass shortages, scarce cultivation employment and seasonality, and extraction process inefficiencies. The latter is a consequence of the use of conventional methodologies. To reduce process impact on the extraction, further implementation of unconventional extraction methods, such as MAE or UAE, is recommended.

When analyzing inulin production, the environmental sustainability of Jerusalem artichoke is comparable or superior to cardoon. However, the shortcomings of Jerusalem artichoke, such as the reduced inulin concentration and the low process yield, still make cardoon the first choice. It is, however, worth noting that cardoon has a low crop yield both on standard and marginal lands. The extraction process cost was not included in this analysis since all the species used for inulin extraction have similar morphological features and undergo extraction protocols. The reasons for inulin's market price stability (independent from the biomass considered) could be due to the treatment and process homogeneity required to obtain the inulin powder independently from the final application. Another reason could be that inulin powder is a pure compound, and therefore does not need expensive testing of formulates [8].

Our study demonstrates that *Cynara cardunculus* is a very promising crop for extracting nutraceutical compounds. However, further studies are needed to improve its economic and technical feasibility, supported by dedicated national and European funds. For example, efforts should be dedicated to improving the efficiency of the CGA extraction process to reduce the process's cost and the final product's price. The innovative extraction methodologies (MAE, UAE, and Supercritic-CO_2 extraction) can reduce process costs and environmental impact while increasing extraction yields. Inulin research should focus on increasing yield and biomass availability through improved cultivation methods and advanced breeding methodologies [82].

Farmers could use cardoon to diversify their production, exploit underutilized and marginal land, and, therefore, explore new market segments and find new sources of income. The cultivation of marginal and non-irrigated soils could maintain biodiversity and soil fertility, thus supporting the local economy [83]. Finally, nutraceutical companies could bring new innovative bio-based products to market, meeting consumer demand for functional and effective compounds that are both sustainable and environmentally friendly [84].

To ensure that consumers purchase sustainable cardoon-based nutraceutical products over already-marketed products, it would be necessary for the companies to involve the consumer in the purchasing decision, increasing awareness through transparency and promoting sustainability initiatives. Many studies have demonstrated that consumers are willing to pay more for a sustainable product as long as they know the environmental benefits and its sustainability index [85,86]. Developing a sustainability certification label for nutraceuticals could award a premium value to the final product. The label should contain clear information on the products' sustainable features, such as the low-input demand for its cultivation and the possibility of growing cardoon on marginal lands.

5. Conclusions

Cynara cardunculus is a promising raw material for the extraction of CGA and inulin due to the high concentration of the two compounds, the low-input growth regime of the species, and the possibility of growing it on marginal and abandoned lands. However, green coffee and *Cynara* are also considered affordable techno-economic options for CGA and inulin extraction, respectively, due to their market maturity and, therefore, the high and continued availability of biomass and advancement in the extraction process. We anticipate that the recently developed extraction methodologies (MAE, UAE, and Supercritical-CO2) may play an essential role in decreasing the cost and environmental impact of the process, especially for CGA extraction. We foresee European incentives and rational policies aimed at companies, farmers, and producers that favor sustainable industrial practices stimulating the cultivation of cardoon and its use. The improvement of the cultivation methods should increase cardoon yield, eventually increasing its market competitiveness. At the same time, developing a label certifying the sustainable nature of the produced nutraceuticals could add premium value to the final product and encourage consumers to purchase cardoon-based nutraceutical products.

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