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Evaluation of the environmental performance of stevia glycosides production using Precision Agriculture and green processing techniques

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Abstract: The aim of the current study was the evaluation of the environmental performance associated with the production of stevia glycosides powder using conventional, as well as green cultivation and processing techniques that aim to the reduction of bitter aftertaste of stevia glycosides. The environmental performance was evaluated using Life Cycle Assessment methodology. Data were collected from farmers and stevia processing companies, as well as validated literature sources, environmental databases and laboratory scale analysis of the new techniques. Various environmental impact categories, such as climate change, freshwater consumption and eutrophication, as well as ecotoxicity were examined. Regarding precision agriculture, it seems that steadily reducing inputs to the field, lead to reducing emissions in most of the impact categories studied. The addition of the new processing technologies leads to further decrease of the environmental footprint.

Keywords: Climate change; Environmental footprint; Green extraction techniques, Life Cycle Assessment; Stevia sweetener

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1. Introduction

In recent years, the growing rate of obesity and the health problems associated with the metabolic syndrome indicators (diabetes, cardiovascular, blood pressure) are turning consumers to exploring healthy, low-sugar alternatives, that offer a sweet taste, with much less calories. A promising alternative is the sweetener from the plant *Stevia rebaudiana Bertoni* (stevia). Stevia's sweet ingredients are called steviol glycosides; among them, stevioside and Rebaudioside A, are the major and sweetest ones, which are almost 300 times sweeter than sucrose [1]. The use of steviol glycosides has been approved by the European Union (EC 1131/2011), however, they are characterized by a bitter and metallic aftertaste, which acts as inhibitory agent for their widespread use [2].

The holistic intervention to all the stages of the agro-food chain of stevia sweetener production - from the field to the final powder production - is necessary for in-depth investigation and improvement of the bitter-metallic aftertaste. In addition, there is an increasing need to find solutions that offer sustainable and environmentally friendly methods of developing the relevant products. Precision agriculture (PA) is an alternative method of cultivation, based on the different inputs needs of the fields. High technology sensor and analysis tools are used, having the ability to reduce agricultural inputs, resulting in lower greenhouse gas emissions. PA is adopted to increase production and quality of crops, as well as to ensure the effective management of fertilizers and irrigation processes [3, 4]. In addition, green technologies, such as Microwave and Ultrasound assisted extraction, are important alternatives for stevia leaves' processing in order to extract the glycosides, reducing the solvent ratio, energy and time needed and leading to lower environmental footprint [5]. Life Cycle Assessment (LCA) has been recognized as the most powerful tool for assessing the environmental performance and comparing the environmental impact of many products and processes over their entire life cycle or a specific part of their life cycle. LCA consists of four stages: i) goal and scope definition, ii) inventory analysis, iii) impact assessment and iv) interpretation, and is conducted under ISO 14040 and ISO 14044 guidelines [6].

The objective of this study was the evaluation of the environmental performance of the application of PA and green processing techniques for the production of stevia sweetener. Four different scenarios were studied and evaluated using LCA methodology.

2. Materials and Methods

2.1 Life Cycle Assessment (LCA) methodology

LCA study was performed on GaBi ts (v8.7.0.18) commercial package. The goal of the LCA study was the assessment of the environmental impacts of the process lines used for the production of stevia powder. Defining the scope of the study, the following aspects are considered and described:

2.1.1 Product systems

Four different systems were examined a) conventional cultivation followed by conventional processing of stevia leaves (extraction and spray drying), b) cultivation using precision agriculture (PA) followed by conventional processing of stevia leaves, c) conventional cultivation followed by innovative processing of stevia leaves (ultrasound and microwave assisted extraction (UMAE), purification with membranes and spray drying) in order to reduce the bitter aftertaste of stevia glycosides, d) cultivation using PA followed by innovative processing of stevia leaves.

2.1.2 Functional Unit

The functional unit is the baseline to which all data in the product systems are normalized. The functional unit selected was 1.0 kg of produced stevia powder product.

2.1.3 System boundaries

The examined system was defined as all relevant life cycle stages and processes involved in the production of stevia powder product (from cultivation of stevia plant until the production of the final powder product, packaging, consumption and storage were not included).

2.1.4 Inventory Analysis

The inputs and outputs (materials, energy, water, emissions to air, soil and water) for all the examined processes were collected in the inventory analysis phase. The data were taken from industrial scale processes or extrapolated from pilot scale and are available upon request.

2.1.5 Impact Assessment Methodology

LCA study was performed on GaBi ts (v8.7.0.18) software, according to ISO 14040 and ISO 14044 guidelines. The impact categories that were evaluated were: 1) Climate change, excl biogenic carbon [kg CO2 eq.], 2) Climate change, incl biogenic carbon [kg CO2 eq.], 3) Fine Particulate Matter Formation [kg PM2.5 eq.], 4) Fossil depletion [kg oil eq.], 5) Freshwater Consumption [m3], 6) Freshwater ecotoxicity [kg 1,4 DB eq.], 7) Freshwater Eutrophication [kg P eq.], 8) Human toxicity, cancer [kg 1,4-DB eq.], 9) Human toxicity, non-cancer [kg 1,4-DB eq.], 10) Ionizing Radiation [Bq C-60 eq. to air], 11) Land use [Annual crop eq.·y], 12) Marine ecotoxicity [kg 1,4-DB eq.], 13) Marine Eutrophication [kg N eq.], 14) Metal depletion [kg Cu eq.], 15) Photochemical Ozone Formation, Ecosystems [kg NOx eq.], 16) Photochemical Ozone Formation, Human Health [kg NOx eq.], 17) Stratospheric Ozone Depletion [kg CFC-11 eq.], 18) Terrestrial Acidification [kg SO2 eq.], 19) Terrestrial ecotoxicity [kg 1,4-DB eq.]

ReCiPe 2016 (H) methodology [7] has been selected in order to be able to compare alternative processing lines. Recipe has 18 midpoint categories and 3 endpoints. Endpoints describe the environmental performance on three higher aggregation levels (Damage to Human Health [DALY], Damage to Ecosystems [species.yr], Damage to Resource Availability [$]) with Hierarchist perspective. The Hierarchist (H) perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms.

2.2 Systems description

2.2.1 System A: i) Cultivation: At the cultivation stage, stevia plants are planted on the plot and fertilization, using NH_4, KCl, P_2O_5 and irrigation streams are used. Spraying (6 applications per year), carving (15 applications per year), which are carried out with the help of a tractor take place in parallel. ii) Post-harvesting: The plants are harvested, dried with hot air and defoliated. iii) Stevia recovery: The extraction is performed using hot water and stirring (24 h, extraction efficiency (EE): 10%). The extract is purified and dried using spray drying. These data were collected from stevia farmers in the region of Lamia, Greece, through questionnaires.

2.2.2 System B: i) Cultivation: Cultivation was performed using precision agriculture. To produce an equal amount of leaves with system A, irrigation water was reduced by 13%, nitrogen fertilizers by 15%, while the amount of herbicides remained constant. ii) Post-harvesting: Similar to System A. iii) Stevia recovery: Similar to System A.

2.2.3 System C: i) Cultivation: Similar to System A. ii) Post- harvesting: Similar to System A. iii) Stevia recovery: Microwave and ultrasound-assisted extraction, using water as a solvent, was used to isolate glycosides (15 min, 60^{o}C, solid to solvent ratio: 1/10, 250 W ultrasound power, 250 W microwave power, EE: 30%). The decolorization of the extract was done by its sequential filtration through a reverse osmosis membrane system. The extract is dried using spray drying at 160^{o}C, using 600 mL/h flow rate.

2.2.4 System D: i) Cultivation: Similar to System B. ii) Post- harvesting: Similar to System A. iii) Stevia recovery: Similar to System C.

3. Results and Discussion

The environmental footprint of the four different systems was evaluated using LCA methodology. Every system process was described as a plan at GaBi ts software. The plan for the overall system is presented in Figure 1.

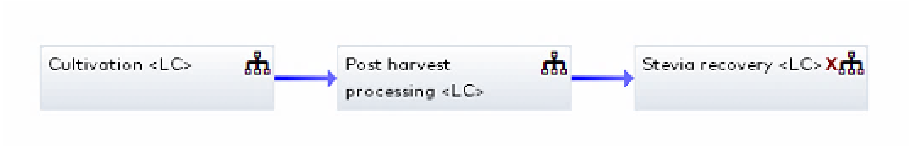

Figure 1. Overall plan for stevia powder production.

Figure 2 presents the percentage contribution of the individual processes to the footprint of System A for the production of 1.0 kg of stevia powder. As it can be seen, the cultivation process contributes more to the categories of fine particulate matter formation, fossil depletion, freshwater consumption, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, marine eutrophication, land use, non-carcinogenic human toxicity and terrestrial acidification. Post-harvest treatment contributes to the categories related to climate change, fine particulate matter formation, fossil depletion, freshwater ecotoxicity, marine ecotoxicity, land use, human toxicity - cancer and non cancer, ionizing radiation, as well as terrestrial acidification, terrestrial ecotoxicity, photochemical ozone formation for ecosystems and human health, while it significantly contributes to the stratospheric ozone depletion category. Glycoside recovery contributes mainly to the categories related to climate change, human toxicity, photochemical ozone formation and terrestrial ecotoxicity. Similar response was observed for the other three systems.

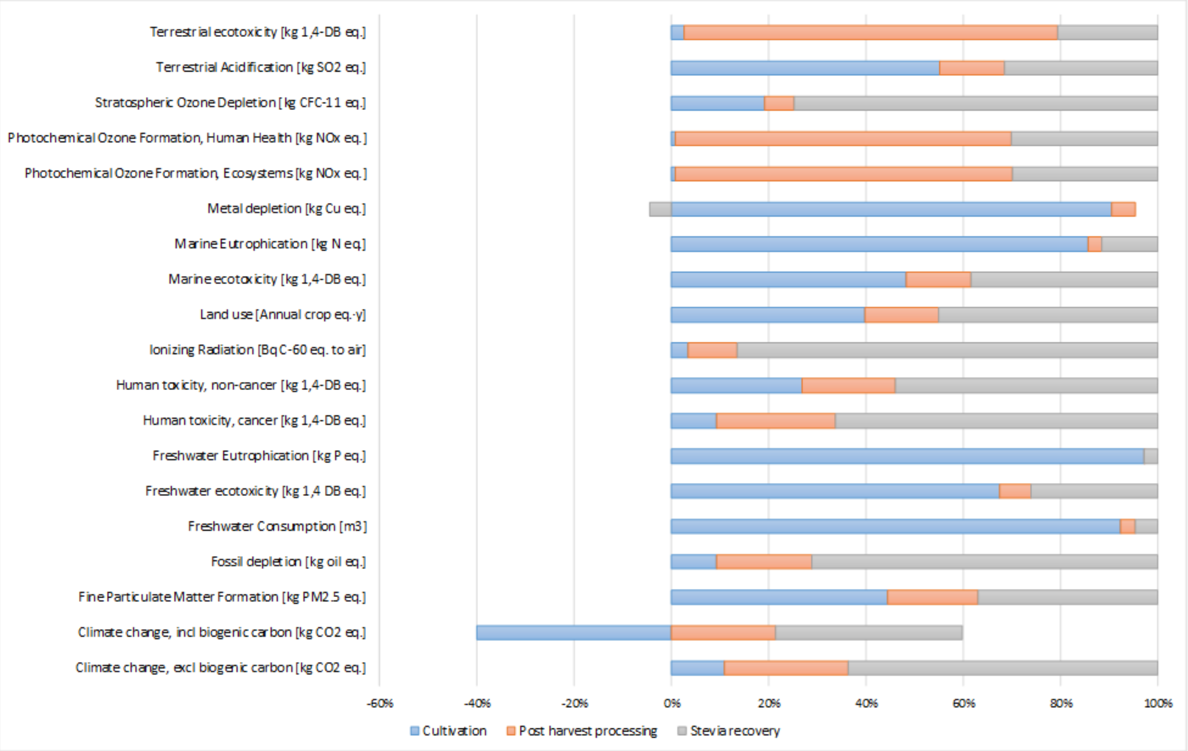

Figure 2. Contribution of the individual processes to impact categories – System A.

Figure 3 shows representative impact categories (climate change, freshwater consumption and eutrophication, ecotoxicity) for the four examined systems in further analysis. The flows that contribute significantly to the environmental footprint of the cultivation process (Figures 3a and 3d) are the emissions from the trucks for the internal transport in the facilities, the emissions from the fuel and the fertilization process. Nitrogen fertilizers also play an important role in the categories of ionizing radiation, photochemical ozone formation and terrestrial ecotoxicity. Thermal energy, electricity and biomass combustion contribute equally to the footprint of the post-harvest processing process (Figure 3b). The flows that contribute significantly to the environmental footprint of glycoside recovery (Figures 3c, 3e, 3f, 3g and 3h) are the emissions from the transport of dry leaves for extraction, the ethanol used during the extraction, as well as the waste water treatment. The use of water as a solvent during extraction affects the consumption of fresh water, while the electricity used during the recovery of glycosides (extraction and drying) affects the category of ionizing radiation.

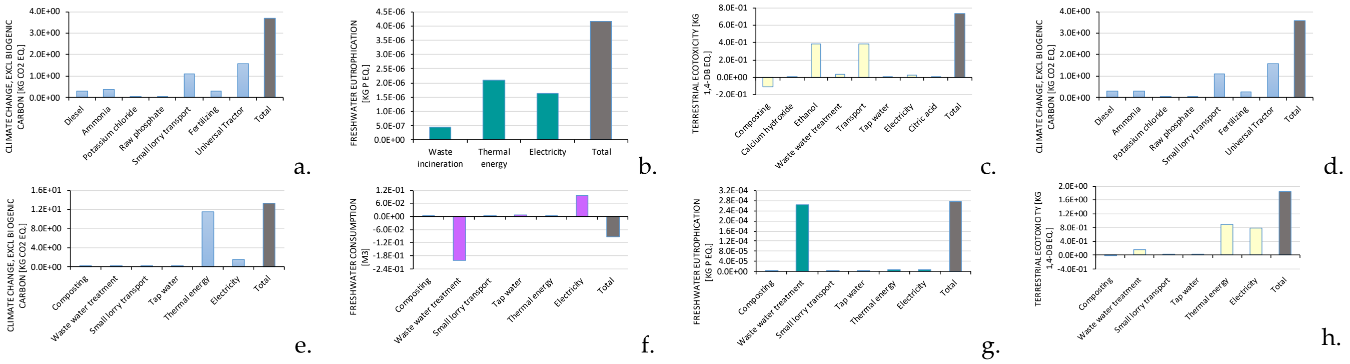

Figure 3. Representative impact categories for the four examined systems: a. System A cultivation - climate change, b. System A post-harvesting - freshwater eutrophication, c. System A stevia recovery – ecotoxicity, d. System B cultivation - climate change, e. System C stevia recovery - climate change, f. System C stevia recovery – freshwater consumption, g. System C stevia recovery - freshwater eutrophication, h. System C stevia recovery - ecotoxicity

Table 1 also presents the endpoint categories for the studied systems. The category "Damage to Human Health", expressed in DALY, is used to measure the years that are lost or the years that a person is disabled due to a disease or accident. As it can be seen the new methodologies for stevia recovery (Systems C and D) significantly decrease, about 30 to 40 %, this category. The category "Damage to Ecosystems", expressed in species.yr, refers to the species that are extinct during a year. This category does not seem to be affected using the new cultivation and processing techniques. Damage to resource availability is expressed in dollars and describes the costs used for future mineral and fossil resource extraction, and is equal to $ 4.81 for systems A and B and significantly lower (2.16 $) for systems C and D, which is more than the half damage [7].

Table 1. Endpoint categories.

Endpoints	System A	System B	System C	System D
Damage to Human Health [DALY]	1.06E-04	1.05E-04	6.48E-05	6.44E-05
Damage to Ecosystems [species.yr]	7.61E-06	7.61E-06	7.83E-06	7.82E-06
Damage to Resource Availability [$]	4.81	4.81	2.16	2.16

Figure 4 presents the comparison of the impact categories for the four different systems. The comparative analysis showed that the use of precision agriculture (Systems B and D) and the application of green processing methods for optimal recovery of glycosides (Systems C and D) lead to a significant reduction of the environmental footprint for the majority of impact categories. Exceptions were the categories of carcinogenic toxicity, and formation of photochemical ozone, due to the high electrical energy used in the membrane system, but also the category of ionizing radiation due to thermal energy during extraction and spray drying, and the treatment of liquid waste resulting from the cleaning process. Regarding Systems A and B, it was observed that the processes of cultivation and recovery of glycosides had the largest contribution to the formation of the environmental footprint for most of the midpoint impact categories. Post-harvest processes appeared to have a significant contribution with a positive impact on the categories related to photochemical ozone formation, terrestrial ecotoxicity, climate change and human toxicity. The use of PA had a significant impact on reducing the environmental footprint. The reduction in most categories was of the order of 10-15%. A sensitivity analysis was also performed regarding the use of water and nitrogen fertilizers, and it was observed that reduction of their use led to a significant decrease of the environmental footprint during stevia cultivation. For Systems C and D, the new extraction method used had almost three times the efficiency of glycoside recovery compared to the conventional one, leading to a significant reduction in the overall impact. The process of recovery of glycosides contributed to the majority of impact categories, due to the high amount of water and electricity used in the cleaning process with membranes, but also the thermal energy during spray drying. This process contributed significantly, approximately 70% to climate change and 85% to the metal depletion.

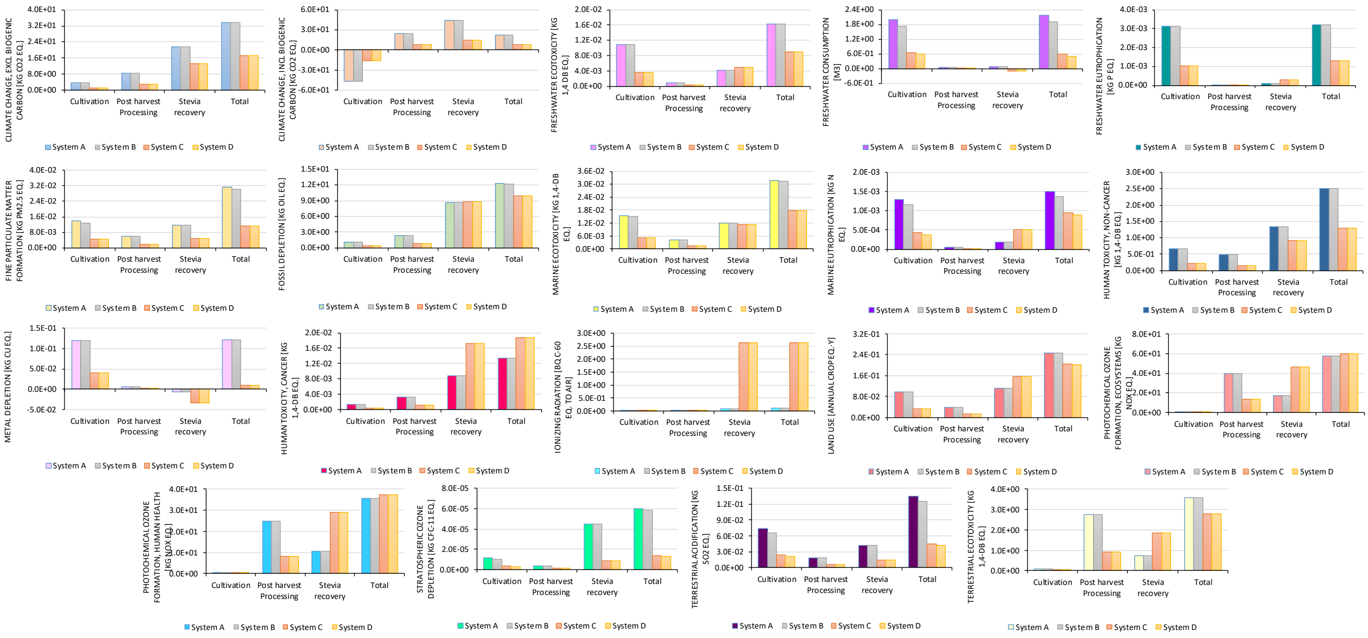

Figure 4. Comparison of the impact categories for the different systems.

5. Conclusions

The effect of various scenarios on the environmental footprint of 1.0 kg stevia powder production was studied. The environmental footprint assessment was performed with GaBi software, using the ReCiPe2016 methodology. The comparative analysis showed that the use of PA and the application of green processing methods for the optimal recovery of glycosides led to a significant reduction of the environmental footprint for the majority of impact categories. The endpoint results showed little damage to humans and ecosystems.

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