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# Evaluating the environmental and economic impact of fruit and vegetable waste valorisation: The lettuce waste study-case

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Abstract: The environmental and economic impact of fruit and vegetable waste (FVW) valorisation on an industrial scale was estimated by applying the "multi-objective method". To this aim, the lettuce waste study-case was considered, since different innovative laboratory-scale strategies have been recently proposed for its valorisation. Investment and running costs, energetic demand and yields of lettuce waste valorisation processes were collected based on laboratory tests and industrial surveys. The application of the multi-objective method estimated that if 20% of lettuce waste annually produced by a large company was valorised, it would present an investment lower than 10 million  $\mathfrak{E}$ , a 1 year-pay-back time and a 72 tons-reduction of carbon dioxide emissions, thus representing a rational compromise between economic returns and environmental advantage. The multi-objective method can be used to develop a decision support system to identify the most sustainable and worthy-of-investment processes for FVW valorisation.

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# Evaluating the environmental and economic impact of fruit and vegetable waste valorisation: the lettuce waste study-case

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Dear Editor,

We send to your attention the research article entitled "**Evaluating the environmental and economic impact of fruit and vegetable waste valorisation: the lettuce waste study-case**" Stella Plazzotta, Mattia Cottes, Patrizia Simeoni and Lara Manzocco. All the authors have read and approved the manuscript. Following, we report the abstract.

The environmental and economic impact of fruit and vegetable waste (FVW) valorisation on an industrial scale was estimated by applying the "multi-objective method". To this aim, the lettuce waste study-case was considered, since different innovative laboratory-scale strategies have been recently proposed for its valorisation. Investment and running costs, energetic demand and yields of lettuce waste valorisation processes were collected based on laboratory tests and industrial surveys. The application of the multi-objective method estimated that if 20% of lettuce waste annually produced by a large company was valorised, it would present an investment lower than 10 million  $\epsilon$ , a 1 year-payback time and a 72 tons-reduction of carbon dioxide emissions, thus representing a rational compromise between economic returns and environmental advantage. The multi-objective method can be used to develop a decision support system to identify the most sustainable and worthy-of-investment processes for FVW valorisation.

We hope that this article could satisfy the requirements of Journal of Cleaner Production, so that you might consider it for publication in this Journal.

Best regards,

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- 1 Different valorisation strategies can be applied to fruit and vegetable waste (FVW)
- 2 The multi-objective method can estimate sustainability of FVW valorisation
- 3 FVW valorisation sustainability estimate requires quantitative industrial-scale data
- 4 Multiple FVW valorisation strategies can be applied to reach sustainability

Phase	Description	Output
Investigative	Data collection using tools of Life Cycle Analysis and techno-economic and profitability assessment	Waste amount quantification Industrial park layout Energy and cost functions Environmental advantage indexes Economic profitability indexes

Design

Stage	Objective	Tool	Done by	
Design of experiment (DOE)	To classify system variables and define system constraints	DOE algorithms	Mode Frontier	Input and output variables; model constraints
Computation	To calculate the value of output variables as a function of input ones, under defined constraints	Mathematical Model	Microsoft Excel	Possible scenarios
Scheduling	To order the obtained scenarios depending on the value of output variables	Scheduling algorithm	MatLab	Scheduled scenarios

Scenario analysis Analysis of possible scenarios

Scenarios allowing the objectives of the study to be reached

Figure 1. Structure of the decision support system.



Figure 2. Flow diagram of resources (lettuce waste, ethanol, carbon dioxide, water and energy) in an industrial park integrating traditional management and innovative valorisation strategies of lettuce waste.

- - 1 Table 1. Yields and outputs of processes involved in traditional management and
  - 2 innovative valorisation of lettuce waste and in related side activities. Output intended use
  - 3 and unit price range are also reported.

Strategy	Process	Yield (%)	Output	Intended use	Price per unit range (€/kg)
Traditional management	Anaerobic digestion	3	Biogas	Fuel for cogeneration	Rec.
	Cogeneration	60	Pure methane	Energy	Rec.
	Composting	30	Fertilizer	Fertilizer	Rec.
	Carbonization	10	Biocarbon	Fuel	0.25-0.90
Innovative valorisation	Preliminary operations	<50	Selected lettuce waste	Raw material for valorisation strategies	Rec.
	Bioactive extraction	80	Lettuce bioactive extract	Food supplement	9.00-18.00
	Homogenisation	85	Lettuce homogenate	Ready-to-eat soups and juice blends	3.00-6.00
	Flour production	5	Lettuce flour	Functional bakery products	0.80-1.60
	Supercritical-CO <sub>2</sub> -drying	5	Lettuce material	Biodegradable expanded material for packaging applications	0.03-0.18
Side activities	Ethanol recycling	80	Ethanol	Resource for industrial facilities	Rec.
	Carbon dioxide recycling	on dioxide recycling 80 Carbon dioxide Resource for supercritical- CO <sub>2</sub> -drying		Rec.	
	Wastewater treatment	60	Water	Resource for industrial facilities	Rec.
Rec.	= Recycl	e	within	the industrial	park

# 5 Table 2. Possible scenarios of lettuce waste valorisation, according to the main study objectives.

	Processed waste (%, w/w)										
Objective	Traditional management				Innovative valorisation			Reduction of greenhouse gas emission	Saved energy (tons of oil equivalent/year)	Investment	Payback
	Carbonisa- tion	Compo- sting	Anaerobic digestion	Lettuce flour	Lettuce homogenate	Lettuce bioactive extract	Lettuce material	(tons CO <sub>2</sub> /year)	· <b>1</b> · · · · · · · · · · · · · · · · · · ·		time (years)
Maximisation of environmental advantage	0	0	60	0	4	24	12	124.4	55.1	9,667,276	2.4
Minimization of investment cost	70	0	20	0	1	9	0	39.1	17.3	8,502,699	3.1
Minimization of pay-back time	20	10	0	0	0	70	0	63.1	28.0	10,535,299	0.3
Compromise	0	40	30	0	12	18	0	71.8	31.8	9,120,427	1.0

Supplementary File Click here to download Supplementary File: Figures\_Supplementary.docx Supplementary File Click here to download Supplementary File: Tables\_Supplementary.docx

1	Evaluating the environmental and economic impact of fruit and vegetable waste
2	valorisation: the lettuce waste study-case
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8	Abstract
9	The environmental and economic impact of fruit and vegetable waste (FVW) valorisation
10	on an industrial scale was estimated by applying the "multi-objective method". To this
11	aim, the lettuce waste study-case was considered, since different innovative laboratory-
12	scale strategies have been recently proposed for its valorisation. Investment and running
13	costs, energetic demand and yields of lettuce waste valorisation processes were collected
14	based on laboratory tests and industrial surveys. The application of the multi-objective
15	method estimated that if 20% of lettuce waste annually produced by a large company was
16	valorised, it would present an investment lower than 10 million $\in$ , a 1 year-pay-back time
17	and a 72 tons-reduction of carbon dioxide emissions, thus representing a rational
18	compromise between economic returns and environmental advantage. The multi-
19	objective method can be used to develop a decision support system to identify the most
20	sustainable and worthy-of-investment processes for FVW valorisation.
21	Key-words: Fruit and vegetable waste; food waste; valorization; feasibility;
22	sustainability; decision support system

#### 23 **1. Introduction**

Fruit and vegetable waste (FVW) valorisation has been extensively and increasingly 24 25 studied in the last years, as evidenced by the enormous number of relevant publications (Supplementary Figure S1). Despite this intense research activity, the current destination 26 of FVW is mainly represented by landfilling, composting, anaerobic digestion and 27 carbonisation (Cristóbal et al., 2018). However, when FVW is used this way, as a 28 feedstock to produce energy and fertilizers, its interesting functional molecules are 29 30 underutilised or lost (Pfaltzgraff et al., 2013). The latter are instead maximally exploited when FVW serves as a source of bioactive compounds, functional food ingredients and 31 biocompatible materials (Papargyropoulou et al., 2014). 32

33 It must be noted that the valorisation of FVW is at an early stage of development and that 34 essential elements must be still clarified to assess its viability (Cristóbal et al., 2018; Heck & Rogers, 2014). Firstly, data on the exact amount of waste produced from food 35 36 processing is nowadays very limited (Pfaltzgraff et al., 2013). Moreover, the resource demand of valorisation strategies as compared to the traditional waste management 37 options should be evaluated. In fact, the implementation of innovative valorisation 38 strategies is viable only if bringing environmental and economic advantages as compared 39 40 to traditional management strategies. Although not discussing at all these crucial aspects, 41 most of literature studies dealing with FVW valorisation generally assume that FVW valorisation would lead to environmental and economic advantages. However, many of 42 them exploit innovative technologies such as high pressure and supercritical fluid 43 processing, which are well-known to require huge investment and maintenance costs, as 44 well as specialized know-how and plants (Garcia-Gonzalez et al., 2007). Also, even when 45 using commonly available technologies (Talens et al., 2016) an accurate cost-benefit 46 analysis should be performed to evaluate the environmental and economic sustainability 47

of the proposed FVW valorisation strategies (Meullemiestre et al., 2016; Sicaire et al.,
2016).

Finally, most studies relevant to feasibility assessment of FVW valorisation do not consider the potential interactions of the proposed valorisation strategy with other possible valorisation pathways or existing waste management options. Nevertheless, the integration of multiple valorisation pathways within the existing waste management system towards a multi FVW biorefinery concept is most likely to represent the real future scenario (Cristóbal et al., 2018; Goula & Lazarides, 2015).

56 In this regard, the "multi-objective" method described by Simeoni et al. (2018) could represent a valuable tool to estimate the environmental and economic implications related 57 to the integration of FVW valorisation strategies in the traditional waste management 58 59 system, on an industrial scale. The final aim of this method is the development of a 60 decision support system (DSS), sustaining the decisionmaker in rationally identifying the most sustainable and worthy-of-investment option among a range of many feasible 61 62 solutions. The application of this method is based on three main phases. Initially, the investigative phase aims at collecting quantitative data on the considered industrial 63 system. Subsequently, in the design phase, input and output variables, their interactions, 64 system constraints and objectives are defined, and combined in multiple scenarios. 65 Finally, in the scenario analysis phase, the latter are scheduled and compared based on the 66 67 study objectives (Simeoni et al., 2018).

In this work, the potentialities of the multi-objective method in assessing the environmental and economic impact of industrial-scale FVW valorisation were investigated. The study-case of lettuce waste was taken into considerations, since this waste was successfully valorised on a laboratory scale by using both traditional and innovative technologies. In particular, ready-to-drink juices, antioxidant extracts,

73 functional flour and a biodegradable expanded material were obtained by using high homogenisation, ultrasounds, air-drying and supercritical-CO<sub>2</sub>-drying, 74 pressure respectively (Plazzotta et al., 2018a, b, c; Plazzotta & Manzocco, 2018a, b). Quantitative 75 76 data relevant to a hypothetic industrial park integrating these valorisation processes with those commonly applied for lettuce waste management (anaerobic digestion, composting, 77 carbonisation) were collected. Different possible scenarios were then obtained and 78 79 compared based on environmental and economic indexes related to lettuce waste valorisation activities. 80

81 2. Materials and methods

A classical DSS model was applied to lettuce waste valorisation. Its structure consisted of three major phases, whose description and main outputs are described in Figure 1: investigative phase, design phase and scenario analysis (Mattiussi et al., 2014; Simeoni et al., 2018).

# 86 2.1 Investigative phase

For the investigative phase, the tools of Life Cycle Analysis (LCA) and techno-economic and profitability assessment were used. All collected data were referred to an annual working period corresponding to 8 working hour/day for 200 working days.

90

## Lettuce waste quantification

A quantitative assessment of the amount of lettuce waste generated by fresh-cut lettuce processing in Italy was performed. Data about fresh-cut lettuce market ( $M_L$ ) were retrieved from official data and dedicated literature (Casati & Baldi, 2012; Confcoperative, 2016). Data relevant to the percentage amount of waste generated during a typical fresh-cut processing of whole-head lettuce ( $\%_{WL}$ ) were collected in a large Italian company, as described in Plazzotta et al. (2017). The total waste amount annually 97 generated in Italy from fresh-cut processing of lettuce heads  $(W_L)$  was thus quantified (eq. 98 1).

$$99 \qquad W_L = M_L \times \mathscr{W}_{WL} \qquad eq. 1$$

100

# Lettuce waste valorisation industrial park

An industrial park integrating traditional lettuce waste management strategies (i.e. 101 anaerobic digestion to produce biogas, composting to produce fertilizers and 102 carbonization to produce biocarbon) with the innovative valorisation options (i.e. high 103 pressure homogenisation to produce fresh juices, ultrasound-assisted extraction of 104 antioxidant polyphenols, air-drying and grinding to produce functional flour, 105 biodegradable 106 supercritical-CO<sub>2</sub>-drying to produce expanded materials) was hypothesized. To this aim, the unit operations involved in processes for traditional waste 107 management, innovative waste valorisation and side activities were identified, along with 108 109 possible interactions among the different processes and mass flows of raw materials, 110 wastes and utilities (energy, water).

111

# Energy demand and costs

112 Data relevant to nominal energy demand and costs of lettuce waste valorisation plants, integrated into the designed industrial park, were collected. Laboratory-scale data were 113 114 directly derived from experimental activity, while industrial-scale data were obtained from company surveys. In particular, data relevant to traditional lettuce waste 115 management strategies were collected from sector experts, engaged in the planning of 116 local industrial activities. By contrast, in the case of innovative valorisation strategies, 117 118 that are not currently present in the market, data collection was based on escalation factors of similar existing plants and equipment (Cristóbal et al., 2018). 119

120 Collected data were elaborated to obtain energy functions, describing all the possibilities

from a small laboratory scale up to large industrial ones. Regression equations describing the variation of absorbed nominal power as a function of maximum plant capacity were obtained and compared based on the R<sup>2</sup> (Microsoft® Excel 2016). The equation presenting the highest R<sup>2</sup> was selected. Cost functions, describing the variation of equipment cost ( $C_E$ ,  $\in$ ) as a function of absorbed nominal power were similarly obtained.

According to sector experts' opinion, additional costs for plant design  $(C_{PD}, \in)$  were calculated as 2% of  $C_E$ . The latter was set as 1/3 of the total capital investment  $(C_I, \in)$ , while the remaining 2/3 was attributed to civil work  $(C_{CW}, \in)$ . Thus,  $C_I$  was calculated as reported in eq. 2.

$$130 \qquad C_I(\pounds) = C_E + C_{PD} + C_{CW} \qquad eq. 2$$

The cost of manufacturing  $(C_M)$ , associated with daily operation of the industrial park, was calculated according to eq. 3:

133 
$$C_M$$
 (€) =  $C_{CI} + C_W + C_U + C_{RM} + C_{WS}$  eq. 3

134 where

135 -  $C_{CI}$  (€) is the cost derived from  $C_I$ . Costs for unscheduled and regular maintenance, 136 and interest rate per year were calculated as 7.5 and 15% of  $C_E$ , respectively 137 (Cristóbal et al., 2018);

138- $C_W(€)$  is the cost of workforce required for plant operation. The latter was quantified139based on common requirements of local waste management installations and food140industries, as defined by experts in the sector. Basic salary was obtained from tables141of national collective labour agreements work in the waste management and food142sector (CCNL, 2018). The workforce requirement was maintained independent on143the lettuce waste amount processed in the industrial park. This simplification was144based on the high level of automation of most of the unit operations involved in the

145 different processes;

146 -  $C_U$  (€) is the cost of utilities. The cost electric power and water, considered as the 147 main utilities, was retrieved from average European prices (EUROSTAT, 2018);

-  $C_{RM}$  (€) is the cost of raw materials. It includes (i) the cost of lettuce waste, that was considered negligible, since it has not (yet) a market value; (ii) the cost of chemicals and reactants (i.e. CO<sub>2</sub> and ethanol), that was obtained by a survey on producers (Sigma Aldrich, Milan, Italy); (iii) cost of transport, that was considered negligible, due to the geographic proximity of companies in the considered industrial park;

153 -  $C_{WS}$  (€) is the cost of waste streams. The cost of ethanol, CO<sub>2</sub> and wastewater 154 streams was considered negligible, since they can be purified and recycled in the 155 industrial process, used as fuels in cogeneration systems or incorporated back in the 156 soil for nutrient uptake (Attard et al., 2015).

# 157 Environmental advantage and economic effort

Energy saving and reduction of greenhouse gas emissions were set as indexes of the environmental advantage of the designed lettuce waste valorisation industrial park. Saved energy was quantified based on the biomethane-derived energy, obtained from lettuce waste anaerobic digestion (eq. 4):

162 Saved energy (tons of oil equivalent) = Energy from biomethane 
$$(kWh) \times 1.87 \cdot 10^{-4}$$
 eq. 4

where  $1.87 \cdot 10^{-4}$  is the standard coefficient for natural gas conversion into oil equivalent (Simeoni et al., 2018). The reduction of greenhouse gas emissions was also calculated from biogas-derived energy through the proper emission conversion factor of electricity for the Italian electricity production system (Simeoni et al., 2018) (eq. 5):

167 Greenhouse gas reduction (tons of  $CO_2$ ) = Energy from biomethane (kWh) × 4.22 · 10<sup>-4</sup> eq. 5

168 Total investment cost ( $C_I$ , eq. 2) and payback time were set as economic effort indexes of

the designed industrial park. Payback time (eq. 6) was calculated as the ratio of  $C_I$  and the annual net profit:

171 Payback time (years) = 
$$C_I$$
/Annual net profit eq. 6

172 The annual net profit is calculated based on eq. 7:

173 Annual net profit 
$$(\mathbf{E}) = R + WhC - C_M$$
 eq. 7

where R ( $\in$ ) are the revenues obtained from selling the valorisation products in the 174 market, WhC are the "White Certificate" incentives ( $\in$ ) (eq. 8) and  $C_M$  is the 175 manufacturing cost ( $\in$ ) (eq. 3). In order to calculate the value of *R*, the outputs of both 176 traditional and innovative lettuce waste management options were individuated, along 177 with their intended use, unit price range and yield. The output price range was based on 178 179 that of corresponding products on the market. The yields of each lettuce waste process were estimated as % ratio of final output as compared to the initial amount of raw 180 materials entering the process. To this aim, industrial yields of traditional lettuce waste 181 management options were retrieved from relevant literature (Keeling et al., 2003; Rossi & 182 Bientinesi, 2016). By contrast, in the case of innovative valorisation strategies, laboratory 183 184 results were scaled up under the assumption that the same yields and performances would be obtained on an industrial scale, given the same processing conditions (Albarelli et al., 185 2016). WhC incentives for saved energy (eq. 4) were also considered as possible sources 186 187 of economic revenues (Oikonomou et al., 2009) (eq. 8):

188  $WhC (\in) = Saved energy \ x V_{WhC}$ 

eq. 8

where  $V_{WhC}$  ( $\in$ ) is the value of the incentives, based on the most recent updates (GME-GSE, 2018).

191 2.2 Design phase

The design phase is the core of the used model and is composed by three subsequentstages (Figure 1):

194 Design of experiment (DOE). DOE was used to classify the system variables and to 195 define the system constraints. In particular, the following quantities were set as input variables: the initial amount of lettuce waste available for valorisation ( $W_L$ , eq. 1); the 196 partition of lettuce waste into traditional waste management options or valorisation 197 198 processes; the energy demand and cost of lettuce waste processing plants; the price of valorisation outputs; the value of energy saving incentives (WhC, eq. 8). The 199 200 environmental advantage and economic effort indexes identified in the investigative phase were set as output variables: saved energy (eq. 4), greenhouse gas reduction 201 (eq. 5), total investment cost ( $C_I$ , eq. 2) and payback time (eq. 6). 202

203 The DOE constraints were based on technical and economic issues. In particular, at least 50% of total lettuce waste was allocated to traditional management strategies, 204 which represent an important source of biogas and fertilizers. Moreover, selected 205 lettuce waste, deriving from removal of spoiled and bruised parts and washing of 206 waste, was set at a value lower than 50% of the initial lettuce waste weight intended 207 for innovative valorisation, due to the possible poor conditions of waste. In addition, 208 a payback time higher than 5 years was not considered, since not economically 209 210 advantageous (Heck & Rogers, 2014).

Computation. This stage aimed at calculating the value of output variables as a
 function of input variable values, under the defined DOE constraints. Computation
 was carried out using ModeFRONTIER® software (Esteco, Trieste, Italy). The
 solutions calculated by the software represented the possible scenarios of lettuce
 waste valorisation.

216 - Scheduling. The objective of this stage was to order the obtained scenarios according

to the value of the output variables. Scheduling was carried out using MatLab®
software (MATLAB R2017a, 64-bit; The Mathworks Inc).

#### 219 2.3 Scenario analysis

Obtained scenarios were compared and discussed in the light of multiple objectives. In particular, the study aimed at the maximization of environmental advantage indexes (eq. 4 and eq. 5) and at the minimisation of economic effort indexes (eq. 2 and eq. 6).

- 223 **3. Results and discussion**
- 224 3.1 Investigative phase

#### 225 *Lettuce waste quantification*

To produce value-added derivatives intended for food use, lettuce waste is required to present a high homogeneity level. In addition, waste generation sites should not be very scattered, to facilitate the collection and thus cut both collection and transport costs (Galanakis, 2012). For these reasons, this work was focused on lettuce waste generated in the food processing stage, that can ensure both a high compositional homogeneity and large amount in a reduced number of locations (i.e. the industrial plants).

232 The first step was thus the collection of data relevant to the amount of lettuce waste generated during fresh-cut processing. Official data report that in Italy the fresh-cut 233 lettuce market amounts up to about 105,300 tons/year (Confcoperative, 2016). Of that, 234 60% is represented by whole-head lettuces, mainly Iceberg lettuce (Casati & Baldi, 235 2012). A survey conducted in a large Italian fresh-cut company revealed that at least 35% 236 of lettuce head weight is wasted, mainly due to initial operations of external leaves and 237 core removal (Plazzotta et al., 2017). Based on these data, the total amount of waste 238 generated in 1 year in Italy by the fresh-cut processing of whole-head lettuce was 239

quantified in about 23,000 tons. Similarly, the total amount of whole-head lettuce waste
generated by the large fresh cut company considered in the survey was evaluated. In this
company, about 20,000 tons of lettuce are processed into fresh-cut derivatives.
Considering 60% of this value to be represented by whole-head lettuces and 35% waste
production, the company would manage every year about 4,200 tons of whole-head
lettuce waste.

246

# Lettuce waste valorisation industrial park

The design of an industrial park integrating the innovative valorisation strategies of 247 248 lettuce waste in the current waste management system was hypothesized. The processes involved in traditional lettuce waste management, in its innovative valorisation and in the 249 side activities of the industrial park are reported in Table S1. Real industrial processes 250 were considered for the process design of traditional waste management strategies (i.e. 251 composting, anaerobic digestion and carbonisation) and side activities (i.e. wastewater 252 253 treatment, ethanol recycling). Such processes, in fact, are already applied on an industrial 254 scale and present high technological readiness levels (TRL). By contrast, innovative lettuce waste valorisation strategies, based on the production of functional beverages, 255 256 antioxidant extracts, vegetable flour and biodegradable materials by means of innovative technologies, present a low TRL. For this reason, process design was based on processes 257 carried out on a laboratory scale and escalation factors of similar existing plants. 258

The hypothesized industrial park is represented in Figure 2, where the flow diagram of the different processes involved in both traditional lettuce waste management options and innovative valorisation strategies, as well as their interactions are reported. Based on information collected from the producers, lettuce waste is commonly subjected to:

- anaerobic digestion to produce digestate (fertilizer), biogas and, in turn, energy (by
 means of the cogeneration unit) (Garcia-Peña et al., 2011);

- composting to produce fertilizers (Himanen & Hänninen, 2011);

- carbonisation to produce biocarbon (Li et al., 2019).

In this case, lettuce waste would be straight directed to the proper industrial facility. By 267 contrast, the implementation of the innovative valorisation strategies would require a 268 preliminary selection of lettuce waste, to remove spoiled and bruised parts. The latter 269 would be managed by means of composting, anaerobic digestion or carbonisation. On the 270 271 contrary, the selected lettuce waste could be exploited as raw material to produce different valorisation outputs. It must be noted that the need for lettuce waste selection 272 273 introduces a high uncertainty in the amount of lettuce waste available for innovative valorisation strategies, since the initial condition of lettuce waste depends on 274 unpredictable factors, such as weather and cultivation conditions. Selected lettuce waste 275 276 could be subjected to:

blanching and high pressure homogenisation to produce fresh juices (Plazzotta &
 Manzocco, 2018b);

- ultrasound-assisted extraction to produce antioxidant polyphenolic extracts
(Plazzotta & Manzocco, 2018a);

- air-drying and grinding to produce functional flour intended for functional bakery
 products (Plazzotta et al., 2018a, c);

- water substitution with ethanol and supercritical-CO<sub>2</sub>-drying to produce
 biodegradable expanded materials for packaging or solvent adsorption applications
 (Plazzotta et al., 2018b).

In addition, side activities for the purification and recycling of spent resources such asethanol residue and wastewater were hypothesized.

Possible interactions among the different processing steps involved in traditional and innovative valorisation strategies were also identified. In fact, the integration of

innovative strategies in the existing waste management framework is surely most likely to represent the real scenario of lettuce waste valorisation, differently from most available literature studies in which waste valorisation processes are described and analysed without considering their integration in the existing waste management system (Cristóbal et al., 2018). In particular, the attention was focused on the possibility to reduce the need for outsourcing of energy, water and raw material of a valorisation process by using the waste streams of other processes integrated in the industrial park.

#### 297

#### Energy demand and costs

Cost and energy functions of equipment required for the various unit operations of the 298 processes involved in the implementation of traditional and innovative lettuce waste 299 management strategies are reported in supplementary Table S1. Such functions allow 300 estimating absorbed nominal power and investment cost of specific plants and equipment 301 as a function of their maximum capacity (tons of processed raw material or semi-finished 302 303 product). Thus, they represent a flexible tool to describe a wide-range of possible scenarios, according to the available lettuce waste amount. This is of extreme importance, 304 considering the overmentioned high uncertainty about the actual amount of lettuce waste 305 306 possibly exploitable for valorisation. In addition to equipment cost, supplementary Table S2 and S3 show workforce, raw material and utility costs, calculated as detailed in the 307 Material and Method section. Although these costs are likely to variate in a real context, 308 they were maintained fixed. Even if possibly reducing result robustness, this choice 309 310 allowed the number of variables in the computing system to be reduced.

#### 311

#### Environmental advantage and economic effort

The environmental advantage of the lettuce waste valorisation was attributed to the biogas produced form anaerobic digestion of lettuce waste, which can be used as sustainable 314 resource to partially fulfil the energy requirements of the industrial park, contributing to reduce the emissions of greenhouse gases. In addition, the recycle of resources other than 315 energy within the industrial park would allow reducing the need for outsourcing. In this 316 regard, Table 1 reports the main outputs of the lettuce waste processes, underlying their 317 potential recycle within the industrial park. As an example, the carbon dioxide deriving 318 from the co-generation unit involved in the conversion of biogas from anaerobic digestion 319 320 in methane, could be used in the supercritical-CO<sub>2</sub>-drying of lettuce waste. Moreover, the digestate and the biogas-based energy deriving from anaerobic digestion could be entirely 321 322 recycled for lettuce cultivation and electrical supply of plants and equipment present in the industrial park, respectively. This strategy integration would not only lead to a higher 323 energy self-sufficiency and independence on primary energy sources (fossil fuels), but 324 325 also to a negligible cost for waste stream management. Moreover, such strategy integration could also allow increasing revenues of the industrial activity. In this regard, 326 White Certificates (WhC) are an energy efficiency market-based instrument, which 327 acknowledge the energy saving obtained by producers through the implementation of 328 energy efficiency measures (Oikonomou et al., 2009). In this study, WhC were thus 329 considered as possible revenues of the designed industrial park. In particular, a variable 330 value, ranging from 0 to 300 €, was set for WhC, based on most recent updates (GME-331 332 GSE, 2018). Besides WhC incentives, the main revenues of lettuce waste valorisation 333 activities would derive from selling valorisation products on the market. In this regard, the yields of innovative valorisation processes of lettuce waste are reported in Table 1. As 334 explained in the Materials and Methods, real industrial data were used for traditional 335 336 strategies, while yields of innovative processes were based on laboratory data. For example, the yield of air-drying and supercritical-CO<sub>2</sub>-drying resulted of 5%, due to 95% 337 moisture content of lettuce waste (Plazzotta et al., 2018a). Similarly, in the ultrasound 338

assisted extraction of lettuce polyphenols, about 20% of solid residue was retained in the
filtration step, leading to 80% yield (Plazzotta & Manzocco, 2018a). Table 1 also reports
the identified outputs of lettuce waste valorisation strategies, along with their intended
use, and the unit price range of corresponding market products. The choice to use a price
range rather than a medium price was based on the extreme variability and uncertainty of
their values over time (Cristóbal et al., 2018; Giraudet et al., 2011).

# 345 *3.2 Design phase*

In the Design phase, data collected in the investigative step were elaborated to estimate 346 347 the effect of the variation of lettuce waste amount, lettuce waste partition into the different valorisation process, energy demand and cost of waste valorisation plants, price 348 of valorisation products and WhC incentives on the environmental advantage and 349 economic effort of the lettuce waste valorisation industrial park. The Design phase 350 computed a total of 121,560 possible scenarios. The latter were then scheduled according 351 352 to the values assumed by the environmental advantage and economic effort indexes of the multi-objective study. 353

#### 354 3.3 Scenario analysis

The objectives of this study were the maximization of environmental advantage and the 355 minimisation of economic effort indexes of the lettuce waste valorisation industrial park. 356 357 Table 2 reports possible scenarios, that were selected based on the achievement of each one of the study objectives. These scenarios took into considerations the amount of 358 whole-head lettuce waste processed during 1 year from a large fresh-cut company (about 359 360 4,200 tons, as discussed in paragraph 3.1). As expected, the scenario allowing to maximise the environmental advantage would be the one managing the major part (60%) 361 of lettuce waste through anaerobic digestion to produce biogas. The remaining lettuce 362

waste fraction would be valorised into fresh homogenates, antioxidant extracts and 363 innovative biodegradable materials. However, the investment cost of this scenario would 364 be of 9.7 million  $\in$  and with a payback time higher than 2 years (Table 2). This can be 365 attributed to the high cost of equipment required for implementing innovative 366 technologies such as high pressure homogenisation, ultrasound assisted extraction and 367 supercritical-CO<sub>2</sub>-drying. The minimisation of investment cost would be reached by 368 369 managing at least 90% of lettuce waste through traditional options, not allowing a proper valorisation of its rich composition. Moreover, this scenario would also present limited 370 371 environmental advantages and a payback time longer than 3 years (Table 2). The latter would be minimized to just 4 months by valorising 70% lettuce waste into bioactive 372 extracts. This valorisation strategy, in fact, would highly increase the value chain of 373 374 lettuce waste, by producing a high-price food supplement (Table 1). Nevertheless, investment cost would be higher than 10.5 million €, while reduced CO<sub>2</sub> emissions and 375 saved energy would still be half that those realised in the scenario maximising the 376 377 environmental advantage of the designed industrial park (Table 2). Therefore, all the scenarios reaching one of the study objectives would present some drawbacks. In this 378 regard, the selection of a specific scenario should be driven by a compromise among the 379 defined economic and environmental objectives. For this reason, a further scenario, 380 381 deriving from a compromise solution is presented in Table 2. In this scenario, 20% of 382 lettuce waste would be valorised by the application of innovative valorisation strategies, presenting an investment cost lower than 9.1 million € and a pay-back time of about 1 383 year. The remaining 80% lettuce waste would be subjected to traditional management 384 385 options, contributing to greenhouse gases emission reduction and energy saving of about 72 tons CO<sub>2</sub>/year and 32 tons of oil equivalents/year respectively (Table 2). 386

387 3.4 Sources of uncertainty

Although representing a valuable support to decision makers, the conducted study entails a high uncertainty, leading to the need for an accurate validation of obtained results before application in a real context. The main sources of uncertainty of this study are those commonly found in similar estimation approaches, as reported by Cristóbal et al. (2018), and include:

cost estimation: for low TRL technologies, cost estimation presents a ±30%
 accuracy, due to possible failures in inflation projection and cost growth due to
 unpredictable events related to the high complex process and unproven technology
 (Tsagkari et al., 2016);

- cost of utilities: the electricity and natural gas prices for industrial users in the
European Union depend on a range of different supply and demand conditions,
including the geopolitical situation, import diversification, network costs,
environmental protection costs, weather conditions, and levels of taxation
(EUROSTAT, 2018);

402 - scaling-up variables: laboratory results were used to scale-up the innovative
403 valorisation process considering that the same performance would be obtained.
404 However, this should be carefully evaluated in pilot plants and corrected if necessary;
405 - start-up issues: in this study, the maximum productivity of processes was
406 hypothesized, without considering possible economic issues of the start-up phase;

407 - wastes: in the present study, wastes were considered to be fully recycled in the
408 industrial park economy. However, if they cannot be fully or partially used within the
409 system, additional waste management costs should be considered;

lettuce waste amount: although based on data collected in a real company, the
estimation of lettuce waste quantity available for the valorisation is uncertain. Waste
amount and quality, in fact, can vary according to unpredictable conditions, including

413 weather, cultivation yield, pests;

transport cost: in the present study, transport cost was considered negligible, due to
geographical proximity of companies in the industrial park. However, a wider
industrial park could be imagined, possibly collecting wastes from the entire country.
In that case, transport cost and environmental impact should be computed in the
system sustainability assessment.

#### 419 **4.** Conclusions

In this study, the "multi-objective" method was applied to estimate the economic and environmental impact of lettuce waste valorisation. The proposed method was demonstrated to be highly flexible, since considering a variable range of waste amount, equipment cost, energy demand, and plant productive capacity. It also allowed considering the integration of innovative valorisation pathways in the existing waste management system, towards a multiple "zero-waste" biorefinery concept.

Although further research is needed for a robust validation of economic and 426 environmental sustainability estimates, the application of the proposed method led to the 427 identification of different rational solutions. The latter could lead either to the 428 maximisation of a specific environmental or economic objective, or to the identification 429 of a compromise among the different sustainability objectives. In particular, the optimal 430 amount of lettuce waste to be diverted from landfilling, anaerobic digestion, carbonisation 431 and composting plants to food industries could be identified, leading to its valorisation 432 433 under different scenarios.

The acquired results would allow the generation of a flexible decision support tool to guide stakeholders' and policy makers' investment in the most sustainable waste valorisation strategies. This tool could be also exploited for promoting advantageous industrial symbiosis opportunities in the waste management sector.

#### 438 **Declaration of interest**

439 All Authors declare no conflict of interest.

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#### 543 **Figure/supplementary figure captions**

544 Figure 1. Structure of the decision support system.

545

Figure 2. Flow diagram of resources (lettuce waste, ethanol, carbon dioxide, water and energy) in an industrial park integrating traditional management and innovative valorisation strategies of lettuce waste.

549

Figure S1. Number of publications relevant to fruit and vegetable waste valorisation from 1995 up to 2018. (Data collected from Web of Science databases, Clarivate Analytics, using as key-words "Fruit and vegetable waste" or "FVW" and "valorisation" or "valorization").

554

# 555 Table/Supplementary table headings

Table 1. Yields and outputs of processes involved in traditional management and innovative valorisation of lettuce waste and in related side activities. Output intended use and unit price range are also reported.

559

Table 2. Possible scenarios of lettuce waste valorisation, according to the main study objectives.

562

Table S1. Cost and energy functions of equipment and plants required for the various unit operations of processes involved in the implementation of traditional management and innovative valorisation strategies of lettuce waste and in side activities.

566

567 Table S2. Cost per unit of raw materials and utilities entering the processes involved in

- 568 traditional management and innovative valorisation strategies of lettuce waste.
- 569 Table S3. Quantification and corresponding salary of workforce required for the various
- 570 unit operations of processes involved in the implementation of traditional management
- and innovative valorisation strategies of lettuce waste.