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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 €, 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 €, 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.

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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## Highlights (for review)

- 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	<table border="1"> <thead> <tr> <th>Stage</th> <th>Objective</th> <th>Tool</th> <th>Done by</th> </tr> </thead> <tbody> <tr> <td>Design of experiment (DOE)</td> <td>To classify system variables and define system constraints</td> <td>DOE algorithms</td> <td>Mode Frontier</td> </tr> <tr> <td>Computation</td> <td>To calculate the value of output variables as a function of input ones, under defined constraints</td> <td>Mathematical Model</td> <td>Microsoft Excel</td> </tr> <tr> <td>Scheduling</td> <td>To order the obtained scenarios depending on the value of output variables</td> <td>Scheduling algorithm</td> <td>MatLab</td> </tr> </tbody> </table>	Stage	Objective	Tool	Done by	Design of experiment (DOE)	To classify system variables and define system constraints	DOE algorithms	Mode Frontier	Computation	To calculate the value of output variables as a function of input ones, under defined constraints	Mathematical Model	Microsoft Excel	Scheduling	To order the obtained scenarios depending on the value of output variables	Scheduling algorithm	MatLab	Input and output variables; model constraints
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Possible scenarios																		
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.

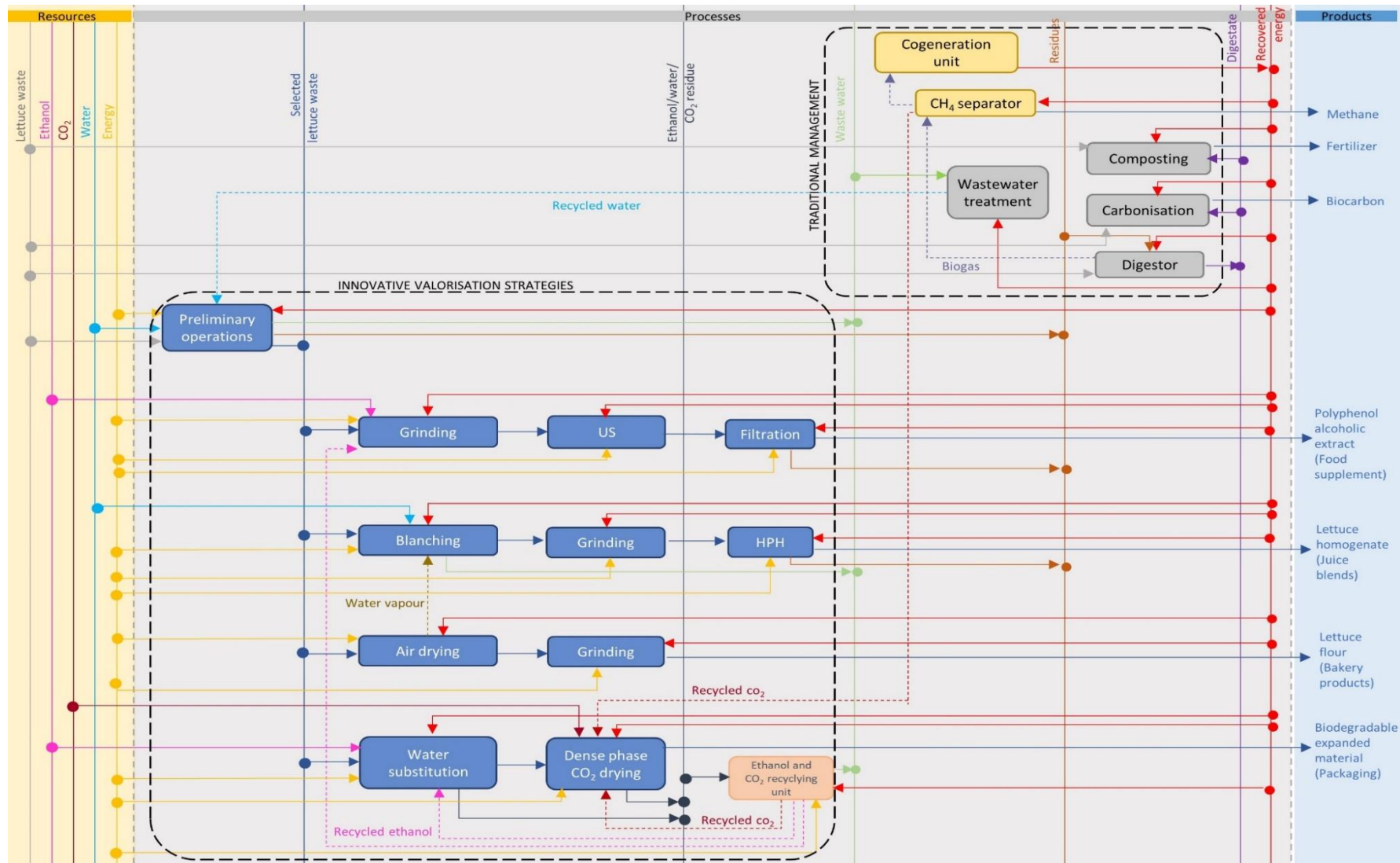


Figure 2. Flow diagram of resources (lettuce waste, ethanol, carbon dioxide, water and energy) in an industrial park integrating traditional management and innovative valorisation strategies of lettuce waste.

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	80	Carbon dioxide	Resource for supercritical-CO <sub>2</sub> -drying	Rec.
	Wastewater treatment	60	Water	Resource for industrial facilities	Rec.
4 Rec.	=	Recycle	within	the	industrial park



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

Objective	Processed waste (% w/w)							Reduction of greenhouse gas emission (tons CO <sub>2</sub> /year)	Saved energy (tons of oil equivalent/year)	Investment (€)	Payback time (years)
	Traditional management			Innovative valorisation							
	Carbonisation	Composting	Anaerobic digestion	Lettuce flour	Lettuce homogenate	Lettuce bioactive extract	Lettuce material				
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

6

**Supplementary File**

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**Supplementary File**

[Click here to download Supplementary File: Tables\\_Supplementary.docx](#)



## 23 **1. Introduction**

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

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  
35 & Rogers, 2014). Firstly, data on the exact amount of waste produced from food  
36 processing is nowadays very limited (Pfaltzgraff et al., 2013). Moreover, the resource  
37 demand of valorisation strategies as compared to the traditional waste management  
38 options should be evaluated. In fact, the implementation of innovative valorisation  
39 strategies is viable only if bringing environmental and economic advantages as compared  
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  
42 valorisation would lead to environmental and economic advantages. However, many of  
43 them exploit innovative technologies such as high pressure and supercritical fluid  
44 processing, which are well-known to require huge investment and maintenance costs, as  
45 well as specialized know-how and plants (Garcia-Gonzalez et al., 2007). Also, even when  
46 using commonly available technologies (Talens et al., 2016) an accurate cost-benefit  
47 analysis should be performed to evaluate the environmental and economic sustainability

48 of the proposed FVW valorisation strategies (Meullemiestre et al., 2016; Sicaire et al.,  
49 2016).

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

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

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

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

## 81 **2. Materials and methods**

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

### 86 *2.1 Investigative phase*

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

#### 90 *Lettuce waste quantification*

91 A quantitative assessment of the amount of lettuce waste generated by fresh-cut lettuce  
92 processing in Italy was performed. Data about fresh-cut lettuce market ( $M_L$ ) were  
93 retrieved from official data and dedicated literature (Casati & Baldi, 2012;  
94 Confcooperative, 2016). Data relevant to the percentage amount of waste generated during  
95 a typical fresh-cut processing of whole-head lettuce ( $\%_{WL}$ ) were collected in a large  
96 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).

$$99 \quad W_L = M_L \times \%_{WL} \quad \text{eq. 1}$$

#### 100 *Lettuce waste valorisation industrial park*

101 An industrial park integrating traditional lettuce waste management strategies (i.e.  
102 anaerobic digestion to produce biogas, composting to produce fertilizers and  
103 carbonization to produce biocarbon) with the innovative valorisation options (i.e. high  
104 pressure homogenisation to produce fresh juices, ultrasound-assisted extraction of  
105 antioxidant polyphenols, air-drying and grinding to produce functional flour,  
106 supercritical-CO<sub>2</sub>-drying to produce biodegradable expanded materials) was  
107 hypothesized. To this aim, the unit operations involved in processes for traditional waste  
108 management, innovative waste valorisation and side activities were identified, along with  
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,  
113 integrated into the designed industrial park, were collected. Laboratory-scale data were  
114 directly derived from experimental activity, while industrial-scale data were obtained  
115 from company surveys. In particular, data relevant to traditional lettuce waste  
116 management strategies were collected from sector experts, engaged in the planning of  
117 local industrial activities. By contrast, in the case of innovative valorisation strategies,  
118 that are not currently present in the market, data collection was based on escalation  
119 factors of similar existing plants and equipment (Cristóbal et al., 2018).

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



121 from a small laboratory scale up to large industrial ones. Regression equations describing  
122 the variation of absorbed nominal power as a function of maximum plant capacity were  
123 obtained and compared based on the  $R^2$  (Microsoft® Excel 2016). The equation  
124 presenting the highest  $R^2$  was selected. Cost functions, describing the variation of  
125 equipment cost ( $C_E$ , €) as a function of absorbed nominal power were similarly obtained.  
126 According to sector experts' opinion, additional costs for plant design ( $C_{PD}$ , €) were  
127 calculated as 2% of  $C_E$ . The latter was set as 1/3 of the total capital investment ( $C_I$ , €),  
128 while the remaining 2/3 was attributed to civil work ( $C_{CW}$ , €). Thus,  $C_I$  was calculated as  
129 reported in eq. 2.

$$130 \quad C_I(\text{€}) = C_E + C_{PD} + C_{CW} \quad \text{eq. 2}$$

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

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

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 quantified  
139 based on common requirements of local waste management installations and food  
140 industries, as defined by experts in the sector. Basic salary was obtained from tables  
141 of national collective labour agreements work in the waste management and food  
142 sector (CCNL, 2018). The workforce requirement was maintained independent on  
143 the lettuce waste amount processed in the industrial park. This simplification was  
144 based 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);
- 148 -  $C_{RM}$  (€) is the cost of raw materials. It includes (i) the cost of lettuce waste, that was  
 149 considered negligible, since it has not (yet) a market value; (ii) the cost of chemicals  
 150 and reactants (i.e. CO<sub>2</sub> and ethanol), that was obtained by a survey on producers  
 151 (Sigma Aldrich, Milan, Italy); (iii) cost of transport, that was considered negligible,  
 152 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*

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

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

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

167  $Greenhouse\ gas\ reduction\ (tons\ of\ CO_2) = Energy\ from\ biomethane\ (kWh) \times 4.22 \cdot 10^{-4}$  eq. 5

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

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

$$171 \text{ Payback time (years)} = C_I / \text{Annual net profit} \quad \text{eq. 6}$$

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

$$173 \text{ Annual net profit (€)} = R + WhC - C_M \quad \text{eq. 7}$$

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

$$188 \text{ WhC (€)} = \text{Saved energy} \times V_{WhC} \quad \text{eq. 8}$$

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

## 191 2.2 Design phase

192 The design phase is the core of the used model and is composed by three subsequent  
193 stages (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  
196 variables: the initial amount of lettuce waste available for valorisation ( $W_L$ , eq. 1); the  
197 partition of lettuce waste into traditional waste management options or valorisation  
198 processes; the energy demand and cost of lettuce waste processing plants; the price of  
199 valorisation outputs; the value of energy saving incentives ( $WhC$ , eq. 8). The  
200 environmental advantage and economic effort indexes identified in the investigative  
201 phase were set as output variables: saved energy (eq. 4), greenhouse gas reduction  
202 (eq. 5), total investment cost ( $C_I$ , eq. 2) and payback time (eq. 6).

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

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

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

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

### 219 2.3 Scenario analysis

220 Obtained scenarios were compared and discussed in the light of multiple objectives. In  
221 particular, the study aimed at the maximization of environmental advantage indexes (eq. 4  
222 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*

226 To produce value-added derivatives intended for food use, lettuce waste is required to  
227 present a high homogeneity level. In addition, waste generation sites should not be very  
228 scattered, to facilitate the collection and thus cut both collection and transport costs  
229 (Galanakis, 2012). For these reasons, this work was focused on lettuce waste generated in  
230 the food processing stage, that can ensure both a high compositional homogeneity and  
231 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  
233 generated during fresh-cut processing. Official data report that in Italy the fresh-cut  
234 lettuce market amounts up to about 105,300 tons/year (Confcooperative, 2016). Of that,  
235 60% is represented by whole-head lettuces, mainly *Iceberg* lettuce (Casati & Baldi,  
236 2012). A survey conducted in a large Italian fresh-cut company revealed that at least 35%  
237 of lettuce head weight is wasted, mainly due to initial operations of external leaves and  
238 core removal (Plazzotta et al., 2017). Based on these data, the total amount of waste  
239 generated in 1 year in Italy by the fresh-cut processing of whole-head lettuce was

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

#### 246 *Lettuce waste valorisation industrial park*

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

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

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

- 265 - composting to produce fertilizers (Himanen & Hänninen, 2011);
- 266 - carbonisation to produce biocarbon (Li et al., 2019).

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

- 277 - blanching and high pressure homogenisation to produce fresh juices (Plazzotta &  
278 Manzocco, 2018b);
- 279 - ultrasound-assisted extraction to produce antioxidant polyphenolic extracts  
280 (Plazzotta & Manzocco, 2018a);
- 281 - air-drying and grinding to produce functional flour intended for functional bakery  
282 products (Plazzotta et al., 2018a, c);
- 283 - water substitution with ethanol and supercritical-CO<sub>2</sub>-drying to produce  
284 biodegradable expanded materials for packaging or solvent adsorption applications  
285 (Plazzotta et al., 2018b).

286 In addition, side activities for the purification and recycling of spent resources such as  
287 ethanol residue and wastewater were hypothesized.

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

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

### 297 *Energy demand and costs*

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

### 311 *Environmental advantage and economic effort*

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

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

### 345 3.2 *Design phase*

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

### 354 3.3 *Scenario analysis*

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

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

### 387 3.4 Sources of uncertainty

388 Although representing a valuable support to decision makers, the conducted study entails  
389 a high uncertainty, leading to the need for an accurate validation of obtained results  
390 before application in a real context. The main sources of uncertainty of this study are  
391 those commonly found in similar estimation approaches, as reported by Cristóbal et al.  
392 (2018), and include:

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

397 - cost of utilities: the electricity and natural gas prices for industrial users in the  
398 European Union depend on a range of different supply and demand conditions,  
399 including the geopolitical situation, import diversification, network costs,  
400 environmental protection costs, weather conditions, and levels of taxation  
401 (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;

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

413 weather, cultivation yield, pests;  
414 - transport cost: in the present study, transport cost was considered negligible, due to  
415 geographical proximity of companies in the industrial park. However, a wider  
416 industrial park could be imagined, possibly collecting wastes from the entire country.  
417 In that case, transport cost and environmental impact should be computed in the  
418 system sustainability assessment.

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

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

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

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

438 **Declaration of interest**

439 All Authors declare no conflict of interest.

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542

543 **Figure/supplementary figure captions**

544 Figure 1. Structure of the decision support system.

545

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

549

550 Figure S1. Number of publications relevant to fruit and vegetable waste valorisation from  
551 1995 up to 2018. (Data collected from Web of Science databases, Clarivate Analytics,  
552 using as key-words “Fruit and vegetable waste” or “FVW” and “valorisation” or  
553 “valorization”).

554

555 **Table/Supplementary table headings**

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

559

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

562

563 Table S1. Cost and energy functions of equipment and plants required for the various unit  
564 operations of processes involved in the implementation of traditional management and  
565 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  
571 and innovative valorisation strategies of lettuce waste.