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1 Assessing the environmental behavior of alternative fertigation methods in soilless systems: The case of
2 Phaseolus vulgaris with struvite and rhizobia inoculation

3

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11

12 **Highlights:**

- 13 • Inorganic fertilizers are a great constrain in urban agriculture due to their emissions.
- 14 • Struvite and nitrogen fixing bacteria can be considered to avoid additional impacts.
- 15 • While results show lower yields, life cycle impacts are significantly reduced.
- 16 • Struvite and nitrogen fixing bacteria rhizobium reduce N and P emitted to water.
- 17 • A yield reduction can be assumed depending on complexity of the infrastructure.

18 **Abstract**

19 Urban agriculture, while being a promising solution to increase food sovereignty in cities, can lead to an
20 unprecedented discharge of nutrient and fertilizer-related emissions into the urban environment.
21 Especially relevant are nitrogen (N) and phosphorus (P), due to their contribution to marine and
22 freshwater eutrophication. Therefore, alternative methods of fertilization need to be put into practice to
23 avoid such impacts to the surrounding environment. Struvite, has been studied as a potential slow
24 releasing fertilizer due to its high P content, while the bacteria rhizobium has been used to fix N directly
25 from the atmosphere. Legumes, like the common bean are N-demanding crops capable of symbiosis with
26 the bacteria rhizobium and have previously shown positive responses to fertilization with struvite. This
27 study aims to analyze the environmental performance of plant production in hydroponic systems
28 combining rhizobium inoculation and struvite (2g, 5g, 10g, 20g) irrigated with a N and P deficient nutrient
29 solution, using life cycle analysis (LCA). The nutrient content of in- and out-going irrigation was analyzed
30 as well as in plants and beans. The functional unit for the LCA was 1kg of fresh beans. The results obtained
31 indicate a yield reduction of 60% to 50% in comparison to the control which was irrigated with a full
32 nutrient solution. The impacts from operational stage are less in all impact categories, where most
33 significant reductions up to 69% and 59% are seen in marine-eutrophication and global warming
34 respectively. Although the infrastructure does not change between treatments, its impacts increase due
35 to lower the yields. We determine that below a 10% of the control yield, the alternative systems have
36 more impact than the use of conventional mineral fertilizers in almost all impact categories, thus pointing
37 to the importance of infrastructure to truly reduce environmental impacts for urban agriculture.

38 **Introduction:**

39 Urban Agriculture (UA) has the potential to replace traditional food supply chains to some degree, thereby
40 reducing transportation, packaging and food losses while increasing food sovereignty of cities (Sanyé *et*
41 *al.*, 2012; Tornaghi, 2017; Sanjuan-Delmás *et al.*, 2018; Siegner, Acey and Sowerwine, 2020). However,
42 the additional need of inorganic chemical fertilizers inevitably results in greater discharge of these
43 chemicals into the environment as well as an increase of the resource depletion potential (Rufí-Salís,
44 Calvo, *et al.*, 2020). This is especially relevant considering the emission of nitrogen and phosphorus
45 species, substantially contributing to marine and freshwater eutrophication, causing oxygen deprivation

46 in aquatic environments. Specifically, urban water cycles and runoff are a great concern with their high
47 implication in water eutrophication damaging ecosystems close to cities as well as close to intensely
48 fertilized agricultural sites (John H. Ryther and Dunstan, 1971; Lewis, Wurtsbaugh and Paerl, 2011). The
49 integration of agriculture within city boundaries could therefore further increase the potential of
50 emissions into the urban water cycles.

51 It is important to find ways for UA to be highly resource-efficient so that urban areas are able to expand
52 these production practices without incurring significant environmental impacts associated with the
53 additional water, energy, and nutrient requirements. To mitigate these environmental impacts,
54 alternative and more environmentally friendly fertilizers have to be applied to attain competitive yields
55 without causing great impacts to the surrounding environment (Lewis, Wurtsbaugh and Paerl, 2011) as
56 well as avoiding further extraction of phosphorous for agricultural purposes (Linderholm, Tillman and
57 Mattsson, 2012).

58 Recent work has been focused on the recovery of nutrients from wastewater treatment plants (Harder *et al.*,
59 2019; Lam, Zlatanović and van der Hoek, 2020; Shaddel *et al.*, 2020), showing a great range of possible
60 alternatives for fertilization generated in urban areas as well as their constraints. One of the available
61 options showing great potential for its use in agriculture, is struvite. The struvite crystal is formed by a
62 spontaneous precipitation in wastewater treatment plants and is regarded as a slow releasing fertilizer
63 due to its low dissolution and high content of phosphorous (12.5%), magnesium (9.9%) and nitrogen
64 (5.7%) (Rahman *et al.*, 2014; Talboys *et al.*, 2016; Degryse, Baird, Rodrigo C da Silva, *et al.*, 2017). It has
65 been reported that the formation of struvite can recover up to 90% of Phosphate in wastewater sludge,
66 reaching even higher percentages depending on the precipitation process and source (Kataki *et al.*, 2016).

67 Studies on the use of struvite in agriculture (Massey, M.S., Davis, J.G., Sheffield, R.E., Ippolito, 2007;
68 Ackerman *et al.*, 2013; Talboys *et al.*, 2016; Degryse, Baird, Rodrigo C. da Silva, *et al.*, 2017) point out that
69 the use of these recovered nutrients can reduce mineral fertilizer requirements while implying little to no
70 cost for farmers (Karak and Bhattacharyya, 2011). The use of struvite has been shown to successfully
71 substitute the use of mineral phosphorous fertilizers, while reducing nutrient losses to the environment
72 due to its slow dissolution rate (Ahmed *et al.*, 2018). Agricultural production with struvite as the main
73 source of P has been tested on a variety of crops ranging from ryegrass (*Lolium perenne*) and broad beans

74 (*Vicia faba*), which experience an increase of fresh yields of 76% and 54% respectively, to canola (*Brassica*
75 *napus*) and wheat (*Triticum aestivum L.*), that suffer a reduction of the nutrient uptake and therefore a
76 reduction of the plant yield (Ahmed *et al.*, 2018). Other crops, however, have been seen to experience no
77 significant changes with the use of struvite like the case of maize (Uysal *et al.*, 2014) and corn (Thompson,
78 2013).

79 The environmental performance of the struvite extraction as P fertilizer has been previously studied (Ishii
80 and Boyer, 2015) and while its benefits in comparison to virgin phosphorous have been identified in the
81 reduction of nutrient emissions and offsets commercial fertilizer production, its total environmental
82 performance depends on the chemical inputs used for the struvite precipitation as well as the
83 infrastructure and the recovery accounted in the life cycle inventory (Linderholm, Tillman and Mattsson,
84 2012; Ishii and Boyer, 2015; Lam, Zlatanović and van der Hoek, 2020).

85 Whereas these studies have mainly substituted phosphorous based fertilizers, the use of nitrogen in the
86 form of ammonium nitrate, urea and monoammonium is still given to the crops. As previously established,
87 the emissions of nitrogen in the environment are greatly damaging and especially crucial for high N
88 demanding crops like legumes.

89 The inoculation of legume crops with the bacteria rhizobium has been explored as a way for the plant to
90 fix its nitrogen directly from the air without boosting its environmental footprint (Olivera *et al.*, 2004;
91 Gopalakrishnan *et al.*, 2015; Kontopoulou *et al.*, 2015, 2017; Savvas *et al.*, 2018; Araujo, Urbano and
92 González-Andrés, 2020; Sammauria *et al.*, 2020; Sanyal, Osorno and Chatterjee, 2020). This bacteria forms
93 an endosymbiotic interaction with the plant, profiting from compounds generated through
94 photosynthesis while fixing atmospheric N₂ that is then given to the plant in form of ammonia (NH₃) (Long,
95 1989; Fisher and Long, 1992). As a result of these previous studies, it has been seen that in terms of the
96 obtained yields, rhizobium tends to diminish the crop production in comparison to synthetic nitrogen
97 fertilizers (Kontopoulou *et al.*, 2015, 2017; Savvas *et al.*, 2018b; Sanyal, Osorno and Chatterjee, 2020)
98 while its use on soil for common bean reduces about 19% per ha of the environmental burden when
99 mineral N fertilization is replaced (Araujo, Urbano and González-Andrés, 2020).

100 To summarize the state of the art in nutrient recovery for mineral fertilizer substitution, the above-
101 mentioned studies have shown that struvite can reduce and substitute a significant amount of P fertilizer
102 while recovering great amounts of phosphate nutrients from wastewater treatment plants (WWTP). On
103 the other hand, rhizobium can reduce the need for nitrogen mineral fertilizers, only partially reducing the
104 environmental impact associated to the use of fossil-dependent mineral fertilizers. However, no study has
105 attempted to use both struvite and rhizobium to completely avoid the application of nitrogen and
106 phosphorous fertilizer, thereby reducing environmental impacts even further.

107 This paper aims to fill this gap by exploring the feasibility and environmental impact of applying struvite
108 combined with rhizobium inoculation as alternative fertilizers of a UA system. To do so, we use the Life
109 Cycle Assessment (LCA) to quantify the environmental impacts of a common bean crop in which the seeds
110 were inoculated with soil bacteria rhizobium and different quantities of struvite were applied, compared
111 to conventionally fertilized bean plants. The bush bean *Phaseolus vulgaris* "Pongo" was used in the
112 experiments due to previous tryouts showing a good production in the perlite substrate as well as for
113 being a highly consumed leguminous crop in Spain. The objective is to show the benefits and costs of this
114 fertilizer alternative when compared to mineral fertilizer and provide knowledge towards reducing
115 resource extraction for Urban Agriculture (UA) as well as avoiding possible emissions into natural
116 ecosystems.

117 **2. Materials & Methods:**

118 **2.1 Description of integrated Rooftop Greenhouse (i-RTG)**

119 The experiments were conducted in the greenhouse laboratories for UA located on the integrated
120 Rooftop Greenhouse Laboratory (i-RTG-Lab) of the Environmental Science and technology building (ICTA-
121 UAB) located in the Universitat Autònoma de Barcelona campus (UTM: 42°29'24" E, 45°94'36" N). The
122 irrigation system is hydroponic on substrate with primary the use of rainwater. The 900m² rainwater
123 harvesting system (RWHS) is included in the building structure as well as a 100m³ storage tank located
124 underground from which the water for irrigation is pumped to the cropping sites. The building structure
125 and its year-round production have been previously analyzed to identify the environmental impact
126 reduction due to the connectivity and synergy between the greenhouse and the building (Sanjuan-Delmás

127 *et al.*, 2018). This building has two greenhouse laboratories for UA on the fourth floor, where this
128 experiment was conducted. The beans were planted on the South- West facing laboratory (Urban
129 Agriculture Laboratory 2) with a total area of 122.8m² as can be seen on the plant layout shown in figure
130 1.

131 <Figure 1>

132 Several sensors were used to monitor temperature (T107 Campbell Scientific) and relative humidity of the
133 i-RTG cropping areas (Table 1 in the supplementary information). Irrigation water, water drainage, electric
134 conductivity and pH for each irrigation line were measured three times a week.

135 **2.2 Plant materials and growth conditions**

136 The seedlings were obtained from a nursery, where the seeds were inoculated with the rhizobium mix
137 and transported to the i-RTG 10 days after planting. The production system is soilless with perlite
138 substrate and nutrient solution given through the 2L/h drip irrigation system. The cropping area was
139 arranged in twelve rows with four 40L perlite bags each (Figure 1). Four bean plants were planted in each
140 1m long perlite bag, making a total of 192 plants, divided in three treatments (64 per treatment). The
141 plantation frame was 0.125m² within a total cropping area of 84.6m². The irrigation was set 4 times a day
142 for 3 minutes giving a total amount of 400ml per day for each plant.

143 Two experiments were performed. The first experiment took place in 2019, starting on the 16th of January
144 and ending on the 10th of April. The second experiment took place in 2020, and the plants were
145 transplanted on the 13th of February and the experiment was finalized on the 7th of May, lasting each one
146 a total of 84 days. We used different concentrations of struvite during the two experiments to determine
147 the N and P assimilation rates and how the yield was affected. In 2019, the bean plants were treated with
148 2g of struvite (0.25g of P; 0.114g of N) per plant (SR2) and 5g of struvite (0.625g of P; 0.285g of N) per
149 plant (SR5). In 2020, we incremented the amount of struvite to 10g (1.25g of P; 0.57g of N) per plant
150 (SR10), and 20g of struvite (2.5g of P; 1.14 of N) per plant (SR20). The inoculation was made prior to their
151 sowing, embedding the bean seeds in the commercial liquid rhizobium mixture before planting. We
152 performed a control experiment both years parallel to the treatments under the same temporal and
153 climatic conditions but fertilized with a full nutrient solution, with zero struvite and without inoculation.

154 These control treatments were also made with the same crop and during the same time, lasting 84 days
155 in the rooftop greenhouse as well.

156 The struvite granules were placed close to the root area to ensure a better absorption by the plant. To
157 avoid possible runoff of struvite granules a 1L bag with small holes for water drainage, was placed around
158 the root area to retain the crystalline granules close to the plant. The granulated urine derived struvite
159 was given directly to the plants rhizosphere after transplanting them into the integrated greenhouse.

160 **2.2.1 Commercial inorganic fertilizer**

161 Two nutrient solutions (Table 1) were made for both campaigns, one standard full nutrient solution (NS)
162 with nitrogen, phosphorous and magnesium and a second solution deficient in nitrogen, phosphorous and
163 magnesium with a higher content in K_2SO_4 to avoid potassium as a limiting factor. All nutrients were mixed
164 into a concentrated solution stored in 50L tanks, further diluted with rainwater when irrigated in a ratio
165 of 1:100 (NS:Rainwater).

166 <Table1>

167

168 **2.2.2 Commercial Rhizobium inoculant**

169 The inoculant used for this experiment was obtained through a company based in Karlsruhe, Germany,
170 nadicom GmbH. This 1L liquid product contained a mixture of two rhizobia strains, *Rhizobium phaseoli*
171 and *Rhizobium giardinii*, that were directly applied on the bean seeds (except for the Control) before
172 planting and again 5 days after transplanting to the ICTA RTG- Lab. The manufacture and transport of this
173 commercial product was not included in the LCA as an input for our alternatively fertilized crops, since
174 the production impact has been considered minimal.

175 **2.2.3 Commercial struvite**

176 The struvite used for the experiment was urine derived, obtained from a wastewater treatment plant
177 (WWTP) in Denmark. The plant recovers struvite from the digestate flow through the addition of reagents
178 to reach stoichiometric levels that trigger struvite precipitation. The obtained struvite ($Mg(NH_4)PO_4 \cdot 6H_2O$)
179 has a composition conformed by 12.5% w/w phosphorous; 5.7% w/w nitrogen and 9.9% w/w magnesium

180 and a granule size of 1 to 3mm. The heavy metal content in struvite from different origins and production
 181 systems has been analyzed and set at levels under the European threshold, also ranging far below the
 182 amount of possible impurities that can be found with the production of phosphate rock as well as
 183 untreated sewage sludge from WWTP (Bastida *et al.*, 2019).

184 2.3 Experimental analyses and nutrient balances

185 Water samples were taken from each irrigation system as well as the drained water 3 times a week.
 186 Production of the bean plants was counted and weighted. The amount of drained leachates were
 187 measured daily and sampled three times a week. The concentrations of Cl^- , NO_2^- , NO_3^- , PO_4^{3-} , SO_4^{2-} , Ca^{2+} ,
 188 K^+ and Mg^{2+} were measured using ionic chromatography. Additionally, the pH and EC were measured daily
 189 for both the nutrient solutions and leachate water. To reduce the possible error generated through the
 190 irrigation and sampling the generated data was adjusted to a curve. The incoming and outgoing nutrients
 191 were quantified as well as the nutrients found in the plant biomass and beans. The plant biomass was
 192 collected at the end of the experiment with a sample number of 8 plants per treatment. These samples
 193 were dried and weighted before being digested with a Single Reaction Chamber microwave with
 194 concentrated HNO_3 . The digested samples were then analyzed using Optical Spectrometry (ICP-OES).
 195 The same procedure was applied to the obtained production of beans, sampled throughout the
 196 experiment. The final balance per plant was assessed with the following equation:

$$197 \quad \text{Eq 1:} \quad F_{ns} + F_s + F_{fix} = F_p + F_b + F_{pl} + F_l$$

198 *Equation 1: F_{ns} = g nutrients in nutrient solution, F_s = g in struvite, F_{fix} = g nutrients, F_p = g nutrients in production, F_b =
 199 g nutrients in biomass, F_{pl} = g nutrients in perlite, F_l = g nutrients in leachates*

200 To calculate the fraction needed per plant to close the balance, the following equation was used (Eq2):

$$201 \quad \text{Eq 2:} \quad \text{Balance \%} = 100 * \frac{F_p}{(F_{ns} + F_s + F_{fix})} + \frac{F_b}{(F_{ns} + F_s + F_{fix})} + \frac{F_{pl}}{(F_{ns} + F_s + F_{fix})} + \frac{F_l}{(F_{ns} + F_s + F_{fix})}$$

202 *Equation 2: F_p = g nutrients in production, F_b = g nutrients in biomass, F_{pl} = g nutrients in perlite, F_l = g nutrients in
 203 leachates, F_{ns} = g nutrients in nutrient solution, F_s = g in struvite, F_{fix} = g nutrients obtained through N_2 fixation*

204 The following results depict the data collected in 2019 for plant biomass, irrigation and leachate nutrient
 205 content as well as yield production and nutrient content. The 2020 study was included to provide further

206 information on the effect of greater struvite quantities to increase the yield. Therefore, the LCA results
207 for 2020 only defer from the 2019 inventory in the amount of struvite used as well as the yield.

208 Additionally an analysis to calculate the fraction of N in the biomass obtained from N₂ fixation was made,
209 using an elemental analyzer- isotopic ratio mass spectrometer (EA-IRMS; Thermo Fisher Scientific),
210 attaining the δ¹⁵N values (in ‰) for our treatments SR2, SR5 and control as well as our alternative fertilizer
211 struvite which was set in 7.1‰. Contributions from each source (atmospheric or struvite) were then
212 calculated with the following equation (Shearer and Kohl, 1993; Unkovich *et al.*, 2002; Arndt *et al.*, 2004),
213 using the lowest δ¹⁵N value obtained as our 'B' value (-1.16‰) (Shearer and Kohl, 1989; Peoples, Boddey
214 and Herridge, 2002; Kermah *et al.*, 2018):

215
$$\text{Eq 3: } \%Ndfa = \frac{\delta^{15}N \text{ Source 2} - \delta^{15}N \text{ Sink}}{\delta^{15}N \text{ Source 2} - 'B' \text{ value}} \times 100$$

216 *Equation 3: %Ndfa (Nitrogen derived from N₂ fixation from the atmosphere), δ¹⁵N Source 2 (‰) corresponds to the*
217 *δ¹⁵N value of struvite, δ¹⁵N Sink (‰) corresponds to the δ¹⁵N value from the sample, 'B' value set at -1.16‰*

218 **2.4 Life Cycle Assessment (LCA)**

219 The LCA is a tool with a standardized methodology (ISO 2006) used to determine the environmental
220 performance of goods in all stages of their life cycle of the four proposed treatments (SR2, SR5, SR10 and
221 SR20) and control. The scope of the LCA study is cradle to gate of the bean production system. The
222 functional unit (FU) chosen is 1kg of fresh beans at the collection point. The cut-off method in the Simapro
223 software was applied which allocates the benefit of the recycled materials to the recycled products. To
224 calculate the life cycle environmental impacts of the treatment, we used the Simapro software and the
225 Ecoinvent 3.5 attributional database. The following impact categories (IC) were selected, all from the
226 ReCiPe (H) Midpoint method: Global warming (GW), Terrestrial acidification (TA), Freshwater
227 eutrophication (FE), Marine Eutrophication (ME), Fossil Resource Scarcity (FRS) and Ecotoxicity (ET), which
228 is the sum of Freshwater, Marine and Terrestrial ecotoxicities.

229 The system definition is illustrated by figure 2, which differentiates between the subsystems
230 infrastructure, operation and end of life. For infrastructure, we considered the production and end of life
231 of the greenhouse, the rainwater harvesting system and the auxiliary equipment such as pumps and

232 fertirrigation installed and all the transportation required. All steps shown in figure 2 for raw material
233 extraction, processing, transport to construction site, construction/ maintenance, as well as the transport
234 to the landfill or recycling site were considered. On the operational side, the study includes the
235 production, use and end of life, including transport, of all the resources required for the duration of the
236 experiments (perlite substrate, fertilizers, struvite, pesticides, water, and energy). Exceptions to this are
237 the production of nursery plants and the composting of the residual biomass as well as the rhizobium
238 production. For the production of struvite the additional inputs for controlled precipitation were
239 accounted, in this case the chemical inputs can be seen in the LCA inventory, which consisted in MgCl,
240 Energy and NaOH for 1kg of struvite as described by the technology developed by Ostara® (Amann et al.,
241 2018). The used wastewater for the struvite precipitation was not considered within the system
242 boundaries for this study.

243 <Figure 2>

244 For the end of life subsystem of our production several assumptions were made. The remaining biomass
245 generated in the greenhouse goes to composting as well as the used substrate after 5 years of use. The
246 composting of the residual biomass was not considered within the system boundaries. The leachate water
247 was discharged into the urban water cycle entering the wastewater treatment plant. All phosphates and
248 nitrates discharged into the water are therefore considered direct emissions to water, in the case of the
249 treatments fertilized with struvite, also as direct emissions to the air. For the system infrastructure it was
250 considered that the RWHS as well as the Auxiliary equipment were assumed to be disposed of into the
251 landfill. The distance to the landfill and recycling site were assumed to be 30 km from the greenhouse.

252 The inventory data for the infrastructure and auxiliary equipment was compiled from Sanyé *et al.*, 2012;
253 Sanyé Mengual, 2015; Sanjuan-Delmás *et al.*, 2018; Rufi-Salís, Petit-Boix, *et al.*, 2020. For both the
254 rainwater harvesting system (RWHS) and the i-RTG System a lifespan of 50 years was considered while
255 the auxiliary equipment was set at 10 years, taking into account previous work by Sanjuan-Delmás *et al.*,
256 2018 and Rufi-Salís, Petit-Boix, *et al.*, 2020. Emission factors for N to air were calculated according to
257 Llorach-Massana *et al.*, 2017, while N and P in water were directly measured. The emissions to air in
258 struvite were calculated taking into account the emission factor of the total nitrogen in the applied
259 quantity of struvite, even when not all struvite was dissolved.

260 For the transportation of all materials average values for the transport to markets were given. The
261 transport to the i-RTG was then added with a distance of 50km for all pesticides, fertilizers and auxiliary
262 equipment as well as the struvite and rhizobium applied. Transport distance of 850km was applied for the
263 substrate bags following the methodology of Sanjuan-Delmás *et al.*, 2018. No transport of the
264 horticultural production was considered since one of the benefits of urban agriculture is the on-site selling
265 of the products, therefore the product procurement by the consumer is located outside our system
266 boundaries.

267 The data for the operation was collected during the experiment, including the amount of fertilizers, the
268 substrate used as well as the energy used to work the irrigation system. The energy used during the
269 campaign was estimated by the water pumps and amount of water pumped to the greenhouse and crops.

270 The full inventory is available in supporting information (Tables 3 to 7 from the supplementary
271 information).

272 **3 Results:**

273 3.1 Yields and nutrient balance

274 The total and average-per-plant production for both campaigns (2019 and 2020) can be seen in Table 2
275 for each treatment. The results show that as struvite concentration is increased from SR2 to SR20,
276 production also increases from 1899.2g to 4821.5g indicating a significant assimilation rate of P by the
277 plants. It is crucial to point out that the two controls differ greatly as well from one campaign to the other.
278 Since the campaign of 2020 began in February and the 2019 campaign in January, we can consider the
279 climatic conditions as an explanation for greater productions, taking into account that minimal
280 temperatures were higher in 2020 (by more than 6°C), as well as the average temperature throughout
281 the experiment (Table 1 supplementary information). These conditions would enable a greater and faster
282 production of flowers and an earlier bean growth. The first bean pod harvest made in 2019 was 49 days
283 after transplanting the bean plants into the greenhouse while in 2020 the bean pod harvest began 39 days
284 after transplanting (Figure 1 in the supplementary information). Due to the different climatic conditions
285 and resulting productions the control treatment for both campaigns has to be considered as a reference.

286 The observed productions do not reach more than 60% of the achieved production in the control
287 treatment, staying between 40 to 60%, in both campaigns.

288 <Table 2>

289 3.2 Nutrient fluxes

290 The obtained nutrient balance can be seen in table 3. Here the nutrient content for Nitrogen,
291 Phosphorous, Magnesium, Potassium, Sulfate and Calcium in the incoming nutrient solution can be
292 observed, as well as the outgoing fluxes of production (bean pods), biomass (leaves, stems, roots), perlite
293 and leachates. In the case of nitrogen the fixated N₂ is also taken into account as seen in figure 3. Table 2
294 in the supplementary information also provides some incoming (struvite input) and out coming flows
295 (leachates) for the SR10 and SR20 treatments for P, N and Mg.

296 <Figure 3>

297 The obtained results for the fixed g of N where achieved thanks to previous studies with isotopic N15
298 analyses where the percentages of fixation for SR2, SR5 and the 2019 control where obtained. The average
299 percentage of fixed nitrogen for SR2 was 82% while for SR5 it was 72% and 16% for the control of the total
300 N found in production and biomass. This fixed Nitrogen was further given as an additional inflow.

301 <Table 3>

302 The balance for nutrients N, H, K, and Ca is close to 100%, indicating that the inflows can be traced almost
303 entirely in the different outflows. On the other hand, there are losses of P and Mg in the SR2 and SR5
304 treatments, which are unaccounted for in the mass balance showing percentages under 50% reaching
305 values as low as 23% for the P balance in SR5. We consider that the reason for such low accounting of the
306 balance for P and Mg is the possibility of them remaining undissolved in the perlite bag. While Sanjuan-
307 Delmas provides information of the amounts of these nutrients in fertigation that can be found in the
308 perlite, the remaining P, Mg and N from struvite left in the perlite bag was not determined. This factor
309 can generate uncertainty in our nutrient balance which has to be taken into account. When observing
310 the percentages of out coming P and Mg in treatments SR10 and SR20 (Table 2 in the supplementary
311 Information) we can observe a trend in the leachated amount being around 8 to 11% for SR10 nd SR20

312 respectively. These leachate percentages close to the observed in the SR2 and SR5 treatments further
313 support the idea of an uncompleted dissolution in the perlite bag. On the other hand the N balance seems
314 to fit the incoming and out coming flows, while the amount of the given N with the struvite is respectively
315 lower to Mg and P and the atmospheric N₂ fixation also amounts to additional nitrogen in plant biomass
316 and production. When regarding the percentage of discarded P and N into the leachates we can observe a
317 reduction of almost threefold in N when comparing the control (23%) to both treatments (SR2 with 8%
318 and SR5 with 9%) and double (SR2 with 17%) or even fourfold (SR5 with 9%) in P compared to the control
319 (37%). When regarding the quantity of P in the leachate water of the control treatment and the SR20
320 treatment we can see that it is almost identical, pointing out that the given quantity of struvite has
321 achieved flows to waste water similar to the control treatment. On the other hand, when considering the
322 percentages in regard to the total amount given to the plant the control treatment has leached more than
323 threefold the added P (37%) compared to the SR20 treatment (11%). When observing the N incoming
324 flows the input given for the control treatment in the irrigation is similar to the quantity given, in form of
325 struvite, in the SR20 treatment. We must bear in mind that for the treatment SR20 the quantity of N
326 gained from atmospheric fixation is not known. On the other hand the leached outflow for the SR20
327 accounts for about a 13%, almost half of the leached amount in the control (23%). The lower quantities
328 of P and N measured in water, although similar or greater N and P quantities were given to the control
329 treatment, indicate a much slower dissolution of this fertilizer, reinforcing the idea of a remaining
330 undissolved amount of struvite in the perlite bag.

331 3.3 Environmental performance of the treatments:

332 The LCA impacts per functional unit (FU) are disaggregated into the life cycle stages that resulted in the
333 highest impacts for all four treatments and controls, as shown in figure 4. Since the controls resulted in
334 higher yields, consequently the impacts are reduced considerably in all categories.

335 <Figure 4>

336 Within each impact category we can clearly state that the greenhouse structure and the rainwater
337 harvesting system account for most of the generated impact especially in GW, TA, ME and FRS. This can

338 be due to the large transport distances, the processing and construction of larger amounts of materials
339 like aluminum and steel.

340 While the auxiliary equipment and fertilizers seem to have lower impacts in most categories, the
341 implication of the latter in the ME, FE and TA categories is of great importance for the control treatments
342 where a full nutrient solution was used. Even when the emissions to air and water of struvite were taken
343 into account, the reduction in these categories for treatments SR2 and SR5 is especially clear.

344 While the higher production in the control treatment reduces impacts of the RTG- infrastructure and
345 RWHS, the impact generated by the fertilizers is still greater in all IC for the control despite the higher
346 yields, only being surpassed in the treatment SR20 for FE. The percentage contribution of the accounted
347 system stages can be further observed in figure 5. The reduction of the impact generated by the
348 alternative fertilizer can be seen when comparing the smaller percentages for fertilization in the
349 treatments SR2, SR5 SR10 and SR20 to the control treatments 1 and 2. For the treatment SR20 we can
350 again observe an increase of the impact in the FE category.

351 <Figure 5>

352 When adding the percentages corresponding to the infrastructure (RTG-structure, RWHS, auxiliary
353 equipment) and operation (energy, fertilizers, pesticides, and substrate) stages of production for each
354 impact category, a shift of the weight of impact contribution with the alternative fertilization can be seen
355 (table 4).

356 <Table4>

357 The change in the fertilization mainly generates a shift in the eutrophication impact categories (FE and
358 ME) which reach up to more than 55% of the total impact of the operation in the control treatment whilst
359 staying under 30% in both treatment SR2 and SR5. It is also worth mentioning that overall the change in
360 the fertilization has an effect on all categories, shifting the weight of the impact from the operational
361 phase to the infrastructure when comparing the control to all other treatments.

362 Due to the great percentage taken up by the greenhouse structure and rainwater harvesting system, the
363 contribution of the operational side of the bean production is overshadowed. Since the infrastructure

364 remains the same for all treatments and is highly specific to this particular site, it was excluded from
365 consideration in figure 6 for a better exploration of the effects of the substituting fertilizer (Figure 2
366 Supplementary information for Environmental performance of the operation system in percentage per
367 IC).

368 <Figure 6>

369 When observing figure 6 the applied fertilization appears to be the main cause for emissions in all IC in
370 the operation subsystem. While yield is smaller in all four struvite and rhizobium treatments, emissions
371 remain lower than controls 1 and 2 in categories GW and AT. In the case of FE, ME ad ET emissions from
372 SR2 and SR5 remain below the control 1 treatment while being higher for the treatments SR10 and SR20.
373 In the case of fossil resource scarcity it is worth mentioning that the reason for a higher emission in these
374 two categories is not bound to fertilization but due to an increase of the weight of substrate and energy
375 in the operation impact.

376 While emissions are mostly lower in the four alternative fertilizer treatments, especially in SR20 we can
377 observe an increase with greater amounts of struvite in both categories FE and ME. To further understand
378 the changes in emissions bound to fertilization, figure 7 depicts all accounted factors considered in the
379 LCA for the fertilization.

380 <Figure 7>

381 When observing the fertilization emission in figure 7, great impact reductions are made due to the
382 reduced emissions to air and water (as seen in TA, GW, FE and ME) and transport of fertilizers (as seen in
383 ET, FRS and again GW). Here we can appreciate that the increase of impact seen for treatment SR20
384 achieved in categories FE and ME is due to water emissions increase due to greater struvite quantities.

385 **Discussion:**

386 The life cycle assessment performed on the bean production experiments in soilless substrate fertilized
387 with struvite and rhizobium has shown that there are significant benefits in terms of eutrophication. These
388 findings confirm studies of other authors such as (Sanjuan-Delmás *et al.*, 2018; Rufí-Salís, Calvo, *et al.*,
389 2020) in which fertilization has been deemed as a major contributor to the environmental footprint of

390 urban agriculture. However, because the yield is lower than that of the conventional mineral fertilizer,
391 the impacts associated to the infrastructure required for the fertilizer substitution increase. Fertilization
392 has shown to be of great importance in the impacts regarding our bean production. The sole removal of
393 the nitrogen, phosphorous and magnesium from the fertigation has shifted the weight of the emissions
394 from the operational part to the infrastructure in a drastic manner. These emission reductions not only
395 affected the expected IC (ME and FE) but all due to their transport (for GW, ET and FRS) and the emissions
396 to Air (for TA) as seen in figure 7. While this information depicts great flaws in the implementation of such
397 production systems it also gives a great chance for improvement. While the application of struvite has
398 shown to fulfill the entire cycle of the crop with some yield reduction its production and transport do not
399 affect the given IC to a greater extent except for the treatment SR20. The accumulation of all three
400 fertilizers (P, N and Mg) in one and the possibility of its local generation and application can considerably
401 improve the operational footprint of our agricultural systems. While the struvite recovery technology
402 developed by Ostara® and used for this experiment requires inputs of MgCl, energy and NaOH, has been
403 seen to have lower environmental impacts compared to other processes (Rufí-Salís, Brunnhofer, *et al.*,
404 2020) further advancements are being made on the use of saltwater, to further reduce the use of chemical
405 resources and potentially lowering its environmental footprint (Martínez-Blanco *et al.*, 2014; Hasler *et al.*,
406 2015; Amann *et al.*, 2018).

407 On the other hand, as we have seen in the nutrient fluxes for the SR2 and SR5 treatments, the percentages
408 of the balances for P and Mg remain low as well as the SR10 and SR20 leachate fluxes. The previously
409 described slow dissolution of the struvite fertilizer (Bhuiyan, Mavinic and Beckie, 2007; Degryse, Baird,
410 Rodrigo C da Silva, *et al.*, 2017) has been identified as the reason for the lower balance percentages,
411 leaving struvite in the bag that has still not been diluted. This dissolution could be remedied with a lower
412 pH in the irrigation as well as an increase of the irrigation points inside the bag. The location of the struvite
413 itself with regard to the root area has also been regarded as relevant for its plant uptake (Degryse, Baird,
414 Rodrigo C. da Silva, *et al.*, 2017). On the other hand the remains of struvite inside the bag can favor the
415 reuse and recycling of the perlite bag for a less P and Mg demanding crop in the case of treatments SR2
416 and even a second production of beans like in the case of SR5. A second bean production without the
417 addition of struvite would even further reduce the needed inputs and its operational footprint.

418 The use of alternative fertilizers like struvite avoids the consumption of mineral or synthetic fertilizers
419 (Lam, Zlatanović and van der Hoek, 2020) described as fertilizer offset accounting. The environmental
420 benefit of the use of struvite should not only be accounted in the moment of its use (emissions to air and
421 water) and transport but in the avoided production of N, P, and Mg fertilizer. Even further, the
422 environmental benefit of the removal of these nutrients from urban waterbodies should be taken into
423 account as well. As described before, the generation of struvite has requirements but removes potential
424 water and air emissions from WWTP (Ishii and Boyer, 2015a; Igos *et al.*, 2017; Lam, Zlatanović and van
425 der Hoek, 2020). While this last benefit has not been taken into account for this study, the further use of
426 struvite as fertilizer and the consequent fertilization offset accounting have, and can be well observed in
427 these results with the emission reductions in almost all IC.

428 The yield reduction in all treatments compared to the respective controls has a great impact on the
429 production footprint. While a higher production has been reported with a greater application of struvite,
430 a limitation to reach greater yields still remains. Plausible explanations for these losses are the reduced
431 struvite dissolution (Degryse, Baird, Rodrigo C. da Silva, *et al.*, 2017), the higher P requirement due to the
432 rhizobia symbiosis (Long, 1989; Olivera *et al.*, 2004) or a possible electrochemical imbalance causing a
433 reduced uptake of cations in the root area as described by Kontopoulou *et al.*, 2015.

434 While the yield reduction remains unclear, its impact on the environmental performance is quick to be
435 identified in the obtained results. The loss of production increases the environmental footprint of
436 production, reaching higher emissions than the control treatments (especially when infrastructure is
437 considered), even with lower total emissions of P and N to water in all treatments (Table 3 in the
438 Supplementary information).

439 A higher yield without the additional use of these fertilizers would decrease the impact of our production,
440 which begs the question as up to what yield loss percentage we can afford and still remain more
441 sustainable than the control treatment.

442 To answer this question the control (2019) yield was regarded as our hypothetical 100% yield and
443 therefore a scenario with 0% yield reduction. From here on the emissions for all IC were calculated with
444 a yield loss of 10% to 60%. The values used for the 60% and 50% yield loss were directly taken from the

445 SR2 and SR5 treatments respectively, since the obtained yields corresponded to the simulated yield losses.
446 The emissions were also derived from the SR2 and SR5 treatments, since the emissions to water from
447 treatments SR10 and SR20 were deemed as too similar to the control with no major yield increase (in
448 comparison to the respective control treatment).

449 Figures 8 and 9 depict these scenarios for the yield reduction impact in infrastructure and operation and
450 only operation respectively. The control treatment line in both figures 8 and 9 is where the baseline from
451 the control treatment was set. Above this control line the emissions are increased with regards to the
452 control (in %), while below this line the impacts are decreased. When considering the infrastructure and
453 operation (figure 8) we can observe that no yield can be lost in order to bring all IC under the control
454 treatment line.

455 <Figure 8>

456 While TA, FE and ME are well below the baseline with a yield reduction of 30% other IC like GW and ET
457 start to decrease at 10% yield loss and below. In the case of figure 9, when infrastructure is not considered,
458 a 50% yield loss can occur and still decrease all emissions in all IC.

459 <Figure 9>

460 The importance of reducing mineral or synthetic fertilizer to avoid emission in all IC has been regarded
461 throughout the experiment, although the importance of maintaining production levels while using
462 alternative fertilization methods has been laid out clearly. While impact categories like FE and ME are
463 greatly decreased, the capacity to affect other categories in a significant way can only be achieved with
464 low yield reductions. Especially when considering urban agriculture, the production system might entail
465 more complex infrastructure (rooftop greenhouse, indoor agriculture), leaving reduced margins of yield
466 loss.

467 The slow dissolution of struvite and the feasibility of its use in soilless agriculture make this fertilizer a
468 good candidate to avoid further P extraction and loss. Due to the uncertainty of the estimation of available
469 mineral P in the next centuries, new ways of nutrient recovery need to be considered in our immediate
470 future (Alewell *et al.*, 2020). This work has demonstrated that the emissions to water, especially for P can
471 be reduced in comparison to conventional fertilization methods. When talking about the extraction of

472 these nutrients to produce struvite further efforts should be made to make this process possible in
473 wastewater treatments plants, reducing transport emissions of agricultural fertilizers to surrounding
474 urban and agricultural areas. Emissions related to transportation of said minerals can be ultimately
475 reduced as well as avoiding emission and loss of nutrients into urban water streams in WWTP (Carpenter
476 and Bennett, 2011; Harder *et al.*, 2019). Ultimately, the capacity to recover P nutrients in local scales can
477 reduce agricultural pressures to obtain said fertilizer in due to its distribution or market instability and
478 increasing prices (Kataki *et al.*, 2016; Alewell *et al.*, 2020).

479 **4 Conclusions:**

480 The present work mainly aimed to analyze the environmental impact of a bean production with the use
481 of alternative fertilizing methods of struvite and the inoculation of rhizobium bacteria. It also aimed to
482 study the feasibility of production with the mentioned change in fertilization, exploring different potential
483 yield losses to gain a broader view of the possibilities this methodology presents. To this purpose, two
484 experiments with different struvite quantities were made and a quantification of the environmental
485 impact using life cycle assessment as our tool. Three main conclusions can be drawn from this study:

486 Firstly, the total reduction of nitrogen and phosphorous mineral and synthetic fertilizers for vegetable
487 production has been shown to be viable with the use of the recycled slow-releasing fertilizer struvite and
488 the bacterial inoculation with rhizobium strains. Although a yield reduction in all cases was observed
489 compromising its efficiency to reduce the environmental impact in all IC except FE and ME.

490 Secondly, the use of struvite and rhizobium inoculation reduced emissions in all IC mainly due to transport
491 and emissions to air and water due to a slower dissolution in the substrate. The struvite, being available
492 in all WWTP installations can be obtained with no great environmental cost in its operation while reducing
493 transport and extraction of three separate minerals (N, P and Mg).

494 Thirdly, the complexity of the infrastructure and operational inputs will increase the environmental
495 impact in all IC, as well as the yield loss. Only the reduction of yield loss up to 0% can equal the
496 environmental impact of the control treatment in all selected categories when the infrastructure is
497 considered. Without the infrastructure the margins for yield loss can range up to 50% staying below the
498 control treatment. Therefore we consider crucial to reduce infrastructure complexity in the prospect of

499 urban agriculture as well as the reduction of mineral and synthetic fertilizers to truly reduce potential
500 environmental impacts.

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512

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516 Methodology, Writing - review & editing; **Xavier Gabarrell:** Conceptualization, Methodology,
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