

1 Article

2 **Global warming and acidification potential** 3 **assessment of a collective manure management** 4 **system for bioenergy production and nitrogen** 5 **removal in northern Italy**

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14 **Abstract:**

15 Collective manure processing facilities to reduce nutrient loads and produce renewable energy are
16 often proposed as feasible solutions in intensive livestock production areas. However, the
17 transferring of effluents from farms to the treatment plant and back to farms, as well as the
18 treatment operations themselves, must be carefully evaluated to assure the environmental
19 sustainability of the solution. This study evaluated the global warming potential (GWP) and
20 acidification potential (AP) of a collective treatment plant for bioenergy production and nitrogen
21 removal as an alternative strategy to conventional on-farm manure management systems. Two
22 manure management scenarios were compared: manure management on individual farms and
23 management by a collective treatment plant. Data were collected at a collective processing plant
24 receiving manure from 21 livestock production units and 660 tonnes day⁻¹ of manure treated, and at
25 the individual farms to estimate emissions of CO₂, CH₄, N₂O, NO_x, NH₃ and SO₂. The GWP and AP
26 indicators were calculated to evaluate the potential impact of the two management solutions. The
27 collective solution reduced both GWP (-52%) and AP (-43%) compared to manure management
28 separately by each farm. Further improvement might be obtained in both indicators by introducing
29 mitigation techniques in farm manure storage and manure application to soil.

30

31 **Keywords:** environmental assessment; manure management; collective treatment plant; gaseous
32 emissions; nitrogen removal; anaerobic digestion

33

34 **1. Introduction**

35 Among agricultural activities, those in the livestock sector have the most critical impact on
36 environmental quality, and manure management causes the main share of pollution [1]. Livestock
37 production makes an important contribution to most economies, and livestock commodities
38 represent the highest value of agricultural production for most countries. In recent decades, the high
39 intensity of livestock production has been accompanied by its dissociation from crop production,
40 because current livestock production techniques substantially rely on imported feed for economic
41 profitability. This approach has generated new challenges related to the treatment and disposal of

42 manure, because increased nutrient concentrations on crop fields and in groundwater and surface
43 water have caused significant environmental problems. The environmental impact of intensive
44 livestock farming is often related to manure management systems and practices that have not
45 implemented updated techniques. Considering livestock intensification, there is a need to develop
46 technology and strategies that address the associated environmental concerns [2,3].

47 In this context and considering the regulatory constraints (for example the Nitrate Directive of
48 the European Union 91/676/EEC and Industrial Emissions Directive 2010/75/EU), the application of
49 novel techniques of collective manure treatment and management represents a possible solution to
50 improve the sustainability of intensive livestock farms [4].

51 A manure management system must address the principal local environmental risks and any
52 surplus of nutrients with respect to crop requirements, bringing the cropping system towards a
53 balanced fertilization status.

54 The design of future manure management systems and the improvement of existing ones
55 should, on one side, focus on maximizing nutrient recycling and controlling manure application
56 rates in order to both reduce the pollution of air, soil and water resources and to improve the human
57 health and safety. On the other side, the systems must be designed minimize the capital and
58 operating costs and the energy requirements [5].

59 The present concern about global climate change should stimulate practical solutions in areas
60 with nutrient surpluses towards an effective reduction of greenhouse gases (GHGs) by
61 implementing improved manure management systems. At the same time such solutions must also
62 reduce other emissions to air (especially ammonia), leaching of nitrate to water resources, and
63 excessive loading of phosphorus in soils.

64 Although the environmental impacts related to manure management have been widely
65 investigated [6–8], there is a need for integrated assessment of management solutions. Regulations
66 aiming to minimize the environmental impact of livestock manure are one of the external constraints
67 that farmers must consider. Indeed, when dealing with livestock manures in a whole-farm
68 perspective, the evaluation of cross- and side-effects of regulations based on scientific knowledge
69 still poses significant challenges for farmers [9]. This is often the case for manure processing aimed
70 to reduce the nutrient load and satisfy regulation requirements because such solutions might, as a
71 consequence, increase the emissions to air.

72 Manure processing facilities can be found both at the individual farm and collective scales.
73 Collective treatment facilities serve several farms and are feasible in areas with intensive livestock
74 production because the concentrated operations facilitate logistic optimization [10]. The operation of
75 these centralized facilities is usually more dependent on road transport than individual plants. The
76 aggregation of farms into a consortium or cooperative for manure treatment benefits from
77 economies of scale. Furthermore, the usual high treatment capacity also facilitates energy
78 production, reducing specific investment and treatment costs, promoting effective operations for the
79 treatment plant and making feasible the introduction of treatment techniques that reduce the
80 effluent nitrogen content. However, the transfer of effluents from farms to the treatment plant and
81 back to farms for utilization must be carefully evaluated to take into account the associated pollutant
82 emissions. Thus, cross effects and emissions to air must be evaluated in the environmental
83 sustainability evaluation of collective manure management/treatment systems.

84 The main emissions to air from farms are methane (CH_4) produced by ruminal digestion and
85 stored manure, as well as ammonia (NH_3) and carbon dioxide (CO_2) from animal respiration and
86 manure storage. In addition, the spreading of manure on fields results in the volatilization of NH_3
87 and nitrous oxide (N_2O). Ammonia emissions cause soil and water acidification, together with
88 emissions of NO_x and SO_2 . Furthermore, NH_3 emissions contribute to particulate matter formation in
89 the atmosphere. In several European countries, approximately 90% of NH_3 emissions are due to
90 agriculture, 40% of which derive from animal housing and manure storage [11]. Carbon dioxide
91 emissions from agricultural systems are usually negligible because they are overshadowed by
92 emissions from burning fossil fuels. However, CO_2 emissions might be significant from the collective
93 management of manure due to road transport of raw and processed manure. Emissions during

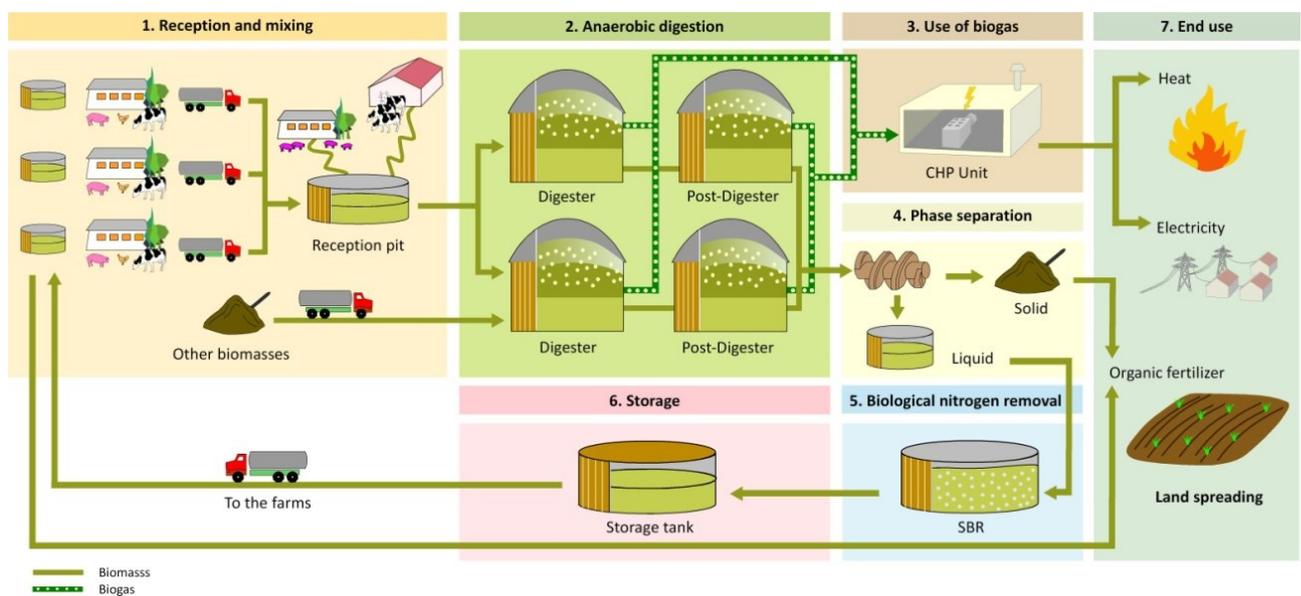
94 transportation include also NO_x and SO_2 . The amounts of CH_4 and N_2O emitted to the atmosphere
 95 are low compared to CO_2 , but their global warming potentials are, respectively, 34 and 298 times
 96 higher than that of CO_2 over a time horizon of 100 years [12]. Within the European Union, CH_4 and
 97 N_2O emissions from agriculture represents about 10% of the total European GHG emissions and are
 98 mainly due to livestock activity and manure (61%) and management of agricultural soil (39%) [13].
 99 The important role played by agriculture and livestock farming in these environmental issues
 100 increases the need for reliable models to estimate pollutant emissions from farming activities. These
 101 models are used both to highlight the critical points of farming systems and to establish sustainable
 102 manure management solutions [9]. In particular, when a new treatment facility is introduced, its
 103 effect on greenhouse gases (GHGs) and acidifying emissions also must be evaluated in order to
 104 verify its sustainability; such an evaluation might be part of a life cycle assessment (LCA). The
 105 magnitude of the potential impact of individual substances can be determined by multiplying the
 106 aggregated emission using an equivalency factor for each impact category to which it may
 107 potentially contribute. For this purpose, global warming potential (GWP) and acidification potential
 108 (AP) indicators are widely used in LCA studies [7,14,15].

109 The objective of this study was to evaluate the GWP and AP of a collective treatment plant for
 110 bioenergy production and nitrogen removal as an alternative strategy to conventional on-farm
 111 manure management systems that commonly are used in N-vulnerable areas of the Lombardy
 112 region (Italy). To this purpose, a methodology to calculate emissions for two scenarios (manure
 113 managed on individual farms or at a collective treatment facility) was defined and implemented.
 114 Data were collected through two years of monitoring at both the collective treatment plant and at the
 115 individual farms in order to estimate emissions of CO_2 , CH_4 , N_2O , NO_x , NH_3 and SO_2 . The emissions
 116 from the two scenarios were then compared both on the basis of individual pollutants and using the
 117 GWP and AP indicators. The results were analysed to evaluate the potential environmental impact
 118 of the two management solutions.

119 2. Materials and Methods

120 2.1. Treatment plant description and data collection

121 The assessment was conducted in the Province of Bergamo, in Northern Italy, in an intensive
 122 livestock production area characterised by a high nitrogen surplus. The area was designated as a
 123 nitrate vulnerable zone. Some farms in the area formed a cooperative with the aim to improve
 124 manure management and reduce the nitrogen excess while producing electricity. The collective
 125 manure treatment plant includes an anaerobic digestion (AD) installation for energy production and
 126 biological nitrogen removal (BNR) from digestate (Figure 1).
 127



129 **Figure 1.** Schematic presentation (flowchart) of the manure management systems for bioenergy
 130 production and nitrogen removal considered in the assessment. (CHP = combined heat and power;
 131 SBR = sequencing batch reactor).

132
 133 The collective treatment plant receives manure from 21 livestock production units where pigs,
 134 cows and poultry are grown. Table 1 reports the main data about these farms. All farms are located
 135 between 0.5 and 16 km from the collective plant. The total daily production of manure for the farms
 136 is around 660 tonnes (t). Most of the incoming products consist of manure (slurries and farm yard
 137 manure), while the processed liquid effluent after AD and nitrogen removal treatment is the main
 138 product transported back to the associated farms.
 139

140 **Table 1.** Main characteristics, manure and nitrogen production by the livestock farms considered in
 141 the assessment. Live weight has been calculated considering the number of animals and average live
 142 weight per head for each category of animal. The amount of manure produced was determined from
 143 the recordkeeping of the transportation system. Total nitrogen was calculated using the average
 144 concentration of total nitrogen contained in the manure that was periodically sampled in the farms.

Farm	Type of livestock	Live weight (t)	Slurry (t)	Solid Manure (t)	Total N (kg)
1	dairy cows	206	10,398	903	33,589
2	dairy cows	151	8,809	296	30,501
3	dairy cows	184	11,791	-	26,177
4	laying hens	162	-	1,055	12,095
5	dairy cows	100	5,383	255	19,477
6	dairy cows	358	25,445	130	78,356
7	beef cattle	25	795	-	2,339
8	dairy cows	164	10,384	270	27,497
9	fattening pigs	76	4,012	-	12,558
10	fattening pigs	242	6,435	-	27,027
11	dairy cows	349	15,373	416	49,837
12	laying hens	176	-	2,687	30,808
13	beef cattle	810	22,371	2,406	71,924
14	dairy cows	117	4,899	539	20,119
15	dairy buffalo	389	17,435	570	53,944
16	dairy cows	59	2,760	286	9,276
17	dairy cows	231	10,329	1,024	55,154
18	dairy cows & laying hens	440	26,955	1,674	128,893
19	dairy cows	181	8,033	279	23,768
20	dairy cows & beef cattle	662	29,026	1,946	97,530
21	dairy cows	140	4,957	90	16,485

145
 146 Trucks and slurry tankers transport raw manure from farms to the treatment plant, except for
 147 one farm near the treatment plant that is directly connected by means of a pipeline. The first stage
 148 involves processing of manure in an AD reactor for energy production. Four digesters and four
 149 post-digesters are present, and the digesters are fed with manure and other biomasses (silage). Then,
 150 the digested effluent is treated to remove nitrogen and reduce the load of nitrogen and phosphorus
 151 on farmers' lands. A solid-liquid separation process produces solid and liquid fractions. The solid
 152 fraction is sold to farms in the surroundings of the plant, while the liquid fraction is subjected to
 153 BNR through four sequencing batch reactors (SBR) operating in parallel. The final stage consists of
 154 storing the effluents in covered tanks and subsequently transporting them back to farms by means of
 155 trucks, slurry tankers or pipelines.

156 Throughout the study, data were collected throughout the production system, and manure
157 characteristics of the 21 livestock farms connected to the treatment plant were determined. In
158 particular, information was gathered on the amount of raw manure transported to the plant and the
159 amount of treated effluent withdrawn from the plant and transported to the farms. Moreover, data
160 were collected about (i) number and type of animals, (ii) storage type and capacity for the treated
161 effluent, (iii) crops and related cultivated surface, and (iv) organisation of manure applications
162 (amounts and scheduling).

163 The process was monitored for two years and data about the amount of manure treated, the
164 characteristics of the manure in the different stages and energy consumption were determined [16].
165 The monitoring activity included the transportation of manure to and from the treatment plant in
166 order to assess the energy and emissions associated with the operation.

167 2.2 Description of the scenarios, system boundaries and stages

168 To compare the collective system with the individual farm management of manure, two
169 scenarios were considered in the assessment. The baseline scenario (BS) was the system in which
170 every farm manages the manure individually without any treatment, storing the manure produced
171 and applying it to the soil. The collective scenario (CS) was the system in which the manure is
172 transported to the collective processing plant and the treated digestate is transported back to the
173 individual farms, where it is stored and applied to the soil.

174 In the system boundaries of the BS the following stages were included.

- 175 • Manure collection and short-term storage. This stage includes manure removal from livestock
176 and manure storage under slatted floors or in pits collecting liquid manure before it is placed in
177 the main manure storage.
- 178 • On-farm manure storage. The slurry and solid manure are stored in open facilities with a
179 capacity of at least 180 days for liquids and 90 days for solid excreta.
- 180 • Transport and field application of manure. The operation is performed by slurry tankers that
181 both transport the slurry to the field and then apply the slurry using a splash plate.

182

183 In the system boundaries of the collective manure management system the following stages are
184 included.

- 185 • Manure collection and on-farm manure short-term storage. A storage capacity of 14 days for
186 each livestock production unit is considered. This storage is functional to the transport system
187 that transports manure to the treatment plant and to intermediate storage.
- 188 • Transport to the treatment plant. This stage includes the transport of raw manure by trucks and
189 slurry tankers from the livestock units to the intermediate storage of the collective treatment
190 plant
- 191 • Intermediate storage of the raw manure in two continuously-mixed pre-treatment tanks (885 m³
192 and 570 m³).
- 193 • Treatment (AD, solid-liquid separation, BNR). This stage encompasses: a) mixture of raw
194 manure with the co-substrates (approximately 10% maize silage, cereals flour, molasses and
195 poultry manure); b) AD; c) solid-liquid separation of digestate; d) BNR; and e) intermediate
196 storage of the treated effluents. AD is carried out in four digesters (mesophilic conditions, 38–
197 40°C) and four post-digesters. The total volume of the digesters is 10930 m³, while the volume of
198 post-digesters is 12740 m³. The slurry mixture is pumped to the four digesters, where it is
199 anaerobically digested and then conveyed to the post-digesters. The produced biogas is
200 dehumidified, chilled and fed to two combined heat and power (CHP) units, each capable of
201 producing 1 MW of electric power. CHP output is partially used to heat the digesters and
202 post-digesters. After retention in the post-digesters, the digested slurry is separated through two
203 decanter-centrifuges. The solid fraction is stored at the plant and sold to nearby farms. In
204 contrast, the liquid fraction is treated through nitrification-denitrification to remove nitrogen in
205 the four SBRs that work in parallel. In each SBR, four phases occur: (i) fill and draw phase (the
206 liquid fraction is pumped in the reactor and the treated slurry conveyed to storages); (ii) mixing

- 207 phase; (iii) aerobic phase; and (iv) sedimentation phase. An overall value of 70% has been used
 208 for nitrogen removal efficiency based on the data collected during the monitoring activity.
- 209 • Storage in the treatment plant. After the BNR unit, the treated effluent is pumped to the
 210 intermediate storage at the treatment plant, which consists of three covered storage tanks having
 211 a total capacity of 12620 m³.
 - 212 • Transport of the end-product to the farms. The treated effluent is moved by trucks and slurry
 213 tankers from the collective treatment plant to the individual livestock units that contributed raw
 214 manure. As the same truck or slurry tanker is used both for the transport of raw and treated the
 215 two transport operations are considered together.
 - 216 • On-farm manure storage. At farm-level the treated effluent is stored in open tanks for an
 217 average period of 100 days.
 - 218 • Field application. The treated effluent is both transported to the field and applied by slurry
 219 tankers. The slurry is applied using a splash plate.

220 2.3. Emissions assessment

221 To compare the two scenarios, emissions of CO₂, CH₄, N₂O, NO_x, NH₃ and SO₂ were calculated
 222 separately for each stage of manure management in the two systems.

223 The calculation methodology differed for each stage. When possible, methodologies in
 224 previously published guidelines for conducting emission inventories were used, mainly those
 225 proposed by the European Environment Agency (EEA) [17] and the Intergovernmental Panel on
 226 Climate Change (IPCC) [18]. When available, data directly collected from the farms and the
 227 treatment plant were used. Table 2 summarises the methods and tier levels used for the different
 228 stages of manure management.

230 **Table 2.** Methodology used for the calculation of the emissions for each pollutant (CO₂, CH₄, N₂O,
 231 NO_x, NH₃ and SO₂) and for each stage of manure management.

Stage	CO ₂	CH ₄	N ₂ O	NO _x	NH ₃	SO ₂
Farm storage	nd	IPCC, Tier 2	IPCC, Tier 2	EEA, Tier 2	EEA, Tier 2	nd
Transport	IPCC, Tier 2	IPCC, Tier 3	IPCC, Tier 3	EEA, Tier 2	EEA, Tier 2	EEA, Tier 1
Intermediate storage	nd	IPCC, Tier 2	IPCC, Tier 2	EEA, Tier 2	EEA, Tier 2	nd
Treatment	Energy mix	IPCC, Tier 2	IPCC, Tier 2	EEA, Tier 2	Monitoring	nd
Transport off-road	IPCC, Tier 2	IPCC, Tier 2	IPCC, Tier 2	EEA, Tier 2	EEA, Tier 2	EEA, Tier 1
Land application	nd	nd	IPCC, Tier 2	EEA, Tier 2	EEA, Tier 2	nd

232 nd: not determined

233 Gas emissions were calculated for both scenarios (BS and CS). All emissions related to the
 234 production and management of co-substrates or additional material before entering the plant were
 235 not included in the system boundary. Also the environmental impact of the structures and
 236 equipment manufacturing was not considered.

237 To evaluate emissions from storage, data about the pits and tanks used on each farm and in the
 238 collective treatment plant were collected. Because the storage period (hydraulic retention time) is
 239 limited when the manure is transported to the treatment plant, a duration factor was introduced to
 240 avoid overestimation of emissions. Therefore, a linear trend of emissions was considered and the
 241 default emission factor (EF) was reduced according to the ratio between the actual storage period
 242 and a period of 180 days.

243 CO₂ emissions from manure storage or treatment were not taken into account because they are
 244 considered to be part of the short-term carbon cycle, i.e. resulting from recent CO₂ uptake by crops
 245 [19]. For transport and off-road transportation IPCC Tier 2 methodology was used. Emissions were
 246 estimated considering fuel consumption and travelled distances that were directly measured during
 247 the monitoring period. The energy balance in the treatment plant was determined as the difference

248 between the energy produced and the energy required to run the treatment plant during the
249 monitored period, and was reported on the basis of 346 g CO₂ eq. kWh⁻¹ [20].

250 Fossil fuels consumption of agricultural machinery and their related emissions were included
251 in the analysis as were the emissions from field application of treated effluents.

252 Methane emissions in both scenarios were calculated using IPCC Tier 2 methodology. For
253 on-farm storage the information was obtained from monitoring data (volume transported to the
254 plant and periodic characterisation of manure). For maximum CH₄ production capacity (B₀), a
255 methane conversion factor (MFC) for each manure management system and default CH₄ density
256 values were used. This method was used also for intermediate storages and final storage. The
257 methane emissions during biogas production were considered to be 1% of the methane produced in
258 the biogas plant. This value was assumed to account for the accidental emissions due to membrane
259 cover permeability [21], leaky gaskets, maintenance operations and flaring or venting of the
260 overproduction [22,23]. For road transportation the IPCC Tier 3 methodology was used. Emissions
261 were estimated from the distance travelled by each vehicle type and road type. For off-road
262 transportation CH₄ emissions were determined using the IPCC Tier 2 methodology and
263 country-specific fuel consumption. For the EF the default value was used.

264 Nitrous oxide emissions from all manure storage (farm storage, intermediate storage and final
265 storage) occurred in direct and indirect forms, and in both cases the quantities were estimated using
266 the EFs of IPCC Tier 2 methodology, whereas the nitrogen supplied to the manure management
267 system was based on actual monitoring data.

268 Direct N₂O emissions occur via combined nitrification and denitrification of nitrogen contained
269 in the manure. Nitrification (the oxidation of ammonia nitrogen to nitrate nitrogen) is a necessary
270 prerequisite for the emission of N₂O. Nitrites and nitrates are transformed to N₂O and dinitrogen
271 (N₂) during the naturally occurring process of denitrification, an anaerobic process. Direct N₂O
272 emissions during treatment (in the SBR units) were obtained using the EF for direct N₂O emissions
273 from a manure management system in accordance with IPCC methodology (0.005% of total
274 nitrogen, aerobic treatment with forced aeration systems). Emissions were estimated from total
275 annual amount of nitrogen treated, which was assessed through direct analysis of manure
276 composition during monitoring period. As for CH₄ emissions, road transportation emissions of N₂O
277 were estimated from the distance travelled by vehicle type and road type (IPCC Tier 3), whereas
278 off-road transportation emissions were determined using the IPCC Tier 2 methodology and
279 country-specific fuel consumption. Direct N₂O emissions from land application were calculated
280 using the IPCC Tier 2 methodology. The EF for direct soil emissions was set at 1% of the nitrogen
281 applied to soils or released from soils through activities that result in mineralisation of organic
282 matter in mineral soils.

283 Indirect emissions result from volatile nitrogen losses that occur primarily in the form of NH₃
284 and NO_x (nitrogen returned to the soil from volatilisation of manure during management). In
285 addition, nitrogen is also lost through runoff and leaching into soils from manure storage. Thus, a
286 portion of the nitrate that is leached can also be denitrified and result in N₂O emissions [24]. The
287 values of the fraction of livestock nitrogen input that volatilises as NH₃ and NO_x, as well as the
288 values of the fraction of the manure nitrogen lost to leaching and surface runoff, were also based on
289 IPCC guidelines.

290 The nitric oxide emissions were estimated following the method proposed by EEA for Tier 2.
291 The EFs, as a proportion of total ammoniacal nitrogen (TAN), were specific for each manure type
292 (slurry or solid) and each stage (storage and treatment) of manure management. Transportation
293 emissions were estimated from the distance travelled by vehicle type and road type using EEA Tier 2
294 methodology. The NO_x emitted during land application was estimated using the EEA 2009 Tier 1
295 method.

296 Ammonia emission occurs from all activities in which manure is in contact with air (storage,
297 land application, and storage in tanks without any cover in treatment plants) and from transport
298 activities. Ammonia emissions that occur during manure storage, treatment, transport and land
299 application were estimated using the EEA Tier 2 methodology and a mass flow approach through

300 the manure management systems. The EFs for each stage in manure handling, expressed as a
301 proportion of TAN, were specific for each manure type (slurry or solid). Transport emissions were
302 estimated from the distance travelled by vehicle type and road type (EEA Tier 2 method). Ammonia
303 emissions from treatment operations were considered to be 1.8% of the total nitrogen treated [25].
304 For the final storage the same EEA Tier 2 methodology was used as for intermediate storage, but the
305 TAN content was calculated according to the transformation in the treatment plant. To evaluate
306 emissions during land application the average conditions, derived from the farm practice observed
307 through recordkeeping on the farms, were used to obtain an average EF. As the EF is expressed as
308 percentage of the TAN content of the manure, the emissions after the treatment considered the
309 nitrogen removed during the treatment process.

310 Sulphur dioxide emission takes place in all those activities in which manure or end-products
311 are transported. The SO₂ emissions were estimated using the EEA Tier 1 methodology and
312 country-specific fuel consumption, and assuming that all sulphur in the fuel is transformed
313 completely into SO₂.

314 2.4. GWP and AP calculation

315 Emissions evaluated for the different stages were utilised to obtain the GWP and AP based on
316 the following equivalency factors:

- 317 - 1, 34 and 298, respectively, for CO₂, CH₄ and N₂O to obtain GWP expressed in CO₂ eq. [12].
- 318 - 1.6, 0.5 and 1.2, respectively, for NH₃, NO_x and SO₂ to obtain AP expressed in SO₂ eq.
319 [14,19].

320 3. Results

321 3.1 Emissions in the baseline scenario

322 The evaluation of the emissions by management systems in the baseline scenario (BS) related to
323 individual livestock production units are summarised in Table 3.

324 The AP (440 t SO₂ eq.) mainly (98%) is due to ammonia emissions. Both the NO_x and SO₂
325 emissions are very limited. NO_x derives mostly from nitrogen transformation after manure
326 application to soil; SO₂ is produced during transportation. Approximately 31% of AP is due to
327 manure collection and storage while the remaining derives from the emissions during manure
328 spreading (Figure 2). The variability of AP among livestock units is high in absolute value reflecting
329 their different sizes and types. However, by referencing the emissions to the live weight of animals,
330 the mean ± standard deviation is 84.2 ± 28.5 kg SO₂ eq. (t of live weight)⁻¹. Thus, even on a live weight
331 basis the variability is still high because the emissions are affected by the type of livestock and
332 management system in place (which, in turn, determine the amount of nitrogen produced, size of
333 the manure storage pits and size of storage tanks).

334 The GWP (22,600 t CO₂ eq.) was mainly contributed by CH₄ (69%) and N₂O (20%). Methane is
335 produced during storage and in very limited quantity during transport, while N₂O is generated in
336 all management stages. The remaining 1% of GWP is due to CO₂ emitted from diesel fuel
337 combustion during manure transport to the field. Figure 3 shows that manure collection and storage
338 account for 84% of the total emissions and the application to soil accounts for only 15%.

339 As is the case for AP, the variability in GWP among livestock production units is large. When
340 referenced to the live weight of animals, the mean ± standard deviation of GWP is 4.3 ± 2.0 t CO₂ eq.
341 (t of live weight)⁻¹. The lower values are related to livestock units with laying hens, where only solid
342 manure is produced and the CH₄ generated represents only 44% of the total GWP. The higher value
343 reflects the high CH₄ production of some dairy cow units with a large number of animals and limited
344 production of solid manure.

345 3.2 Emissions in the collective treatment scenario

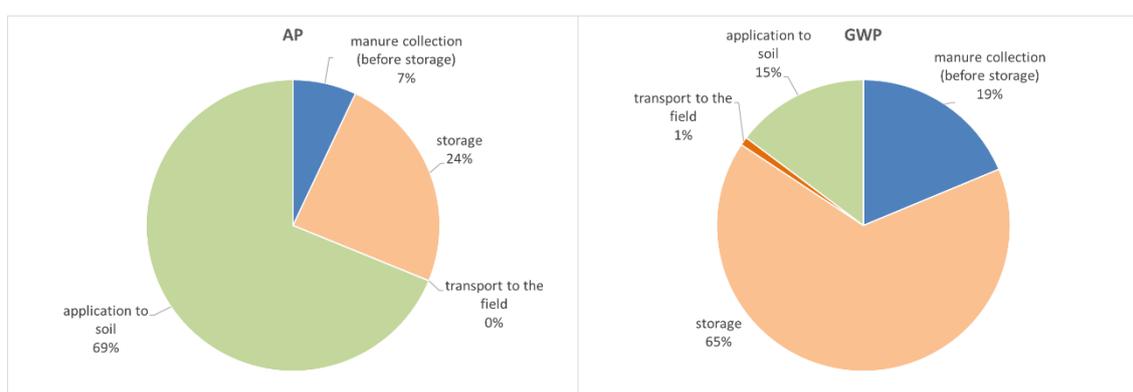
346 To better compare results for the BS and CS scenarios, the results for the CS scenario are
 347 reported for each livestock production unit even though a collective treatment plant was adopted in
 348 CS (Table 4).

349 As in the BS, the AP (253 t SO₂ eq.) in the CS derives mainly (98%) from NH₃ emissions. As
 350 shown in Figure 3, approximately 50% of the emissions occur during land application, while the
 351 emissions from the treatment plant account for 13% of the total. The remaining AP is contributed by
 352 the collection and storage of manure on the farms, both before and after manure processing. The
 353 mean ± standard deviation AP referenced to the unit of live animal weight is 48.4 ± 15.7 kg SO₂ eq. (t
 354 of live weight)⁻¹.
 355

356 **Table 3.** Emissions, acidification potential and global warming potential for each livestock
 357 production unit in the baseline scenario (manure managed individually on each farm).

Livestock unit	NH ₃ (kg year ⁻¹)	NO _x (kg year ⁻¹)	SO ₂ (kg year ⁻¹)	SO ₂ eq. (kg year ⁻¹)	CH ₄ (kg year ⁻¹)	CO ₂ (kg year ⁻¹)	N ₂ O (kg year ⁻¹)	CO ₂ eq. (t year ⁻¹)
1	9,747	791	0.06	15,991	22,785	11,003	636	975
2	9,888	711	0.03	16,177	25,902	6,453	578	1,059
3	7,876	622	0.06	12,913	25,809	11,489	494	1,036
4	4,368	300	0.00	7,139	1,052	752	153	82
5	6,704	451	0.02	10,952	13,063	4,000	373	559
6	26,703	1,830	0.13	43,640	73,300	24,907	1,489	2,966
7	668	55	0.00	1,096	1,615	567	44	69
8	8,672	644	0.04	14,198	21,005	7,574	523	877
9	4,662	292	0.01	7,604	5,758	2,851	240	270
10	9,725	629	0.02	15,874	13,869	4,567	515	630
11	17,826	1,155	0.08	29,099	30,726	15,384	956	1,343
12	11,126	764	0.01	18,183	2,679	1,900	389	209
13	21,339	1,682	0.09	34,983	34,756	17,572	1,378	1,610
14	6,387	468	0.02	10,454	12,631	3,858	385	548
15	19,287	1,245	0.07	31,481	27,179	12,764	1,033	1,243
16	2,670	218	0.01	4,381	7,022	2,156	177	294
17	17,108	1,288	0.04	28,017	36,704	8,042	1,048	1,568
18	41,756	3,041	0.10	68,330	75,914	20,296	2,290	3,288
19	6,785	562	0.03	11,137	19,214	5,886	448	793
20	29,792	2,283	0.11	48,809	62,350	21,969	1,856	2,693
21	5,728	382	0.02	9,356	11,124	3,574	314	475
Total	268,815	19,415	0.96	439,813	524,455	187,562	15,318	22,588

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361 **Figure 2.** Contribution to acidification potential (AP) and global warming potential (GWP) of the
 362 different stages of manure management in the baseline (BS) scenario (manure managed on
 363 individual farms).

364 The GWP indicator for CS is affected by the renewable energy produced, which reduces the
 365 total CO₂ eq. emissions. However, the saving does not completely offset the emissions of GHGs in
 366 the form of CH₄ and N₂O. Thus, the GWP is still positive (10,721 t CO₂ eq.). Without accounting for
 367 the energy produced, the GWP of CS would be 14,969 t CO₂ eq., only 65% of which is due to CH₄
 368 emissions, while 29% is due to N₂O.

369 The contribution of the different stages of the system to GWP, reported in Figure 4, provides
 370 evidence that the emissions during collection of manure and storage on the farms are approximately
 371 60% of the total. Treatment contributes 15% of total GHGs emissions due to the N₂O production
 372 during the nitrification-denitrification process.

373 The GWP, including the offset from energy production, referenced to the animal live weight, is
 374 2.1 ± 0.9 t CO₂ eq. (t of live weight)⁻¹.

375 **Table 4.** Emissions, acidification potential and global warming potential for each livestock unit of the
 376 collective treatment scenario (manure is transported from each farm to a collective treatment system
 377 and treated effluent is transported back to the farms).

Livestock unit	NH ₃ (kg year ⁻¹)	NO _x (kg year ⁻¹)	SO ₂ (kg year ⁻¹)	SO ₂ eq. (kg year ⁻¹)	CH ₄ (kg year ⁻¹)	CO ₂ (kg year ⁻¹)	N ₂ O (kg year ⁻¹)	CO ₂ e (t year ⁻¹)
1	5,908	505	0.17	9,705	13,145	-148,289	603	478
2	5,609	445	0.16	9,198	13,801	-152,399	533	476
3	4,664	416	0.21	7,670	13,136	-133,448	481	456
4	2,595	164	0.03	4,234	846	-67,930	173	12
5	3,740	277	0.07	6,122	7,233	-85,329	341	262
6	14,874	1,129	0.32	24,364	37,578	-430,560	1,377	1,257
7	389	35	0.01	639	838	-11,202	41	30
8	5,047	405	0.09	8,277	11,501	-137,457	497	402
9	2,697	182	0.10	4,406	2,803	-31	217	160
10	5,567	372	0.16	9,093	6,748	-15,371	453	349
11	9,874	718	0.22	16,157	16,816	-183,507	880	650
12	6,610	413	0.04	10,782	2,154	-179,324	439	25
13	12,934	1,130	0.60	21,260	23,135	-265,626	1,311	912
14	3,693	286	0.07	6,052	7,695	-94,058	354	273
15	10,777	828	0.47	17,657	15,313	-155,152	959	651
16	1,619	135	0.02	2,658	4,223	-52,912	167	141
17	9,664	765	0.17	15,845	20,806	-248,511	938	738
18	23,425	1,849	0.70	38,405	40,431	-472,312	2,129	1,537
19	4,033	355	0.11	6,630	10,431	-115,066	424	366
20	17,447	1,428	0.41	28,629	35,990	-416,836	1,734	1,324
21	3,178	237	0.08	5,204	5,843	-62,659	288	222
Total	154,341	12,075	4.22	252,987	290,466	-3,427,979	14,339	10,721

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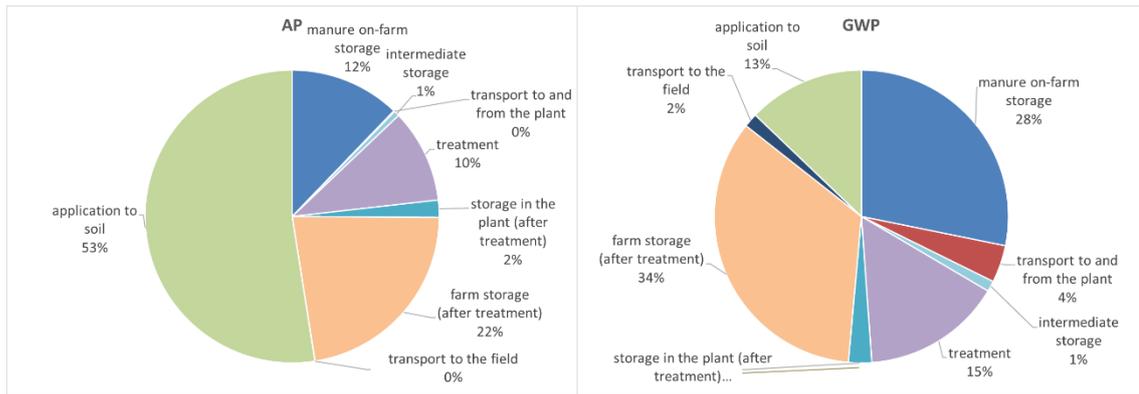


Figure 3. Contribution to acidification potential (AP) and global warming potential (GWP) from different stages of manure management in the collective treatment (CS) scenario (manure is transported from each farm to a collective treatment system and treated effluent is transported back to the farms). The GWP shares have been calculated without considering the emissions offset of the energy produced.

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3.3 Comparison of scenarios

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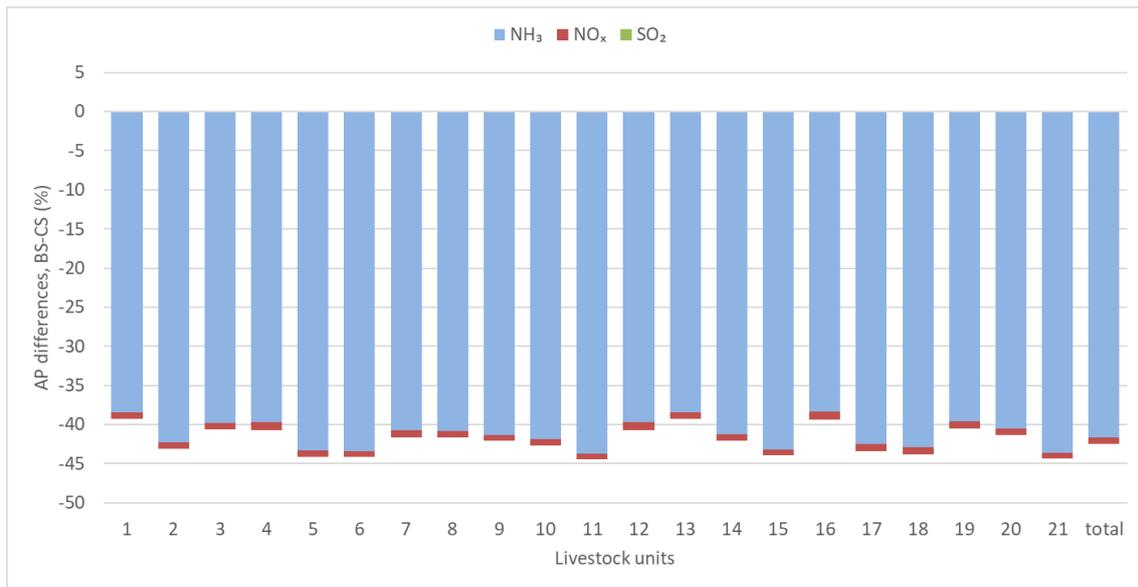
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Figure 4 shows the differences in AP comparing CS to BS for each livestock unit in order to better understand the effect of the collective treatment plant. As expected the variations are mainly influenced by the differences in NH_3 emissions. However, the differences in emissions of NO_x and SO_2 are relevant in relative terms. Compared with those from the BS, NO_x emissions from the CS are 38% lower. This reduction derives from an increase of the emissions during transport (+ 455 kg year⁻¹) and a reduction of emissions during land application (-7960 kg year⁻¹) due to the reduced nitrogen content in the manure after treatment. On the contrary, SO_2 emissions increase significantly (+425%) in the CS due to the transport of manure to and from the treatment plant. Although relevant in terms of variation of emissions, NO_x and SO_2 emissions have little influence on the overall result, where the variation of NH_3 emissions (-43%) is predominant in the AP value.

The average reduction of AP achieved by the CS was $43\% \pm 1.8\%$, which was mainly due to the reduced emissions during manure storage and field application. The effect of the CS on ammonia emissions does not vary significantly among livestock production units. The main differences are between farms that produce mostly liquid manure and those that produce solid manure. In fact, solid manure is mixed with liquid in the treatment plant and, considering the nitrogen removal, the emissions are reduced.

The emissions of GHGs are greatly influenced by the collective treatment system (Figure 5). The methane emissions are lowered significantly (45%) due to the recovery of energy in the biogas plant. Of course, the methane emissions in the intermediate storage before the transportation to the treatment plant entails some methane emissions (collection was made weekly in each farm) and the treated effluent has still some methane production potential (the volatile solids were 1.4–1.5% of the total mass of slurry applied to the land). However, the main methane emissions in CS are related to the emissions during farm manure storage, both before and after treatment of the manure.

The additional benefit of the treatment plant in the CS refers to the reduction of CO_2 emissions due to energy production. The overall benefit in term of total CO_2 eq. reduction is 55%, which seems to be a very good achievement. The reduction is relatively uniform for all the farms except for two (n. 4 and n. 12). The explanation of this different behaviour is related to the livestock type of these farms (i.e., laying hens that produce solid manure with high nitrogen content). When used in the treatment plant, this type of manure affects N_2O emissions, especially in the nitrification-denitrification process, and these are just partially compensated by the reduction obtained in the field application of treated manure.



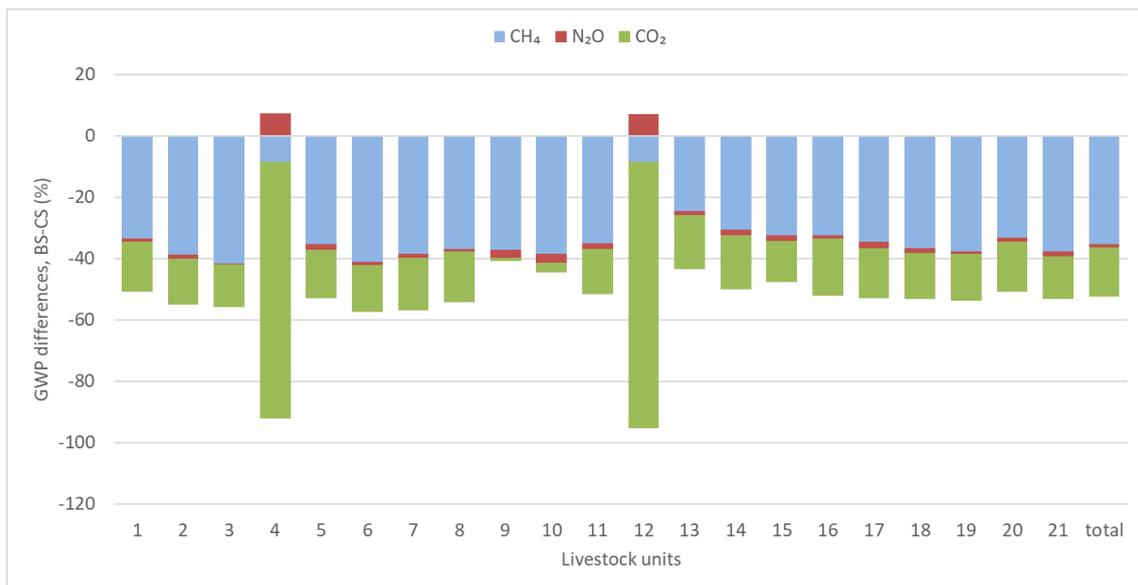
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Figure 4. Comparison of acidification potentials for each livestock production unit for the two management systems. CS = collective treatment scenario; BS = baseline scenario without collective manure treatment.



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Figure 5. Comparison of GWP for each livestock production unit for the two management systems. CS = collective treatment scenario; BS = baseline scenario without collective manure treatment.

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The reduction of GHGs demonstrates how a collective manure management system can be environmentally sustainable, considering climate change impact, despite the higher emissions due to transportation. Thus, collective manure treatment should be carefully considered as a management option in intensive livestock production areas because it can contribute significantly to the overall emissions reduction. In the case study considered, the CO₂ emissions in the scenario with the collective manure treatment plant were over four times those in the scenario without collective manure treatment because slurry transported to and from the treatment plant is mostly accomplished using trucks and tractors with slurry tankers. However, even without considering the CO₂ “saved” by renewable energy production, the effect of collective manure treatment is positive (albeit lower) due to the general decrease of methane emissions.

436 The assessment highlighted that the two stages in manure management that might be further
437 improved are on-farm manure storage and the application of manure to soil. In fact, both operations
438 typically use the standard techniques (uncovered storages and broadcast spreading); therefore,
439 significant reductions of AP and GWP can be obtained if Best Available Techniques are adopted.

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441 4. Conclusions

442 The methodology used in this study was effective for assessing the environmental impact of
443 different manure management systems (one including a collective treatment plant and one without
444 the treatment plant). The case study highlighted how a collective manure treatment system might be
445 effective in the reduction of AP and GWP. The combination of anaerobic digestion and nitrogen
446 removal treatment was demonstrated to be sustainable even if the benefits of renewable energy
447 production are not considered. In a collective manure treatment system, the reduction of emissions
448 related to methane collection can compensate the increase in CO₂ emissions from the transport of
449 manure from the livestock farms to the treatment plant and back. Moreover, the income obtained
450 from selling the electric energy produced might reduce the cost of the nutrient removal treatment,
451 helping to make this solution economically sustainable as well as environmentally sustainable.
452 Further benefits may derive from the reduction of odours and the production of a stabilized effluent
453 that can be used as fertilizer more efficiently, with a possible reduction in the use of mineral
454 fertilizers and the consequent further economic and environmental benefits.

455 Although the methodology used was shown to be adequate for the assessment, it should be
456 pointed out that some aspects, such as the emissions from the different treatments, will benefit from
457 further studies in order to better consider the possible effect of different technological alternatives on
458 the emissions to air.

459

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461 G.M., M.C. and E.R.; Formal Analysis, G.P., G.M. and A.F. X.X.; Writing-Original Draft Preparation, G.M., A.F.
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