Agricultural reuse of the digestate from low-cost tubular digesters in rural Andean communities

Marianna Garfí [a,b], Pau Gelman [b,c], Jordi Comas [c], William Carrasco [d], Ivet Ferrer [a,b,*]

[a] Environmental Engineering Division, Department of Hydraulic, Maritime and Environmental Engineering, Universitat Politècnica de Catalunya, c/ Jordi Girona 1-3, Building D1, E-08034 Barcelona, Spain
[b] Research Group on Cooperation and Human Development (GRECDH), Universitat Politècnica de Catalunya, Avda. Diagonal 647, E-08028 Barcelona, Spain
[c] Department of Agrifood Engineering and Biotechnology, Universitat Politècnica de Catalunya, Parc Mediterrani de la Tecnologia, Building D-4, E-08860 Castelldefels, Barcelona, Spain
[d] National Institute for Agricultural Innovation (INIA), Jr. Wiracocha, Baños del Inca, Cajamarca, Peru

A B S T R A C T

This research aimed at assessing the properties of guinea pig manure digestate from low-cost tubular digesters for crops fertilization in rural Andean communities. To this end, field trials were carried out to evaluate the effect of the digestate on two common Andean crops: potato (*Solanum tuberosum*) and forage (*Lolium multiflorum* and *Trifolium pratense* L.). The potato yield (20–25 $t\,ha^{-1}$) increased by 27.5% with digestate, by 15.1% with pre-compost and by 10.3% with the mixture, compared to the control. The forage yield (20–21 $t\,ha^{-1}$) increased by 1.4% with digestate – 50% dose, and by 8.8% with digestate – 100% dose and digestate – 150% dose, compared to the control. The results suggest that the digestate is an appropriate substitute of manure pre-compost for potato fertilization. The results with forage indicate that it can be applied in a range of doses, according to the amount produced by the digester. Currently, manure is either used for cooking or as fertilizer. With low-cost tubular digesters implementation, it could be used to feed the digester, using the digestate for crops fertilization and biogas for cooking; improving household living conditions and protecting the environment. Since soil properties in rural Andean communities differ from experimental layouts, the effect of fertilizers should be re-evaluated *in-situ* in future research studies.

1. Introduction

Anaerobic digestion is a renowned sustainable technology contributing to an integrated management of manure in small-scale agriculture and farming. In anaerobic digesters organic residues are transformed into biofuel (biogas), while the resulting effluent (digestate) can be reused in agriculture as biofertilizer or soil conditioner (Ferrer et al., 2009).

The benefits of digesting livestock wastewater at household scale in developing countries include (Garfí et al., in press): (i) providing a clean biofuel to substitute traditional biomass (i.e. firewood and air-dried cattle dung) which is generally used in rural areas; (ii) improving indoor environment by reducing firewood consumption for cooking and heating; (iii) protecting the environment by treating wastewater, reducing greenhouse gases emissions and deforestation; (iv) reducing workload for firewood collection by women and children.

With the aim of improving household living conditions, during the last years low-cost tubular digesters adapted to the conditions of the Andean Plateau have been implemented to treat livestock wastewater and generate biogas for cooking. Biogas production from cow and guinea pig manure at high altitude has been characterised (Ferrer et al., 2011; Garfí et al., 2011); but digestate properties for land application are yet to be determined.

According to the literature, physico-chemical properties of digestates have been widely investigated (Garfí et al., 2011; Lansing et al., 2010; Tambone et al., 2010; Tani et al., 2006; Thy et al., 2003), whereas fertilization studies are still scarce. The characteristics of digestates depend on the origin and composition of the feedstock, in the case of manure livestock species, feeding and management practices; and operating conditions of the digestion process. During anaerobic digestion, complex organic matter is hydrolysed into simpler molecules; which are then fermented into organic acids that are finally converted into methane. In this way, organic nitrogen from proteins is hydrolysed releasing ammonia nitrogen, which is found in the digestate and biogas. Since ammonia concentration tends to increase from the influent to

* Corresponding author at: Environmental Engineering Division, Department of Hydraulic, Maritime and Environmental Engineering, Universitat Politècnica de Catalunya, c/ Jordi Girona 1-3, Building D1, E-08034 Barcelona, Spain. Tel.: +34 934016463; fax: +34 934017357.

E-mail addresses: marianna.garfi@gmail.com (M. Garfí), paugelman@gmail.com (P. Gelman), jordi.comas-angelet@upc.edu (J. Comas), ivet.ferrer@upc.edu, ivet.ferrer@gmail.com (I. Ferrer).

the effluent, and ammonia is much easily available than organic nitrogen, the digestate seems more appropriate for crops fertilization than manure (Massé et al., 2007; Lansing et al., 2010; Thy et al., 2003). Moreover, digestate phosphorus and potassium contents are considerable and readily available. Tani et al. (2006) obtained a higher forage yield using digested cattle slurry compared to raw manure. It should be noticed, however, that some components of the digestate might be less favorable for crops. Zaldivar et al. (2006) observed a lower lettuce yield using the digestate from brick masonry digesters compared to compost, and Brechelt (2004) recommended digestate dilution in water not to damage crops foliage.

The aim of this study was to assess the properties of the digestate from low-cost tubular digesters for agricultural reuse in rural Andean communities. The digestate was obtained from a pilot low-cost tubular digester treating guinea pig manure. Field trials were carried out to evaluate the effect of the digestate on two common Andean crops: potato (*Solanum tuberosum*) and forage (*Lolium multiflorum* and *Trifolium pratense* L.). The potato trial was intended to compare the effect of the digestate vs. manure pre-compost; whereas in the forage trial the effect of increasing doses of digestate was evaluated.

2. Context

In rural communities of the Peruvian Andes, economy is based on subsistence agriculture (self-sufficient farming). In most cases, there is still a lack of basic services such as potable water, sanitation or electricity. Indeed, 42% of the population does not have access to sanitation facilities (INEI, 2008) and most households do not treat livestock wastewater, leading to water and soil pollution with concomitant health risks. Traditional biomass, including firewood and air-dried cattle dung, is used for cooking without improved cookstoves or smoke control systems, generating indoor air pollution (especially particulate matter) and unhealthy environments (He et al., 2010; Visser and Khan, 1996).

The Department of Cajamarca is located in the Northern region of the Peruvian Andes. Here, more than 50% of the population lives in rural areas (INEI, 2008). The region is characterised by heavily eroded desert soils, with low moisture and organic material, and high mineral salts contents (FAO, 2000). Soil erosion, desertification and acidity increase with altitude, and are responsible for low crops yields (INEI, 2010). Thus, the application of organic matter is an important strategy to maintain or restore soil quality, which is a matter of concern provided that manure is mostly used for cooking.

The main crops are sweet corn, potatoes and forage for livestock nutrition. The main livestock are cows, llamas and guinea pigs, which play an important role in household economy. In fact, this area produces over 3 million guinea pigs out of the total 70 million produced in Peru. Traditional biomass consumption accounts for 65–75% of the total fuel consumption for cooking (INEI, 2008). Recently (2008–2010), 12 low-cost tubular digesters have been implemented in rural communities to substitute traditional biomass by biogas (Ferrer et al., 2011).

3. Materials and methods

3.1. Anaerobic digestion of guinea pig manure

The experiments were carried out in a pilot plant located at 2800 m above sea level (m.a.s.l.) in the National Institute for Agricultural Innovation (INIA) (Cajamarca, Peru). The tubular PVC digester used has a total volume of 10 m^3 and a useful volume of 7.5 m^3. It is covered with a greenhouse and unheated. Design and operational parameters of low-cost tubular digesters implemented at high altitude are described in detail by Ferrer et al. (2011).

The digester was operated over a period of 1 year treating guinea pig manure diluted in water (solids concentration ~ 6–8%). The hydraulic residence time (HRT) ranged between 60 and 75 days, and the organic loading rate (OLR) between 0.6 and 1 $kg_{VS}\ m^{-3}{}_{digester}\ d^{-1}$. Guinea pig manure was monthly collected from farms and pre-composted to ease dilution in water. The manure was placed in piles, humidified and aerated during 7 days. Each pile corresponded to 1 week digester feeding.

3.2. Crops fertilization

In order to evaluate the fertilizer value of the digestate, potato and forage field trials were conducted in relatively uniform fields of 150 and 420 m^2, respectively; located at 2800 m.a.s.l. in the National Institute for Agricultural Innovation (INIA) (Cajamarca, Peru). Composite soil samples were obtained from these fields (MAPA, 1994): they consisted of 5 cores taken randomly at a depth of 0–30 cm from the potato and forage fields.

3.2.1. Potato field trial

In the potato (*S. tuberosum*) field trial, four treatments were compared: control without fertilization (T1); digestate (T2); manure pre-compost (T3); and a mixture of digestate and manure pre-compost (50–50% on a nitrogen basis) (T4). T3 represents the fertilization scenario preceding digesters implementation. Four replicates per treatment were randomly distributed within the experimental plot; each replicate consisting of six plants (Fig. 1).

Fertilizer doses were calculated based on the amount of digestate produced in household digesters, which farmers should presumably be able to apply. The same dose of TKN (around 50 kg N ha^{-1}) was applied in T2, T3 and T4 (Table 1). Taking into account that soil brings about 54 kg N-NO_3^- ha^{-1} per year, and the contents of phosphorous and potassium in soil, the expected yield was 17.5–25 t ha^{-1} (Jacob and Uexküll, 1968). The total dose of manure pre-compost was applied during potato planting; whereas the digestate was applied every 10 days, in different doses according to the nutritional needs of the plant at each growth stage (Jacob and Uexküll, 1968).

The effect of each treatment was compared in terms of potato yield per hectare, number of marketable tubers per plant and tubers quality (total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN) and total phosphorus (P-P_2O_5)).

3.2.2. Forage field trial

The digestate fertilizer value was also evaluated in a forage crop (*L. multiflorum* and *T. pratense* L.). The trial compared four treatments: control without fertilization (T1); digestate – 50% dose (T2); digestate – 100% dose (T3) and digestate – 150% dose (T4). T1 represents the fertilization scenario preceding digesters implementation. Five replicate plots per treatment were randomly distributed; each replicate comprising an area of 20 m^2 (Fig. 2).

Again, fertilizer doses were calculated based on the amount of digestate produced in household digesters, crop field availability and farmers readability to apply it. The dose of digestate corresponded to 17 kg N ha^{-1} per cut in T3 (100% dose), 8.5 kg N ha^{-1} per cut in T2 (50% dose) and 25.5 kg N ha^{-1} per cut in T3 (150% dose), as shown in Table 1. The digestate was applied every 7 days, always in the same dose. This field campaign comprised three forage cuts.

The effect of each treatment was compared in terms of total forage yield per hectare and its quality (TS, VS, TKN and P-P_2O_5).

3.3. Analytical methods

Biogas production was monitored using a commercial low pressure diaphragm gas meter (Elster, BK-G 1.6). Biogas composition was estimated by measuring the concentration of carbon dioxide (CO_2) and hydrogen sulphide (H_2S) using colorimetric tubes

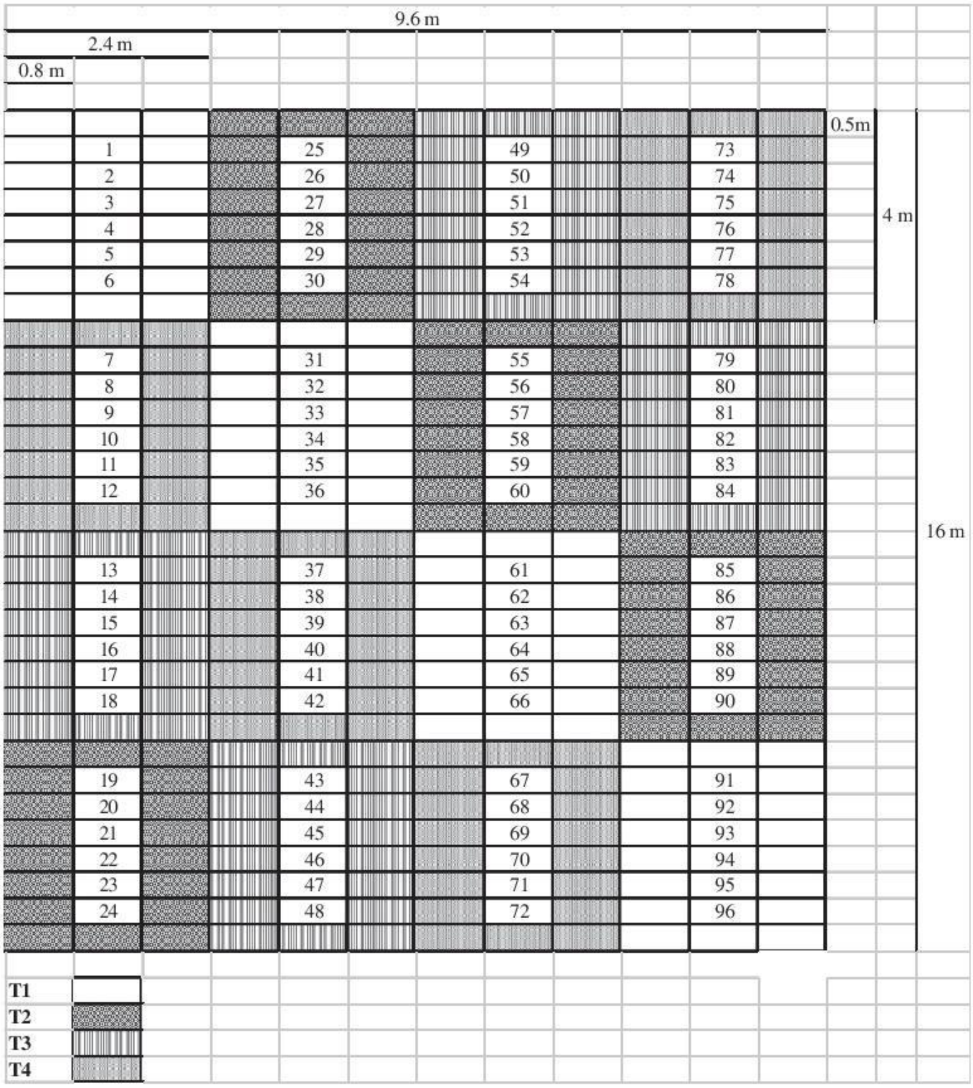

Fig. 1. Experimental design of the potato field trial.

Table 1
Doses of digestate, pre-compost and nutrients in the potato and forage field trials.

Parameter	Unit	T1	T2	T3	T4
Potato trial					
Digestate	$L ha^{-1}$	0	200,000	0	75,000
Manure pre-compost	$L ha^{-1}$	0	0	30,000	15,000
TKN	$kg ha^{-1}$	0	49.82	49.24	43.30
$P\text{-}P_2O_5$	$kg ha^{-1}$	0	41.78	23.48	27.41
$K\text{-}K_2O$	$kg ha^{-1}$	0	122.97	86.74	89.48
Forage trial					
Digestate	$L ha^{-1}$	0	24,079	48,159	72,237
TKN	$kg ha^{-1}$	0	8.50	17	25.50
$P\text{-}P_2O_5$	$kg ha^{-1}$	0	5.33	10.65	15.98
$K\text{-}K_2O$	$kg ha^{-1}$	0	14.71	29.42	44.13

(Gastec 2.2HH and Gastec 2.4H, respectively), as proposed by Ferrer et al. (2011) and Garfí et al. (2011). The concentration of methane was deduced from carbon dioxide and hydrogen sulphide contents.

Manure pre-compost and digestate were characterised in terms of TS, VS, total organic carbon (TOC), TKN, ammonia nitrogen ($N\text{-}NH_4^+$), $P\text{-}P_2O_5$, potassium ($K\text{-}K_2O$), pH, electrical conductivity (EC), density, *Escherichia coli* and *Salmonella* following standard methods (APHA, 1998). Total coliforms (TC) were analyzed according to the Mexican Official Standards (NOM, 1994).

The following soil physico-chemical properties were determined: pH, organic matter (Walkley and Black), available phosphorus (Olsen) and available potassium (NH_4OAc extraction) (Page et al., 1982), as well as soil texture (Bouyoucos, 1936).

Tubers and forage quality (TS, VS, TKN and $P\text{-}P_2O_5$) were determined according to the standard methods (APHA, 1998).

3.4. Statistics

The effect of treatments on crop yields was determined by the ANOVA and LSD tests ($\alpha = 0.05$) using the SAS System software.

4. Results and discussion

4.1. Biogas production and composition

The pilot digester was monitored over a period of 1 year. The average biogas production rate was 0.04 $m^3_{biogas}\, m^{-3}_{digester}\, d^{-1}$ (Table 2), fluctuating between 0.01 and 0.13 $m^3_{biogas}\, m^{-3}_{digester}\, d^{-1}$; and the average specific biogas production was 0.05 $m^3_{biogas}\, kg_{VS}^{-1}$ (Table 2), fluctuating between 0.02 and 0.16 $m^3_{biogas}\, kg_{VS}^{-1}$. Such fluctuations are attributed to the variability of process temperature,

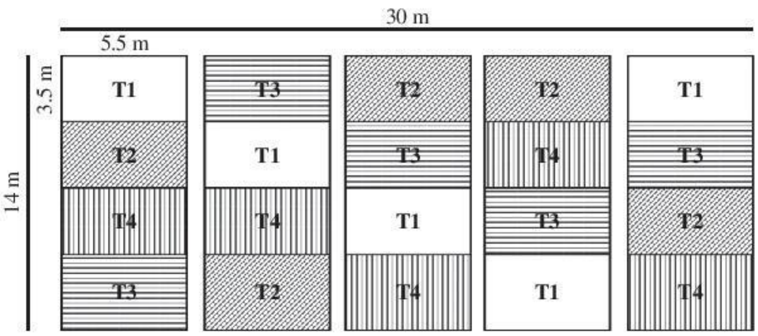

Fig. 2. Experimental design of the forage field trial.

HRT and OLR throughout the experimental period. Nevertheless, the methane content in biogas always exceeded 60% (Table 2).

The results obtained are in accordance with a previous study on guinea pig manure digestion at high altitude (Garfí et al., 2011). In general, the amount of biogas produced (0.04 $m^3_{biogas}\, m^{-3}_{digester}\, d^{-1}$) was low and the specific gas production (0.052 $m^3_{biogas}\, kg_{VS}^{-1}$) was slightly lower than the values reported for llama, cow and sheep manure digestion under similar operating conditions (18–25 °C, high altitude) but with a higher OLR (2 $kg_{VS}\, m^{-3}_{digester}\, d^{-1}$) (Alvarez and Lidén, 2008). Poor biogas production may be attributed to a low working temperature (<24 °C); to the quality of organic matter in guinea pig manure (i.e. low proteins and lipids content; low digestibility) and to current management practices (i.e. manure pre-composting, which decreases the amount of biodegradable organic matter), as suggested by Garfí et al. (2011).

4.2. Pre-compost and digestate characteristics

Physico-chemical characteristics of guinea pig manure pre-compost and digestate are shown in Table 3. According to the results, the concentration of TS decreased from 24.46% in the pre-compost (6–8% in the influent) to 0.7% in the effluent. Manure biodegradation was shown by the decrease in organic matter from 68.17% VS/TS in the pre-compost to 43.56% VS/TS in the effluent. Such high TS removal (>90%) results from the retention of solids inside the studied system. This phenomenon typically occurs in low-cost tubular digesters without mixing (Garfí et al., 2011; Lansing et al., 2010).

The concentration of nutrients (TKN, $N\text{-}NH_4^+$, $P\text{-}P_2O_5$, $K\text{-}K_2O$) in guinea pig manure was lower than the reported values for cow, sheep and poultry manure (Pomares and Canet, 2001). This may be attributed to the digestion and absorption of nutrients by guinea pigs (Flachowsky and Hennig, 1990), as well as manure pre-composting (Garfí et al., 2011).

The digestate contained nitrogen, potassium and phosphorus in more available forms than those contained in manure pre-compost: during anaerobic digestion the hydrolysis of organic matter leads to soluble nitrogen, potassium and phosphorus forms which can be easily uptaken by crops (Lansing et al., 2010; Thy et al., 2003; Tambone et al., 2010). In our case, the TKN concentration decreased by 72% from the influent to the effluent, due to solids retention in the digester; while $N\text{-}NH_4^+$ concentration increased by 28% from the influent to the effluent. Thus, the $N\text{-}NH_4^+$/TKN ratio was higher in the digestate than in manure pre-compost (0.81 vs. 0.16); which is in accordance with previous studies by Thy et al. (2003) (0.5–0.6) and Massé et al. (2007) (0.8).

The C/N ratio was calculated from the TOC and organic nitrogen fraction, determined as the difference between the TKN and $N\text{-}NH_4^+$ (Tambone et al., 2010). In manure pre-compost the C/N ratio was 17, corresponding to a partially stabilised material. This figure is within the range reported for cow, sheep and poultry manure (14–20) (Pomares and Canet, 2001). The digestate C/N ratio was much lower (2.9) due to organic carbon biodegradation and solids sedimentation. In general, nutrients concentrations (TKN, $N\text{-}NH_4^+$, $P\text{-}P_2O_5$, $K\text{-}K_2O$) in the digestate were relatively low, due to feedstock dilution before feeding and solids retention inside the digester, but this fact is partially offset by its rapid availability. However, fertilizing crops implies the use of large volumes of digestate (Table 1).

Table 2
Biogas production and composition in the pilot digester.

Parameter	Unit	Value
Biogas production rate	$m^3_{biogas}\, m^{-3}_{digester}\, d^{-1}$	0.04 ± 0.02
Specific biogas production	$m^3_{biogas}\, kg_{VS}^{-1}$	0.05 ± 0.03
Carbon dioxide	% CO_2	37.64 ± 5.94
Hydrogen sulphide	% H_2S	0.18 ± 0.05
Methane (deduced)	% CH_4	>60%

Table 3
Average characteristics of guinea pig manure pre-compost and digestate.

Parameter	*Pre-compost*		*Digestate*	
	Unit	Value	Unit	Value
TS	%	26.46 ± 3.96	%	0.70 ± 0.07
VS	% TS	68.17 ± 3.62	% TS	43.56 ± 5.58
TOC	% TS	13.84 ± 4.45	$mg L^{-1}$	139.30 ± 21.83
TKN	% TS	0.94 ± 0.11	$mg L^{-1}$	249.11 ± 37.89
$N\text{-}NH_4^+$	% TS	0.15 ± 0.08	$mg L^{-1}$	201.83 ± 13.50
$P\text{-}P_2O_5$	% TS	0.16 ± 0.06	$mg L^{-1}$	188.94 ± 36.97
$K\text{-}K_2O$	% TS	0.98 ± 0.06	$mg L^{-1}$	250.90 ± 2.37
pH		8.80 ± 0.30		7.10 ± 0.26
EC	$\mu S\, cm^{-1}$	17.38 ± 3.71	$\mu S\, cm^{-1}$	6.88 ± 2.09
Density	$kg L^{-1}$	0.66	$kg L^{-1}$	1.10
E. coli	$MPN mL^{-1}$	1.70×10^9	$MPN mL^{-1}$	1.70×10^7
Salmonella	P/A 25 g	Not detected	P/A 25 g	Not detected
Total Coliforms	$MPN mL^{-1}$	5.10×10^9	$MPN mL^{-1}$	1.70×10^8

Table 4
Physico-chemical properties of soil in the potato and forage field trials.

Parameter	Unit	*Potato trial* Value	*Forage trial* Value
pH		6.2	6.8
Organic matter	%	4.09	3.08
P	ppm	10.49	24.33
K	ppm	310	340
Sand	%	51	51
Silt	%	15	15
Clay	%	34	34

Table 5
Potato yield and marketable tubers per plant with the following fertilizers: control (T1), digestate (T2), manure pre-compost (T3), and a mixture of digestate and manure pre-compost (50–50%) (T4); forage yield with the following fertilizers: control (T1), digestate-50% dose (T2), digestate-100% dose (T3) and digestate-150% dose (T4).

Parameter	Unit	T1	T2	T3	T4
Potato trial					
Potato yield	$t\,ha^{-1}$	19.83 ± 3.65	25.28 ± 7.49	22.82 ± 7.30	21.88 ± 2.45
Dry matter yield	$t\,ha^{-1}$	5.56 ± 1.02	6.22 ± 1.84	5.65 ± 1.81	6.01 ± 0.67
Number of marketable tubers per plant		5.35 ± 1.07	5.92 ± 0.87	5.34 ± 0.96	5.66 ± 1.10
Forage trial					
Forage yield	$t\,ha^{-1}$	19.29 ± 6.81	19.67 ± 5.06	20.99 ± 6.01	21.00 ± 5.07
Dry matter yield	$t\,ha^{-1}$	3.14 ± 0.89	3.16 ± 0.62	3.33 ± 0.84	3.17 ± 0.58

Note: No significant differences were found between values in columns ($\alpha = 5\%$).

4.3. Soil properties

The soil quality in experimental plots was exceptionally high (Table 4), as a result of the research conducted during the last decades by the INIA. Soil properties in the potato and forage plots were similar except for phosphorous, which is attributed to previous trials carried out by the INIA. According to sand, silt and clay contents (Table 4), the soil texture was sandy clay loam, suitable for growing crops. The organic matter content (3–4%) was as high as in forests. Phosphorus and potassium contents (Table 4) were well above standard critical levels of 20 and 150 ppm, respectively. This reduces the probability of crop response to fertilizers containing these elements. Nevertheless, providing these elements is still important for maintaining soil fertility. It should be mentioned here that this was not the case of soils in rural Andean communities located at 3500–4500 m.a.s.l, where household digesters are implemented. At high altitude, with deforestation increasing relentlessly, soils are characterized by very low phosphorous contents (around 0.5 ppm) and acidic pH (3–4), decreasing soil fertility.

4.4. Crops fertilization

The potato yield ranged between 20 and 25 $t\,ha^{-1}$ in all treatments assayed (Table 5). The results are in accordance with expected values (17.5–25 $t\,ha^{-1}$) from the doses of nitrogen applied (Jacob and Uexküll, 1968). Compared to the control (T1), the potato yield increased by 27.5% with digestate (T2), by 15.1% with pre-compost (T3) and by 10.3% with the mixture (T4); while the dry matter yield increased by 11.9% with digestate (T2), by 1.6% with pre-compost (T3) and by 8.1% with the mixture (T4). Similarly, the number of marketable tubers per plant increased by 10.6% with digestate (5.92) and by 5.8% with the mixture (5.66) compared to the control (5.35) (Table 5). Thus, despite the high level of soil fertility, digestate application enhanced the potato yield and caliber. On the other hand, the potato composition was similar in all treatments: 26% TS, 86% VS/TS, 1% TKN and 0.58% P-P_2O_5.

The forage yield ranged between 20 and 21 $t\,ha^{-1}$ in all treatments (Table 5). Experimental data showed a mild but consistent trend when increasing the digestate application dose up to 100% on a nitrogen basis. Compared to the control (T1), the forage yield increased by 1.4% with digestate – 50% dose (T2), and by 8.8% with digestate – 100% dose (T3) and digestate – 150% dose (T4). The highest dry matter yield was obtained with T3, representing an increase of 5.9% compared to T1. The forage composition was similar in all cases: 16.15% TS, 91.12% VS/TS, 2.53% TKN and 0.48% P-P_2O_5.

The lack of statistical differences between treatments should rather be attributed to the high soil quality in the experimental layout, leading to high yields even in control treatments without fertilizer (Table 4). This is not the case in most rural Andean communities where digesters are implemented; meaning that the effect of fertilizers should be re-evaluated *in-situ* in future field campaigns.

The results suggest that the digestate from low-cost tubular digesters is an appropriate substitute of manure pre-compost for potato fertilization. Besides, the results with forage indicate that the digestate can be applied in a range of doses, according to the amount produced by the digester. Currently, in rural Andean communities, manure is either used for cooking or as fertilizer. In a scenario with low-cost tubular digesters, manure can be used to feed the digester, the digestate can replace manure or composted manure for crops fertilization, and the biogas produced can be used for cooking; improving household living conditions and protecting the environment.

5. Conclusions

This study aimed at assessing the properties of guinea pig manure digestate from low-cost tubular digesters for agricultural reuse in rural Andean communities. In field trials the potato yield (20–25 $t\,ha^{-1}$) increased by 27.5% with digestate, by 15.1% with pre-compost and by 10.3% with the mixture, compared to the control. The forage yield (20–21 $t\,ha^{-1}$) increased by 1.4% with digestate – 50% dose, and by 8.8% with digestate – 100% dose and digestate – 150% dose, compared to the control. The results suggest that the digestate is an appropriate substitute of manure pre-compost for potato fertilization. The results with forage indicate that it can be applied in a range of doses, according to the amount produced by the digester. Currently, manure is either used for cooking or as fertilizer. With low-cost tubular digesters implementation, it could be used to feed the digester, using the digestate for crops fertilization and biogas for cooking; improving household living conditions and protecting the environment. Since soil properties in rural Andean communities differ from experimental layouts, the effect of fertilizers should be re-evaluated *in-situ* in future research studies.

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