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Research article

Performance evaluation of digestate spreading machines in vineyards and citrus orchards: preliminary trials

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ABSTRACT

This research was carried out to evaluate a local biogas plant's solid fraction digestate spreading in a citrus orchard and vineyard. Three spreaders were tested: a broadcast manure spreader in the citrus orchard, and two cylindrical-shaped spreaders in the vineyard; the first one working in broadcast configuration, the second one in localised configuration. Experimental tests assessed effective work time, mean work speed, digestate flow rate and longitudinal and transverse spreading uniformity. In the citrus orchard, the digestate was mainly spread in the centre of the inter-row (around 66%), with low variability between inter-rows (coefficient of variation (CV) equal to 2.7%) and much higher variability within inter-rows (CV = 31.4%). The effective work time was about 28% of total field time and real work capacity was about 0.96 ha h^{-1}. In the vineyard, broadcast spreading released more on the right compared to the left (ratio 1.74) due to distributor disc rotation, whereas localised spreading was more uniform. Overall, variability between inter-rows had CV = 15.1% and within inter-rows CV = 33.3%. Real work capacity was about 0.16 ha h^{-1} for broadcast spreading and 0.26 ha h^{-1} for localised spreading. A preliminary economic evaluation, based on sub-contractor tariffs, produced the mean tariff for transaction and spreading costs of digestate in farms near the biogas plant.

1. Introduction

Environmental sustainability policies are widespread and 'clean' energy production is one of the main issues. At present, energy is mainly derived by fossil fuels that are both limited and harmful to the environment. So, a growing interest in alternative energy sources has emerged (Koszel and Lorencowicz, 2015) in which biogas production by anaerobic digestion (AD) is quite common, also due to the large quantity of biodegradable residues and by-products produced by livestock and agro-industrial activities (Alburquerque et al., 2012a; Comparetti et al., 2013; Morgan, 2014; Cerruto et al., 2016; Nayal et al., 2016; Valenti et al., 2018; Valenti and Porto, 2019).

Anaerobic digestion completes the production cycle and answers current issues such as decreasing pollution from agricultural and industrial activities, and reducing the use of both fossil fuels and mineral fertilisers (Vilanova Plana and Noche, 2016). In fact, the anaerobic digestion by-product, the digestate, is a stabilised bio-fertiliser with a significant reduction in unpleasant odours, and with an amount of nutrients, which depends on feedstock features, considering that the AD process doesn't change the total nutrient content but only its bio-chemical characteristics (Li et al., 2018; Stürmer et al., 2020). Pathogen dye-off is obtained too (Crolla et al., 2013), especially when digestion is developed in thermophilic conditions (Orzi et al., 2015).

Usually, digestate is defined as that part of the biogas chain that is an optimum example of circular economy: during the process, all the products are considered resources, and none are wastes (Selvaggi et al., 2018a). Circular agriculture means recovering the natural resources still circulating in the system rather than importing them from the outside (EEA – European Environment Agency, 2018). In a circular economy, a biogas plant should operate on a locale scale, collecting organic products from farms in its agricultural area and distributing digestate, which farmers use as an organic soil improver in the same area.

The environmental value of the digestate is greater if it is produced in plants respecting Biogasdoneright™ principles as defined by Dale et al. (2016): the input biomasses for the plants are principally by-products from agro-industry (olive mill wastes, citrus pulps, whey, etc.) or agriculture (livestock, poultry manure, cereal straw, etc.). According to these principles, crop rotation can be diversified, chemical fertiliser

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consumption can be reduced by using digestate, and renewable energy can be produced (Valli et al., 2017; Selvaggi et al., 2018b).

The optimum use of the digestate is crucial to improving agricultural production and reducing environmental impacts of the anaerobic digestion (Tambone et al., 2009; Maucieri et al., 2017). Moreover, economically, digestate is an opportunity for farmers, both in terms of reducing costs and farmers' dependence on industrial fertilisers (Montes et al., 2013). Digestate can play a role in improving energy access, providing opportunities for social and economic development in agricultural communities, contributing to local food security, improving the management of resources and agro-wastes and providing environmental benefits (Manetto et al., 2016; Valenti et al., 2020). Digestate is an effective source of plant nutrients, both macro and microelements, and can contribute to organic soil matter turnover too (Makádi et al., 2012). Its spreading rate is generally regulated on the basis of nitrogen content, not to exceed legislation limits. Due to its complexity, digestate affects the physical, chemical and biological properties of the soil (Alburquerque et al., 2012b; Nkoa, 2014; Maurer et al., 2019).

Digestate management strategies are planned not only for safe disposal but also to increase value and marketability (Logan and Visvanathan, 2019). So, before storage, transport and distribution, digestate is very often mechanically or physically separated into two fractions: a solid palatable fraction and a clarified liquid one (Provenzano et al., 2018).

The liquid fraction has a high rate of readily available nitrogen (Bolzonella et al., 2018), while the solid portion has more amendment properties; its nutrient concentration and its amending properties vary widely depending on the biogas feedstock (Dahlin et al., 2017). After separation, the solid fraction can be further processed, often being used in composting (Bustamante et al., 2013; Czekała et al., 2017), second drying and pelletisation (Koszel and Lorencowicz, 2015). In general, digestate improves soil fertility, plant quality and yield, and plant resistance to biotic and abiotic stress (Kouřimská et al., 2012; Barzee et al., 2019).

The environmental benefits of both composting and digestate use include increases in organic soil matter, erosion reduction, increased water retention and physical structure of the soil (i.e., aggregate stability, density, pore size) (Wood Environment & Infrastructure Solutions UK Limited, 2019). In the literature, it is well known that digestate is a soil improver that can solve soil fertility and erosion problems. In particular, the advantages of solid digestate are as a soil enricher and source of organic carbon. In fact, more generally, biofertilisers show a positive impact on the humification process (Slepetiene et al., 2020).

Like every organic soil improver, digestate as it is or its fractions should be spread at specific rates and at the most suitable time for the best plant uptake, minimising losses to the atmosphere, ground and water. In particular, nitrogen and phosphorous compound emissions are affected by climatic and soil characteristics, and by spreading techniques (Tambone et al., 2010; Bacenetti et al., 2016). So, it is very important to choose the best method for the accurate application of digestate, too, for its technical and economic affordability. Generally, slurry and manure spreaders have been widely used for spreading the liquid and solid fraction of digestate. Then, to improve results, some manufactures started designing new spreaders, although initially they concentrated on only the liquid fraction. By contrast, manure spreaders were adopted for the solid fraction (Manetto et al., 2019).

By 2017, the number of biogas plants in Europe was over 17 700 units, Italy being in second place for biogas plants with over 1600 units (EBA, 2018). The number of anaerobic digestion plants has grown mainly in northern Italy, where the use of digestate as an organic soil improver is common. In other areas, such as in the Mediterranean regions, even if there is a lot of available biomass, there are few digesters and the use of digestate is still very limited (Chinnici et al., 2018; Pappalardo et al., 2019).

Our research focused on the Mediterranean area, where a new market for digestate would be welcome to create new income opportunities for plant managers (Fabbri et al., 2010) and reduce the typical dependence of plants on public subsidies (Appel et al., 2016; Dahlin et al., 2017). In northern Italian regions, biogas plants are usually built on very large farms and plant owners have a lot of land available for spreading digestate. Instead, in the study area, and more generally in Sicily (southern Italy), farms are smaller in size and plant owners give away their digestate for free (what's left after their own use). Consequently, new markets for digestate could be opened up and farmers' incomes could be improved (Dahlin et al., 2015; Pappalardo et al., 2018).

Clearly, the transaction and spreading costs are fundamental in evaluating digestate feasibility. In some conditions, it might not be economically viable to use digestate beyond a certain distance from the AD plants or, more generally, where the level of mechanisation cannot be improved and the mechanic spreading is not achievable. Furthermore, the most suitable technique depends on the methods of digestate processing, type of fertilised crops and time of fertilisation.

In this research, one manure spreader was tested in a citrus orchard and two in a vineyard for spreading the solid fraction of the digestate; assessments were carried out mainly in terms of spreading uniformity and performance. Also, the transaction and spreading costs were evaluated economically.

2. Materials and methods

2.1. General information

Digestate spreading trials were carried out in July 2018 in a citrus orchard and a vineyard. The plots were located in the south-eastern part of Sicily, at Vittoria in the province of Ragusa. The citrus plot had a 6 × 4 m spacing, with 192 m long rows; the vineyard had 250 m long rows, spaced at 2.4 m apart and the vines were separated by 1.0 m. Both fields were drip irrigated and weeds were mechanically controlled. The climatic conditions during the trials were collected from the nearest SIAS (Sicilian Information Agro-meteorological Service) meteorological station of Acate (province of Ragusa).

The solid fraction of the digestate distributed came from a 600 kW electrical anaerobic digestion plant processing agri-food industry by-products, mainly citrus pulp. It was obtained by means of a mechanical separator, particles being less than 1 cm long. The digestate was loaded from a pile where it had been stored after the separation process, transported to the field by means of a 20 m^3 trailer (Bossini, model RA 160 CSI) towed by a tractor (John Deere, model 6220, 66.2 kW) and discharged in a heap in the citrus orchard.

Three product samples of about 2.3 kg were taken from the heap just after the digestate had been discharged to assess total solid (TS) content. In addition, three samples of about 2.0 kg were taken from the in-field spread product after the last spreading trial of the day. Each sample was subdivided in three sub-samples and TS content was assessed after drying the sub-samples in a laboratory oven at 105 °C until a steady mass was obtained (after three days). Calculations for sub-sample k were carried out according to Eq. (1):

$$TS_k = \frac{m_{d_k}}{m_{w_k}} \times 100, \tag{1}$$

being TS_k (%) the total solid content, m_{d_k} (g) the dry mass (after drying at 105 °C) and m_{w_k} (g) the initial wet mass. Masses were measured by means of a laboratory scale (Mettler Toledo, model PB3002-S).

In this first study, digestate spreading tests were carried out under effective field conditions, using implements provided by a local agricultural subcontractor (the same in citrus orchard and in vineyard) and with spreader settings and operating parameters (work speed, tractor power take off rotation speed) usually adopted by him. Finally, the spreaders' performance and suitability were assessed. No evaluations about the quantity of digestate needed for the crops were carried out. Assuming characteristics similar to one of the digestates of the same origin reported in the literature (Rossi and Mantovi, 2012), the amount of nitrogen distributed remained within the limits fixed by current regulation and in line with the directives on integrated production in Sicily both for citrus orchards and vineyards (Regione Siciliana, 2019).

2.2. Trials in the citrus orchard

Digestate was spread using a broadcast manure spreader with two rear vertical rollers equipped with a 2.1 m^3 hopper (Mutti Amos, model SLM 18), driven by a Fendt 211 P tractor (max power 82 kW) operating at 56 rad s^{-1} power-take-off (PTO) rotation speed (Figure 1). Spreading was carried out in three inter-rows and each inter-row was treated as a repetition for field evaluations. All operations were videotaped and clocked to evaluate work times, in particular effective spreading time and work speed.

In every inter-row where the spreader worked, 2 × 2 m plastic sheets were spread out on the ground in three positions 18 m apart (S1, S2 and S3, Figure 2) for sampling the quantities spread and assessing transverse (left, middle, and right with respect to travel direction) and longitudinal spreading uniformity. Assessment was carried out by putting the digestate scattered on the sheets into buckets and then weighing each with a field scale (Omega Bilance, model Smally) immediately after spreading. The layout of sampling points is shown in Figure 2.

2.3. Trials in the vineyard

The digestate was spread by two spreaders (Figure 3) equipped with cylindrical-shaped hopper, driven by a BCS Vithar 950EP RS tractor (max power 67 kW), suitable for working in vineyards and operating at 56 rad s^{-1} PTO rotation speed. One (Gamberini, model SCD 600, with a 0.6 m^3 hopper) was used in its standard configuration (centrifugal broadcast spreading in the inter-row by means of a distribution disc) whereas the second, equipped with a 0.7 m^3 hopper, had been built by its owner in such a way to spread the digestate in a localised manner (two lines near the vine rows).

For each experimental setting, three repetitions were carried out, each consisting of emptying the spreader hopper in different inter-rows. Operations were again videotaped and clocked to evaluate the work times. As in the citrus orchard, transverse (left and right with respect to the travel direction) and longitudinal spreading uniformity was assessed by weighing the amount of digestate scattered on the 2.0 × 1.2 m plastic sheets spread out on the ground in three positions 8.2 m apart in every inter-row. The layout of sampling points is shown in Figure 4.

2.4. Data analysis

Work times were computed by applying the CIOSTA methodology (Bodria et al., 2006). In particular, based upon video footage and clocked operations, effective spreading times, refilling times, and travel times

Figure 1. Refilling of the digestate spreader used during trials in the citrus orchard.

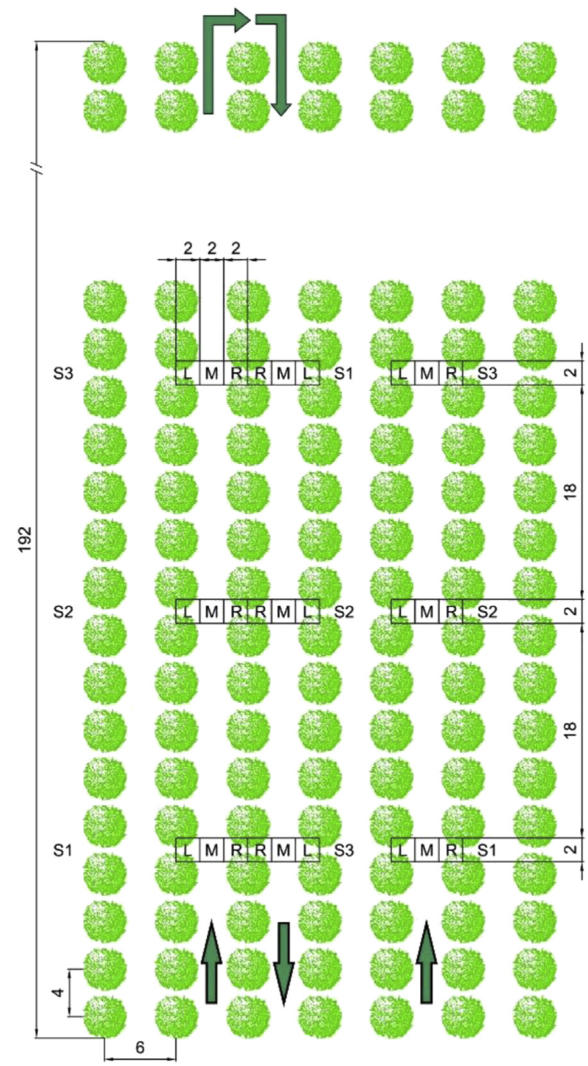

Figure 2. Layout of digestate sampling points in the citrus orchard (L = left, M = middle, R = right with respect to travel direction; sizes in metres).

were evaluated per each repetition in citrus grove. Whereas, in the vineyard, as the digestate had been discharged in the citrus orchard and then the refilling point was too far (about 1 km) with respect to a realistic condition, the effective spreading times were evaluated per each repetition on the basis of the recorded times, the refilling times were assumed equal to half of those in the citrus orchard due to the lower capacity of the hoppers, and the travel times were evaluated hypothesising the same tractor speed.

Spreading uniformity was assessed by analysing the quantities of digestate scattered on the plastic sheets, separately in the citrus orchard and vineyard. Firstly, the masses were referred to the sheet surface, according to Eq. (2) for the sample k:

$$q_k = \frac{m_k}{S}, \tag{2}$$

being q_k (kg m^{-2}) the digestate per square metre (unit mass), m_k (kg) the mass of digestate scattered on the plastic sheet and S (m^2) the sheet surface (4 m^2 in the citrus orchard and 2.4 m^2 in the vineyard).

Unit masses were analysed by applying the mixed model procedure. In the citrus orchard, the transverse sampling position (left, middle and right) was treated as a fixed factor and inter-row as a random factor (Figure 2). Similarly, in the vineyard, the transverse sampling position (left and right) and spreader type (broadcast and localised) were treated as fixed factors and inter-row as a random factor (Figure 4). When

Figure 3. Spreaders used in the vineyard: broadcast spreading on the left and localised on the right.

measuring unit masses, any changes due to natural drying were neglected due to the short time required by the weighing procedure after the digestate was spread.

Finally, considering the total mass of digestate present in each sampling line (S1, S2 and S3, Figures 2 and 4) and knowing the work speed, the digestate flow rate was calculated according to Eq. (3):

$$\dot{m}_{ki} = \frac{m_{Sk} \cdot v_i}{L}, \tag{3}$$

being $\dot{m}_{ki}$ (kg s^{-1}) the digestate flow rate for sampling line Sk ($k = 1, 2, 3$), v_i (m s^{-1}) the average work speed in the inter-row i, and L = 2 m the length of the plastic sheets.

All statistical analyses and graphical representations were carried out by using the open source software R (R Core Team, 2019).

2.5. Economic aspects

The economics of this research were aimed at determining the spreading and transaction costs for digestate in farms where different crops are cultivated. Data were collected by face-to-face interviews with three specialised operators. In particular, information on typical tariffs was collected as suggested by Selvaggi et al. (2017).

The costs of two agricultural operations were analysed: 'transport' of the digestate from the biogas plant to the farm and its 'spreading' on the farm as an organic soil improver. The costs we identified were over three years (from 2017 to 2019), to reduce any possible influence of local phenomena, such as digestate availability, multiple sellers, etc. Consequently, all the costs are the average values for all the surveys.

Unfortunately, the usual method for calculating unit production costs suggested by Sgroi et al. (2014) was not suitable. It was not possible to define the typical cost categories: fixed costs (specific and regular) and proportional ones. In fact, Sicilian farmers do not own machinery for transporting and spreading the solid digestate on the farms. So, hire tariffs must be paid to specialised subcontractors.

In the analysis, the price of digestate was assumed 0 Euro because the digester owners could not sell all their digestate and so they give it away. The farmers were little informed about digestate and considering their distrust of new products, the only way to get them to try it out was to give it away. According to the authors' experience, this assumption is real and of great importance in Sicily where the research was conducted.

The costs for spreading the solid fraction of digestate were calculated according to Eq. (4):

$$D_c = V_r \times U_c, \tag{4}$$

being D_c (€ ha^{-1}) the spreading cost, V_r (m^3 ha^{-1}) the volume rate of digestate, and U_c (€ m^{-3}) the unit cost (from the subcontractors).

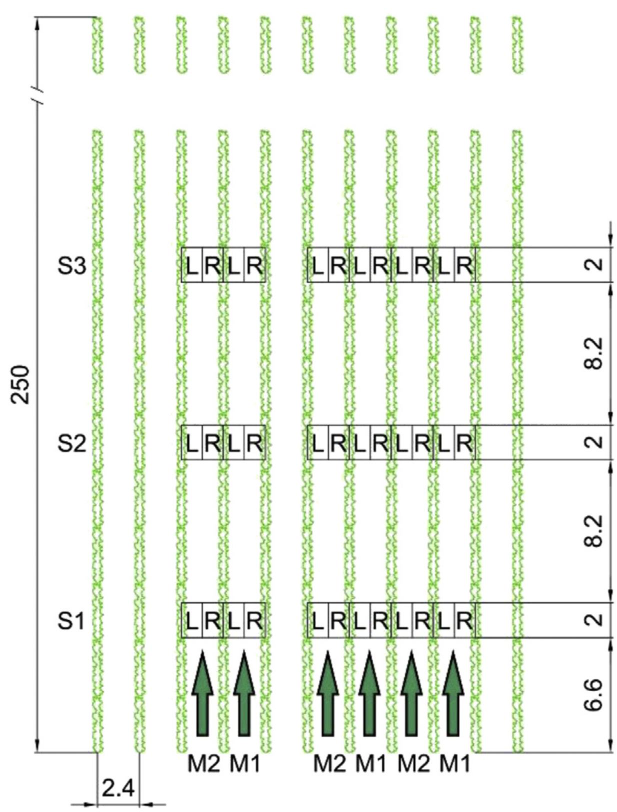

Figure 4. Layout of digestate sampling points in the vineyard (L = left, R = right with respect to the travel direction; M1 = localised spreading, M2 = broadcast spreading; sizes in metres).

3. Results and discussion

3.1. General results

The day of the spreading trials was sunny, with a mean temperature of 26.8 °C (from 26.4 to 27.2 °C) and a mean relative humidity of 89% (from 87 to 92%) in the hours of the research activities (from 9:00 am to 4:00 pm); the wind speed was quite slow, with a mean velocity of 2.8 m s^{-1} (from 2.3 to 3.3 m s^{-1}) at 2 m from the ground and maximum blowing speed at 6.4 m s^{-1}.

Laboratory analysis of the digestate total solid content showed values of 42.7% ± 0.5% (mean ± standard deviation) and 63.9% ± 3.9% for the two collection times at the beginning and end of the day. The corresponding humidity values (wet basis) were 57.3% ± 0.5% and 36.1% ± 3.9% due to water loss from sun exposure during the day.

3.2. Citrus orchard trials

Analysis of the video footages enabled a calculation of work speed in each row during spreading, which ranged from 1.34 to 1.64 m s^{-1} (global mean 1.52 m s^{-1}). The effective work time was about 28% of total field time (sum of times for spreading, refilling, regulation, and preparation) and, taking into account the treated surface, real work capacity was about 0.96 ha h^{-1}.

Figure 5 shows the digestate spread at each sampling point. The global mean was 1.56 kg m^{-2}, corresponding to around 6.7 t ha^{-1} of dry matter, assuming a solid content of 42.7%. The digestate spread in the inter-rows was quite uniform, ranging on average from 1.40 to 1.74 kg m^{-2}. The longitudinal spreading (differences between sampling lines S1, S2 and S3) was rather variable, with differences maximum-minimum ranging from 0.06 to 2.17 kg m^{-2}, attributable to instantaneous speed changes of the tractor and to the progressive emptying of the hopper. Finally, the transverse spreading (differences between sampling points left, middle and right) always showed a greater amount of digestate in the middle of the inter-rows, due to the direction of rotor rotation.

Statistical analysis confirmed the previous observations. The analysis of variance (ANOVA) revealed statistically significant differences between the central sampling position and the lateral ones, with these latter statistically similar between each other. On average, the amount of digestate was 3.12 kg m^{-2} in the centre part of the inter-rows and on average 0.80 kg m^{-2} (ratio 3.9) in the lateral ones (0.84 kg m^{-2}, left and 0.75 kg m^{-2}, right). Finally, variability between inter-rows had a coefficient of variation equal to 2.7% and that within inter-rows a CV = 31.4%.

The average digestate flow rate was 14.2 kg s^{-1} (CV = 24.6%), ranging from 11.4 to 22.2 kg s^{-1}. It ranged in each inter-row from 12.7 to 16.2 kg s^{-1}.

3.3. Vineyard trials

In the vineyard, the spreaders were slower than that used the in citrus orchard; their mean speed was 0.66 m s^{-1} (from 0.58 to 0.78 m s^{-1}) for broadcast spreading, and 1.05 m s^{-1} (from 1.03 to 1.07 m s^{-1}) for localised spreading. Real work capacity was about 0.16 ha h^{-1} for broadcast spreading and 0.26 ha h^{-1} for localised spreading.

Figure 6 shows the digestate spread at each sampling point. The global mean was 1.09 ± 0.54 kg m^{-2} (mean ± standard deviation) for broadcast spreading and 1.61 ± 0.49 kg m^{-2} for localised spreading (ratio 1.47). The corresponding dry matter was around 6.9 t ha^{-1} and 7.1 t ha^{-1}.

The data show great variability both between inter-rows and within inter-rows. On average, the amount of digestate spread in the inter-rows ranged from 0.90 ± 0.52 to 1.26 ± 0.72 kg m^{-2} for broadcast spreading and from 1.33 ± 0.31 to 2.08 ± 0.55 kg m^{-2} for localised spreading. Longitudinal spread ranged from 0.71 ± 0.27 kg m^{-2} to 1.48 ± 0.47 kg m^{-2} for broadcast spreading and from 1.33 ± 0.28 kg m^{-2} to 1.94 ± 0.64 kg m^{-2} for localised spreading. Moreover, the data show a decreasing trend in the digestate spread from S1 to S3 sampling lines, more evident in localised spreading, attributable to the progressive emptying of the hopper. Finally, the transverse spreading (differences between left and right) was rather uniform in localised spreading and asymmetric in broadcast spreading, due to the direction of distributor disc rotation.

ANOVA confirmed the difference between the two spreading techniques (broadcast and localised) as statistically significant, as well as the interaction between the transverse sampling position (left and right) and the spreading technique. On average, the amount of digestate was 0.80 ± 0.32 kg m^{-2} on the left side of the inter-rows and 1.39 ± 0.57 kg m^{-2} on the right one (ratio 1.74) for broadcast spreading (differences statistically significant at p-level = 0.05 by Kruskall-Wallis test). The difference between the left and right side for localised spreading was not statistically significant: 1.67 ± 0.53 kg m^{-2} and 1.55 ± 0.48 kg m^{-2}. Finally, variability between inter-rows had coefficient of variation equal to 15.1% and within inter-rows CV = 33.3%.

For broadcast spreading, the digestate flow rate ranged from 0.64 to 2.27 kg s^{-1}, with a mean value of 1.41 kg s^{-1} and a CV of 40.1%. For localised spreading, it ranged from 2.61 to 6.78 kg s^{-1}, with a mean value of 4.05 kg s^{-1} and a CV of 29.0%.

3.4. Economic evaluation

In general, all subcontractor tariffs are in 'Euros per cubic metre'. The mean value for solid fraction transaction costs within 20 km from the anaerobic digestion plants of origin was 10 € m^{-3}. Further distances are not considered because the high transport costs are not economically viable.

There were different spreading costs for the two cultivation systems. For the vineyard the mean tariff was 10 € m^{-3} and for the citrus orchard the medium value was 7 € m^{-3}. The reasons for this disparity come out in the face-to-face interviews and are linked to the real work capacity.

In these field tests, in the citrus orchard the subcontractor spread the digestate solid fraction over one hectare in about one hour, whereas in the vineyard the real work capacity was limited to 0.26 ha h^{-1} for localised spreading near the trees and 0.16 ha h^{-1} for broadcast spreading.

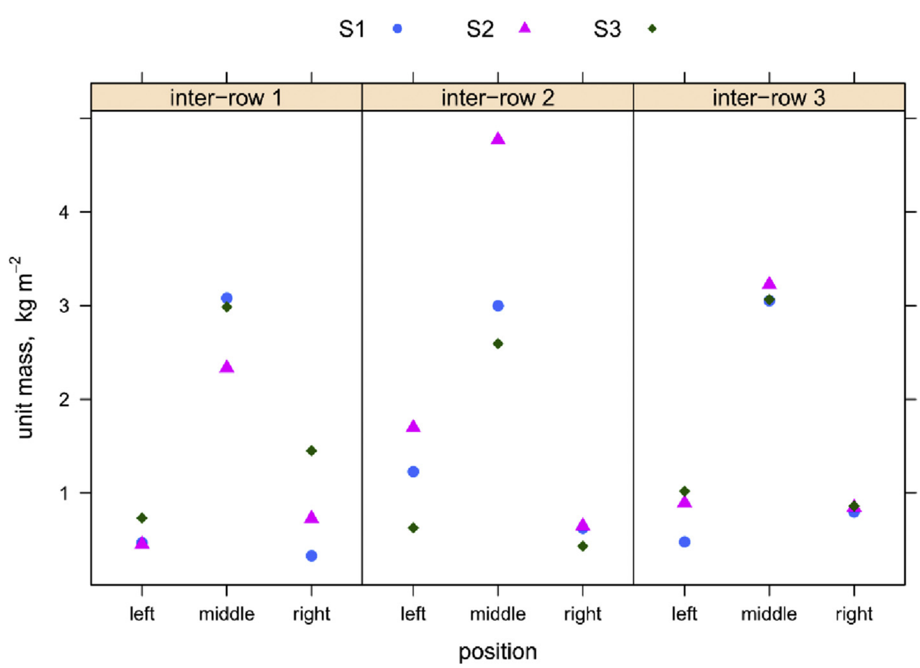

Figure 5. Unit mass of digestate spread at each sampling point in the citrus orchard.

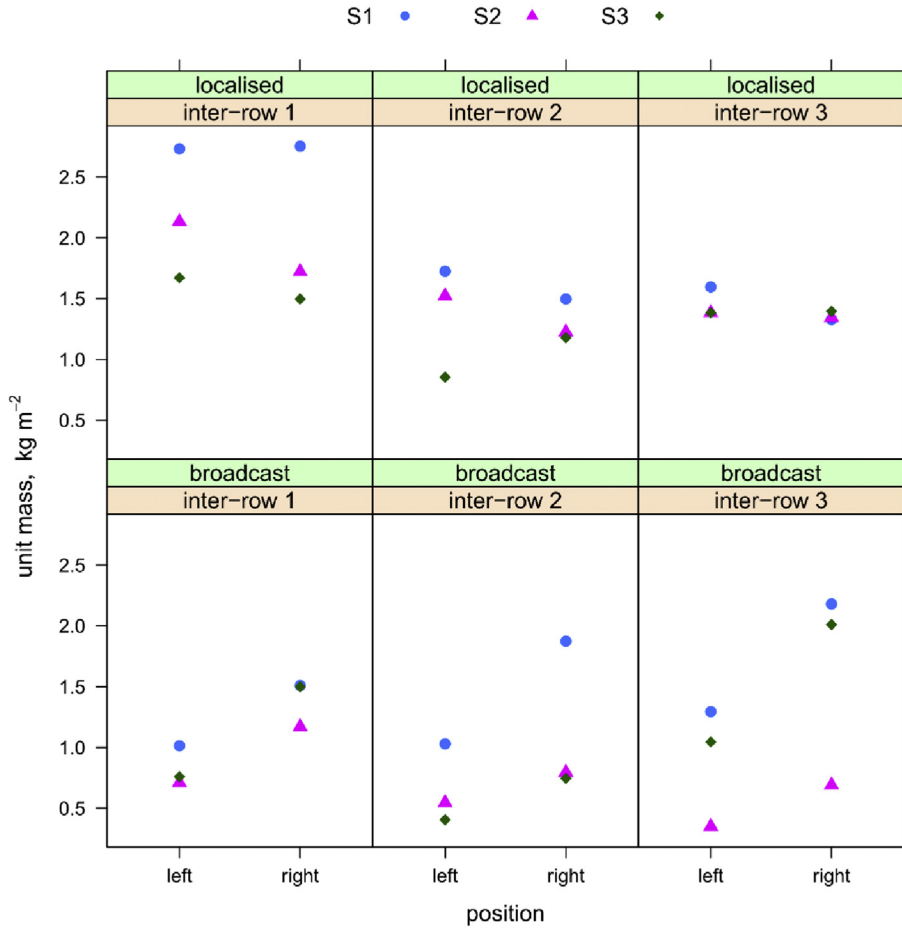

Figure 6. Unit mass of digestate spread at each sampling point in the vineyard.

Moreover, the amount per hectare of digestate spread in the two crops was different. In the citrus orchard, there were 28.6 m^3 ha^{-1} of digestate and in the vineyard there were 36.1 m^3 ha^{-1} for broadcast spreading, and 25.5 m^3 ha^{-1} for localised spreading. Consequently, taking into account the real work capacity of spread, there were 27.6 m^3 h^{-1} in the citrus orchard and 5.7 (broadcast) or 6.7 m^3 h^{-1} (localised) in the vineyard, resulting in greater spreading efficiency in the citrus orchard and justifying the different subcontractors costs.

Finally, the spreading costs, calculated by means of the Eq. (4), were 200 € ha^{-1} in the citrus orchard, 360 € ha^{-1} in the vineyard for broadcast spreading and 255 € ha^{-1} for localised spreading. Therefore, the citrus orchard spreading costs are less than the vineyard because subcontractors can spread the digestate more efficiently.

It should be highlighted that the economics could be influenced by specific characteristics of the territory. In Sicily, there is little competition between anaerobic digestion plants, due to their relative rarity. Moreover, sellers and subcontractors have not competitors and the prices are unavoidably affected.

This is one limitation of our research but it is typical of Mediterranean regions. Also, assuming a digestate price of 0 € is very significant, but it is an observed fact in that area where digestate is not widespread. The general applicability of our results is tempered because the level of competition varies by geographic region.

4. Conclusions

In this study, three manure spreaders were tested for spreading digestate solid fraction in a citrus orchard and vineyard; the machines were properly chosen for the characteristics of the plots, especially for inter-row distance, and they were provided by a local agricultural subcontractor. The results, despite other experimental tests being necessary, helped us to draw the following conclusions:

- Using the subcontractor's ordinary settings, around 6.7 t ha^{-1} of dry matter were spread in the citrus orchard and around 7.0 t ha^{-1} in the vineyard. These quantities should be re-evaluated according to the chemical composition of the digestate solid fraction and crop needs, here not considered.
- Spread was rather asymmetric for broadcast spreading in both the citrus orchard and vineyard, due to rotor or distribution disc rotation. In the citrus orchard, the digestate was mainly spread in the centre of the inter-row (66%), whit 18% on the left and 16% on the right. In the vineyard, 36% of the digestate was spread on the left of the inter-row and 64% on the right.
- Variability between inter-rows was always lower than within inter-rows, mainly due to the variation in digestate flow rate with the emptying of the hopper.
- The average transaction cost was 10 € m^{-3} within 20 km of the AD plants. Transport to further than this distance is uneconomical for farmers.
- Average spreading costs were different for the two crops. In terms of the typical subcontractors' tariffs (€ m^{-3}), the least cost (7 € m^{-3}) was for the citrus orchard, where spreading is faster than in vineyard and subcontractors can reduce the unitary cost of the product.

Further studies could usefully investigate the suitability of other spreaders, possibly with the support of precision agriculture equipment to control real time spreading uniformity.

Declarations

Author contribution statement

Manetto Giuseppe, Cerruto Emanuele, Papa Rita, Selvaggi Roberta & Pecorino Biagio: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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