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Band spreader for the application of slurry solid fractions to orchards

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Abstract

Mechanical separation of pig slurry is widely used in the Piedmont region of northwest Italy, where it is considered a reliable technique to reduce livestock nutrient load on farms. Transport of solid slurry fractions to areas of low animal density, such as where cereals and fruit trees are grown, is considered straightforward. However, because equipment specifically designed to distribute the solid fraction of slurries in orchards was not available a prototype spreader was developed. The machine, with a $4.5 m^3$ volume hopper, included a chain conveyor metering device and hydraulically-driven spinning plate so that the working width can be adapted to tree row space and shape differences enabling its use in a variety of operating conditions and orchard types. To ensure application of solid fraction was in compliance with crop requirements and regulations, the spreader was equipped with an electronic rate control system enabling target nutrient rates ranging from 10 and 120 kg [N] ha^{-1}. It was tested for longitudinal and transverse distribution at different application rates and forward speeds. Test results showed that the control system maintained suitably even distribution patterns and steady application rates regardless of forward speed.

Keywords: automatic rate control, orchards organic fertilisation, manure band application.

Nomenclature

N	Nitrogen

SRF	Short rotation forestry
GPS	Global positioning system
TN	total nitrogen
q	manure flow rate, kg min^{-1}
Q	target nutrient application rate, kg [nutrient] ha^{-1}
W	working width, m
F	forward speed, km h^{-1}
T_n	target nutrient content in manure, kg Mg^{-1}
TS	total solids
CV	coefficient of variation
cv	cultivar

1. Introduction

In livestock farming systems, animal manure generally plays a positive role by acting as a source of nutrients and organic matter to maintain soil productivity. However, several areas in Europe suffer from a problematic nitrogen (N) surplus where the difference between N soil inputs and soil removal by the crops is too high. This often occurs where there is a concentration of livestock farms. The over-application of N to crops or grasses in the form of manure can result in nitrate leaching to ground water or high N levels in surface waters leading to eutrophication and low dissolved oxygen levels (Durand et al., 2011). To prevent such adverse effects, European Union Nitrate Directive (91/676/EC) mandated that the animal manure N application rates in “nitrate vulnerable zones” should not exceed 170 kg [N] ha^{-1} year^{-1}.

Furthermore, farmers in these areas were asked to find additional lands for disposal of the N surplus; a difficult task in areas where raising livestock is widespread and animal loading is high. This issue is relevant in Italy as more than 70 % of its livestock production is concentrated in the western Po Valley (Capri et al., 2009) in the regions of Piemonte, Lombardia, Emilia Romagna, and Veneto (ISTAT, 2012). Consequently, mechanical slurry separation has been recognised as being important and used as a reliable technique to reduce farm N loadings. The nutrients content in the solid fraction can be economically transported from high intensity animal farming areas to adjacent areas with lower animal densities. In the Piemonte region of northern Italy, orchards, vineyards, and short rotation forestry (SRF) areas are often only a few kilometres away from areas characterised by high livestock densities. In Cuneo province for instance, 63,000 ha of orchards are available, representing 20 % of cropped land (ISTAT, 2012). Orchards, as well as vineyards, are currently managed using chemical fertilisers and characterised by a lack of soil organic matter content (Cerutti et al., 2011). Historically, humified farmyard manure was used in orchards, but it has become quite difficult to obtain. The transfer of solid fraction to orchards could, therefore, represent an opportunity to utilise local nutrient surpluses.

An impediment to the widespread adoption of applying separated slurry solid fraction in orchards is the attitude of the farmers who are not in favour of its use mainly due to the lack of appropriate specific methods of application. Conventional machines, such as spreader for farmyard manure or chemical fertilise, are occasionally used, but they are rarely good options because the slurry solid fraction characteristics (e.g., heterogeneous particles sizes) affect spreading uniformity and cause the metering device to clog. Moreover, separated solid slurry applied in orchards requires equipment to be adaptable to fit different row spacings (from 3 m in SRF to 5 or 6 m in hazel groves) and for application to the areas of optimal plant nutrient uptake. The ability to accurately apply the target application rate is also crucial for orchard crops since their nutrient requirements are lower than for open field crops; for example it is 80-100 kg [N] ha^{-1} $year^{-1}$ for peach orchards.

To cope with these requirements and operational limits, a prototype spreader for solid fraction band application in orchards was designed, constructed and tested. Tests were carried out to assess spreader performance in several areas: i) distribution evenness, ii) application rate accuracy, and iii) working capacity.

2. Materials and methods

2.1. Definition of the application surface

Prior to the development of the separated solids spreader, a study was carried out to define the typical orchard row spacing application area. To optimize tree fertilisation it is necessary to apply the solid fraction at the correct rate and where roots are able to take up nutrients. The proper separated fraction application rate depends on the orchard cultivar and age. In the peach orchards across the western Po Valley, the application rates ranged from 50 and 120 kg [N] $ha^{-1}year^{-1}$ (PSR, 2006). To obtain maximum organic fertilisation efficiency, the material must be applied in early spring. Baldini (1986) and Baldoni et al. (1992) prescribed the optimal separated solids application area in orchards as being in a band approximately 1.0 m wide and 0.5 m from the tree row while avoiding direct contact with the trees in order to limit the risk of plant disease development. This latter consideration dictated that the separated solids spreader be designed so as to enable distribution in a 1.0 m wide band beside the machine and 0.5 m from tree rows (Fig. 1). A metering device able to accommodate the rates described above was developed as shown in Fig. 2.

2.2. Prototype solid fraction spreader

A band application separated fraction spreader was designed and constructed consistent with maintaining working autonomy and operating within the characteristically narrow row spacings (3.0 – 5.0 m) found in orchards and SRFs northwest Italy. The constructed spreader included the following components:

- square tube steel frame;
- 4.5 m^3 hopper;

- non-steering axle fitted with wide section and low pressure tyres (500/60 -22.5) to reduce soil compaction and sward damage;
- band spreading device consisting of two hydraulic-powered spinning plates, one per side, mounted on a hydraulic-powered frame for the proper placement of the separate solids (0.5 m from tree row in a 1.0 m wide band);
- automatic rate controller;
- global positioning system (GPS) receiver.

The hopper, with a volume of 4.5m^3, was constructed using wooden plank lateral walls supported by steel profiles. The rear steel wall of the hopper is lowered during loading operations and during transport to avoid accidental material spillage. It was raised during the distribution phase to let the solid material flow toward the distribution system using the chain conveyor mounted on the steel floor. The automatic rate controller was designed to apply manure nutrients at target application rates ranging from 10 and 120 kg [N] ha^{-1}. This range was chosen to address the nutrient application needs of the most common orchards in the western Po Valley, and while considering nutrient content ranges (e.g., total nitrogen [TN] = 4-8 kg Mg^{-1}) (Dinuccio et al., 2014) in the various types of livestock slurry solid fractions produced in this area.

The automatic rate controller includes several components:

- proximity sensor mounted on the right wheel rim for spreader forward speed determination;
- moving floor comprised of a chain conveyor driven by a hydraulic motor;
- rotation speed sensor for control of the sprocket-wheel and chain conveyor speed;
- electronic unit (DIKEY-John® IntelliAg AI50, DICKEY-John Corporation, Auburn, IL, USA) to control operational parameters;
- a GPS receiver for manure application traceability.

The on-board computer had a clear, simple, and logical operation and large low-reflection display. Its small size required little tractor cab space. To apply the desired rate (kg [target nutrient] ha^{-1}), the operator needed to sample the separated slurry fraction and have it its nutrient content analysed in a laboratory. The obtained value (in kg Mg^{-1} of manure), the target application rate (in kg [nutrient] ha^{-1}), and the working width were then entered on the control panel (Fig. 2).

The on-board computer calculated the application rate using Eq. (1):

$$q = \frac{Q \cdot W \cdot F}{0.6 \cdot T_n} \qquad (1)$$

Where

q is manure flow rate (kg min^{-1}),

Q is target nutrient application rate (kg [nutrient] ha^{-1}),

W is working width (m),

F is forward speed (km h^{-1}) and

T_n is target nutrient content in manure (kg Mg^{-1}).

Specific capacity (kg rev^{-1}) of the conveyor sprocket was found by a preliminary test to depend on chain conveyor velocity, hopper rear wall height over the moving floor, and product characteristics. To ensure manure nutrients are applied at the desired rates, the metering device had to be calibrated whenever a new source of manure with different characteristics (e.g., moisture content) was used. The automatic controller adjusted the product application rate to the travel speed and working width of the spreader. The system checked if the applied application rate matched the target value by determining the rotating speed of the chain conveyor sprocket, and if necessary, altering its speed. The spreading system consisted of two hydraulically-driven belt conveyors and two hydraulically-driven spinning plates positioned on both sides of the machine. The pulleys of the belt conveyor counter-rotate (the left runs counter clockwise and the right runs clockwise) when the material was being spread on both sides of the machine. The plates rotated clockwise (or counter clockwise) when the material was applied on one side only (i.e. left or right, respectively). The chain conveyor pushed the solid fraction through the opening in the rear wall of the hopper that was held 0.1 m above the moving floor during spreading in order to deliver a constant flow of solid fraction onto the belt conveyors. The product is then carried to the spinning plate and spread onto the soil.

The spinning plates were mounted on a frame that could be adjusted 0.5 m from the sides of the machine, allowing for working width to be adjusted from 3.9 to 6.0 m. Both rotation speed and spinning plate inclination were adjustable for the spreading ranges found in different orchard row spacings (Fig. 3).

2.3. Functional trials

Machine performance was tested for transverse and longitudinal distribution evenness (European Standard EN 13080 indications) and accuracy of the automatic rate controller. All tests used pig slurry separated solid fraction obtained by a screw-press (Chior® model 300, Chior Meccanica SRL, Campitello di Marcaria, Mantova, Italy) installed at a “farrow to finish” farm in Cuneo Province. Pig slurry solid fraction produced by a screw press was used, since mechanical slurry separation by screw press is commonly performed on pig farms in the Piemonte region. Specifically, the trial solid fraction had a 24% total solids (TS) content, a 3kg Mg^{-1} TN content, and a density of 650 kg m^{-3}.

2.3.1. Longitudinal distribution evenness

The separated fraction flow of the test unit was calculated from measurements of changes in mass and elapsed time from start to the point when the flow dropped by 5.0 kg s^{-1}. A portable single axle weighbridge scale (Sinergica® model WWSD10T, Sinergica Soluzioni S.r.l., Montesilvano, Pesaro, Italy) was employed for this purpose. The rate controller was set to apply 50 and 25 kg [N] ha^{-1} to a 4.0 m width at 5.0 km h^{-1} forward speed, and the scale control device was set to record the weight every 5 s during hopper emptying. The tests took place on a separated solid platform near an above-ground storage tank.

2.3.2. Automatic rate controller accuracy

A series of tests was conducted to assess precision and response time of the automatic rate controller with variations in spreader forward speed. The tests were performed by adding a proximity sensor to the spreader wheel on a hydraulic-driven roller device to allow simulation of different forward speeds (1.0 - 10.0 km h^{-1}). A data logger recorded the signals from the wheel proximity sensor and from the speed sensor mounted on the chain conveyor sprocket shaft. The central unit was set to three different application rates (20, 40, and 60 kg [N] ha^{-1}); forward speed was continuously changed by an average value of 3.5 km h^{-1}. In a second set of tests, machine forward speed was continuously altered by an average value of 5 km h^{-1} with an application rate of 60 kg [N] ha^{-1}. The response of the chain conveyor sprocket to forward speed changes was continuously recorded in all tests.

2.3.3. Transverse distribution evenness

Tests were carried out on a horizontal surface with negligible wind velocity and the forward speed was set to 5.0 km h^{-1} (EN 13080, 2002). To measure transverse distribution evenness, 0.5 x 0.5 x 0.1 m collection containers were placed to the right of the spreader (when viewed in the direction travel), with their edges parallel to the ground surface and perpendicular to the line of travel of the machine, along its total spreading width. The spinning plate was maintained in a horizontal position and operated at 330 rpm. The amount of solid fraction collected in each container was weighed using an electronic scale (Kern ECB 50K50, KERN & Sohn GmbH, Balingen, Baden-Wu¨rttemberg, Germany; capacity 50 kg, accuracy 0.05 kg). The data were then processed according to EN 13080 (2002) to obtain the distribution pattern of the machine and the coefficient of variation (CV).

A test was also performed to assess the potential range of band width with adjustment of the spinning plate incline and rotation speed (Fig. 4). Three rotating speeds (250, 330, and 400 rpm) and two inclinations of the plate (0 and 30°) were compared.

2.3.4. Separated solids spreader productivity

Machine capacity is used to predict equipment performance in a farm system, which determines operating efficiency. If a series of operations contain an activity that is a “system bottleneck,” the capacity of the entire system will be reduced due to the prolonged time for a single step (Bochtis & Sørensen, 2010). Most farmers consider capacity (ha h^{-1}) as a quick way to evaluate the ability of a machine to complete a task in a timely fashion. However, on most farms, other associated operations must be completed during manure spreading (Grisso et al., 2008). For example, during manure spreading operators must refill the spreader hopper as it empties and transport the manure from storage to the field.

Fertilisation tests were performed with the prototype in a peach orchard (cv Spring bright, orchard design 1.80 x 3.90). The solid fraction was applied during the second half of April to a plot of 5500 m^2. During the trials, two N application rates (25 and 50 kg [N] ha^{-1}), forward speeds from 5.5 to 6.5 km h^{-1}, and a working width of 3.9 m were tested. To verify the ability of the spreader to maintain the required application rate, the spreader was weighed before and after the two distributions on a portable, single axle weighbridge scale (Sinergica® model WWSD10T, Sinergica Soluzioni S.r.l., Montesilvano, Pesaro, Italy) with a 10,000 kg capacity and ±1.0 kg accuracy. During manure application, the following working times were recorded following ASABE (2010) Standard indications:

- theoretical field time (effective manure distribution time);
- in-field displacement time (machine time in the field with metering and distribution systems off, such as travel in the field and turning time)

- travel time (travel to and from field, farmstead movement to reach the separated solids platform);
- loading time (time required to fill hopper);
- time to repair, maintain, and set machine.

These factors were used to determine theoretical field product capacity and machine field efficiency. Recorded data led to development of a worksheet to value the effect of different operating conditions on machine efficiency, alternative transport options, and suitable distribution chains for pig slurry separated solids distribution in orchards. Spreader productivity was measured under the following conditions: machine forward speed of 6.2 km h^{-1}, manure spread at a working width of 3.9 m, and average transport distance of 1450 m. In this scenario, N was applied at 25.0 kg ha^{-1} and 50.0 kg ha^{-1}.

3. Results and Discussion

3.1. Longitudinal distribution evenness

The flow of separated fraction during hopper unloading in conditions of 50 kg [N] ha^{-1} and 25 kg [N] ha^{-1} averaged 8.7 kg s^{-1} and 4.6 kg s^{-1}, respectively. A steady product flow produces good longitudinal distribution and is fundamental to proper application rate control (Hansen, 2004). For each longitudinal distribution test, the stretch within the tolerance zone was determined as the sum (in %) of the sub-stretches during which momentary flows lay within ± 15% (EN 13080, 2002). Results were 69.7% at 50 kg[N] ha^{-1} and 71.3% at 25 kg[N] ha^{-1} of unloading time (Fig. 7).

One of the main problems in longitudinal evenness is the management of the distribution tail, that is, as the hopper becomes empty, product flow falls below the tolerance zone (15% of the steady flow limit). However, under our test conditions, the shape of the overlapped longitudinal distribution diagram indicated that good longitudinal evenness (CV below 15%, data not shown) was attained.

3.2. Automatic rate controller accuracy

The tests showed that the controller read the output signals well from the various sensors and that the control devices sufficiently managed (solenoid valves that control the hydraulic system) the engine that moved the sprocket of the chain conveyor.

The automatic rate controller demonstrated its ability to rapidly adjust the rotation speed of the sprocket following variations in machine forward speed. The system adjusted the hydraulic pump rotational speed in < 2 s (Fig. 6).

The rate control system enabled the operator to apply the desired amount of TN, regardless of spreader forward speed. Errors between programmed and measured N application rates ranged between 1 and 10 %. With a working width of 4 m and a N content of separated solids of 3 kg m^{-3}, the machine applied nitrogen at a rate of 40.0 ± 0.4 kg [N] ha^{-1} despite two significant forward speed changes that required about 10 s each to return to the specified application rate (Fig. 7). Similar good responses to speed variations were also obtained with application rates of 20 and 60 kg [N] ha^{-1}.

3.3. Transverse distribution evenness

Tests performed to assess the transverse distribution pattern according to the incline and rotation speed of the spinning disk resulted in a CV from 8.5 % to 28.8 % (Fig. 8), which complied with EN Standard 13080 (2002) requirements (i.e., CV <30 %) for good uniformity of manure spreading. The 30 ° rearwards inclination at 330 rpm spread most of the product across 1.0 m wide area, which is considered as meeting the requirement to apply the solid fraction to the area where plant nutrient uptake occurs. This setting also gave higher uniformity (Fig. 8).

3.4. Separated solids spreader productivity

For the scenario where N was applied at 25.0 kg ha^{-1} (8.3 Mg ha^{-1} material with 3 kg [N] Mg^{-1} content), the machine recorded a product capacity of 6.8 Mg h^{-1} and a field capacity of 0.8 ha h^{-1} (32.8 % field efficiency) (Fig. 9). At an application rate of 50 kg [N] ha^{-1} (16.6 Mg ha^{-1}), the machine recorded a product capacity of 8.1 Mg h^{-1} and a field capacity of 0.5 ha h^{-1}, which gave a field efficiency of 19.5 %.

The low values of field efficiency were primarily due to the high incidence of travel time to and from the field and secondly the incidence of in-field movements (to arrive at the distribution starting point and to arrive at the field hedge following hopper emptying). Field efficiency can be improved by optimising spreader in-field runs and avoiding hopper emptying in the forward path and/or filling it in-field. Taking the scenarios described above, and assuming a forward operating speed of 6.2 km h^{-1}, and a working width spread of 3.9 m, calculations demonstrated how it was possible to increase field efficiency to 62.3 % and 46.5 % at application rates of 25.0 kg [N] ha^{-1}and 50.0 kg [N] ha^{-1}, respectively. These values correspond to field capacities of 1.5 and 1.2 ha h^{-1} and to product capacities of 12.9 and 19.2 Mg h^{-1} (Fig. 10).

In-field loading of the spreader hopper required that a product heap be formed at the edge of the field. To avoid nitrogen loss of nitrogen in the form of ammonia emissions and nutrient leaching during storage (Petersen & Sørensen, 2008), it is preferable to transport the material immediately before spreading. In this case, the transport chain, from the separated solids platform to the field, must achieve a product capacity equal to, or above that, of the spreader. Thus, if separated solids are distributed at 16.6 Mg ha^{-1}, then the transport chain must operate with a minimum product capacity of 19.2 Mg h^{-1}. Therefore, if a three-axle trailer of 15 Mg (i.e. maximum legal gross weight 20 Mg) is used and unloaded closed to the field hedge, the transport distance has to be no greater than 8.5 km. If a 16 Mg dumper were mounted on the three-axle truck (i.e. maximum legal gross weight 25 Mg), it would be possible to operate with a transport distance of 19.0 km.

4. Conclusions

The prototype spreader appeared to be a reliable machine for swine slurry separated solids application in orchards when nutrients are applied at the proper amounts and uniformity with a well-performing automatic rate controller. Specifically, under the test conditions, the spreader application rate uniformity performance satisfied the EN 13080 standard requirements for efficient manure field handling. Since manure characteristics may affect machine performance, confirmatory trials should be performed using different doses and manure types (e.g., cattle slurry solid fraction, digested slurry solid fraction).

The spreader accommodates a wide range of settings that enables the operator to fit different row spacing and operating conditions, such as solid fraction application in narrowly spaced orchard rows. By setting the rotation speed and spinning plate incline, manure can be applied correctly to meet row spacing and plant dimensional needs. To achieve the best field capacity results required that the spreader hopper be loaded close to the field hedge. In addition, this technique needs to be paired with the proper transport chain that dictates more investment and higher running costs, supportable only by large farms or contractors. Until now, the GPS system has only been tasked with manure N application traceability, but it could be integrated into a solid fraction precision application system.

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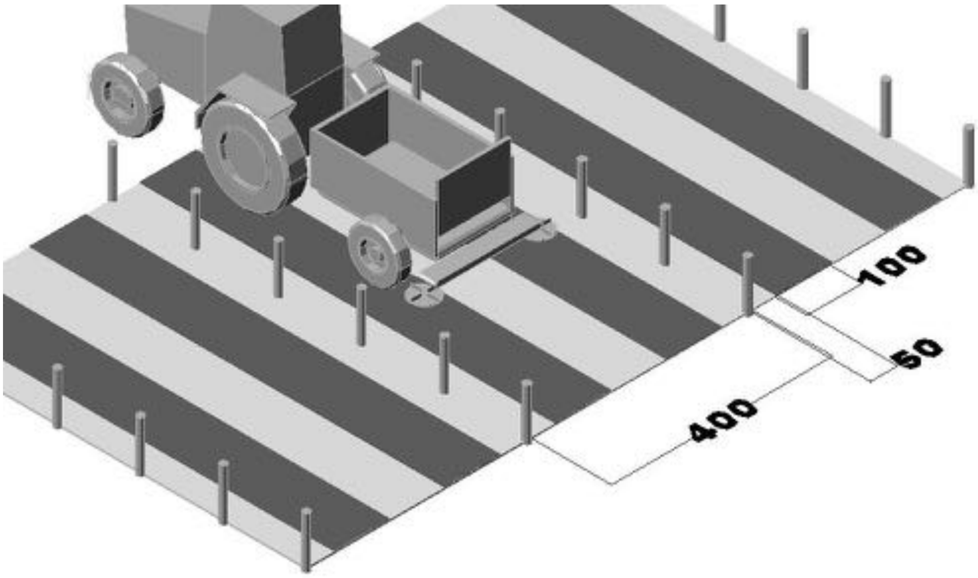
100
50
400

Fig. 1.

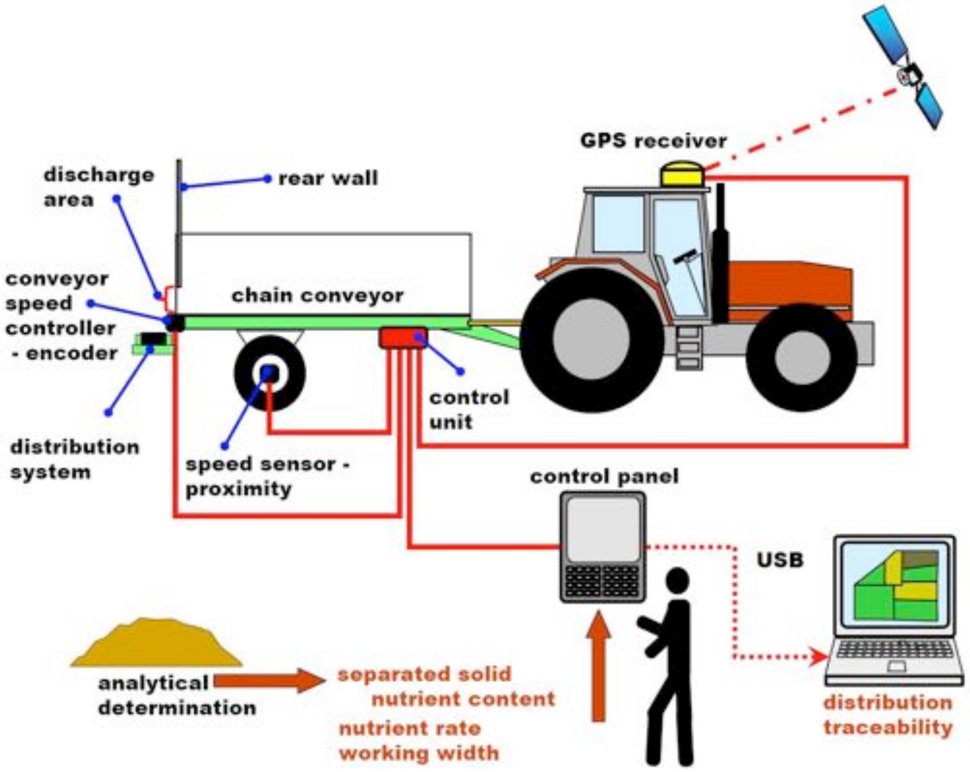
GPS receiver
discharge area
rear wall
conveyor speed controller - encoder
chain conveyor
control unit
distribution system
speed sensor - proximity
control panel
USB
analytical determination
separated solid nutrient content
nutrient rate
working width
distribution traceability

Fig. 2.

(a) (b)

Fig. 3.

Fig. 4.

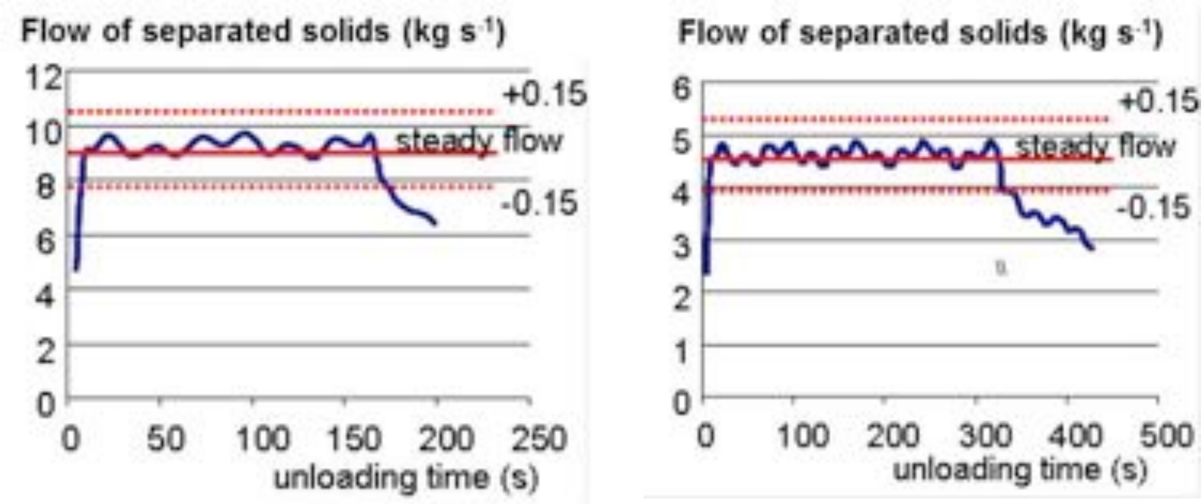

Fig. 5.

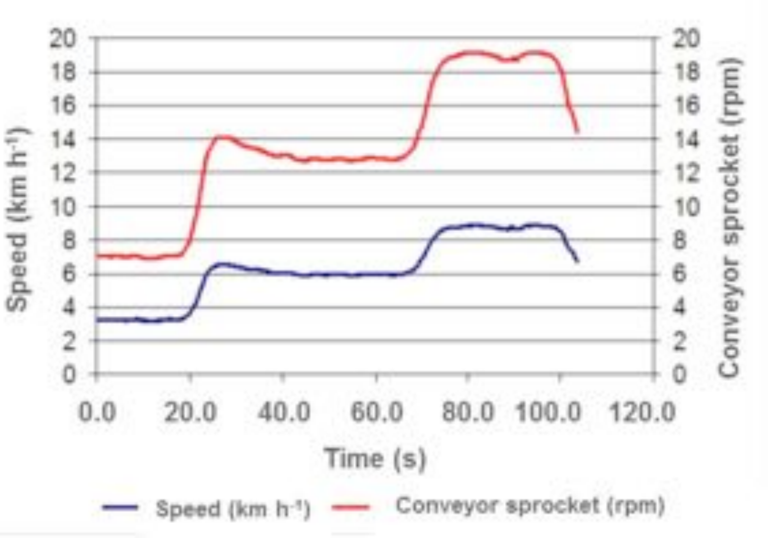
Speed (km h-1)
Conveyor sprocket (rpm)
0
2
4
6
8
10
12
14
16
18
20
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time (s)
Speed (km h-1)
Conveyor sprocket (rpm)

Fig. 6

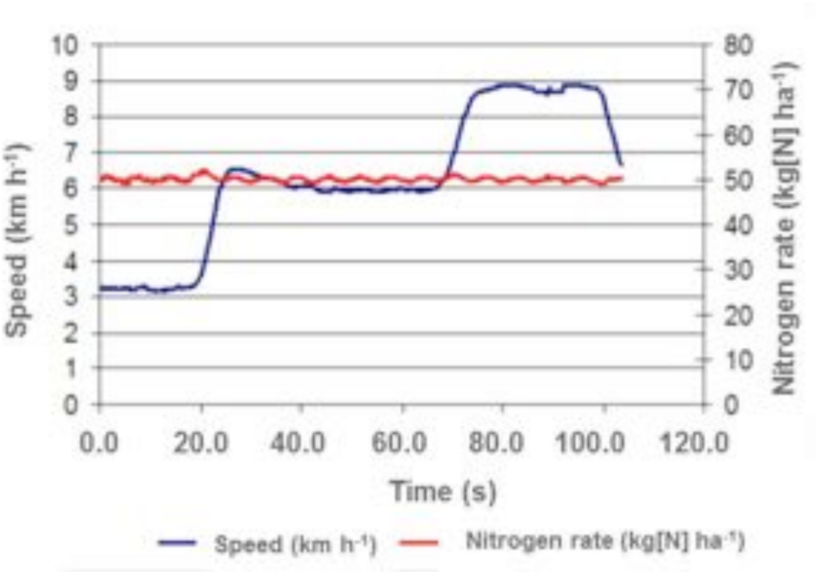
Speed (km h-1)
Nitrogen rate (kg[N] ha-1)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Time (s)
Speed (km h-1)
Nitrogen rate (kg[N] ha-1)

Fig. 7

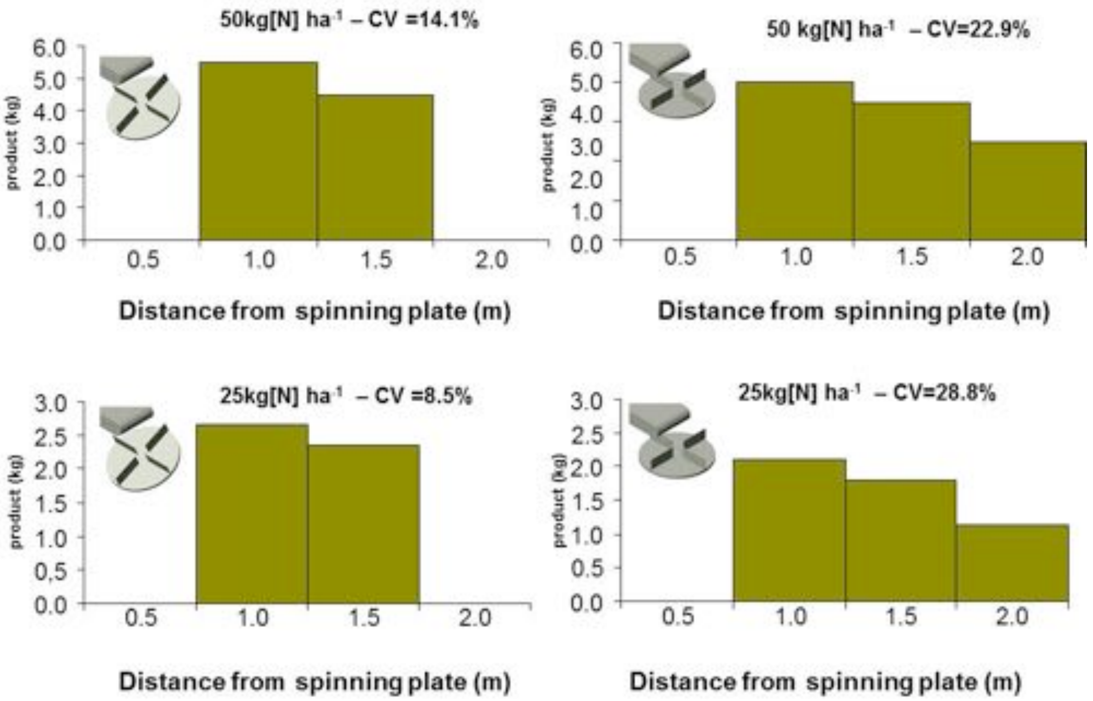
50kg[N] ha-1 – CV =14.1%
50 kg[N] ha-1 – CV=22.9%
25kg[N] ha-1 – CV =8.5%
25kg[N] ha-1 – CV=28.8%
product (kg)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
2.5
1.5
0,5
0.5
Distance from spinning plate (m)
0.5
1.0
1.5
2.0

Fig. 8.

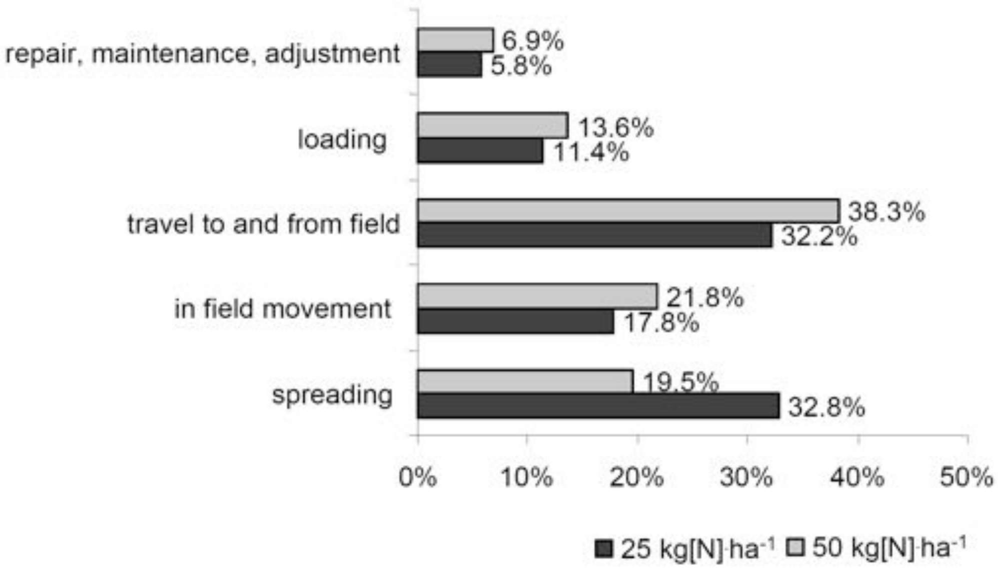
repair, maintenance, adjustment
loading
travel to and from field
in field movement
spreading
6.9%
5.8%
13.6%
11.4%
38.3%
32.2%
21.8%
17.8%
19.5%
32.8%
0%
10%
20%
30%
40%
50%
■ 25 kg[N]·ha-1 □ 50 kg[N]·ha-1

Fig. 9.

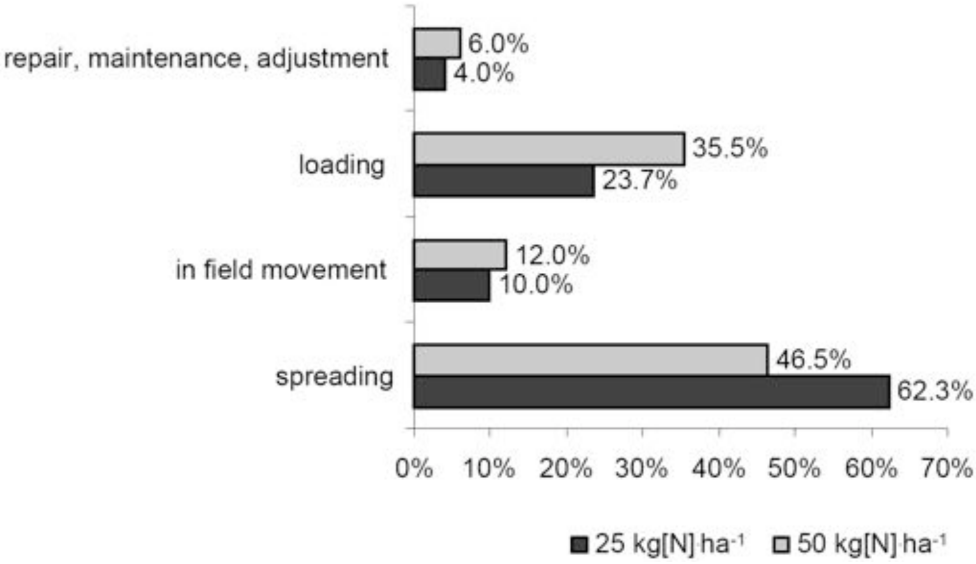
repair, maintenance, adjustment
6.0%
4.0%
loading
35.5%
23.7%
in field movement
12.0%
10.0%
spreading
46.5%
62.3%
0%
10%
20%
30%
40%
50%
60%
70%
■ 25 kg[N]·ha-1
□ 50 kg[N]·ha-1

Fig. 10.

Figure captions

Fig. 1. Separated solids spreader with application device and tree fertilization manure bands (dark grey). Measurements in cm.

Fig. 2. Schematic of the automatic rate control system.

Fig. 3. Belt conveyors (a) and right spinning plate (b).

Fig. 4. Spinning plate at 0 ° (left) and 30 ° inclination (right).

Fig. 5. Flow of separated solids (3 kg [N] Mg^{-1}) during hopper unloading time in the case of a 4.0 m working width, 5.0 km h^{-1} velocity, and application rates of 50 kg [N] ha^{-1} (left) and 25 kg [N] ha^{-1} (right).

Fig. 6. Response time of the conveyor sprocket rotation vs the machine forward speed.

Fig. 7. The automatic rate controller allows a steady application rate. In this case, 40 kg [N] ha^{-1} of separated solids was applied with spreader forward speeds ranging between 3 and 9 km h^{-1}.

Fig. 8. Distribution patterns at different application rates and spinning plate inclines at 330 rpm.

Fig. 9. Incidence of different work times in field trial conditions. Total time: 25.9 min with the rate of 25.0 kg [N] ha^{-1}; 21.8 min with the rate of 50 kg [N] ha^{-1}.

Fig. 10. Incidence of different work times in the case of in-field spreader tank load. Total time: 12.4 min with rate of 50.0 kg [N] ha^{-1}; 16.5 min with rate of 25.0 kg [N] ha^{-1}.