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PNEUMATIC FERTILIZER SPREADERS
– a Review of the Literature

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1 SUMMARY

Swedish agricultural soils are reported to receive an annual application of plant nutrients as fertilizer amounting to a value almost as large the total new-investment made during one year. Poor precision in nutrient supply results in yield decreases and environmental loading.

The purpose of this work is to summarize the knowledge available today on factors that influence fertilizer distribution achieved by pneumatic fertilizer spreaders. The work is mainly concentrated on technical design parameters that influences the spreading uniformity parallel to and at right angles to the direction of travel.

The average coefficient of variation for the evenness of spreading of today's fertilizer spreaders is 25% in the field. In practise, there is no significant difference between centrifugal spreaders and pneumatic spreaders.

During the work of which this report accounts for, 87 Swedish and international references have been studied in order to find factors influencing the result of fertilizer spreading.

Factors influencing the spreading result can be divided into: the fertilizer, the machine, the field the weather and the operator.

The flow properties of **the fertilizer** and its tendency to deposit on working mechanism are affected by its physical properties. The particle size distribution influences length of throw, flow properties and tendency of separation. The durability of the fertilizer will affect the particle size distribution. Particle shape and surface texture affect the flow properties. Density influences throw properties. Hygroscopicity influences water uptake and thereby flow properties and tendency to deposit within the machine. Thixotropic fertilizers lead to hard deposits being placed on working mechanisms and transport ducts against which the fertilizer glides.

The machine can be divided into fertilizer hopper, feeder mechanism, fan, piping, spreader boom and spreader mechanism.

When filling a hopper separation generally occurs. Severe separation influences the resulting distribution. When emptying the hopper the slope of the floor will influence the amount of fertilizer remaining in the hopper. 60-65° slope of the bottom of the hopper will ensure complete emptying.

Metering mechanisms can be divided into active and passive mechanisms. The function of passive mechanisms depend on the flow properties of the fertilizer. The studded roller is a semi-active metering mechanism. Cyclic variations in out-flow may occur in metering devices that measure out the fertilizer in portions, e.g. cell wheels, star wheels and augers. Shaking and slope of hopper influences the mass flow from passive metering mechanisms.

The fan is used to transport the fertilizer within the machine. The flow of air can be used to reduce drift caused by wind if both the flow of fertilizer and the flow of air are directed downwards at the spreading mechanism. At high fertilizer application rates the fan-pipe system in modern fertilizer spreaders tend to overload, with pulsating flows as a result. These pulsating flows are reflected in a severe deterioration of the spreading uniformity.

The piping functions as a way of transport of the fertilizer. Piping with a high coefficient of friction leads to a rapidly attained even radial distribution of granules in the pipe. Curves induces pressure losses and deteriorated radial distribution in the pipe. Bends immediately before the spreading mechanism should be avoided.

Movements of the spreader boom influences the final result of fertilizer spreading. Boom movements occur largely as a result of the torque of the fertilizer vehicle along its respective longitudinal and vertical axles. The response of a boom suspension to the rolling motion of the vehicle to which it is attached should be such that the boom is insulated from the high frequency random rolling movements but is able to follow the low frequency undulations of the ground. An example of such a boom suspension is found in the literature.

In the literature, spreader mechanisms are found in many different shapes. Significant for the majority of them is that their evenness of distribution is sensitive to the radial distribution of granules in the pipe immediately before entering the spreader mechanism. The evenness of distribution is also sensitive to the working height above the ground.

The field will through its geometry (shape, slope and bumpiness) affect the working result in form of unevennesses in the spreading pattern, gaps and overlapping. Soil type variations and varying cultivation capacity demand variable application rates.

The weather factors that mainly influence the spreading accuracy are wind speed, air temperature and relative humidity. The wind speed influences the length and direction of throw. Air temperature and moisture are together with the temperature of the fertilizer decisive for the water uptake of the fertilizer. Large water uptake will change the flow properties of the fertilizer in a negative direction.

The operator is the overall regulator in the "granule spreading system". The operator adjusts and maintain the machine. It is the operator who choses driving technique and the way the work is done. A technically very good fertilizer spreader cannot compensate fully for a bad operator. The operator should have assistance in steering the tractor and information of and possibility to adjust the application rate.

What requirements can be placed on **the future fertilizer spreader**? The requirements placed on the fertilizer spreader of the future involve large control ability, i.e. high spreading accuracy and possibility to continuously vary the application rate. Furthermore, some kind of control over the mass flow of fertilizer will be needed.

This review of the literature is concluded with a presentation of a new type of fertilizer spreader. The concept gives precedence to low manufacturing cost, active metering mechanism, variable mass flow and even distribution of fertilizer to the spreader mechanisms.

2 INTRODUCTION

Swedish agricultural soils are reported to receive an annual application of plant nutrients as fertilizer amounting to a value of about 2.4 milliard SEK (Yearbook of Agricultural Statistics, 1989). This is an amount that is almost as large as the total new-investments made during one year, or 10% of the total costs of agriculture. Plant nutrient supply largely takes place through spreading on the surface (B. Nilsson, pers. comm.). Modern fertilizer spreaders today have a spreading uniformity with a coefficient of variation of about 25% (Nilsson, 1986).

Yield decreases, quality deterioration and environmental loading as a result of poor precision in nutrient supply can only be stated as a qualified guess. The relevant plant-physiological relationships and the prevailing field conditions are still not fully known. However, there are indications that the costs are of a magnitude of 500-600 million SEK (T. Bergström, pers. comm.).

The reduction of profitability as a result of poor spreading uniformity is nothing new. Already 20 years ago it was considered that "There was no question that agriculture threw away millions of SEK through poor quality of fertilizer spreading" (A:son Moberg et al, 1969).

The requirements placed on the fertilizer spreader of the future involve large control ability, i.e.,

* High spreading accuracy
* Possibilities to continuously vary the application rate.

These require that the spreader has a good basic design with a good spreading pattern together with some form of control that enables the flow of fertilizer to be checked and modified. In the future, there will probably also be a need to be able to vary the spreading pattern in order to be able to control the application rate according to the need of nutrients within the bout.

2.1 EXTENT OF THE STUDY

Fertilizer spreading and its effects have been studied by many researchers throughout the present century. If a literature study of this kind is not to become unsurveyable owing to its volume, then some kind of limitation must be introduced. The author has chosen to restrict himself to a certain type of spreader, namely the pneumatic fertilizer spreader. Despite this limitation, much of the material in this study of the literature applies in general to all fertilizer spreading.

The pneumatic spreader has been chosen since it has been found to have advantages over other types of spreaders. The spreading pattern can be made trapeze-shaped with steep flanks (see Fig. 2.1), which permits a fairly constant working width regardless of the fertilizer's physical properties. The shape of the spreading pattern in combination with a good bout marking system provides possibilities for high spreading uniformity in the field. Broadcasters have a variable working width depending on the throw properties of the granules varying with the type of fertilizer. In addition, a broadcaster requires large overlapping in order to obtain a uniform pattern of spread. This implies problems when applying fertilizer along ditches, etc.

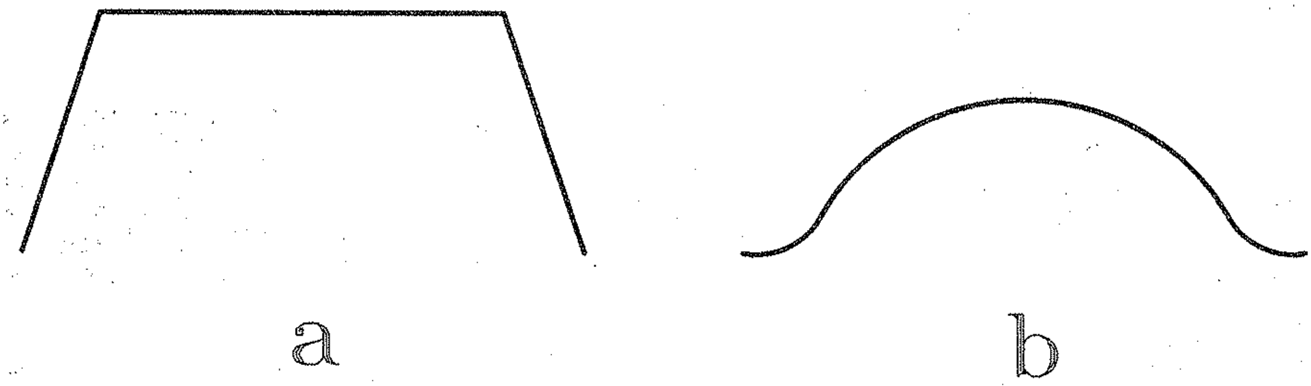


Figure 2.1. Principle pattern of spread from a pneumatic spreader (a) and from a single-disc centrifugal spreader (b). Source: Own illustration.

According to available research results, the pneumatic system has higher potential than other systems as regards moving fertilizer without problems from the delivery mechanism to the spreaders (Heege and Hellweg, 1982a; 1982b).

In a broadcaster, the transport (the throw) is outside the control of the machine. Consequently, precision in the transport largely depends on factors involving the weather and the terrain. In pneumatic transport systems most of the transport takes place within the machine where the granules are protected from the influence of wind. In addition, the influence of air humidity should decrease slightly since the fan adds some heat to the transport air. It is only during the last few metres that material is exposed to the full influence of the weather and the field factors.

Mechanical transport systems grind the fertilizer into powder and increase the risk of separation, in contrast to the situation in pneumatic systems (Heege and Hellweg, 1982a, 1982b). Transport systems that expose the material to rubbing increase the risk of thixotropic deposits (Nilsson, 1975). The material in a pneumatic transport system is rubbed considerably less than in a mechanical system. In addition, a pneumatic transport system can be designed to handle hygroscopic material (Hilbert, 1986). Hygroscopicity may cause problems in mechanical transport systems since the flow properties of the fertilizer are drastically changed upon uptake of water.

2.2 DESIGN OF THE STUDY

The study is designed in the following way. Initially, an orientation is given on how spreading uniformity is measured, and how the measuring methods can influence the result. In addition, a discussion is given of the links between the crop requirements for spreading accuracy and the results obtained during tests.

Most of the study deals with factors that influence the spreading result. These factors are divided into the fertilizer, the machine, the field, weather factors and the operator.

The study ends with a discussion.

Discussion on and criticism of individual details are taken up in direct conjunction to the chapter where the detail is mentioned. The more principal questions are returned to in the concluding discussion.

3 PURPOSE OF THE STUDY

The purpose of this work is to summarize the knowledge available today on factors that influence the fertilizer distribution achieved by pneumatic fertilizer spreaders. The work is mainly concentrated on technical design parameters that influence the spreading uniformity parallel to and at right angles to the direction of travel.

4 DETERMINATION OF SPREADING UNIFORMITY

In analyses of the work done by a granular spreader it is important to distinguish between the spreading pattern and the spreading uniformity. The spreading pattern is defined as the fertilizer's distribution at right angles to the driving direction in one single bout. Spreading uniformity refers to deviations in application rate between two or more selected areas where the fertilizer has been spread.

In order to compare the ability of different fertilizer spreaders as regards spreading uniformity, the spreading pattern must be determined in some way. Generally, one or other variations of the following method are used:

1. Place out a row of collection vessels at right angles to the direction of travel.
2. Drive past the collection vessels with the spreader working.
3. Weigh the amount of fertilizer in each vessel.
4. Compile and present the results.

If the fertilizer distribution parallel to the direction of travel is to be measured, the vessels are instead placed parallel to the direction of travel. When measuring the spreading uniformity in the field across the direction of travel, then space for the wheels must be left between the collection vessels. The testing institutes usually instead run the spreader on a grid or on rails above the collection vessels in order to be able to also measure the amount of fertilizer that falls in the wheel tracks.

4.1 WHAT IS A MEASURE OF DISPERSION?

The intention of fertilizer spreading is to supply the crop with the necessary amount of fertilizer. Today, there is no suitable method of rapidly reading-off the fertilizer requirement on small areas. Instead, the farmer tries to give the crop a certain total amount that is evenly distributed over the entire field. In describing the uniformity of spread given by different granular spreaders, use is generally made of a statistical spreading measure. However, the spreading measure of fertilizer dispersion given by a fertilizer spreader may refer to several different things.

In repeated measurements of the spreading pattern according to the method mentioned above, the amount of fertilizers that falls into a specific vessel will, in practice, vary between different experiments even when a good spreader is used. This variation is random under the condition that the adjustment of the machine is not changed during the test. For each vessel a mean value and a measure of dispersion for the amount of fertilizer can be calculated. The spreading measure shows the stability of the fertilizer delivery mechanism.

When determining the spreading pattern, the divergence from the mean rate can be calculated for each specific collection vessel. By varying the distance between the central point of two such spreading patterns, it is possible to obtain an optimal working width. This optimal working width generally includes some overlapping. At this working width a spreading pattern can be determined for the best possible spreading uniformity. The alternative is to remain at a given working width and calculate the measure of dispersion for this width. Both methods show the systematic deviations of the spreader from the mean value. The method to be chosen depends on the aim of the tests. If the aim is to find a machine to be used in a cropping system with tram-lining at drilling, then the working width should be fixed at an even multiple of the width of the seed drill. If the intention is to find the spreader with the highest possible spreading uniformity that can be obtained, then the best possible working width should be calculated.

When spreading fertilizer in the field, random and systematic deviations will overlap each other. This overlapping depends not only on the machine's properties but is also influenced by the operator, the field and weather. The final result of the work, the spreading uniformity in practice, will subsequently here be called practical spreading uniformity. This is done to distinguish it from the spreading uniformity measured in laboratory tests. Practical spreading uniformity thus refers to the actual result of fertilizer spreading and the spreading pattern is only one of several influencing factors. It is possible to determine a measure of dispersion also for spreading uniformity. This can be done by a random placement of the collection vessels in a field that is to be fertilized.

Examples of measures of dispersion for evaluation of distribution experiments have been given by Papatheodossiou (1970), Rühle (1975) and Bergström (1987).

1. Mean absolute deviation
2. Standard deviation
3. Coefficient of variation
4. Aspect ratio
5. Autocorrelation
6. Distribution index

Among these measures, the coefficient of variation is the measure of dispersion generally used. Standard deviation is also an accepted spreading measure. Mean absolute deviation and aspect ratio are not used in Sweden, but are found in the reference literature and thus are explained below.

4.1.1 Mean Absolute Deviation

The mean absolute deviation (in the literature also called linear deviation) is the sum of the absolute figures for the deviations of individual observations from the mean value of the experiment divided by the number of observations (Wonnacott and Wonnacott, 1977). The reason for using the absolute figures is that positive and negative deviations would otherwise counter-balance each other and the sum of the deviations would be zero.

$$la = \frac{1}{n}\sum_{i=1}^{n}\left|x_i - \bar{x}\right| \qquad [1]$$

la = Mean absolute deviation
n = Number of observations
x_i = Value of an individual observation
$\bar{x}$ = Mean value of all observations

In mean absolute deviation the influence of the deviations is proportional. This implies that the deviation of 10 from the mean value has the same influence as two deviations of 5 from the mean. This is in contrast to the standard deviation (author's comment).

4.1.2 Mean Squared Deviation and Standard Deviation

Even if the mean absolute deviation intuitively is a good spreading measure, the absolute figures imply that there are difficulties in further mathematical calculations (e.g., when seeking extreme points). An alternative way of handling negative deviations is to square the deviations. This will give a measure of the variation within the test.

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \qquad [2]$$

σ^2 = Mean squared deviation
n = Number of observations
x_i = Value of an individual observation
$\bar{x}$ = Mean value of all observations

This measure describes the spread within the test. By proceeding one further step, it is possible to make a statistical prediction of the variation within the population from which the sample is taken.

By dividing the squared deviations by the number of observations (n) we get an estimate of the mean square deviation within the test. By decreasing the degrees of freedom, it is possible to make a statistical prediction of the population. In this case, n-1 is placed instead of n in the denominator (Wonnacott and Wonnacott, 1977).

$$\hat{\sigma}^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 \qquad [3]$$

$\hat{\sigma}^2$ = Variance
n = Number of observations
x_i = Value of an individual observation
$\bar{x}$ = Mean value of all observations

By obtaining the root of the variance it is possible to obtain the standard deviation (s).

$$s = \sqrt{\hat{\sigma}^2} \qquad [4]$$

4.1.3 Coefficient of Variation

The coefficient of variation is a relative measure of dispersion that gives the standard deviation as a percentage of the mean value (Rühle, 1975):

$$CV[\%] = \frac{100 \cdot s}{\bar{x}} \qquad [5]$$

CV = Coefficient of variation
s = Standard deviation
$\bar{x}$ = Mean value of all observations

4.1.4 Aspect Ratio

Since most of the dispersion organs are designed to give a symmetrical spreading pattern it may be of interest to compare the delivered volumes on each side of the symmetry axis. The aspect ratio gives the proportion of the totally collected amount of granules dispersed during the tests to the left and to the right (Papatheodossiou, 1970).

As mentioned earlier, this measure is not used in Swedish tests. Nonetheless, it could be used when testing fertilizer spreaders. The Swedish National Machinery Testing Institute generally states the change in delivered volume on the left or the right side on sloping machines in comparison with when the machine is on a horizontal surface. This value could be replaced by the aspect ratio.

$$\mathrm{AR}_l \quad [\%] = \frac{M_1}{M} \cdot 100 \quad : \quad \mathrm{AR}_r \quad [\%] = \frac{M_2}{M} \cdot 100 \qquad [6]$$

AR = Aspect ratio, left (l) and right (r)
M_1 = Sum of observations on left side
M_2 = Sum of observations on right side
M = Sum of all observations

4.1.5 Autocorrelation

The autocorrelation function for a time discrete magnitude can be estimated by

$$r_{uu}(t) = \frac{1}{N} \sum_{\tau=1}^{N} u(\tau) u(\tau + t) \qquad [7]$$

$r_{uu}(t)$ = Autocorrelation
$u(\tau)$ = Value of the magnitude at time τ
$u(\tau + t)$ = Value of the magnitude at time $\tau + t$
N = Number of observations

Thus, it is the mean value of the magnitude's value at a certain time multiplied by its value (t) units of time later. $r_{uu}(t)$ can, in itself, be used to, e.g., reveal any periodical fluctuations in a measured time series.

If one has access to measurement data extending over numerous cycles, even very small cyclic fluctuations that are impossible to directly observe in measurement data, owing to disturbances in the data, can effectively be revealed by the autocorrelation function (Gustafsson et al., 1982).

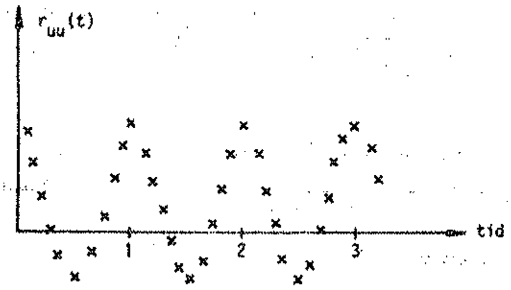


Figure 4.1 An example of an autocorrelation function for measurement data containing cyclic fluctuations (Source: Gustafsson et al., 1982).

In order to be able to compare or assess spreading results after fertilizer application as regards biological effects, data is required on the actual distribution on the field. Bergström (1987) proposes a measuring procedure based on the autocorrelation function. The proposal is to randomly distribute collection trays on a field to be fertilized. This can suitably be done by pacing out and placing trays in one or more lines across the field. The number of steps between different trays should be randomly chosen. The direction of these lines should be such that a number of spreader widths are crossed. The trays, fitted with a separator, should be orientated so that the separator is parallel to the direction of travel. By means of the separator it is possible to obtain a variance for both the entire tray and half the tray. This provides the opportunity, assuming there are, e.g., sinus-shaped patterns of spread, to estimate the auto-covariation between tray-halves (Autocorrelation = autocovariation / standard deviation).

That the separator should be parallel with the direction of travel depends on unevennesses along the direction of travel being frequently of systematic character. Naturally, it is also possible to have a separator at right-angles to the direction of travel in order to confirm whether the distribution longitudinally is of systematic character or not.

The experiences discussed by Bergström (1987) suggest that the trays should be about 50 cm wide and at least 50 cm long with a separator placed longitudinally.

4.1.6 Distribution Index

A less common approach to describing the spread, or the distribution pattern, in a population of plants, animals or granules, is to calculate a distribution index for the population concerned. Normally, there are three items of information looked for at the start of a quantitative study of a population. These are the individual density, whether the individuals are randomly distributed or not, and the degree of non-randomness if this is the case (Pielou, 1959).

Clark & Evans (1954) present a distribution index that is based on the distance from a selected individual to its nearest neighbour. Either a number of individuals is selected randomly or measurements are made of all individuals in the population. The index obtained by calculating the ratio between the measured and the anticipated mean distance to the nearest neighbour.

$$R = \frac{\bar{r}_A}{\bar{r}_E} \qquad [8]$$

R = Measure of the degree to which the observed distribution diverges from expected randomness with regard to the distance to the nearest neighbour.

$\bar{r}_A$ = Mean distance to the measured values to the nearest neighbour.

$\bar{r}_E$ = The expected mean distance to the closest neighbour in an infinitely large random distribution.

In a completely random distribution, $R = 1$. At maximum aggregation (clumping) $R = 0$ since all individuals are then at the same place. At maximum distances between individuals the population will form an hexagonal pattern, where $R = 2,1491$. This implies that within a restricted numerical range R describes different types of distributions.

Thompson (1956) developed the model of Clark & Evans (1954) by including the second, third, etc., nearest neighbours. Thompson (1956) considers that this improves the possibility to discover more large-scale heterogeneties in a population.

Pielou (1959) considers the method of Clark & Evans (1954) to be extremely laborious and that the result depends on the choice of individual at the measurements being truly random. Pielou (1959) prefers measuring from points with randomly selected coordinates to the nearest individual in a population, and a resulting independent determination of individual density. If ω is the square of the distance from a randomly chosen point to the closest plant in a randomly distributed population then, according to Moore (1954), quoted by Pielou (1959),

$$E(\overline{\omega}) = (n-1)/n\lambda \qquad [9]$$

$E(\overline{\omega})$ = Expectancy for $\overline{\omega}$.

λ = Individual density (number of distances/circle with a unity radius).

n = Number of measured distances.

If the individual density is independently measured and called πD, where D = number of individuals/unity area, then according to Pielou (1959),

$$E(\pi D\overline{\omega}) = (n-1)/n \qquad [10]$$

If $\alpha = \pi D\overline{\omega}$ is calculated and the result does not significantly differ from $(n-1)/n$, the population may be assumed to be randomly distributed. In an aggregated population an excess of large values of ω can be expected, which gives a high value on α. Similarly, a randomly distributed population would give fewer large values of ω and α would be smaller than $(n-1)/n$. Thus, α can be used as a measure of non-randomness (Pielou, 1959). The advantage of using this index (α) is that it provides an opinion of the total divergence from randomized distribution, not only at the lowest levels, which is the case if the distance between individuals is measured.

The authors mentioned above, who have worked with the distribution index, have only considered the distribution of points. Also a plant may be considered as a kind of point with this type of calculation (author's note). In fertilizer spreading and pest control it is, in addition, of interest to obtain sufficient cover of a given surface for the treatment to have the intended effect. Here, not only the distribution but also overlapping and gaps will be of importance.

Garwood (1947) presents an empirically developed formula which states the average proportion of a target area which is not covered by randomly placed circles. Erbach et al. (1976) continued the work on the problem involving distribution and cover. By assuming that each granule has a circular area within which it is effective, it was possible to calculate the cover given by granules and the overlapping between granules.

The distribution efficiency (E) is a measure of effectively used granules in comparison with totally distributed granules. The efficiency is given by

$$E = C/(C+O) \qquad [11]$$

C = The part of the area which is covered by the effective area of one or more granules.

O = Half of the area that the granule has in common with other granules (overlapping).

By defining the adequacy of the distribution (A) as the product of a covered surface (C) and the efficiency in the distribution (E) Erbach et al. (1976) considered that they had obtained a measure of how acceptable the distribution was. A high adecuacy requires both high degree of cover and high efficiency. The adecyacy (A) is given by

$$A = CE = C^2/(C+O) \qquad [12]$$

By using these measures of distribution Erbach et al. (1976) considered that they could demonstrate during pest control how the dose could be reduced by 50-75 % of what today is essential.

The disadvantage with these types of distribution indexes is that they are laborious. A number of distances must be measured for each test run (author's note). In addition, consideration is not paid to the mass of the individuals/population. The dispersed mass is of major importance for the result of the work when sowing, in pest control and in fertilizer application. However, the calculations made by Erbach et al. (1976) take indirect consideration to the mass since the effective area of the granule is included in the model.

There is, in addition, a serious objection to the argument by Pielou (1959). Pielou (1959) refers Equation [8] to Moore (1954). This is incorrect. Moore (1954) demonstrates that

$$E\left(\frac{n-1}{n}\cdot\frac{1}{\pi\overline{\omega}}\right) = D \qquad [13]$$

This implies that

$$E\left(\frac{1}{\overline{\omega}}\right) = \frac{n\pi D}{n-1} = \frac{n\lambda}{n-1} \qquad [14]$$

Assuming on the basis of Equation [14] that

$$E(\overline{\omega}) = (n-1)/n\lambda \qquad [9]$$

is incorrect. Equation [10] is not correct but, instead, the following applies (B. Lindqvist, pers. comm.)

$$E(\pi D\overline{\omega}) = 1 \qquad [15]$$

This implies that the index of Pielou (1959) is not theoretically unassailable. The consequence will be that Erbach et al. (1976) lose reliability since their evaluation of their own work is based on Pielou's index. Naturally, this need not imply that the method of Erbach et al. (1976) is incorrect.

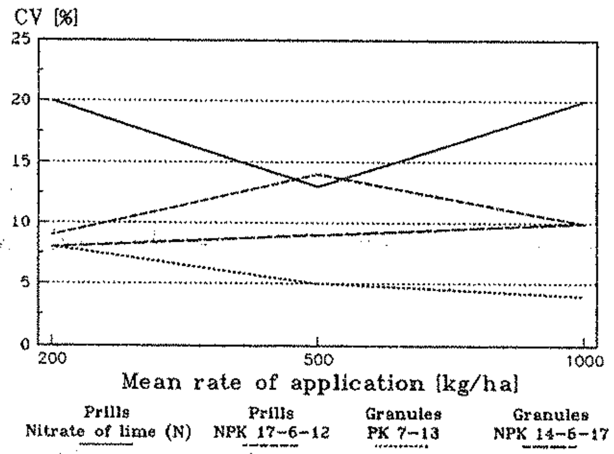
5 COMPARISONS BETWEEN DIFFERENT DISTRIBUTION TESTS

It is not always easy to compare evaluations of fertilizer spreaders. The presentation of results and evaluation methods may differ between different trials and tests. This will complicate comparisons between different tests and cause problems when interpreting the results.

5.1 PRESENTATION OF RESULTS

Different authors may chose different statistical measures of dispersion. There are examples where both the mean absolute deviation and the standard deviation have been placed in relation to the mean dose.

The measure of dispersion in itself may also complicate interpretation of the results. The coefficient of variation is placed in relation to the mean dose and thus a larger absolute variation is permitted at higher mean doses without the coefficient of variation increasing, which can be seen from Equation [5] (author's note).



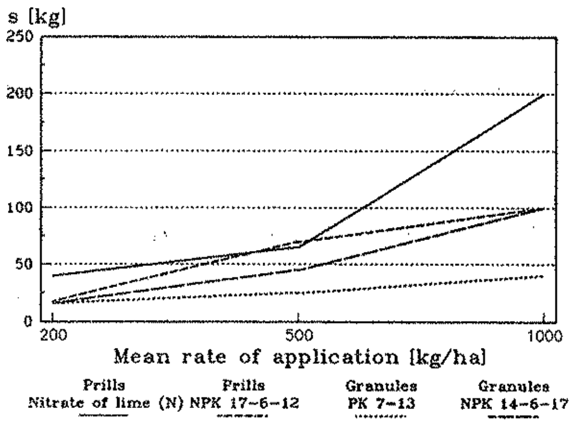


Figure 5.1. Comparison between relative (coefficient of variation, left diagramme) and absolute (standard deviation, right diagramme) deviation in spreading uniformity (Source: Author's own illustration).

Figure 5.1. shows the variation in spreading patterns at different mean doses (200, 500 and 1 000 kg/ha) and different types of fertilizer measured at the National Swedish Machinery Testing Institute (SMP Bulletin 3073).

The coefficients of variation that are normally reported give a varying impression of the spreader's precision in the diagramme showing coefficients of variation. However, the diagramme showing standard deviation clearly shows that the variation increases with dose

The evaluation of fertilizer spreaders should be based on the needs and conditions of the crop. Figure 5.1 illustrates the question whether it is the absolute or relative deviation from the mean dose that has the greatest importance for the yield. The author has no answer to this question. If we assume that it is the absolute deviation in spreading uniformity and not the relative deviation that is of importance for yield level in intensive crop production, then relative measures may be confusing.

It should be emphasized that Bergström's (1987) evaluation model (see "4.1.5. Autocorrelation") may be considered as a first step in taking consideration to the biological factors that are of importance when spreading fertilizer.

5.2 INFLUENCE OF THE COLLECTION PROCEDURE

The area of the collection vessel influences the coefficient of variation (T. Bergström, pers. comm.; Rühle, 1975). If the collection area increases, it is expected that the deviations will decrease. This occurs when small sub-areas have a larger dispersal than the sum of the sub-areas. This can be better explained in an example.

The fertilizer in a test is collected in square vessels with 6.25 cm sides. These vessels have an area that is so small that some vessels will probably not contain any fertilizer. The coefficient of variation will be large. If, however, the amount of fertilizer in 64 vessels (0.5 x 0.5 m) is added together before calculating the coefficient of variation, the empty vessels will be compensated to some extent by their "neighbours". The coefficient of variation will be lower.

The design of the collection vessel influences the amount of fertilizer that remains in the vessel during the experiment (Whitney et al., 1987; Parish, 1986; K.E. Svensson, pers. comm.).

The amount of fertilizer caught by a collection vessel depends on the particle properties, the design of the aperture of the collection vessel, the vessel's ability to absorb energy, the wind speed, and properties of the surrounding ground (Whitney et al., 1987). According to Whitney et al. (1987), a good collection vessel should have sharp edges, an energy-absorbing interior (so that the granules will not bounce out of the vessel) and sufficiently high edges to prevent granules from bouncing into the vessel.

The fertilizers used in the tests differ from country to country. This may influence the test results, since the behaviour of a spreader depends on the physical properties of the fertilizer (author's comment).

Parish (1986) compared six different collection systems when testing fertilizer spreaders. Each system was tested with the spreader at two different heights above the collection vessel. Two different granular materials were used in the tests. The comparisons were made in-doors under laboratory conditions. The adjustments to the test machine remained unchanged throughout for a given fertilizer. Parish (1986) found that the results differed considerably between the different collection methods. Significant differences could be established for fertilizer flow, optimal working width, coefficients of variation, and max. and min. points in the spreading pattern.

In addition, naturally, the site for the test is of importance. Tests out-doors are influenced by wind, ground slope, etc., which will influence the results.

5.3 WHY ARE TESTS MADE?

Two primary objectives should be fulfilled when testing fertilizer spreaders:

1. The tests should reveal the basic ability of the machine to accomplish a task.

2. The tests should reveal whether it is possible under practical conditions to achieve the basic requirements.

It is doubtful whether these requirements can be considered to be fulfilled in tests made to date. The evaluation of the work done by fertilizer spreaders should be based on the requirements of the crop. There are methods to establish the crop requirements, but the extent of investigations made implies a lack of knowledge on the variation in parameters both as regards models and prevailing field conditions (T. Bergström, pers. comm.).

As regards the first requirement, a certain degree of the machine's basic ability can be revealed in laboratory tests. However, there are several different test methods, depending on where in the world a machine is tested, which may lead to problems in comparisons between different machines. In Sweden, the tests are based on current ISO standards (ISO 5690/1-1982). However, there are minor modifications, e.g., as regards requirements for weighing accuracy (K.E. Svensson, pers. comm.) This implies that within Sweden the tests are comparable. However, it is not certain that tests between different countries are directly comparable with each other (author's comment).

The second requirement is difficult to fulfil. The machine's ability to fulfil the basic requirements will vary with the field, the crop and the fertilizer. A complete account of this would be difficult to handle with regard to the numerous influencing parameters and their variation. In order to obtain replicable and comparable tests, the evaluation of the machine with regard to Requirement 2 should be standardized. At the same time, this implies a certain restriction of the scope of Requirement 2.

6 REQUIREMENTS ON SPREADING UNIFORMITY

The distance from which a plant can take up a fertilizer is determined by the horizontal extent of the roots and the horizontal movement of fertilizer in soil (Nilsson, 1972).

6.1 HORIZONTAL MOVEMENTS OF FERTILIZER IN SOIL

The horizontal movements of fertilizer in soil are fairly limited. Phosphorus fertilizers move only a few centimetres in the horizontal direction (Haahr et al., 1965; Savant et al., 1970). Blue and Eno (1954) studied movements of liquid ammonia and found that most of the ammonia could be recovered within 8 cm, and only small amounts were found 13 cm from the original site. Also McIntosh and Fredrick (1958) and Nömmick and Nilsson (1963) fertilized with liquid ammonia. They found that ammonium-N and nitrate-N moved 5-10 cm horizontally. In these experiments, measurements were made up to 5 months after fertilizing.

Dombovari (1960) reported that nitrogen diffusion of nitrate after fertilizing with nitrate of lime is proportional with time and soil moisture content. At 20 days after fertilizing, the nitrogen diffusion extended 6-12 cm. In experiments with rice in water-saturated soil, the nitrogen was transported about 20 cm.

6.2 HORIZONTAL EXTENT OF PLANT ROOTS IN SOIL

Haahr et al. (1965) demonstrated using phosphoric fertilizer that the roots of individual plants of barley and oats can extend up to 60 cm horizontally. The extent of the roots, however, has no quantitative importance at distances exceeding 30 cm. Haahr et al. (1965) report only indirectly on row spacing and these appear to be about 15-30 cm.

A root length of 30 cm should give the plant the possibility of looking for nutrients over a larger area and thereby compensate itself for uneven fertilizer distribution. In modern crop production, this is counteracted by the area that is available to the plant (Russel, 1961). Roots from neighbouring plants of the same species intermingle only slightly with each other (Russel, 1961; Kaserer, 1911). When roots from different rows reach each other they tend to turn downwards (Miller, 1938; Kaserer, 1911).

This implies that in crops with narrow row spacing, e.g., cereals, the dispersal of roots of individual plants will be limited. When encountering competition from neighbouring plants the roots prefer to turn downwards (Nilsson, 1972).

6.3 EFFECTS OF UNEVEN FERTILIZER DISTRIBUTION

Prummel and Datema (1962) show that the percentage yield loss is closely related to the coefficient of variation for fertilizer distribution (see Fig. 6.1). This result is based on data obtained from tests of spreaders under practical conditions. The size of the collection vessel was 5 dm^2. The yield losses as a function of uneven fertilization were calculated using yield curves from carefully hand-fertilized experimental plots.

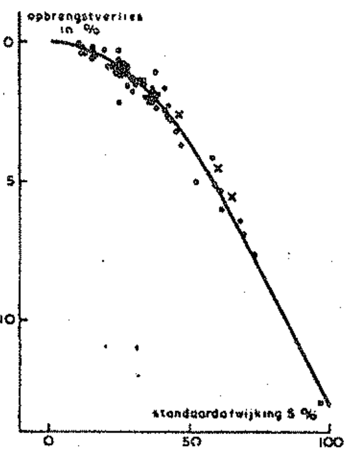


Figure 6.1. Relationship between yield loss in % and the coefficient of variation for fertilizer distribution (Source: Prummel and Datema, 1962).

In general, when a given resource is to be divided and when the function relationship between the input intensity and the yield is degressive, then the total yield will be maximal if the different parts have similarly large proportions of the resource (Bergström, 1987). Fig. 6.2 shows the anticipated yield of inputs x1 and x2 and for the mean value x. of these two inputs. In the figure, y marks the mean yield and y(x.) the yield of the mean input. The figure shows that the difference between y(x.) and y. depends on the shape of the curve.

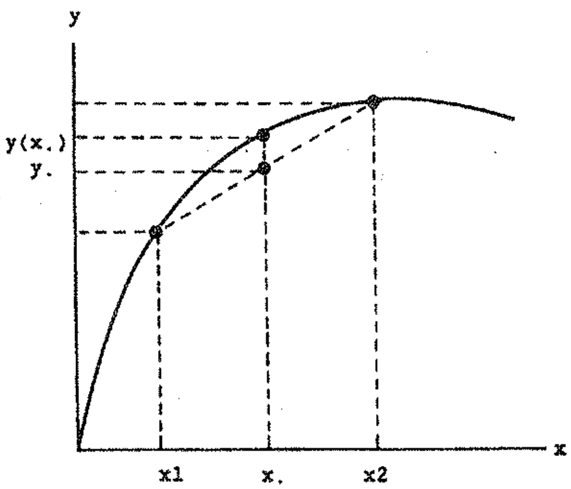


Figure 6.2. Anticipated yield of inputs x1 and x2 and for the mean value x. The figure is explained in the text (Source: Bergström, 1987).

"The law of diminishing returns" implies degressive function relationships, and the yield in kg grain as a function of the fertilizer dose largely depends on this law. Consequently, it is generally important that fertilizer is distributed as evenly as possible over the field. An exception would be if the resource can be distributed under controlled conditions unevenly so that, for example, soil variations in nutrient status and fertility can be considered (Bergström, 1987).

Mitchell (1975) studied the effects of uneven fertilizer intensity by spreading fertilizer from a spreader with different overlapping. Clear yield losses could be demonstrated for incorrect working width.

Lutz et al. (1975) conducted a 3-year experiment on different soils with different crops and fertilizer intensities. The results are mixed but in several cases the highest yield was obtained with uniform fertilizer distribution.

Nilsson (1972) found that neither yield nor quality was particularly deteriorated even when there were large unevennesses in fertilizer distribution. This slightly unexpected result probably depends on the low mean rate. In uneven fertilizer distribution at high average rates there will be lodging, which severely deteriorates the yield prospects (L.G. Nilsson, pers. comm.).

Nilsson (1972) also investigated border effect using radioactively labelled nitrogen. It was only in plant rows immediately neighbouring the area with labelled nitrogen that the grain could take up so much labelled nitrogen that one could speak of levelling-out effects.

Dam Kofoed (1960) demonstrated in his experiments that it is hardly profitable to attempt to improve a poor fertilizer distribution by soil tillage after application. Njös and Steenberg (1962), demonstrated, on the other hand, that one cannot completely neglect compensation effects when soil tillage is done after fertilizer application. The difference in results between the two investigations can be explained by Dam Kofoed (1960) measuring the distribution after soil tillage corresponding to one year's soil tillage. Njös and Steenberg (1962) studied the influence of individual implements on the fertilizer distribution. Njös and Steenberg (1962) thus demonstrate the effects of covering the fertilizer with different soil tillage implements, where Dam Kofoed (1960) shows that the distribution when conducting basic fertilization with phosphoric fertilizer is not particularly influenced from year to year (author's comment).

The literature is not fully in agreement as regards the effects of uneven fertilizer distribution. One explanation of the mixed results may be the definition used with regard to uniform fertilizer distribution.

Lutz et al. (1975) varies the fertilizer distribution by varying the application rate per hectare between 0.9 m wide and 7.3 m long strips. The spreading pattern of the fertilizer spreader used in the trials is not mentioned. There is a risk that local variations in application rate delivered by the fertilizer spreader will have influenced the results on both "uniformly" and " ununiformly" fertilized plots.

Several authors use manual fertilization (Nilsson, 1972; Prummel and Datema, 1962). This method may give coefficents of variation up to 25% at 0.2 x 0.2 m vessel sizes (Lorenz, 1954, recalculated by Rühle, 1975). However, when fertilizing experiments there is a special procedure which decreases the divergences from the mean application rate. However, also here there is some risk that local variations in rate have influenced the results for both "evenly" and "unevenly" fertilized experiments.

6.4 HOW SHOULD SPREADING UNIFORMITY BE MEASURED?

The literature shows fairly good agreement that the roots of cereal plants have a limited extent horizontally when row spacing is narrow. In addition, it is clear that the horizontal movements of fertilizer in soil are very limited. This suggests that the fertilizer should be placed as close to the plant as possible. In combi-drilling at least every second row should be fertilized in order that all plants will have access to fertilizer.

Since there is no equipment available today to provide precision readings of the nutrient content of soil or the nutrient requirement of plants at fertilizing, the fertilizer should be spread as evenly as possible. Since, in addition, the plants are closely placed together and all of them should achieve access to nutrients in order to obtain the maximum possible yield in relation to the cultivation intensity, then also local variations in fertilization intensity should be kept at a minimum.

Two questions must be answered before it is possible to assess the ability of a fertilizer spreader to fulfil its task:

1. How large should the collection vessels be during the tests?

2. Which coefficient of variation is acceptable at this size of vessel?

Bergström (pers. comm.) answers these two questions in his proposal for an evaluation method (see "4.1.5. Autocorrelation"). By stating a measure of dispersion for a given collection area, together with autocorrrelations between neighbouring areas, one and the same test can be re-calculated to a suitable collection area depending on the crops to be fertilized.

Prummel and Datema (1962) consider that within plots smaller than 0.5 m^2 there is a levelling-out between good and poorly fertilized plants. This opinion is supported by the National Swedish Machinery Testing Institute (SMP Bulletin 3003). However, Holmes (1968) is of a different opinion and considers that plant density and row spacing probably influence the area over which the levelling-out takes place. Holmes (1968) considers that 1-1.5 foot (about 30-45 cm) is a suitable vessel size.

By means of hypothetical reasoning, a vessel width of 12.5 cm may be considered to be suitable. According to the literature, plant roots turn downwards when they meet. If the conditions for all plants are similar, then this meeting-place should be approximately in the middle of the space between two rows. When row spacing is at 12.5 cm, then plant roots can extend about 6.25 cm horizontally in both directions. Consequently, a suitable width of vessel would then be 12.5 cm. This argumentation is supported by the border effect studies conducted by Nilsson (1972).

There are three factors that oppose this. Firstly, the fertilizer in combi-drilling is placed in strips spaced at 25 cm. This would lead to a very high coefficient of variation if the measuring area had a width of 12.5 cm. Similarly, combi-drilling gives a good yield result. Thus, the measuring method gives a results that does not reflect the true result of the fertilization method.

Secondly, the fertilizer moves slightly in the soil. The distance between the seed and the fertilizer placement can, theoretically, be equal to the horizontal extent of the roots added to the horizontal movement of fertilizer in the soil. However, this objection is weak. There are several experiments that demonstrate that plants have difficulties in taking up fertilizer placed beyond the neighbouring row of plants.

Thirdly, the local yields of the crop will continuously vary. Competitive situations, compensatory growth, and varying orientation of plant roots will influence on the nutrient uptake and thus the yield results regardless whether the fertilizer is distributed absolutely uniformly or not.

Small collection vessels can be combined to larger collection areas when subsequently processing the results. This enables calculation of autocorrelation between neighbouring areas (Bergström's 1987 method, see "4.1.5. Autocorrelation"). In this respect, the author asserts that measurements made in scientific experiments should be done using small collection vessels (12.5 cm width).

As regards acceptable coefficients of variation for the pattern of spread, the literature is reasonably unanimous. The National Swedish Machinery Testing Institute considers that coefficients of variation in excess of 10% are not fully satisfactory (SMP Bulletin 3003). Holmes (1968) also places the 10% coefficient of variation as an upper limit for uneven spreading. Mitchell (1975) places more severe requirements and considers that a dispersal of more than 10% around the mean dose leads to yield losses on most soils.

The 10% permitted coefficient of variation stated in the literature is placed neither in relation to the width of the measuring area or to the application rate of fertilizer, which means that this requirement becomes undefined. The present author refrains from giving an exact figure for maximum coefficient of variation.

7 SPREADING UNIFORMITY IN MODERN FERTILIZER SPREADERS

Fertilizer spreaders are tested throughout the world. Official testing institutes investigate the fertilizer spreader's pattern of spread under laboratory conditions. The reason for this is, naturally, to obtain comparable and reproduceable results. The best spreading uniformity can then be calculated from these patterns of spread by studying the coefficients of variation at different amounts of overlapping.

7.1 TESTING IN LABORATORY ENVIRONMENT

During 1984-1986 a series of tests of 11 of the fertilizer spreaders available on the Swedish market were made at the Swedish National Machinery Testing Institute (SMP Bulletins 3003, 3068). Of these spreaders, three were pneumatic spreaders.

The average coefficient of variation for different adjustments and different fertilizers in these tests varied between 5 and 18% at right-angles to the direction of travel. The smallest coefficient of variation in an individual test was 4% and the largest was 42%. This applies with overlapping and when crossing the field and returning. Parallel with the bout, the evenness of distribution varied between satisfactory (6-10% coefficient of variation) and not fully satisfactory (11-20% coefficient of variation).

The two pneumatic systems tested by Rühle (1975) both had a coefficient of variation parallel to the bout that was less than 3% (see Figures 8.1 and 8.2). This difference may be considered to be surprisingly large. The explanation of the large difference in comparison with the Swedish National Machinery Testing Institute can certainly be found in the method used.

At the Swedish National Machinery Testing Institute the distribution along the direction of travel is measured by placing out three parallel rows, each 10 m long, of collection vessels (0.5 x 0.5 m). One row is placed in the centre between the wheels of the machine and one row is placed one on each side below the side-booms. The machine drives over these rows of vessels once at 8 km/h, the fertilizer in each vessel is weighed and the distribution along the direction of travel immediately below the machine and under the side-booms is calculated.

Rühle (1975) measured the distribution parallel to the direction of travel by driving the machine at 4.2 km/h over a 6 m long grid. The boxes in the grid along the direction of travel were spaced at 20 cm. Rühle (1975) sums all fertilizer along the width of the boom in these experiments. This has the result that a low application rate from one of the spreader devices can be compensated by a high rate from another. In other words, unevennesses in the pattern of spread parallel to the bout can be compensated by unevennesses in the pattern of spread at right-angles to the direction of travel when this measuring approach is used.

7.2 TESTS UNDER PRACTICAL CONDITIONS

Nilsson (1986) investigated the uniformity of spread under practical conditions in 30 different fertilizer spreaders. In addition, he reports tests of the studded roller variators in 9 of the pneumatic spreaders included in the tests.

The variator speed was measured by means of a photocell that transmitted signals to a tape-recorder on every occasion that a link from the variator chain passed by. Nilsson (1986) found that the variator rate had a coefficient of variation of 1-3%. This unevenness probably depended on unevennesses in the driving speed and not as a result of the variators slipping.

Nilsson (1986) used an early version of Bergström's (1987) method for measuring the evenness of spreading. Nilsson (1986) placed collection vessels in three lines across the field. The distance between the lines varied with field size. The collection vessels measured 0.5 x 0.5 m with a separator in the middle of the vessel. The correlation between the collected amount in each half of the vessel was calculated.

The coefficient of variation for the evenness of spreading in Nilsson's investigation (1986) varied between 11 and 40%. The average coefficient of variation was about 25%. The results revealed no clear difference between pneumatic spreaders and centrifugal spreaders. The absence of this difference may be explained by deficient cleaning and that pneumatic spreaders are more susceptible to the absence of this type of maintenance than centrifugal spreaders.

A complementary explanation may possibly be found in the testing conditions. The tests were done in different fields and on different days. This may imply that the tests are not entirely comparable. In addition, extreme boom movements may have a very negative influence on the spreading pattern. Spreaders with booms are also sensitive to overlapping errors (author's comment).

It is interesting to note that 4 of the spreaders tested by Nilsson (1986) had correlation calculations that suggested that they tended to spread unevenly on smaller areas. All of these spreaders were of the same model and make. Subsequently, an error in the transport system was discovered and has now been corrected on this spreader (N. Möller, pers. comm.).

8 DISTRIBUTION OF FERTILIZER TO THE PNEUMATIC TRANSPORT SYSTEM

8.1 METHOD USED IN PNEUMATIC FERTILIZER SPREADERS

A pneumatic spreader consists of four main components:

1. Fertilizer hopper
2. Delivery system
3. Transport system
4. Spreading mechanism

Normally, the fertilizer spreader has one single central hopper. The load capacity of the hopper varies from about 0.5 to 6 tonnes.

Delivery is generally done by means of some kind of delivery rollers. There are also examples of hoppers with central injection delivery and delivery by means of belt conveyers with scrapers.

The transport system consists of a fan and air distribution system. The air distribution starts at the fan and ends at the spreading mechanism. The fertilizer is added somewhere in between.

The spreading mechanism is frequently mounted on a boom. There are several different types of spreading mechanisms, e.g., spreader plates, spinners, nozzles, etc.

8.2 DIFFERENT DELIVERY PRINCIPLES

There are two main principles for delivery of fertilizer from the hopper; central delivery or delivery in separate flows. Rühle (1975) used two pneumatic spreaders which illustrate the two delivery principles.

One of the machines used by Rühle (1975) had central delivery from the hopper via an injector to a main pipe (Fig. 8.1). The fertilizer was sucked up into the main pipe and delivered to a distribution head which divided up the mixture of air and fertilizer among the various transport pipes. At the end of the transport pipes, there were spreader plates which broadcast the fertilizer over the width of the boom. The present author is not aware of any fertilizer spreader today which uses this principle of delivery.

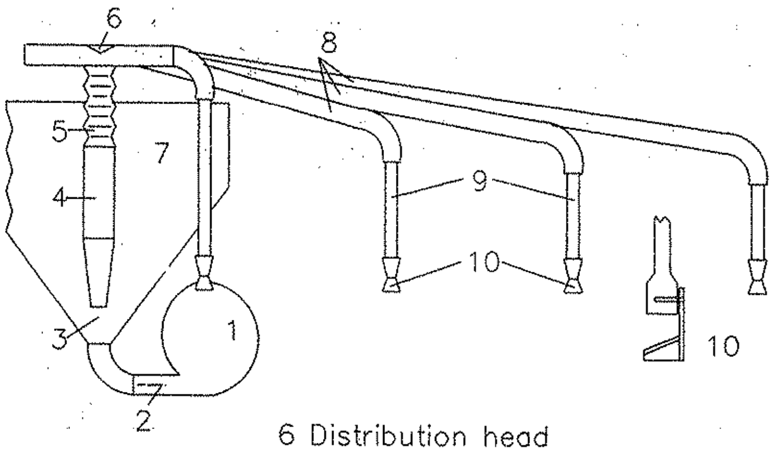


Figure 8.1. Distribution system with central injector delivery (Source: Author's own drawing after Rühle, 1975).

The other machine used by Rühle (1975) had separate delivery from the hopper using a studded roller mechanism (see Fig. 8.2). The studded roller distributed the fertilizer directly into injector funnels which were linked to the transport pipes. The mixture of air and fertilizer was then transported to the respective spreader nozzles which broadcast the fertilizer over the width of the boom. There are many examples of fertilizer spreaders using this delivery principle, e.g., Överum Tive.

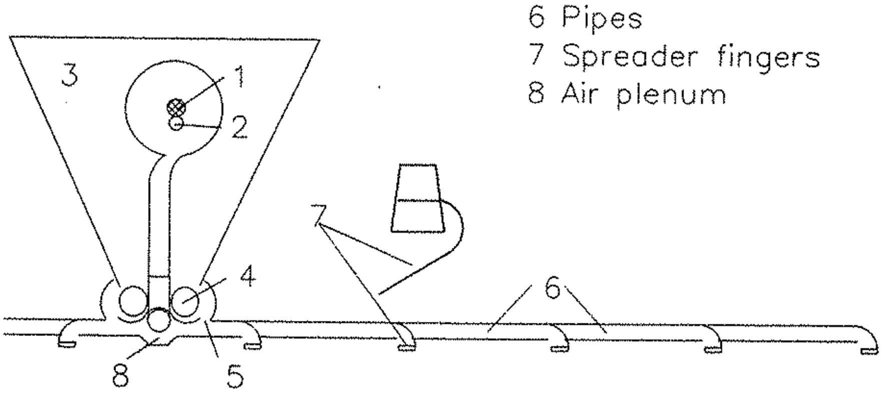
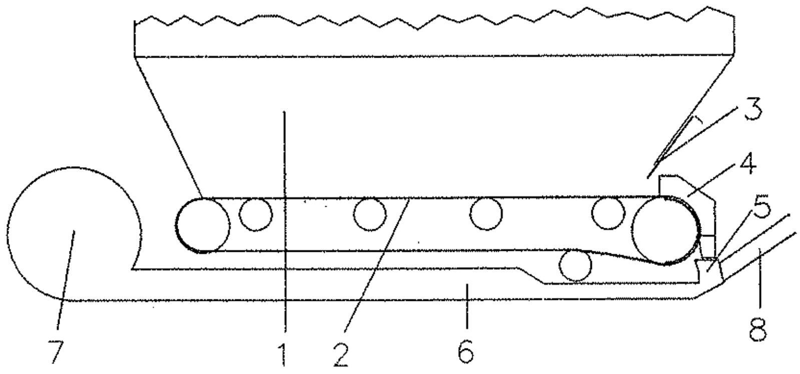


Figure 8.2. Distribution system with separate delivery by means of a studded roller mechanism (Source: Author's own drawing after Rühle, 1975).

Another type of separate delivery is shown in Figure 8.3. The fertilizer is fed backwards in the hopper by means of a conveyer belt towards an adjustable hatch. Immediately behind the hatch are separating plates which divide up the flow of fertilizer on the conveyer into separate flows. Each separate flow then falls down a slope into an injector funnel from which the fertilizer is blown out to the various spreader mechanisms. This method is found in fertilizer spreaders manufactured by Ysta-Maskiner.



1 Fertilizer hopper
2 Conveyer belt
3 Adjustable hatch
4 Separation plates
5 Injector funnels
6 Air plenum
7 Fan
8 Pipes

Figure 8.3. Distribution system with delivery via a conveyer and separation plates (Source: Author's own drawing based on material from Ysta-Maskiner).

9 FACTORS INFLUENCING THE SPREADING RESULT

The result of spreading granular fertilizer is influenced by a number of different factors. Bergström (1979) divides these factors as follows:

* The fertilizer
* The machine
* The operator
* Other factors (e.g., the field and weather)

The division of factors must not overshadow the situation that the interaction between all factors provides the final result (Bergström, 1979).

9.1 THE FERTILIZER

Fertilizer properties are of major importance for the result of the spreading. The particle properties of fertilizer are influenced by their composition, method of manufacture and handling during storage and transports. Particle properties can be divided as follows:

* Particle size
* Particle shape
* Surface texture
* Density
* Durability
* Moisture
* Other factors

These particle properties are of importance for the flow properties of the fertilizer and its liability to form deposits in the machine (Möller, 1987; Kämpfe et al., 1982; Bergström, 1979; Nilsson, 1975; Brübach, 1973). The flow properties influence the spreading properties of the fertilizer spreader, foremost the behaviour of the delivery mechanisms. From the spreading viewpoint, good fertilizer must be homogeneous, have good flow properties and be resistant to external influence.

The flow ability of fertilizer is reversely proportional to the fertilizer's friction angle. Fertilizer with high friction angles are spread unevenly since the material does not flow freely (Kepner al., 1972).

9.1.1 Influence of Particle Size

The air-floating rate of particles increases with the particle size (Brübach, 1973). In addition, particle shape and density is of importance for the air-floating rate. In its turn, air-floating rate is of major importance for the length the particle is thrown when broadcast. At larger particle sizes, the differences in length of throw decrease between particles of different density.

According to Brübach (1973) there is also a relationship between particle size and the friction coefficient of the material. The friction coefficient decreases with increasing particle size. This is of importance for the flow properties of the granules.

As soon as a product with particles of different sizes is handled, there is a risk that it will separate so that the proportion of fine particles will increase in certain places and the proportion of large particles in other places (Greiner and Kämpfe, 1984; Nilsson, 1975). The fine material shows particular trends to collect below down-flow apertures, whereas the coarser particles tend to roll away from this area. When handling fertilizer, separation of this kind may severely influence the spreader's work as it results in varying metering and uneven spreading patterns (Nilsson, 1975).

Heege and Hellweg (1982a) investigated how fertilizer separated according to particle size along the working width of a spreader during the spreading of a fertilizer. They found that the physical properties of fertilizer and the handling of the fertilizer influenced the separation. Pneumatic spreaders do not lead to any particular separation of the granules. Spreaders with lateral mechanical distribution result in a severe separation of the material.

By means of using results from the above-mentioned investigation, Heege and Hellweg (1982b) could simulate the separation as regards nutrients caused by different spreader types when mixing different single fertilizers, so-called bulk-blending. The condition was that if the single nutrients included in the fertilizer mixture had differing particle size spectra, then a nutrient separation may occur at right-angles to the direction of driving. The result of the simulations suggests that a pneumatic spreader does not skew the spreading pattern of the nutrients, in contrast to spreaders with mechanical distribution laterally. The separation of broadcasters is influenced by the overlapping.

Pahlman (1988) compared an NPK fertilizer made through mechanical mixing of single fertilizers with a factory-made NPK fertilizer. A broadcaster was used in the test. Pahlman (1988) found that the mechanically mixed fertilizer separated considerably more than the factory-made fertilizer at right-angles to the direction of travel. This separation was of both physical and nutrient nature. Pahlman (1988) concludes that if mechanically-mixed fertilizer generally separates as strongly as this, then the advantages of taylor-made fertilizer mixtures will disappear.

Also Karnok (1986) studied nutrient separation in fertilizer mixtures. His results differ slightly from those of Heege and Hellweg (1982a, b). The difference may depend on different particle size spectra being investigated. Karnok (1986) found, however, that the particle size spectra influenced the result of the spreading and that a uniform particle size gave the lowest coefficient of variation for accuracy of distribution.

Phillipson and Dwyer (1966) discuss problems with spreading material with fine particles using studded rollers. There were problems in getting ground limestone to flow through the delivery mechanism.

9.1.2 Influence of Particle Shape

There are several reports in the literature that particle shape influences the flow properties (Deming and Mehring, 1929; Brinschwitz and Hagemann, 1980; Greiner and Kämpfe, 1984; Kohsiek, 1970; Kämpfe et al., 1982). Unfortunately, however, the authors usually only make a general comment and refrain from going into details (author's comment).

Deming and Mehring (1929) found that particle shape of non-spherical particles must diverge sufficiently from spherical shape so that the bulk density or the angle of repose changes before the mass flow diverges from that for spherical particles.

9.1.3 Influence of Surface Texture

The surface texture of granular material is of importance for its friction and thus its flow properties. Two concepts are distinguished; internal angle of friction and the angle of repose. The friction of a granular material is a result of gliding friction and rolling friction since the granules can both glide and rotate (Brübach, 1973).

The internal friction angle refers to the friction angle that occurs when friction arises between individual granules under the influence of compressive forces. The dynamic angle of repose consists of the angle between the bed and one side of the cone that is formed when a granular material is allowed to freely run out of a hopper down onto the bed. The static angle of repose is obtained by measuring how much a hopper holding granular material can be sloped before the topmost layer of granules starts to move (Sitkei, 1986). The angle of repose thus concerns the friction between individual granules under the influence of tensile forces.

Apart from the internal friction angle and the angle of repose, the friction of the material against surrounding surfaces of other material (e.g. steel) will influence the ability of the fertilizer spreader to achieve an acceptable uniformity of spreading (author's comment).

In Sweden, two principally different methods of achieving a granulated product are used for most of the fertilizer marketed in the country; granulation and prilling. In granulation, the particle becomes slightly irregular and has a rough surface, whereas the prilled particles are round and smooth (Nilsson, 1975). Prilled particles have a lower angle of repose than granular particles, which implies that prilled material flows more easily than granular material (author's comment).

Brübach (1973) investigated the importance of the friction angle for the mass flow. Two different fertilizers with the same particle size spectrum, but with different internal friction, were allowed to flow freely from openings in a hopper. The difference in internal friction between the two material was 6%. The difference in mass flow was 17%. Also other properties than internal friction might have differed between the fertilizers. The difference in mass flow may, to some extent, also have been influenced by the other differences, but most of the difference is probably a result of the difference in internal friction (author's comment).

9.1.4 Influence of Density

When analysing properties of granular material, we speak of two different types of density. The first type is simply called density (sometimes absolute density) and refers to the density of individual granules. This density depends largely on the manufacturing process but may also be influenced by, e.g. moisture.

The other type of density is called bulk density and refers to the density in a batch of granular material. Bulk density varies with, e.g., degree of compaction.

Fertilizer density is of importance for the air-floating rate and thus the particle's trajectory when broadcast (Brübach, 1973).

Vibrations and bumps influence the degree of compaction and thus the bulk density of the entire batch of fertilizer. During the emptying of a hopper, different parts of the fertilizer will, in addition, have different bulk density depending on where it is in the shifting area above the out-flow apertures or whether it is in a more stable part of the hopper (Kohsiek, 1970).

Variations in bulk density will cause variations in mass flow from volume based fertilizer feeders (author's comment).

9.1.5 Influence of Durability

Kohsiek (1970) mentions that the durability of the particle influences the changes in particle size distribution during the period from manufacture of the fertilizer until it is spread. In turn, particle size influences the spreading accuracy (see "9.1.1. Influence of Particle Size" above).

When handling granular material, which is allowed to flow freely or is forced through a transport mechanism, the action of the particles against each other will cause rubbing and tension. In addition, the material will be processed against the working parts of the mechanism. The material worn off then generally occurs in the product as meal but sometimes crushed products may occur (Nilsson, 1975). The powder thereby formed fastens easily in the delivery mechanism which causes interference (Möller, 1987).

9.1.6 Influence of Moisture

All fertilizers are more or less water-soluble. Consequently, throughout storage and handling up to spreading they must be protected from precipitation. In addition, several fertilizers are more or less hygroscopic, i.e., they have the ability to take up moisture from the air without being exposed to precipitation (Nilsson, 1975). The water uptake ability varies with the fertilizer, the relative humidity in the air and the temperature. Nitrate of lime has the largest ability to take up moisture, whereas superphosphate is fairly insensitive (Larsson, 1980). Mixtures of fertilizer or contamination caused by foreign objects may considerably increase the moisture uptake (Larsson, 1981).

If fertilizer takes up water, it will become looser and stickier, which will influence all its physical properties.

9.1.7 Other Factors

Chemical reactions may occur when mixing certain fertilizers or when mixing fertilizer and lime, which may lead to lumping. When manufacturing mixed fertilizer (bulk-blending) it is important to select components that do not react chemically with each other before they are spread (Larsson, 1980).

Some fertilizers have the property that they soften on the surface when they are exposed to rubbing. This change in state reverses as soon as the rubbing ceases. These fertilizers are called thixotropic. This property leads to hard deposits being placed on working mechanism and transport ducts against which the fertilizer glides. The deposits become very strongly attached and are therefore generally difficult to remove. The deposits also have the property of growing continuously. In due course they become so thick that they start rubbing against transporting mechanism of soft material. Therefore, we find that devices that expose the fertilizer to rubbing against working parts and transport ducts are not suitable for thixotropic fertilizers (Nilsson, 1975).

The fertilizer industry has observed the thixotropic problem. During the last decade the properties of thixotropic fertilizers have changed in order to minimize the problem (U. Lundquist, pers. comm.).

The National Swedish Machinery Testing Institute reports two cases of deposits occurring during practical tests conducted during the last three years (SMP Bulletins 3025 and 3075). The Machinery Testing Institute did not report what type of deposits were involved. In one case, there are reasons to suspect thixotropic deposits in the other deposits as a result of increasing moisture content.

In order to form an opinion on the thixotropic problem the present author conducted a small experiment. The experiment included 3 fertilizers; NP 26.6, superphosphate, and PK 7.13. All fertilizers were made by SUPRA. NP 26.6 was prilled, the others were granular. The reason for all fertilizers containing phosphorus is, according to Nilsson (1975), that these are the most thixotropic fertilizers.

The experiment was conducted as follows. About 4 dl fertilizer was filled into a hopper with a base of 85 x 85 mm and a height of 165 mm. The fertilizer in the hopper was processed by an agitator for 3 h. The agitation rate was 100 turns/min. Deposits on the agitator and the relative humidity were measured every hour.

Superphosphate and the PK fertilizer showed a very limited indication for thixotropic deposits (< 0.5 mm). On the other hand, the granules were ground into powder during the test.

NP 26.6 showed a clear tendency for deposits. However, these deposits were not of a thixotropic nature but more of a rubber or resin type of deposit. During these tests the relative humidity did not on any occasion exceed 28%. The durability was excellent and only a few disintegrated granules were discovered after the test.

The experiment discussed above suggests that at low air humidity the thixotropic deposits of phosphoric fertilizers are moderate. No problems should arise if the machine is regularly cleaned. However, the durability of superphosphate and the PK fertilizer could have been much better.

As regards the prilled NP fertilizer, it is very possible that the deposits that occurred were the result of some kind of encapsulation. Admittedly, the deposits only amounted to 2 mm but showed no tendency to decrease. In addition, already 2 mm deposits can certainly disturb the function of a delivery mechanism. The test illustrated the importance of daily cleaning of the fertilizer spreader during the period of use.

9.1.8 What Requirements Can Be Placed on a Fertilizer?

From the spreading viewpoint it is most important that the fertilizer can be handled without its properties being changed so much that the work performance of the spreader is markedly influenced.

The durability should be sufficiently good that the fertilizer can be loaded, moved to the delivery mechanism, transported through the machine and spread.

Particle size should be so uniform that bulk weights do not vary between different samples taken from the same batch of fertilizer. If these requirements are fulfilled, then the mass flow can be estimated by weighing material in the hopper from time to time. This, however, is a last resort in the absence of a mass flow meter which fulfils the requirements placed when spreading fertilizer.

The tendencies of the fertilizer to deposit on working mechanism should be minimum.

It is important to remember that a good fertilizer spreader is not one that spreads fertilizer with great accuracy and thereby fulfils the above-mentioned specification. A good fertilizer spreader is one that with accuracy can spread the fertilizer available today.

9.2 THE MACHINE

Bergström (1979) makes a rough division of the machinery factors that influence the spreading performance as follows:

* Machine design
* Machine adjustment
* Machine condition
* Ease of operating the machine

In this study, the emphasis will be placed on the first point; machine construction.

9.2.1 The Fertilizer Hopper

Kohsiek (1968) remarks that already in stationary hoppers there are problems with filling and unloading of granular material. When sowing and fertilizing, there is also the requirement for a constant mass flow from a hopper in motion. The movements of the hopper make it even more difficult to keep a constant mass flow.

When filling a hopper, separation generally occurs (see "9.1.1. Influence of Particle Size"). When spreading fertilizer, a severe separation cannot be tolerated since it may have a negative influence on the metering accuracy (Nilsson, 1975). The solution to this problem is to move the point of release while filling in progress (Gunsell, 1975; Nilsson, 1975).

When emptying a hopper, only the material above the out-flow aperture is in movement. Mass flow is influenced by the physical properties of the fertilizer together with the size, shape and position of the out-flow aperture (Kohsiek, 1968).

Kvapil (1959) found that when a hopper is emptied, the granules move within an area of two rotation ellipses (see Figure 9.1). When the particles move vertically without mixing, we talk about primary movements. When particles rotate we talk about secondary movements (see Figure 9.2).

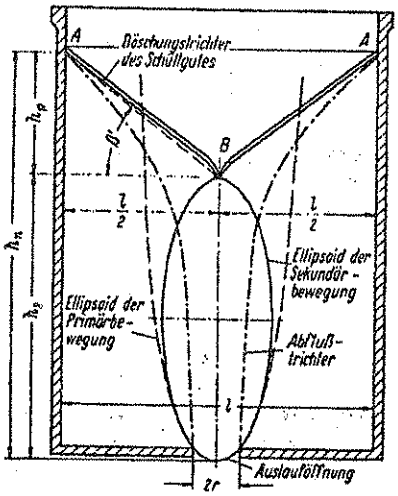


Figure 9.1. Movement ellipse in a rotation-symmetrical hopper with a restricted height of material (Source: Kvapil, 1959, reported by Kohsiek, 1968).

Both primary and secondary movements result in an increase of the material's degree of compaction, but only secondary movements cause a mixture. The interaction between primary and secondary movements make the out-flow more stable (Kohsiek, 1968).

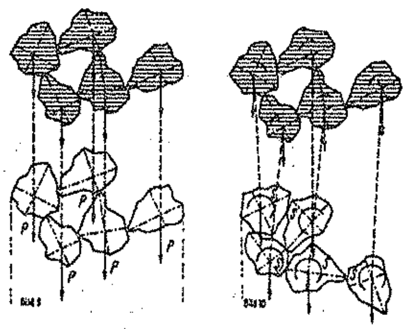


Figure 9.2. Primary movements (left) and secondary movements (right) of particles during their flow out of a hopper (Source: Kvapil, 1958, reported by Kohsiek, 1968).

The slope of the hopper floor does not influence the out-flow, only the amount remaining in the hopper. In order to completely empty a hopper, the angle of the floor must exceed the friction angle of the material (Kohsiek, 1968; Kvapil, 1959). A recommendation to be on the safe side is that the bottom of the hopper should slope 60-65° (Kohsiek, 1968).

9.2.2 How Should Fertilizer Hoppers Be Designed?

The literature is incomplete as regards the influence of the fertilizer hopper on the unloading process. Most works are based on stationary hoppers which are emptied by gravity from fixed openings. It is reasonable to assume that a hopper, that is driven over a field and emptied in another way than by means of fixed openings, will have a different unloading process.

It is hardly probable that the pressure against the delivery mechanism would influence the delivered flow to any particular extent. On the other hand, the difference in bulk density between different layers of material may possibly influence the metering uniformity. A reduction in the pressure in the hopper, which breaks up any density in the material immediately before metering, may have a positive influence on the metering uniformity. However, the hopper and the pressure reduction system must be divided in such a way, that the metering mechanism is guaranteed a sufficient flow of fertilizer.

9.2.3 Metering

The metering from the fertilizer hopper fills an important function in a fertilizer spreader. A fluctuating flow from the metering mechanism will have a negative influence on the uniformity of spreading. An uneven flow from the metering mechanism is, in addition, extremely difficult to compensate at other places in the machine.

9.2.3.1 Influence of Type of Feeder Mechanism

Metering mechanisms can be divided between active and passive mechanisms depending on their basic principle. Active metering mechanisms are those that collect a given amount of fertilizer in the hopper and actively move it to the transport system where it is deposited (e.g., cell wheel systems). Non-active metering systems depend on the flow properties of the fertilizer (e.g., fixed openings).

Active volumetric metering is not influenced by the fertilizer's angle of friction provided that the fertilizer flows sufficiently freely to fill and run out of the metering system (Kepner et al., 1972). The flow from non-active metering systems is influenced by the type of fertilizer, its specific weight and condition (Kepner et al., 1972; Kohsiek, 1970). However, today many metering systems are something in between active and passive metering.

Kohsiek (1970) investigated the flow from a hopper with regard to plant protection granulate and fertilizer. He found that the mass flow was influenced by the physical properties of the granules. The conclusion is that the use of simple openings as a dose control device (non-active, author's comment) when applying fertilizer and plant protection compounds has a restrictive future.

The Swedish National Machinery Testing Institute studied the relationship between metering and the flow properties of fertilizer by comparing the metering of Norwegian nitrate of lime and N28 (SMP Bulletin 3068). Norwegian nitrate of lime has a considerably larger proportion of small particles than N28. In addition, the particles in Norwegian nitrate of lime have a smooth surface. As a result, this fertilizer flows more easily than N28. When using a spreader with metering through apertures in the bottom, the metering of N28 was 65-73% of the metering when using Norwegian nitrate of lime. The corresponding values for metering using studded rollers was 80%. Metering using scrapers on conveyer belts gave 75-85% of the metering with Norwegian nitrate of lime measured earlier.

Cyclic variations owing to the design of the metering mechanism lead to unevenness in the spreading of freely-flowing material (Kepner et al., 1972). This type of pulsation may arise in all metering devices that measure out the fertilizer in portions, e.g., cell wheel, star wheel or augers (author's comment).

9.2.3.2 Influence of the Design of the Metering Mechanism

According to Rühle (1975), machines with studded roller mechanisms where the granules fall freely from the upper edge of the metering roller to its lower edge where the injector funnel is placed, suffer from deteriorated spreading patterns if the air velocities vary between the delivery pipes. This depends on the fertilizer being drawn laterally towards pipes with a low static pressure. The static pressure decreases in pipes with high air velocities. It should be emphasized that modern machines normally meter the fertilizer below the rollers and thus this problem should be of a minimal extent. Also in machines with central injector metering there would be an increased metering to those pipes that have the highest air velocity at the expense of the other pipes.

If the studded roller works with its ends directly against the walls of the metering compartment the mass flow may decrease at the ends of the rollers (Rühle, 1975). The conditions for the outer ends will be different than for the centre part. The friction between the granules and the walls of the metering compartment may influence the mass flow. Rühle (1975) presents no evidence but supports this opinion with regard to experiments using pneumatic seed-drills. These drills were not built with the end of the studded roller directly against the wall of the hopper. In these experiments it was not possible to establish a lower mass flow in the outermost feed pipes.

Vestesson et al. (1987) demonstrated that in practice there will be damage to and changes to the adjustments made to the studded roller mechanism of fertilizer spreaders. A conclusion from this report is that fertilizer spreaders receive less maintenance and service than required by their design (author's comment).

9.2.3.3 Influence of Shaking

In fixed openings there may occur cyclic variations in the flow of fertilizer caused by the shaking of the hopper (Kepner et al., 1972).

Kohsiek (1968) found that mechanical vibrations influence the compaction degree in the material. The vibrations either lead to compaction or loosening of the material. Strong impacts do not, according to Kohsiek (1968), have a disturbing influence on the flow provided that the material is well loosened.

Phillipson and Dwyer (1966) investigated, among other things, the influence of a jolt on the studded roller delivery mechanism. The experimental equipment they used was a conventional seed-drill with a studded roller that was operated with fertilizer. When the wheels of the seed-drill hit the ground after the bump, the fertilizer lying on the bottom flaps of the studded roller was emptied into the seed pipes and caused a peak in the distribution parallel to the direction of travel. This unloading was immediately followed by the moment required to fill up the empty space above the bottom flaps again, which caused a reduction in the delivered amount. Since the seed-drill bounced on its rubber wheels a couple of times after the bump in the ground, this sequence of events was repeated. Thus, with the type of metering tested there are risks that there will be harmonically decreasing vibrations in distribution running parallel to the direction of travel (author's comment).

9.2.3.4 Influence of Slope

Depending on the machine's design, the slope of the hopper may influence the metering in different ways (Crowe, 1985). At the Swedish National Machinery Testing Institute, 4 pneumatic spreaders have been tested during recent years (SMP Bulletin 3024, 3074, 3075, 3118). The four machines were each equipped with two studded rollers, one for the left and one for the right side of the boom.

On three of the machines the feed rollers were mounted parallel to the direction of travel, one on each side of the longitudinal axle of the fertilizer spreader. The metering of these machines was sensitive to lateral slopes. When the machine sloped to the left (10°), the delivered amount on the left side increased (2-7% depending on type of machine) at the same time as the amount delivered on the right side decreased (3-5%). The reverse situation occurred when the machine sloped to the right. The differences in the total delivered amounts were negligible (no figures mentioned). The machines were not sensitive to slopes forwards or backwards (10°).

The feed rollers on the fourth fertilizer spreader were mounted at right-angles to the longitudinal axle of the machine, in front of and behind the mid-line of the hopper. This machine was fairly tolerant to lateral slopes. On the other hand, it was sensitive to slopes forwards or backwards. When sloping backwards (10°), the delivered amount to the left side of the boom increased (5%), whereas the amount delivered to the right side of the boom decreased (5%). The situation was the reverse when sloping forwards (10°). The differences in the total amount delivered to the entire boom when sloping forwards or backwards were negligible (no figures mentioned).

The test results discussed above indicate that the metering is influenced by the slope of the machine. An explanation to the variations in the amount metered may be that the bottom flaps of the feed rollers when the machine slopes will be shorter on one side and longer on the other side of the hopper in relation to the direction of the gravitation. The flow may then increase on the lowered side. In these tests, the slope was, admittedly, small but even a minor change in the length of the bottom flaps in relation to the direction of gravitation can influence the size of the layer in the delivery mechanism where motion occurs. If this is, in fact, the case, then a different type of delivery mechanism should be used.

By means of placing fertilizer spreaders on a slope, Rühle (1975) tested how the spreading pattern is influenced by uneven terrain. The machines were sloped parallel to and at right-angles to the direction of travel. Two angles were tested; 7.5° and 15°.

The slope influenced the pattern of spread in both the systems tested (separate and central metering systems). In the studded roller machine the skewed distribution depended on the testing method. No change in the fertilizer distribution in the actual spreader could be established. Rühle's (1975) machine with central injector metering was, however, influenced by the slope so that the fertilizer moved by gravity towards the lowered side of the distribution head. This implied that the pipes on this side the distribution head were metered with a larger amount of fertilizer than the other pipes.

9.2.4 How Should the Metering Mechanism Be Designed?

Iwako and Hayashi (1985) proposed a general requirement for metering, which also applies to fertilizer spreaders:

1. Metering accuracy must be high and stable.
2. The metered flow must be simple to adjust and control.
3. The metering must be adaptable to different types of material.
4. Maintenance should be simple and the power requirement low.

Kepner et al. (1972) mentions that the metering mechanism should actively meter out the fertilizer since the flow properties of fertilizer vary strongly. In addition, the flow of fertilizer should be proportional to the driving speed. The metering should not be sensitive to the remaining amount of fertilizer in the hopper or to the slope of the hopper.

These requirements and the conclusions obtained from the literature suggest that the hopper and the metering must be adapted to each other and function as one unit. The hopper should not influence the flow of material into the metering mechanism negatively. Consequently, it should be designed in accordance with the guide-lines listed in the section on "9.2.2 How Should the Fertilizer Hopper Be Designed?"

The metering must be capable of delivering varying volumes of material with different flow properties at a uniform rate without unacceptable pulse flows arising. In addition, the fertilizer should be handled (rubbed, crushed or ground) as little as possible. This suggests that the metering mechanism should be active with enclosed cells of variable size through which the fertilizer is portioned out to the transport system. In addition, the portioning rate must be variable. Consequently, the amount of fertilizer in each portion, and the number of portions per unit of time, can be determined on the basis of prevailing conditions.

In order to be able to control the metering, it is also necessary that it does not have hysteresis, i.e., that a metered volume at a certain adjustment depends on the former adjustment of the metering mechanism. A metering mechanism with hysteresis would have unacceptably long damping times when the application rate was changed.

9.2.5 Fan

The pipes are generally supplied with air from a centrifugal fan through some kind of air distribution system. The task of the air is to transport the fertilizer from the injector funnels to the spreading mechanism on the boom without deteriorating the uniformity of spreading of the spreader in question. In addition, the flow of air can be used to reduce drift caused by wind if both the flow of fertilizer and the flow of air are directed downwards at the spreading mechanism.

At high fertilizer application rates the fan-pipe system in modern fertilizer spreaders is frequently overloaded, with pulsating flows as a result. These pulsating flows are reflected in a severe deterioration of the spreading uniformity (SMP Bulletins 3024, 3074, 3075, 3118, SJF Report 423). The rate at which the system becomes overloaded depends on the type of machine and type of fertilizer.

In practice, a change to the p.t.o. speed implies a change to the air velocity. Rühle (1975) investigated how changes to the p.t.o. speed influenced the spreading pattern. Speeds of 380, 430, 490, 540 and 650 r.p.m. were tested. The spreading patterns in spreaders with separate metering mechanism remain fairly stable over a wide range of air velocities. However, the system with central metering is severely influenced (see Figure 9.3).

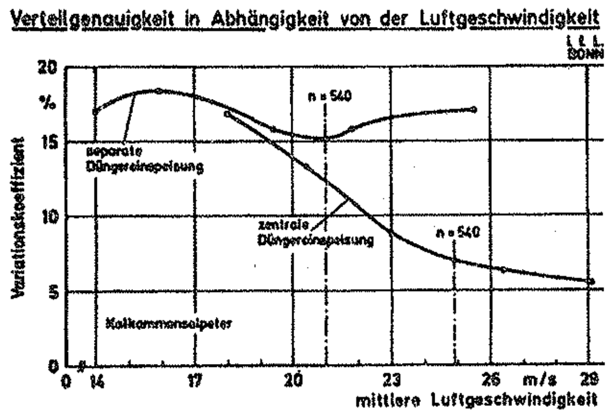


Figure 9.3. Distribution accuracy as a function of air velocity (Source: Rühle, 1975). Vertical axis: Coefficient of variation [%]. Horizontal axis: air velocity [m/s]. Upper graph: separate metering. Lower graph: central metering. Fertilizer: nitrate of lime and ammonia (Source: Rühle (1975)).

The system with central metering in Rühle's (1975) experiments had high air velocity, which increased the disintegration of the granules against the different parts of the distribution system, including the boom spreaders. An increased disintegration leads to increased drift with wind and thus a further decrease in the uniformity of spread (author's comment).

9.2.6 How Should the Fan Be Adjusted to the Fertilizer Spreader?

The literature reveals that modern fans on fertilizer spreaders are not entirely adapted to their task. It is necessary that the fan-piping system can transport different application rates of different fertilizers. This must be done with minimal disintegration of the fertilizer and without tendencies for pulsating flows.

When air is used to carry a granular material, then problems occur owing to the low density of the air and its poor carrying ability. These properties are compensated by an increased air velocity and a low relationship between the fertilizer's flow and the air's mass flow (Weber, 1986).

The type of material transported and its particle size distribution, together with the material of which the piping is made and the diameter of the piping also influence the ability of the fan to avoid pulsating flows (Rizk, 1986; Morikawa and Sakamato, 1986). The influence of these factors on the behaviour of the fan-piping system is extremely complex and outside the scope of this work. Nonetheless, they must be considered when making decisions on fan dimensions (author's comment).

Finally, the power of the tractors to be used places a ceiling on fan size. Already today there are pneumatic spreaders which require tractors with large power.

The above discussion indicates that the fan-pipe system must probably be optimized as a unit. In this optimization it is important to be able to vary the fertilizer application rates within wide limits. It is also probable that both air velocity and fan pressure must be variable.

9.2.7 Piping

The task of the piping is to transport the fertilizer from the injector to the spreaders. The design of the piping will influence the distribution of the granulate mixture in the piping, as well as the wear inside the piping and the disintegration of granules.

9.2.7.1 Distribution of Granules in the Piping

Papatheodossiou (1970) reports that the behaviour of granules in piping depends, among other things, on the particle size. In vertical pipes the radial distribution is not influenced by gravity since it is directed parallel to the pipe. As regards larger granules (>1 mm), these are influenced only negligibly by air velocity. This is because of their mass inertia.

In horizontal piping, there should be a concentration of granules along the bottom of the pipe. This particularly applies to larger granules which should rapidly sink to the bottom. However, this is not the case. The increasing vertical velocity of the larger particles causes an increased bouncing vertically between the walls of the pipe. This bouncing levels out the concentration of granules through a section of the pipe (see Figure 9.4).

When granular material is fed by injector into a vertical pipe, a good radial distribution is rapidly attained. Zähres (1974) investigated whether this had a relationship with the narrowing of the pipe immediately before the injector funnel. The assumption was that the jet of air was then concentrated to the centre of the pipe. When the granules start to be influenced by the jet of air, they are located fairly centrally in the pipe's section. When the pipe then widens and the air velocity decreases, there will be a radial distribution of the granules. By making the narrowing even narrower, it should be possible to further improve the radial distribution of the granules. In a limited investigation by Zähres (1974), the expected result was not obtained.

A large difference between air velocity in the tube and the velocity of the granules also leads to a rapid radial distribution (Zähres, 1974).

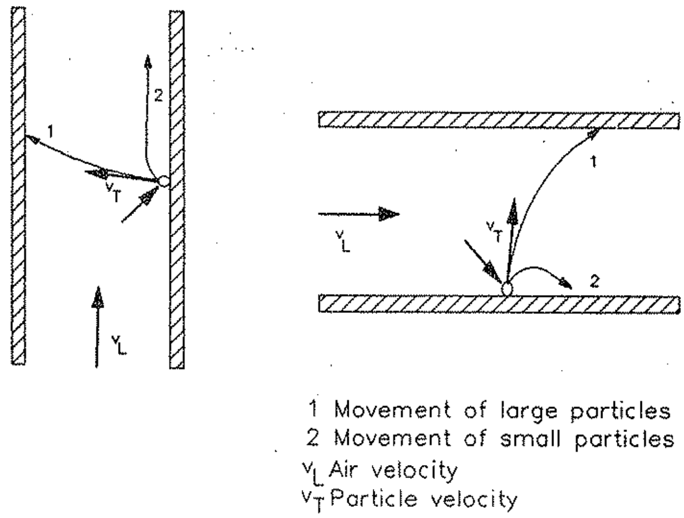


Figure 9.4. Behaviour of granules when bouncing in a tube (Source: Author's own drawing after Papatheodossiou, 1970).

Homogeneity of the mixture of granules and air when entering the spreader nozzle is of great importance for the uniformity of spread (Papatheodossiou, 1970). When changing the direction in the flow of material, e.g., in bends of the pipe, the granules will separate regardless of particle size. After the bend, however, the material starts to mix again. Nonetheless, the homogeneity of the mixture is not fully recovered until a certain transport distance has been covered. Thus, bends immediately before the spreading mechanisms should be avoided (Papatheodossiou, 1970).

Papatheodossiou (1970) included devices for re-mixing the material in the pipe. The mixing device should be placed 300-600 mm before the spreader nozzle. Zähres (1974) also tested a number of methods of rapidly obtaining a good distribution in the pipe. In vertical pipes he installed mixing devices at a distance of one pipe diameter from the distribution head of a pneumatic seed-drill (the same principle as used in the fertilizer spreader in Fig. 8.1). This improved the uniformity of spread.

The re-mixing of pneumatically-transported material can be achieved using fairly simple methods. In the fertilizer spreader with central metering used by Rühle (1975), the fertilizer was uniformly distributed over the main pipe's section by means of a corrugated pipe (see Fig. 8.1). Rühle's results suggest that this gave good homogeneity to the mixture of granules and air. An alternative to using a mixing device is to use pipes made of rubber (Y. Andersson, pers. comm.). The friction between the granules and the pipe will then be so high that the bouncing of the granules is increased (see Fig. 9.4).

9.2.7.2 Disintegration of Granules and Wear in the Pipe

Pipe wear and disintegration of granules largely occurs when the pipe bends. Very little is known about the mechanisms causing disintegration. Particle size, particle velocity, the distance transported and the design of the curves are, however, of importance for this phenomenon (Agarwal et al., 1986).

Wear in the pipe depends on particle magnitudes (size, shape, density, etc.), the material from which the pipe is made and magnitudes involving impact (particle velocity, impact angle, ratio between mass flows of the granule and the carrying gas, etc.). Wear will increase with particle velocity and decrease with the relationship between the mass flows of the granules and the carrier gas (Agarwal et al., 1986).

The design of curves in the pipe will influence the wear. In industrial applications, three main types of curves can be distinguished; curve with a long radius, curve with a short radius and a T-curve with a blind shank (see Figure 9.5; Hilbert, 1986).

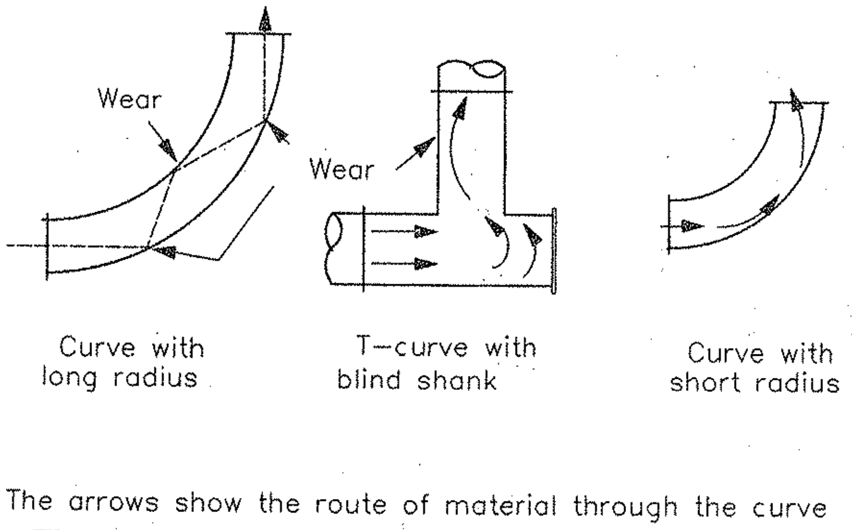


Figure 9.5. Flow of material through different types of curves (Source: Author's own drawing after Hilbert, 1986).

As regards wear, the T-curve is the most favourable, closely followed by the curve with a short radius. The curve with a short radius has an advantage over the T-curve since it can cope with moist, sticky and hygroscopic material (Hilbert, 1986).

9.2.7.3 Losses of Pressure in the Pipe

The largest losses of pressure in a pneumatic transport system usually occur in connection with the acceleration of the granulate/air mixture and in curves. Consequently, there should generally be an acceleration stretch immediately after a curve in the pipe. The type of delivery mechanism will also influence the losses in pressure when the material accelerates. In a transport system with a low ratio between the mass flows of granules and the carrier gas, it is important to have a straight acceleration stretch after the injector device (Marcus et al., 1986).

Among the three types of curves (see Fig. 9.5) the curve with a short radius gives the lowest drop in pressure (Hilbert, 1986; Marcus et al., 1986). An acceleration stretch should also be present after curves in order to prevent the material fastening and thus starting to form deposits on the walls of the pipe (Marcus et al., 1986).

9.2.8 How Should the Piping System be Designed?

The literature suggests that a system for transportation of granular hygroscopic material should have curves with short radius and acceleration stretches after the injector together with curves to minimize wear, disintegration and losses of pressure. In addition, the piping system should be made of rubber or be fitted with mixing devices in order to ensure good radial distribution. Finally, the spacing between the spreading mechanism and the nearest curve must be sufficiently long to permit re-mixing before the granules enter the spreading mechanism.

9.2.9 The Spreading Boom

Bondesson (1985) studied by means of a survey of the literature the influence of boom movement on the performance when spraying using an agriculture field sprayer. In applicable parts this study should also apply to fertilizer spreaders with a spreading boom.

The vertical movements of the boom imply that its height above the ground and the plants changes continuously. The horizontal movements of the boom superimpose the driving speed of the spray vehicle and result in its spot speed in relation to the surface varying continuously. These position and speed variations largely occur irregularly and randomly when the sprayer is operated under normal working conditions.

Available experimental results show that the movements of the sprayer boom can seriously deteriorate the result of pesticide application. Consequently, it is important to reduce these movements to a minimum. This can be done by giving the sprayer a certain amount of freedom in its movement in relation to the boom (Bondesson, 1985).

Bondesson (1985) reports that boom movements occur largely as a result of the torque of the spray vehicle along its respective longitudinal and vertical axles. In general, we can state that the amount of interference energy to which the spray vehicle is exposed will increase the more uneven the soil surface is and the faster the sprayer is driven over this surface.

Frost (1984) presents a mathematical model that shows that a passive inclined link suspension can attenuate the high frequency rolling motions but that errors in following ground undulations can occur due to the deflection of the spray vehicle suspension or sinkage of the vehicle wheels into the ground. This error will be reduced if the suspension is able to maintain the boom parallel to the ground. The mathematical model is extended to show that this could be done if one of the inclined links is replaced by one whose length varies automatically in response to signals from proximity transducers mounted on the boom tips.

Frost's (1984) model is verified by Frost and O'Sullivan (1986) on a 90 kg model of a spray boom. Frost and O'Sullivan (1986) extend the model to include the response to yaw input. Frost and O'Sullivan's (1986) model shows good agreement between predicted and measured performances of the suspension in both roll and yaw.

Frost (1987) supplements the work on the boom suspension model with a design procedure for twin universal link spray boom suspensions. The principles of the design procedure can easily be applied to other types of boom suspension provided that an accurate mathematical model is available. Such a design has been introduced on a commercially available pneumatic fertilizer spreader (P. Miller, pers. comm.).

9.2.10 How Should the Boom Be Designed?

The response of a boom suspension to the rolling motion of the vehicle to which it is attached should be such that the boom is insulated from the high frequency random rolling movements but is able to follow the low frequency undulations of the ground (Frost, 1984).

Bondesson (1985) gives the following advice for minimizing the movements of the boom:

1. The boom should consist of a free-bearing construction that is both rigid and resistant to torque. It should be just as rigid horizontally as vertically.

2. The boom should preferably be without hinges. If the boom must be hinged, then the hinges must consist of a rigid link between the boom sections when at work. If this is not possible, then the hinges should be fitted with suspension and shock-absorbing equipment. Loose hinges and hinges that allow the boom to be angled during work may otherwise contribute to difficultly controllable movements of the boom.

3. Hinges for impact protection should have damped return function and fixation to the neutral position following an impact.

4. Any buffer devices to prevent the boom from hitting the ground should be fitted with a damping function, in order to reduce the recoil effect.

9.2.11 Spreader Mechanism

When the granules have been distributed to the pipes and transported through them, the fertilizer is broadcast by the spreader mechanism. The change in the direction of the fertilizer particle's movement towards the spreader device gives a distribution parallel to and at right-angles to the direction of travel. Since the spreading mechanisms overlap each other along the spreader boom, even full-width spreaders will require a certain, although small, overlapping between bouts (Rühle, 1975).

As far as the author is aware there are only two types of spreading mechanisms on full-width spreaders; spreader plates and revolving discs. Rühle (1975) investigated also spreader fingers in his work. As regards spreading of pesticide granules, Papatheodossiou (1970) also investigated fish-tail nozzles, cone nozzles and distribution ducts.

9.2.11.1 Spreader Plates

Papatheodossiou (1970) and Rühle (1975) investigated spreading patterns and uniformity of spread given by spreader plates. The appearance of the spreader plates is shown in Figure 9.6. It should be mentioned that Papatheodossiou (1970) worked with fine-grained material.

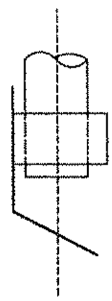


Figure 9.6. Spreader plate (Source: Author's own drawing after Papatheodossiou, 1970).

The slope of the spreader plate is of great importance for its spreading pattern (Papatheodossiou, 1970). The slope influences the re-direction of the mixture of granules and air and thus the area over which the granules are spread. A disadvantage with spreader plates is that the spreading pattern, and thus the uniformity of spread, are very sensitive to lateral slopes of the plate (Papatheodossiou, 1970; Rühle, 1975).

The air velocity in combination with type of spreader mechanism is of importance for the uniformity of spread. With a spreader plate, an increase in the air velocity may lead to improved uniformity of spread as a result of increased overlapping. If air velocity is too low, then there would be a small overlapping which will result in a deteriorated uniformity of spread (Papatheodossiou, 1970). In the fish-tail nozzle, on the other hand, increased air velocity may cause deteriorated uniformity of spread (see "9.2.11.3 Fish-Tail Nozzles").

The height of the spreader plate above the ground also influences its spreading pattern. High height above the ground lengthens the distance the granules must move through the air and thus increases the influence of wind (Rühle, 1975). If the spreader plate is turned so that the flow of material is directed downwards, then the free flight of the material is shortened, but at the same time the overlapping decreases (author's comment).

9.2.11.2 Spreader Fingers

Rühle (1975) also investigated the spreading properties of fingers (see Figure 9.7). These spreader fingers are located at the out-flow of the piping system. The upper part of the out-flow is lengthened so as to guide the mixture of granules and air down towards the spreader finger.

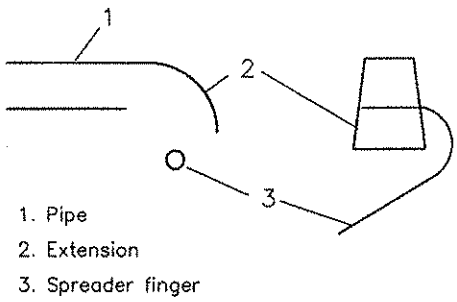


Figure 9.7. Spreader finger (Source: Author's own drawing after Rühle, 1975).

Rühle (1975) found that immediately below and close to the spreader finger, there will be a depression in the fertilizer distribution. High fertilizer rates strengthen this effect and lead to an almost linear increase in the coefficient of variation for uniformity of spread across the direction of travel. Figure 9.8. shows an outline diagramme of the spreader finger's spreading pattern.

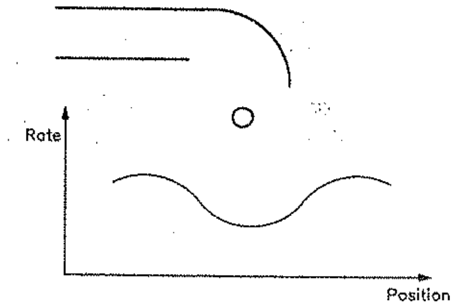


Figure 9.8. Outline drawing of the spreader finger's spreading pattern (Source: Author's own drawing).

9.2.11.3 Fish-Tail Nozzles

Fish-tail nozzles have been evaluated by Papatheodossiou (1970) who found that fish-tail nozzles of the straight type (see Fig. 9.9) gave the best spreading patterns.

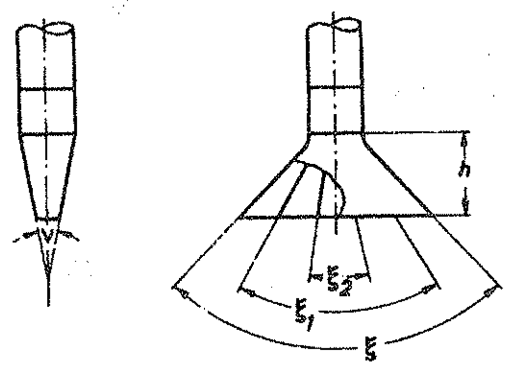


Figure 9.9. Fish-tail nozzle, straight type (Source: Papatheodossiou, 1970).

The aperture angle of the fish-tail nozzle should permit a relatively large working width at low working heights. For this to be possible, it is necessary to have some form of guiding device in the nozzle in order to be able to change the direction of the air-granule mixture. The guiding device can be designed in order to obtain trapezoidal spreading patterns.

Papatheodossiou (1970) found that the fish-tail nozzle is relatively insensitive to changes in the mass flow relationship between granulate and air. In addition, the spreading pattern was not particularly influenced by the type of granulate. Neither do normal variations in air velocity disturb the spreading pattern. At very low air velocities the fine proportion of granulate can easily be exposed to wind drift. At very high air velocities at low working height the fines of the granulate may be exposed to drift caused by the air flow reflected from the ground surface.

The fish-tail nozzle is extremely sensitive to skewed metering in from the pipe system. This depends on the guiding edge of the nozzle dividing up the flow of granules into several smaller sub-flows. This implies also that high demands are placed on the manufacturing accuracy of fish-tail nozzles (Papatheodossiou, 1970).

In summary, we may state that the fish-tail nozzle can keep the working width constant with good uniformity of spread fairly independently of the particle size spectra of the granules. However, it is important to remember that Papatheodossiou (1970) worked with very fine-grained granules. At the particle sizes found in fertilizer the properties of the nozzle may be completely different. However, the spreading properties of the fish-tail nozzle are so interesting that this type of spreading mechanism should be mentioned (author's comment).

9.2.11.4 Cone Nozzles

The cone nozzle (see Figure 9.10) divides the granules into a circular application pattern on the ground. The working width is approximately the same as for corresponding fish-tail nozzles. However, the cone nozzle is extremely sensitive to uneven flows of granules and variations in the position of the spreader body. Consequently, it should not be used in practical applications (Papatheodossiou, 1970).

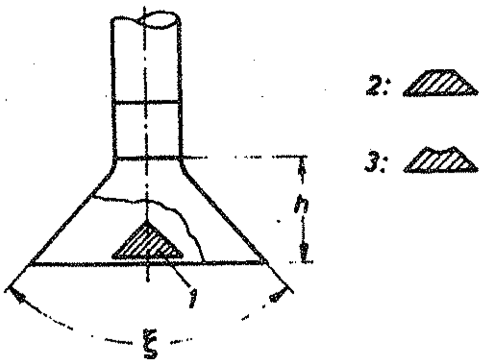


Figure 9.10. The cone nozzle (Source: Papatheodossiou, 1970).

9.2.11.5 Distribution Ducts

Papatheodossiou (1970) built and evaluated six different types of distribution ducts. An example of a distribution duct is shown in Figure 9.11.

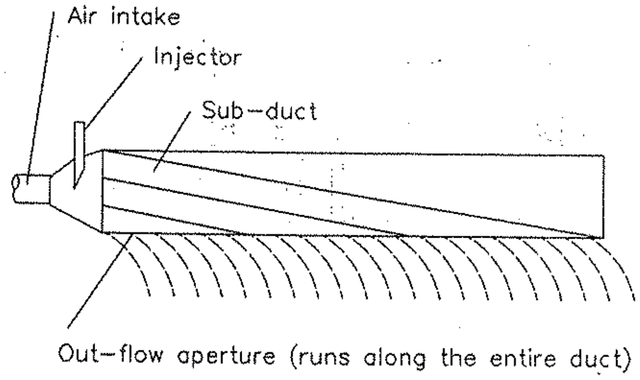


Figure 9.11. Example of a distribution duct (Source: Author's own drawing after Papatheodossiou, 1970).

Papatheodossiou (1970) reports that the distribution of material by means of horizontal air flows has a restricted use. This depends on the sensitivity of the duct to the type of granule. The fine material forms flows along the bottom of the distribution duct and is influenced by turbulence around the out-flow aperture.

Weiste (1988) developed a spreading mechanism that has certain similarities with the distribution duct (see Fig. 9.12). The intention with his work was to design a spreader mechanism with a symmetrical spreading pattern and a large working width. The aim of the large working width was to decrease the need of a piping system at large working widths.

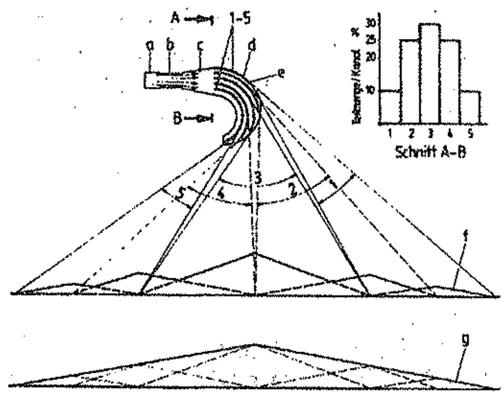


Figure 9.12 Weiste's (1988) spreading mechanism (Source: Weiste, 1988).
a: Pipe; b: Flow director; c: Flow divider; d: Blades; e: Out-flow; f: Spreading pattern from a duct; g: Spreading pattern of the spreading mechanism.

By means of better utilization of the kinetic energy in the granules, Weiste (1988) was able to achieve a considerable increase in the working width of the individual spreading mechanism. This type of mechanism was found, in addition, to be moderately sensitive to lateral slopes of the boom in comparison with conventional spreader plates (see Fig. 9.13). According to Weiste (1988), hygroscopic deposits were avoided with this type of spreading mechanism. In addition, the uniformity of spread in this type of mechanism is fairly constant regardless of the particle size of the granulate.

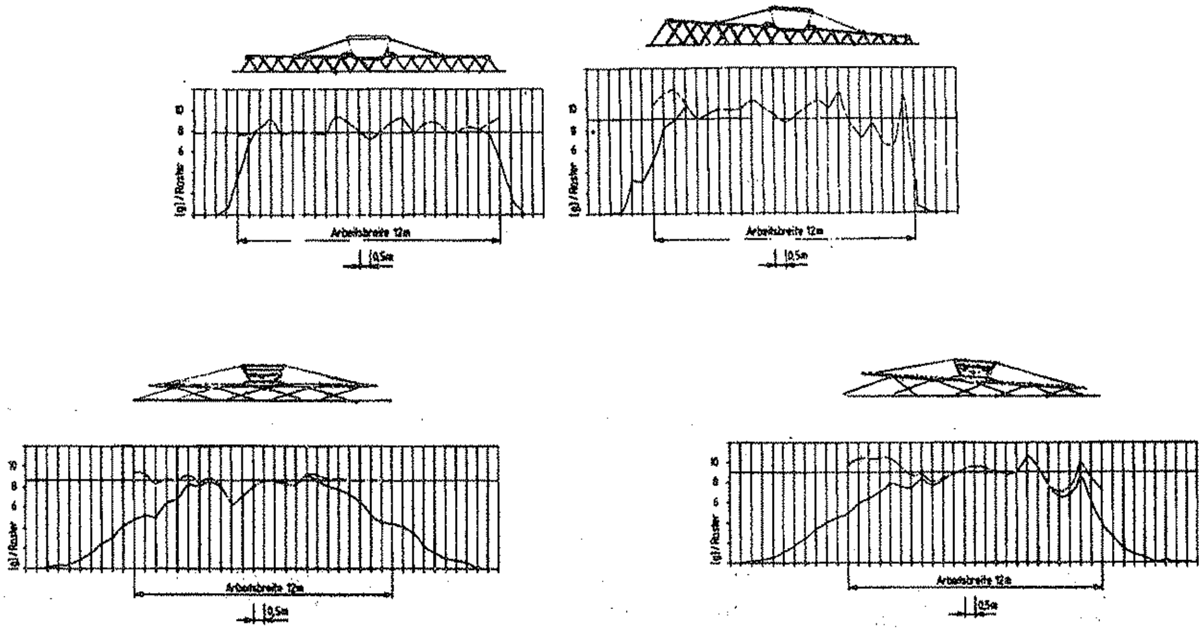


Figure 9.13 Above: Spreading pattern of a sprayer with conventional spreader plates. The coefficient of variation with the horizontal boom is 8%. With the boom sloping 4° the coefficient of variation will be 23.6%. Below: The same slope as above using Weiste's (1988) spreading mechanism. Here the coefficients of variation are 8,4% (horizontal) and 11.7% (sloping).

It should be mentioned that Weiste (1988) makes no mention about the new spreader mechanism's sensitivity to wind drift. However, he may be interpreted to consider that the influence of wind is less with this device than with a spreader plate since the spreader plate frequently throws the granules upwards, whereupon their air-borne period is extended (author's comment).

9.2.11.6 Revolving Discs

Revolving discs powered by the air flow of the transport system have been used to spread the granules over the working width (YstaMaskiner, 1972). These revolving discs throw the material in a circle. The author has been unable to find any test where the actual revolving disc has been evaluated. However, this type of spreading mechanism is extremely sensitive to variations in air velocity (SJF Report 423).

9.2.12 How Should the Spreading Mechanism Be Designed?

On the basis of his investigations, Rühle (1975) considers that the design of the spreading mechanism and the ways whereby the granules are supplied to the spreading mechanism are of great importance for the spreading pattern and, consequently, the uniformity of spread.

Göhlich et al. (1970) present the requirements that must be placed on individual spreading units in order to achieve good distribution accuracy:

1. The spreading pattern must be stable and not sensitive to changes in working conditions (e.g., air velocity and wind speed).

2. The area over which an individual spreading unit distributes fertilizer must lie symmetrically in relation to the spreading unit and the direction of travel.

3. The spreading unit must permit good overlapping and wide working width.

4. Large losses of pressure must not occur in the spreading unit.

The literature suggests that none of the spreading mechanisms used today have fully satisfactory properties. Here, it is probable that new approaches are required to find a spreading mechanism which fulfils the demands that future fertilizer spreading will require (author's comment).

9.2.13 Regulation of Flow

The literature is in agreement as to the importance of an even flow through the metering mechanism. From there it is only a short step to making attempts to control the delivered flow by means of some sort of metering equipment. If the delivered flow can be controlled and varied, then the application rate could be controlled as required on different parts of the field. The problem is to obtain control of the mass flow.

Klensmeden (1984) designed a system for weighing the fertilizer hopper during operation. By integrating measurements during a period of 6 sec. it was possible to obtain information on the current weight of the hopper. After a further period of operation, a new measurement for 6 sec. is made. The difference between the two measured weights provides an estimation of the mass flow.

The disadvantage with Klensmeden's (1984) system is that a new 6-sec. measurement cannot be initiated immediately after the previous one. In such a situation the measurement error would comprise a far too large part of the measured difference in weight. In the form presented (Klensmeden, 1984), the system is suitable for monitoring the application rate per hectare but not for controlling the mass flow. The spreading pattern at right-angles to the direction of travel may, in addition, vary without the mean flow per spreading unit changing. This type of spreading unevenness is not discovered by the measuring system. The advantage with Klensmeden's (1984) system is that it permits weighing during operation (author's comment).

Tsaturjan and Kazarjan (1978) controlled the delivery in a disc meter by applying an electric current between the aperture of the delivery mechanism and the disc. The delivered material was red clover seed and the current varied between 0 and 6 kV. The maximum divergence in application rate for 10 measurements was 1%, the mean deviation being 0.5%. The length of the measurements was 20-120 sec.

Tsaturjan and Kazarjan's (1978) control equipment appears to be intended for stationary use. No mention is made of the influence of bumps or vibrations. In addition, the measurement times reported are far too long for use when adjusting according to the need on different parts of a field (author's comment).

Green and Foo (1986) report a system for a measurement of mass flow in pneumatic transport pipes. Two sensors mounted as part of the pipe wall measure the mass flow in the pipe by means of cross correlation. The mass flow meter is intended for applications where weighing of continuous flows are required.

Green and Foo (1986) do not report the measuring accuracy and calibration requirements of the system. Neither is it clear whether the sensor can measure material of varying size without re-calibration. However, the solution of the weighing problem is interesting for three reasons:

1. The weighing is "touch-free". Admittedly, the sensor is included as an incorporated part of the pipe wall but no re-direction or flow division of the material is required. This decreases problems with deposits, thixotropy and spreading unevenness as a result of disturbances to the flow.

2. The system does not require extra construction in the delivery mechanism. This simplifies the design of the delivery mechanism, since no consideration need to be taken to any influence of a weighing device on the metering accuracy.

3. The system implies measuring in each pipe. This is both an advantage and a disadvantage. The advantage is that control of sections of the spreader boom is possible. In this way, it is possible to measure variations across the bout. The disadvantage is the increase in expense. Instead of one central weighing device, it is necessary to have one in each pipe.

Naturally, there are other systems of measuring mass flow. However, the author has not found any that is suitable for the conditions applying during the spreading of fertilizer. Fertilizer is corrosive, its physical properties vary and the machine is constantly exposed to vibrations during the metering. However, the three systems mentioned above may have a potential for further development.

9.3 THE FIELD

Field parameters of importance are (Elinder, 1984):

* Field geometry (shape, slopes, bumpiness)

* Distribution of soil type

* Cultivation capacity of the headland.

Field shape and driving pattern cause gaps and overlapping (Jonsson, 1987). Consequently, it is important to be able to spread evenly also when part of the boom is closed (M. Elinder, pers. comm.). By being able to work with parts of the boom closed it is possible to get the tramlining, etc., to "go evenly out" on fields with edges that are not parallel. Field shape and slopes may, admittedly, frequently be changed to the better but with the severe economic climate today it is hardly probable that this will be attempted.

The width of the headland is influenced by field shape and the turning radius of the machine. A large turning radius will have a negative influence on the driving pattern and the labour requirement (M. Elinder, pers. comm.).

The bumpiness of the field may be influenced to some extent by the seed-bed preparation (author's comment). In addition, the design of the machine should dampen the influence of bumpiness on the field.

Machine design should also counteract such field properties as moisture content and soil type influencing the performance. As an example, it may be mentioned that moist clay which fastens to the wheels should not have a negative result on the uniformity of spread.

The lower cultivation capacity that is normally found on headlands requires that the machine can vary the application rate.

9.4 WEATHER

The weather factors that mainly influence the spreading accuracy are:

* Wind speed
* Air temperature
* Relative humidity

Wind speed influences the length of throw, mainly as regards the small particles. This will also influence the spreading pattern of a full-width spreader (author's comment).

Air temperature and moisture are, together with the temperature of the fertilizer, decisive for the water uptake of the fertilizer. Since the fertilizer has a very low moisture content at packaging, it will rapidly take up water from the moment the package is opened if the conditions are favourable. Large water uptake will change the flow properties of the fertilizer and thus the metering (Kämpfe et al., 1982; Bergström, 1979). However, it is hardly probable that correctly stored fertilizer will have time to change so much during the actual spreading that the result is severely deteriorated (U. Lundquist, pers. comm.). On the other hand, the parts of the spreader that work in contact with the ambient air (e.g., the spreader plates) may become extremely sticky (E. Nilsson, pers. comm.). This tendency for deposits on the spreading mechanism may, naturally, have some effect on the spreading result (author's comment).

9.5 THE OPERATOR

The operator is the overall regulator in the "granule spreading system". The quality of the work performed depends on how well the operator can cooperate with the towing vehicle, spreader, and the information supplied by any other equipment (M. Elinder, pers. comm.).

It is the operator who adjusts the required value on the delivery mechanism and it is also the operator who must observe whether there is a risk for incorrect function owing to moisture, deposits of fertilizer or contaminating objects among the granules, that granules are metered correctly, etc. It is the cperator who choses the driving technique and the way the work is done (transports, spreading, checks of function) in each field. The uniformity of spread resulting from the most perfect machine largely depends on operator performance (M. Elinder, pers. comm.).

According to Bergström (1979), the lack of information is the factor that complicates the operator's situation in modern agriculture. In high-technological agriculture the situation may be the reverse. Too much information will disturb the operator (author's comment). If the operator is to be able to work well, it is necessary that he is supplied with a carefully balanced volume of high-quality information.

The operator should have assistance in steering the tractor. In addition, the operator should have the possibility to adapt the application rate to the needs of the crop. Using modern techniques, this implies steering with the help of markers or tramlining and the adjustment of the application rate in different parts of the field based on experience. With technology of the future, this may imply that the fertilizer spreader warns the operator about unacceptable deviations from the correct course and when it is not possible to supply fertilizer in accordance with the needs of the crop (either according to a predetermined programme or as a result of direct reading on the field). It is important to remember that the operator must be given training in new systems so that he/she can utilize the system to achieve good performance (author's comment).

10 DISCUSSION

This survey of the literature suggests that a lot must be done before we fully understand or can assess and influence the factors controlling uniformity of spread.

In order to understand the processes that determine the yield result we also require better knowledge of the crop's ability to adapt itself to the nutrient supply. The influence of competition and compensatory growth on the end result has great importance on the requirements we place for precision in fertilizer spreading.

In order to assess the performance of a fertilizer spreader, we require comparable and replicable data based on crop requirements. It is the effect of the work that is interesting and not the exact spreading pattern.

In order to influence the uniformity of spread, we require knowledge on how a granular mass flow can be controlled within the machine. In addition, the part of the spreading that takes place outside the machine, and thus outside our control, must be minimized.

10.1 WHICH FACTORS CAN BE INFLUENCED?

Of the five general factors influencing the accuracy of spreading (the fertilizer, the machine, the operator, the field and the weather) the weather can hardly be changed. Admittedly, windy days can be avoided when spreading fertilizer but the relative humidity cannot be influenced. Also the field is fairly difficult to influence, at least in the short term.

The physical properties of fertilizer can be changed. However, fertilizer manufacture is a process industry with high capital requirements and modifications will require both time and money. There is little hope that fertilizers with "taylor-made" physical properties will be available within the near future.

The two remaining factors are the machine and the operator. Consequently, we must conclude that at least in the short term **the machine and operator must compensate for disturbances from the fertilizer, the field and the weather.**

The need for new technology for increasing the precision in fertilizer spreading can be divided into two sectors: Spreading technology and control. A short summary of the requirements that should be fulfilled in the future is given below.

10.2 REQUIREMENTS ON SPREADING TECHNOLOGY

The actual machine design falls under the heading spreading technology. The machine must have the potential to perform good work with the correct control/information equipment.

The hopper should be designed as a unit coordinating with the delivery mechanism. This is in order to obtain a stable and reliable metering of the granules. A well-designed hopper and metering mechanism will prevent tendencies for bridging or variations in mass flow depending on the uneven flow of material to the metering mechanism.

There are also aspects with regard to the hopper concerning work methods, mainly as regards the size. A large hopper implies a high working capacity depending on a small proportion of driving when unloaded and fewer needs to refill. The high work capacity leads to low timeliness costs. The disadvantages with large hoppers is that the longer emptying times increase the risk for moisture uptake and consequently deposits of fertilizer in the metering mechanism. In addition, the soil compaction will increase with increased load weights. If tramlining is used, then the compaction is concentrated, however, to the wheel tracks where all machines will be driven during the cropping season.

The metering mechanism should be capable of delivering fertilizer of varying physical properties in an unaltered flow. In addition, it should be possible to adjust the mass flow within wide limits. The metering mechanism must not suffer from hysteresis. In addition, it is to be fairly tolerant to shaking, vibrations and bumps. In order to fulfil these requirements, it appears that some type of cell wheel might be a possible solution. The metering from a cell wheel of this kind is extremely enforced which would minimize the influence of disturbances. The questions with regard to cell wheel design concern the capacity it can achieve, whether the pulsating mass flow that normally occurs is acceptable and how the cell is to be kept clean of fertilizer deposits.

An interesting idea would be to design a cell wheel that is based on the same principle as a fluted roller. By varying both the roller's speed and its effective length, it would be possible to obtain a wide spectrum with different fertilizer application rates. At the same time, this would also retain the precision in the mass flow. It has become increasingly important to be able to meter out doses of very variable size with good precision. The highest doses today are more than 800 kg/ha. The lowest application rates are between 90 and 120 kg. A metering spectrum that is so wide places extremely high demands on the mechanism.

The transport system must be capable of moving the fertilizer to the spreading mechanism without deteriorating its physical properties. The evenness of flow achieved in the metering must not be deteriorated. The fertilizer must have a good radial distribution in the pipe at the entry to the spreading mechanism. The transport system must be able to cope with varying application rates without suffering from pulse flows and formation of strips along the bottom of the pipes.

The spreading mechanism must broadcast the fertilizer evenly over the entire working width. The distance the granule flies through the air must be as short as possible with regard to wind drift. Uniformity of spread must not be influenced by varying application rate per hectare or changes to the physical properties of the fertilizer.

One way of improving the spreading mechanism would be to utilize the kinetic energy in the material. This is achieved by the spreading device presented by Weiste (1988). High velocity of the material can be retained by the spreading device throwing the material parallel to the boom. In the commonly-occurring spreader devices the material changes direction 1-3 dm before it reaches the spreading device. This leads to large energy losses.

Nonetheless, it is not the distribution between the spreading devices that is of importance for the crop, but the distribution the material has when it reaches the ground. Consequently, it would be interesting to investigate whether trailed tubes might also be a solution when spreading fertilizer. If trailed tubes are used, then the problem with wind drift will largely disappear. In addition, the actual spreading device at the end of the tube might become unnecessary and thus could imply a saving. The disadvantage of this system is, however, that the tubes must probably be trailed fairly close to each other. This would imply numerous tubes and pipes which might make the machine considerably more expensive.

The boom must be stable and its movements in relation to the spreader must be minimized. Technique for this is available (Frost, 1987; Frost and O'Sullivan, 1986; Frost, 1984), but is patented and thus has limited availability (P. Miller, pers. comm.).

10.3 CONTROL REQUIREMENTS

Even the best fertilizer spreader will require some kind of automatic control, if not for any other reason than for the operator to be able to vary the application rate on different parts of the field from the driving seat. In the present context, the term regulate is intended to have a slightly wider interpretation than normal.

The desired mass flow through the machine must be adjustable from the operator's seat. This mass flow must remain constant until the desired rate is changed. When necessary, each part of the boom must be adjusted separately. This can be done by, e.g., having separate power units for each delivery roller in a roller metering system.

In this context the possibility to close part of the boom should be mentioned. The increasing environmental consciousness in agriculture will demand that a fertilizer spreader must be designed in a way that prevents fertilizer to be spread outside the field and into ditches. In order to make a driving pattern "to go evenly out" on irregular fields, it must be possible to close part of the boom.

10.4 FERTILIZER SPREADING IN THE FUTURE

Being aware of on-going research and developmental projects, the author will here attempt to describe a possible future scenario as regards spreading fertilizer.

The future fertilizer spreader will largely fulfil the above-mentioned requirements as regards spreading technique and adjustments. Consequently, a variable spreading pattern can be achieved with a low range of variation.

In order to have good performance, it is necessary that the spreading patterns overlap each other in the correct manner. This will be done by means of some kind of localization system. The simplest method is already used today, namely tramlining. In the future, computerized localization systems will certainly be available.

In order to be able to apply fertilizer according to the needs of the crop, it is necessary to have knowledge of these needs. Today, this knowledge can be obtained from soil mapping and entered on a digital map. This map can then be interpreted by the tractor's computer. The localization system and the automatic control of the fertilizer spreader will ensure that the correct amount of fertilizer will be applied in the right place.

Another solution is to continuously measure the nutrient requirement during the actual spreading and apply fertilizer accordingly. Developmental work on a sensor for the nutrient requirement is presently on-going.

A third approach is to apply fertilizer on the basis of yield potential. This requires that the mass flow into the combine's hopper can be measured and linked to the actual position. Technique for measuring this mass flow is available today (P. Miller, pers. comm.).

10.5 NEW TYPE OF FERTILIZER SPREADER

On the basis of available literature and the discussion above, the author has presented an idea for a new type of fertilizer spreader. This would largely fulfil the requirements that will be placed in the future on spreading accuracy.

The new type of fertilizer spreader presented above is intended for the spreading of granules. It is possible that the crop sprayer, or some other kind of sprayer, will be used for spreading liquid fertilizers in the future. However, pilot studies at the Swedish University of Agricultural Sciences indicates that liquid fertilizers should have a carefully balanced mix of nitrogen compounds in order to reach the same plant nutrient effect as nitrate of lime (Nilsson & Olsen, 1990). Furthermore, potassium and phosphatic fertilizer are difficult to dissolve in water. Problems occur with precipitation etc.

Sweden also have strict legislation concerning storage of liquid chemical solutions. If the fertilizer is stored in a tank, measures must be taken against any leakage to reach the surrounding environment.. The conclusion is that the granular fertilizer will be part of the agricultural machinery in the forseeable future.

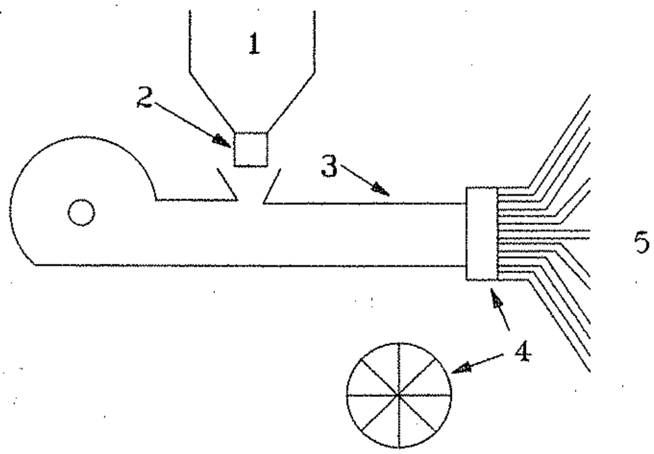


Figure 10.1. Illustration of the delivery and transport system in a new type of fertilizer spreader. Explanations: 1. Hopper. 2. Cell wheel delivery. 3. Pipes. 4. Flow distributor. 5. Pipes to the boom. (Source: Author's own illustration).

Figure 10.1 shows that the delivery and transport system is designed in a new approach. The delivery consists of three cell wheels which feed the granules into a common pipe. After a certain transport distance, the material is divided in a flow distributor into pipes leading to the respective boom spreaders.

The cell wheels permit a more stable delivery than the studded roller. The influence of slopes, shaking and vibration is reduced. By phasing the cell wheels so that they empty their cells at different times, pulses can be reduced. The flow will be more uniform. If, in addition, the cell wheels are designed according to similar principles as a sliding roller (controlled cell volume), a wide spectrum of application rates can be achieved with high delivery accuracy. The small number of delivery organs ensures inexpensive delivery. In addition, future control delivery of the mass flow need only be fitted at one place.

The transport distance following the delivery is in order that the granules will attain good radial distribution before they reach the flow distributor. Also this solution will be more inexpensive than the conventional approach, since only one pipe is required for this transport. Since the transportation is pneumatic, horizontal and placed at a low level in the machine, the distribution of the granules along the pipe will be minimally influenced by slopes, vibrations and bumps. However, this does not apply if the granules are finely ground. Finely-ground granules can flow along the bottom of the pipe and thus case extremely poor distribution in the flow distributor.

Possibilities to partly close the booms can also be built into the flow distributor. However, closures in the flow distributor must be linked to the delivery so that it can adjust the mass flow to the working width.

After passing through the flow distributor the material is transported to each respective boom spreader. The boom spreader should throw the material parallel to the boom in order to utilize as much as possible of the material's kinetic energy. High kinetic energy implies short flight distances and thus less influence from wind. In addition, the working width of each boom spreader can be increased and thus the number of boom spreaders can be reduced. This implies that manufacturing costs will decrease. An alternative solution would be to use trailed piping. However, this would require a large number of pipes (c/c = 0.25 m) which would severely increase the cost of the machine.

Naturally, the boom should be suspended in a way which filters off high frequencies. This will provide a stable boom and give increased accuracy of spreading.

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