The potential contribution of separation technologies to the management of livestock manure

C.H. Burton *

Cemagref, Groupement de Rennes, 17 Avenue du Cucillé, 35044 Rennes, France

Abstract

Separation processes have a distinct role in the management of livestock slurries, but it is important to recognise their limitations. Such technology can direct certain manure components into a small volume of a concentrated stream which is useful for the production of organic products in subsequent processes. Equipment generally falls into systems based either on mechanical screening (which can produce a fibrous and seemingly dry product), filtration processes (producing a cake), or sedimentation leading to a sludge product. Although physical separation can remove up to 80% of the total solids content from livestock manures, this will only include a relatively small part of the soluble nutrient and of the reactive organic matter; this is particularly so where separation is based on screens. The complete removal of all suspended matter (total clarification) of an effluent is theoretically possible by settling — a decanter centrifuge will accelerate the process. This can remove most of the phosphorous, especially if coupled with chemical pre-treatment to raise the pH. However, the clarified stream still retains a significant polluting potential in terms of the residual nitrogen content (as ammonia) and potassium. Only membrane separation can greatly reduce the potassium concentration, but such technology is rarely suitable for the farm situation.

Keywords: Livestock manure; Separation; Sedimentation; Clarification; Pollution; Treatment

1. Introduction

Treatment techniques for livestock manure at a farm may be implemented (a) to make the farm operation more efficient (improved handling), (b) to reduce the various pollution risks from manure, (c) to reduce nuisance factors such as offensive odour, (d) to respond to hygienic concerns, and (e) to draw some value from the solid and liquid wastes produced at the farm. A wide range of treatment processes already exists that can respond to these needs such as reviewed in detail by Burton and Turner (2003), but many of the systems are considered too expensive for livestock farming. However, separation systems tend to be the exception and often represent a cheaper treatment option. Furthermore, in many instances, the process falls comfortably into the farming system — they are often relatively cheap and simple and require little attention. It is therefore not surprising that separation is often the preferred option in dealing with the problems associated with manure. However, it is important that the true value of such systems is appreciated, and that unrealistic expectations are avoided.

The objective of this review is to establish the scope of separation technologies within the context of liquid animal manures, marking out what can be achieved and that which requires additional steps, such as biological or chemical treatment. The principles (rather than specific equipment) are considered in the light of the

* Tel.: +33 223 48 21 28.
E-mail address: colin.burton@cemagref.fr.

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The apparent performance of a separation system will depend on the volume of the solids fraction produced as % of the feed stream. A simple mass balance can show that this will rapidly increase as the feed concentration approaches that of the final solids stream (Martinez et al., 1995). As an example, livestock slurry at a nominal 3% solids concentration passing through a settling system where all solids are removed to a concentrate at 8%, will produce sludge representing 25% of the feed volume. This proportion is approaching the point where there is a questionable value in the separation process. If raw slurries with an even higher dry matter content are to be processed, then clearly the concentration process must be intensified, suggesting such technology as centrifugation.

On the other side of the process, performance may be determined by the degree of clarification of the supernatant phase produced, especially if this represents the principle volume to be irrigated or otherwise used locally. If duties around the farm are envisaged such as flushing manure channels, a high degree of clarification is necessary, but without producing large volumes of dilute sludge.

Given several methods of defining separation performance, selection of the most appropriate measure will depend on the objective of the process: this is summarized in Table 1.

One final performance factor is that of speed of separation. This is especially so for gravity settling, where the number of days required directly affects the size of vessels required. High temperatures, low feed concentration, and the use of flocculants all contribute to a faster process (Martinez et al., 1995), but the effect is to move the whole settling curve: the finer particles invariably need the longer period of time as predicted by Stokes Law. In addition, some degree of “sludge compression” can also occur during settling, increasing

<table>
<thead>
<tr>
<th>Process</th>
<th>Suggested means to define efficiency on the basis of component $X$</th>
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<tbody>
<tr>
<td>Clarification to produce a low strength supernatant stream for flushing of pens or irrigation to limited land</td>
<td>$X_u/X_f \times 100%$</td>
</tr>
<tr>
<td>Solids concentration to produce an enriched stream for anaerobic digestion or for use as an organic fertiliser (including composting)</td>
<td>$X_{s}/X_{f} \times 100%$</td>
</tr>
<tr>
<td>Volume reduction to enable exportation of a solid concentrate product and local irrigation on limited land: volume of solids less than 20% of feed volume</td>
<td>$U/S \times 100%$</td>
</tr>
<tr>
<td>Volume reduction to enable exportation of a solid concentrate product and local irrigation on limited land: volume of solids greater than 20% of feed volume</td>
<td>$S/F(X_{s}/X_{f} - 1) \times 100%$</td>
</tr>
</tbody>
</table>

The letters $F$, $S$ and $U$ refer to feed, sludge (or solids concentrate) and supernatant streams, respectively: as a lower-case subscript to $X$, this is as a concentration; as the capital letter, this is as mass flow rate.
its solids content, but if settlement extends over very long periods (i.e., weeks) the onset of anaerobic activity can lead to some particle re-suspension.

3. Appropriate separation technologies based on particle size

The total solids content of a liquid manure or slurry is divided, in general terms, between that dissolved and that present as suspended matter. Beyond this, a useful fractionation of the suspended matter can be made to reflect the performance of the main groups of separating equipment available (Fig. 1).

Fibrous material screened from animal manures has a distinctive texture due to the animal hairs, bedding and larger particles that make up much of the solid material. It can be removed by a wide range of separators following a screening process (Fig. 2) — the implication is the passage of the slurry through a screen, the solid matter being retained. The principle follows that of filtration, but it is not necessarily equivalent to a simple sieving process in that a proportion of particles finer than the hole size can also be retained, which is in part due to the fibrous nature of much of the matter removed. The hole size varies from 1 to 5 mm or larger, with the inevitable loss of capacity as finer screens are used to retain a higher proportion of the suspended matter. In some cases, finer screens can also lead to a wetter solid product, and to operational problems. To combat this limitation, more intensive machines have been developed, such as screw presses or sieve centrifuges, but these also tend to be more costly and offer a relatively low throughput.

The cut-off point for separators when used alone are particles with an effective size of around 1 mm: Møller et al. (2002) gave such a figure for trials with a screw press. However, the physical nature of fibre makes the definition of particle size imprecise. For cattle slurries where a large amount of straw and related material is present, more open screens are often necessary to allow reasonable separator performance, and one can define a coarse fibre fraction of particles in excess of a nominal 5 mm.

For particles finer than 1 mm, the appropriate technology is based on a sedimentation principle — either by gravity or accelerated as observed in centrifuges. Settling processes often follow a biological treatment for the very good reason that many natural, but degradable, organic surfactants exist in raw slurry that can inhibit flocculation and settling. The separation process relies on the higher density of suspended particles than of water, but for animal slurries this difference is small. A preliminary screening operation is useful to remove the lighter fibrous material; much of

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**Fig. 1.** The division of the solid matter of animal manure into fractions that can be removed by the main categories of separator or separation process.

**Fig. 2.** Common separation and screening technologies for liquid animal manures. F denotes the feed stream, L the screened liquid stream produced and S the solids output. The general names for the devices are: I. rotating screen; II. brush-roller; III. vibrating screen; IV. screw press; V. belt press; VI. run-down screen.
what remains can be settled, even if slowly, in many cases. The lower end of particle size is theoretically around 1 μm, at which point Brownian motion begins to dominate and the behaviour is that of a colloidal particle. However, for practical systems the lower size limit of separated particles is larger: Møller et al. (2002) gave a cut-off of 20 μm based on trials with a decantor centrifuge. Sneath et al. (1988) gave results of centrifuged pig slurry that produced sludges with a mean (x50) particle size of 5 μm, but the proportion of the original suspended matter removed was only 40–60%.

The size of an individual bacterium lies between 0.5 and 5 μm, but their removal by sedimentation processes is significant, as they tend to form flocs which are also often attached to larger particles. Adding flocculants can increase this effect whilst enabling the removal of other colloidal material via the same process. Raising the temperature can accelerate the process, but usually to the same end-point — no additional separation is necessarily implied.

A single separation process rarely both removes a high proportion of the suspended matter and produces a solids phase high in dry matter; one objective is usually at the expense of the other. Therefore, a second or further steps may be needed if both are important (Fig. 3).

For the sludge phase, this subsequent processing amounts to thickening or drying options, the removed water being sent back to the feed stream. For the liquid phase, filtration may be considered if the amount of suspended matter is relatively small. This involves the use of a filter cloth with pore sizes typically 20 to 50 μm, but down to 10 μm in the finest applications. Inevitably, flow through such media will be greatly inhibited, and filtration units often make use of increased pressure in some way, such as a filter press. The retained particle size is likely to be smaller than the pore size on account of the development of a filter cake (sometimes encouraged by the inclusion of a filter aid such as fine sand into the feed stream). Clearly, the technique is best suited to the clarification of dilute streams; the presence of large amounts of suspended matter will require the frequent discharging and cleaning of equipment. When working well, filtration can also remove a large part of the colloidal material, leaving a wastewater that is almost totally clarified. However, there is no guarantee that all bacteria will be removed, and the effect on the much smaller viral particles (0.05 to 0.5 μm) will be substantially less.

For the removal of the finest particles and, indeed, of the dissolved matter itself, the only separation option is that based on membranes. The underlying principle is again filtration, but often the configuration is “cross-flow”. This implies the circulation of effluent across the membrane under pressure; clarified water (permeate) is effectively squeezed out, leaving a concentrated stream behind. Such a process is only suitable for the most dilute of effluents for two reasons: (i) the build-up of deposits on the membrane that will inhibit the flow rate of the permeate and thus require more frequent cleaning cycles, and (ii) the increasing process back pressure caused as the concentration of the feed stream increases with time.

Membranes can be grouped under four headings: microfiltration, with a pore size of 100 to 2000 nanometres (nm); ultrafiltration (10 to 100 nm); nanofiltration (1 to 10 nm); reverse osmosis (pore size below 1 nm) (Tchobanoglous et al., 2002). Microfiltration will remove most bacteria, and ultrafiltration will remove viruses as well. Nanofiltration and reverse osmosis (RO) work as much by a process of particle diffusion as by a filtering mechanism. Membranes can uniquely filter dissolved material from the feed stream; in the case of RO, salt ions can also be removed, leaving almost pure water. However, other than microfiltration, the practicality of such potentially costly systems in treating even dilute farm effluents is very limited.

4. The scope of separation technologies

4.1. The potential effect of separation on the solids content of livestock slurries

Invariably, the potential of any separation system depends on the solubility of the component of concern (or at least its readiness to flocculate or precipitate when chemically pre-treated). Typically, this leads to
considering the fractions that together characterise the effluent (Table 2). These include the nitrogen content (subdivided into ammoniacal and organic forms), phosphorous (which can also be divided into mineral and organic forms) and organic matter. The latter is a mixture of many chemical species, which may be quantified as the fraction degradable biochemically in 5 days (BOD$_5$), or that defined as volatile (either in the suspended or total solids fraction). In addition there are “heavy” metals (e.g., copper, zinc), and various salt ions (e.g., potassium, chlorine, sodium, calcium).

The total dry matter content of any livestock effluent will comprise all components dividing into that truly dissolved, that clearly in suspension, and the colloidal matter lying between the two. By definition one might expect all suspended matter to be removable by separation technologies, but in reality the fine filters used in the laboratory for the measurement protocol are rarely equalled in farm equipment. Consequently, the fraction of total solids found in the clarified liquid after separation, even after centrifugation, is significantly greater than the analysis of dissolved matter might have suggested (Sneath et al., 1988; Martinez et al., 1995).

<table>
<thead>
<tr>
<th>Typical analysis (% of total solids)</th>
<th>Insoluble proportion of component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total solids (TS)</td>
<td>100</td>
</tr>
<tr>
<td>Volatile solids (VS)</td>
<td>70–85</td>
</tr>
<tr>
<td>Total suspended solids (TSS)</td>
<td>80–90</td>
</tr>
<tr>
<td>Volatile suspended solids (VSS)</td>
<td>70–75</td>
</tr>
<tr>
<td>Chemical oxygen demand (COD)</td>
<td>100–150</td>
</tr>
<tr>
<td>5-day biochemical oxygen demand (BOD$_5$)</td>
<td>30–40</td>
</tr>
<tr>
<td>Volatile fatty acids</td>
<td>4–12</td>
</tr>
<tr>
<td>Kjeldahl nitrogen (N$_{K}$)</td>
<td>7–12</td>
</tr>
<tr>
<td>Organic nitrogen (N$_{org}$)</td>
<td>3–5</td>
</tr>
<tr>
<td>Ammoniacal nitrogen (N$_{ammon}$)</td>
<td>3–7</td>
</tr>
<tr>
<td>Phosphorous (as P)</td>
<td>2–3</td>
</tr>
<tr>
<td>Potassium (as K)</td>
<td>2–4</td>
</tr>
<tr>
<td>Copper</td>
<td>0.1–0.2</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.1–0.2</td>
</tr>
</tbody>
</table>

Table 2
Typical analysis of a livestock slurry (fattening pig in this example) illustrating the main components that characterise the effluent (Williams and Evans, 1981; Williams et al., 1989; Martinez et al., 1995)

4.2. The effect of separation processes on the organic matter component

The fraction of volatile solids (VS) is sometimes used as a basis for estimating biogas production from animal manures (e.g., Burton and Turner, 2003). Compared to total solids (TS), one would expect a slightly lower solubility from the VS fraction, as the soluble inorganic salts present in the manure are not included. Sedimentation systems to produce a concentrate with a higher biogas yield per unit volume of liquid might be expected, and this is reported in practice (Møller et al., 2004).

The BOD$_5$ value for a livestock slurry would be expected to relate more closely to the soluble fraction. The aerobic degradation of any insoluble organic matter will first require the slower hydrolysis step ahead of the complete oxidation process. In consequence, the fraction of solid matter defined by the comprehensive COD (chemical oxygen demand) measurement will include a much higher proportion of insoluble material which can be chemically digested, but not degraded by microbes within five days. Separation processes can thus be expected to reduce the overall organic load in the liquid fraction, but in terms of the reactive component (as represented by the BOD$_5$ fraction) a much smaller effect can be expected.

An important part of the organic material making up the BOD$_5$ fraction is the volatile fatty acids (VFA’s). These include chains of up to 5 carbon atoms (but mostly ethanoic or propanoic acids) that can serve as an indicator of the production of offensive odour (Williams, 1984; Sneath, 1988), and also of biogas production. This part of the organic content of animal slurries is almost entirely soluble, and one would thus expect little benefit from separation. This was indeed observed in the work reported by Zhu et al. (2001). Other workers (e.g., Zhang and Westerman, 1997) have reported some measurable reduction in manure odour as the result of separation processes alone. However, a detailed analysis by O’Neil and Phillips (1992) of 168 organic compounds revealed none associated with offensive odour that were insoluble. The removal of suspended matter from manure could reduce the production of VFA’s during the subsequent storage of the liquid fraction, but no immediate effect can be explained. Indeed, Ndegwa et al. (2002) reported no significant effect on odour generation if the separation was limited to particles larger than 75 μm, as might be expected. However, it is noted that some odourous molecules that can be smelled at very low concentrations can attach to solid particles — arguably, clarification of an effluent may achieve a small reduction in odour by this mechanism. Odour remains a
complicated parameter to measure and quantify, which can make objective research difficult.

4.3. The effect of separation on the nitrogen component

Nitrogen in livestock wastes comprises ammonia, derived from the breakdown of urinary urea and organic constituents, and nitrogen in non-degraded organic material originating mainly from the solid dung produced. Total nitrogen can be analysed as Kjeldahl nitrogen, although this measurement will not normally include any nitrates or nitrites present. Ammonia is completely soluble, and one would not normally expect any removal by separation beyond that of partition. Some ammonia can be removed as struvite in what is also known as the MAP process (magnesium–ammonia–phosphate) (Munch and Barr, 2001; Laridi et al., 2005), but the quantity precipitated is modest compared to the large amounts of magnesium and phosphorous required. An alternative strategy is to adsorb the ammonia using zeolites, and then to separate as a nitrogen rich sludge. The use of a range of such minerals has been well studied with some promising results, but the quantities needed can be large — as much as 5% of the slurry volume (Lefcourt and Meisinger, 2001). This limitation was avoided by Henriksen et al. (1998) by the use of calcium chloride to periodically regenerate the mineral by a process of ion exchange. However, in this case it was crucial to include an initial clarification step to produce a clear liquid.

Organic nitrogen is largely insoluble and includes any bacterial floc material. Sedimentation of a concentrate containing most of the organic nitrogen is readily possible, but screening processes will have relatively little effect. The use of soil filters can remove all nitrogen except ammonia, which is biologically oxidized to nitrates that will end up in the final leachate (Martinez, 1997). A subsequent biological step is necessary to ensure breakdown of the nitrates produced by denitrification, the nitrogen being lost as di-nitrogen gas.

4.4. Phosphorous and heavy metals

For phosphorous and some of the “heavy” metals, the effluent pH will have a strong influence on solubility. In livestock effluents, phosphorous exists in both organic forms and as salts and compounds of inorganic phosphate. In acid conditions, the latter forms the relatively soluble hydrogen phosphate ion which can remain in solution in the presence of calcium. Raising the pH will see the chemical equilibrium move towards the formation of phosphate (PO$_4^{3-}$) and subsequent precipitation as calcium phosphate. The addition of lime in particular will induce a high degree of precipitation, the particles of calcium hydroxide aiding the settling process. In addition, a wide range of metal ions will be precipitated as insoluble salts such as copper and zinc carbonates. The main drawback of raising the pH (i.e., the substantial increase of ammonia volatilisation) is avoided if the manure has been pre-treated biologically to remove nitrogen as di-nitrogen gas (Vanotti et al., 2003).

Separation of a precipitated phosphorous-rich sludge can be difficult owing to the very small size of the particles. Even if rendered insoluble by the addition of a precipitant, the removal by settling alone may be incomplete, as fine particles tend to carry over. Szogi et al. (2006) used cloth filters to recover a phosphate-rich sludge, but to avoid excessive blockages they found it necessary to use a polyacrylamide additive as a flocculant. Greaves et al. (1999) reviewed the potential for recovering phosphorous from livestock wastes as a valued product rather than simply a waste treatment option. They advocated a process referred to as EBPR (Enhanced Biological Phosphorous Removal), in which the phosphorous is removed either as calcium phosphate or as the previously described struvite. Removal of phosphorous as struvite has been studied as a complete process by Estevéz-Rodriguez et al. (2005), including initial pre-screening of the slurry by screw press and flocculation by ferric chloride.

The use of large scale soil filters can remove a large part of the suspended matter, leaving entrained material within the soil system. Efficient removal of the heavy metals is possible, but subsequent accumulation in the soil is inevitable, leaving a long-term problem in managing the land involved (L’Herroux et al., 1997).

4.5. Removal of salts

In the presence of certain anions, such as carbonate or phosphate, metals such as calcium and magnesium can be removed as insoluble precipitates. For sodium and, especially, potassium virtually all the related salts are soluble, and likewise for chlorine. For the physical removal of such components the only option is membrane separation. This requires the effluent to be, firstly, clarified to a high degree, and even then the process can have operational problems. Nonetheless, Pieters et al. (1999) demonstrated such a system treating sow slurry with a volume reduction of 77%. The use of reverse osmosis in the final stage produced a permeate largely free of salts, but the reported cost was high at 7 euros per tonne of slurry.
4.6. The effect of separation on microorganisms

Micro-organisms rarely exceed 1 mm, most being much smaller, yet treatments based on separation can have a pronounced effect. This is due either to the tendency to form flocs, or to entrapment by, or attachment to, other solid matter. The formation of flocs by bacteria is a crucial step in the retention of biomass in water treatment processes (Tchobanoglous et al., 2002), and the same mechanism can be expected from any sedimentation operation. However, whilst the collection of 90% of bacteria in a sludge phase represents a good separation in process terms, it is only a one log_{10} reduction. This is relatively modest in microbiological terms, and any benefit in hygiene would be deemed small. Entrapment of bacteria within soil potentially approaches a complete process, and indeed sand filters are used as part of water purification. Lam et al. (1993) found no E. coli in samples of leachate from soil columns fed with piggery slurry. However, in terms of viruses, the reduction is less pronounced, with Turner and Burton (1997) reporting at best a two log_{10} reduction from sand filters. In addition there are concerns of accumulation of microorganisms in the media leading to eventual release. The best and most reliable results come again from the use of membranes. Based on pore size, microfiltration will retain all bacteria, but some viral particles can pass through; the finer ultrafiltration will retain all microbes.

5. Discussion: applications of separation in whole-farm models

In the evaluation of a proposed manure separation process as part of a whole-farm model, the key question should be what is the objective(s) of the wider farm strategy. This is a crucial starting point, as it will shape the strategy that in turn will enable selection of the cheapest technology that is also effective. The fact that clarification of liquid manure allows easier handling and a reduced environmental impact may be a sound enough reason for installing a separation system at a farm. The technology (especially sedimentation) may also be appropriate if surplus phosphorous is a problem. However, an additional biological step would be needed if ammonia (or the soluble organic matter) were the issue — this might be the case if there is a local nutrient surplus which ultimately will contribute to water or air pollution.

If the main local concern is health risks from pathogens, then separation will make little difference, and storage, biological, thermal or chemical treatment alternatives must be considered instead. Furthermore, there is little scientific evidence to suggest that separation alone will greatly reduce the offensive odour produced from manure during storage or following land spreading. Soluble salts, including potassium, are also largely unaffected by any treatment. The production of organic materials for different end uses is a common reason for introducing separation technologies at the farm. These include feed material for composting schemes (especially based on the fibre from screening processes), or dried products made from sludge production. The attraction of these processes is that they enable exportation away from the farm of nutrient surpluses as a useful and stabilized product. However, this may be constrained by disease and health concerns, which may demand special additional treatments.

Monitoring the production of solids from a separator can give an indication of manure concentration, thus enabling some degree of process control in a subsequent biological treatment (Burton and Sneath, 1995). Sedimentation processes themselves can be used to both enable the production of a clarified wastewater for cleaning or flushing duties (Sneath, 1986; Hoeksma et al., 1992), or for the purpose of pre-concentrating a dilute stream ahead of anaerobic digestion (Schofield and Rees, 1988). In either case, there are implications for other aspects of the farm operation — if there is the option for flushing technologies or if there is interest in anaerobic digestion. To work, investments in separation processes must reflect the wider farm requirements in a comprehensive plan.

6. Conclusions

What can not be reasonably expected from farm-based separation processes alone:

- to adequately deal with an offensive odour problem;
- to remove excess ammonical nitrogen;
- to significantly reduce the BOD_{5} load;
- to achieve a reduction in the overall volume of manure to be handled;
- to change the overall nutrient content — “what goes in must come out”;
- to improve or worsen health risks— either to food crops or to livestock.

What can separation processes alone can achieve:

- make liquid manure easier to handle — reduced risk of blockages in pipelines;
- produce solid by-products containing most of the original solid material;
• produce clarified liquids with greatly reduced levels of insoluble organic matter, phosphorous and heavy metals;
• enable the easier targeted application of livestock effluents to cropland;
• enable the easier export of solid concentrates for crop use in other arable farm areas.

Coupled with biological technologies, the role of separation technology can also:

• support aerobic biological processes in removing relatively indigestible material from the feed stream;
• enhance anaerobic digestion performance by producing a concentrated feed from a dilute effluent;
• produce a compostable solid fraction from liquid manures.

Introducing a separation technology is the right option if the main purpose is either (a) the improvement of manure handling, (b) the removal of specific insoluble components of the effluent, including non-reactive organic matter and some of the phosphorous, organic nitrogen, copper and zinc, or (c) the preparation of a concentrate to produce an organic fertiliser product. Alone, separation has little effect on pathogens, offensive odour or soluble components, including ammoniacal nitrogen.

References
