Journal of Agricultural Engineering 2012; volume XLIII:e9

Effect of different technologies and animal manures on solid-liquid separation efficiencies

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Abstract

Solid-liquid separation is a widely used manure treatment option. However, little information is available to predict separator performance in a specific operating condition. This study investigates the effect on the separation efficiency of animal species (cattle and swine), use of flocculants, and separator construction and operating characteristics (filtration, pressurised filtration, settling and centrifugation). Using data available from published experiments, we evaluated correlations of the separation efficiencies with the physical and chemical characteristics of the inlet slurries (dry matter, total nitrogen, ammoniacal nitrogen, phosphorus and potassium). Dry matter concentration of the input manure was found to be the best parameter used to calculate and validate regression equations. Regressions for the operating conditions of 7 of the 14 subgroups evaluated were significant ($P<0.05$) for at least one parameter. Pressurised filtration seems to be the process best represented by these regressions that can predict dry matter and nitrogen efficiency with relative root mean squared errors of less than 50%. However, they could only be used for some of the parameters and separation techniques. Therefore, it was not possible to use the available experimental data to define and validate empirical predictive models for all the conditions. Specific studies are needed to define more precise and physically-based models.

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Key words: correlation, efficiency, manure, separation, treatment.

Acknowledgements: supported by Progetto AGER, grant n. 2010-2220.

Received for publication: 3 May 2012.
Accepted for publication: 3 August 2012.

Journal of Agricultural Engineering 2012; XLIII:e9
doi:10.4081/jae.2012.e9

Introduction

Globally, intensification of agricultural systems increases the environmental impact of food production, leading to large amounts of manure that are used in crop systems in excess of crop requirements (Petersen *et al.*, 2007). These excesses may result in discharge and emission of pollutants, such as nitrogen (N) and phosphorus (P) compounds, to the environment.

In order to face these environmental problems, many farmers need to find technologically and economically effective solutions (Balsari *et al.*, 2006). Nowadays, there is a wide range of manure treatment processes that meet various requirements (Burton and Turner, 2003). Among these techniques, solid-liquid separation is one of the cheapest treatment options and is often feasible within the specific farming system (Burton, 2007). Solid-liquid treatment allows farmers to separate solids from slurry, producing two final products; a dry matter (DM)-rich and nutrient-rich fraction, and a liquid fraction that can both be managed separately. In particular, the nutrient- and DM-rich fraction could be more easily transported off farm or to fields far from the farmstead, reducing transportation costs (Møller *et al.*, 2000; Bertora *et al.*, 2008). Furthermore, solid-liquid separation can be followed by other manure treatments, such as anaerobic digestion, composting or N reduction (Zhang and Lei, 1998; Tilche *et al.*, 1999; Møller *et al.*, 2007; Brito *et al.*, 2008). Two solid-liquid separation technologies could also be coupled in order to increase the efficiency of the treatment process, as demonstrated by previous studies (Westerman and Bicudo, 2000; Chastain *et al.*, 2001b; Converse and Karthikeyan, 2004; Balsari *et al.*, 2006; Fangueiro *et al.*, 2008a, 2008b and 2008c). Several separation devices have been designed to carry out the solid-liquid separation treatment by different processes. Hence, separation techniques can be classified according to their operation (Table 1) (Zhang and Westerman, 1997; Ford and Flemming, 2002; Hjorth *et al.*, 2010). To more efficiently remove nutrients, which are in smaller particles, physical and mechanical separation can be performed with the addition of chemical additives, flocculants and/or coagulants (Vanotti *et al.*, 2002). Several additive types have been studied in various experiments to coagulate manure, to flocculate it or to remove ortophosphorate (PO_4^{3-}). These are iron (Fe), aluminium (Al) and calcium (Ca) salts, several types of polyacrylamides (PAM), and clay (Henriksen *et al.*, 1998; Vanotti and Hunt, 1999; Vanotti *et al.*, 2002; Westerman and Arogo Ogejo, 2005; Møller *et al.*, 2007; Rico *et al.*, 2007; Garcia *et al.*, 2009; Hjorth *et al.*, 2009). The performance of the different separation techniques mentioned above is often expressed by the separation efficiency. This could be expressed thorough the removal efficiency or the separation index (Burton, 2007; Hjorth *et al.*, 2010). The removal efficiency (R) expresses efficiency in removing a specific compound (DM or nutrients) from slurry to the solid fraction:

$$R\ (\%) = 1 - \frac{c\ (x)liquid}{c\ (x)slurry} \cdot 100 \qquad \text{(Eq. 1)}$$

where $c(x)$ slurry and $c(x)$ liquid are the concentrations of DM or nutrients (N, P) in the slurry and the liquid fraction.

The separation index (Et) is the ratio of the total mass recovery of a given component (DM or nutrients) in the solid phase as a proportion of the total input of that component (DM or nutrient) (Svarovsky, 1981; Møller *et al.*, 2000; Burton 2007). This index expresses the distribution of a specific compound in the solid and the liquid fraction:

$$Et = \frac{m\,(x)solid}{m\,(x)slurry} \cdot 100 \qquad \text{(Eq. 2)}$$

where $m(x)$ slurry and $m(x)$ solid are the mass of DM or nutrients (N, P) in the slurry and the solid fractions.

The separation efficiency is influenced by several factors (Burton and Turner, 2003):

- Type of separator;
- Sieve mesh size or centrifugal force;
- Manure type (species, pre-treatments and total solids' content);

Use of additives.

Therefore, as described by Zhang and Westerman (1997), the above-mentioned separator types have different separation efficiencies, leading to the production of end products with different characteristics that make them preferable for certain uses. Thus, because the performance of the various separator types differs, a decision support tool is necessary to identify the separation technology most suitable for the farmer's needs, given particular manure properties.

In recent years, several decision support systems for manure management have been developed (Karmakar *et al.*, 2007), but only some of them take manure treatment processes into consideration. Additionally, few models have been elaborated for solid-liquid separation processes. For instance, Rico *et al.* (2006) obtained a predictive empirical model to estimate the concentrations of DM, volatile solids (VS), carbon oxygen demand (COD) and total organic carbon in the solid fraction, as functions of the doses of ferric chloride ($FeCl_3$) and a medium cationic polyacrylamide (MCP1). In other studies, Chastain and Vanotti (2003) defined some correlation equations to predict the separation efficiencies for DM, VS, COD, N and P for gravity settling of swine manure. However, the proposed models for solid-liquid separation concern only one separation process (*i.e.* chemical separation or gravity settling). For this reason, they could not be used as tools to support our decisions because they do not estimate and compare the separation efficiencies of different devices and then identify the better solution according to the farmer's needs.

Table 1. Separator types grouped according to their separation technique.

Separation technique	Separator type
Gravity filtration	Inclined screen Vibrating screen Rotating screen
Pressurised filtration	Screw press Roller press Belt press
Centrifugation	Decanting centrifuge Settling Sedimentation Settling

Table 2. Values count for separation efficiencies and references for collected data. Data are divided according to separator type.

Separator type	Efficiency (%)				Source
	DM	N	NH_4	P	
Belt press	10	11		12	Campos *et al*., 2002; Henriksen *et al*., 1998; Hjorth *et al*., 2009; Møller *et al*., 2000; Pieters *et al*., 1999; Walker and Kelley, 2005; Zhang and Westerman, 1997.
Centrifuge	69	68	19	68	Balsari *et al*., 2006; Duarte *et al*., 2001; Fangueiro *et al*., 2009; Hansen *et al*., 2006; Karakashev *et al*., 2008; Loyon *et al*., 2006; Melse and Verdoes, 2005; Møller *et al*., 2002; Møller *et al*., 2007; Petersen and Sørensen, 2008; Pieters *et al*., 1999; Sørensen and Møller, 2006; Westerman and Arogo Ogejo, 2005; Zhang and Westerman, 1997.
Inclined screen	67	66	7	60	Barrow *et al*., 1997; Chastain *et al*., 2001a; Chastain, 2009; Garcia *et al*., 2007a; Garcia *et al*., 2009; Gonzàlez-Fernàndez *et al*., 2008; Hill and Baier, 2000; Kaparaju and Rintala, 2008; Kunz *et al*., 2009; Meyer *et al*., 2007; Møller *et al*., 2000; Rico *et al*., 2007; Vanotti *et al*., 2002; Wright, 2005; Zhang and Lei, 1998; Zhang and Westerman, 1997.
Roller press	14	14	1	14	Balsari *et al*., 2006; Curnis, 2008.
Rotating screen	2	2		12	Garcia *et al*., 2007b; Gooch *et al*., 2005; Marcato *et al*., 2008; Møller *et al*., 2000; Walker and Kelley, 2005; Zhang and Westerman, 1997.
Screw press	44	28	4	29	Balsari *et al*., 2006; Bertora *et al*., 2008; Brito *et al*., 2008; Burns *et al*., 2003; Burton and Turner, 2003; Chastain *et al*., 2001b; Converse *et al*., 2000; Converse and Karthikeyan, 2004; Curnis, 2008; Dinuccio *et al*., 2008; Fangueiro *et al*., 2008a, 2008b and 2008c; Loyon *et al*., 2006; Melse and Verdoes, 2005; Møller *et al*., 2002; Møller *et al*., 2000; Pieters *et al*., 1999; Westerman and Bicudo, 2000; Westerman and Arogo Ogejo, 2005; Wu, 2007.
Sedimentation	69	86	19	86	Barrow *et al*., 1997; Campos *et al*., 2008; Chastain *et al*., 2001a; Converse and Karthikeyan, 2004; Fangueiro *et al*., 2008a, 2008b and 2008c; Garcia *et al*., 2007b; Gooch *et al*., 2005; Henriksen *et al*., 1998; Loughrin *et al*., 2009; Martinez-Almela *et al*., 2003; Martinez-Almela and Barrera Marza, 2005; Møller *et al*., 2007; Ndegwa, 2004; Rico *et al*., 2007; Szögi and Vanotti, 2007; Vanotti and Hunt, 1999; Westerman and Bicudo, 2000; Westerman and Arogo Ogejo, 2005; Worley and Das, 2000.
Vibrating screen	18	6	3	7	Curnis, 2008; Pieters *et al*., 1999; Zhang and Westerman, 1997.

DM, dry matter; N, nitrogen; NH4, ammonium; P, phosphorous.

The present study aims to: i) identify the effect of animal species, manure pre-treatment, use of additive and type of separator on the separation efficiency to distinguish different operational groups; and ii) for each of the identified groups, evaluate correlations of the separation efficiencies with the physical and chemical characteristics of the inlet slurries, using data available from published experiments on manure solid-liquid separation.

Materials and methods

Database

To define and validate the model, we first collected the necessary data. We conducted a bibliographical search that allowed us to collect papers about solid-liquid separation published in the last decade.

To obtain data expressed in the same units of measurement, the collected data were revised, if necessary, using the relationships between the relative density and the DM or nutrient concentrations in the raw slurry proposed by Piccinini *et al.* (1990).

Bibliographical data were collected in a database, organised as follows:

- Input related to the effluent: animal species (cattle and swine), effluent type (raw, digested and liquid from separation);
- Input related to the technology: separator type, use of chemical additives (*additive yes/no*);
- Slurry characteristics: DM concentration, N, P, potassium (K);
- Output: separation efficiency for DM (Eff. DM), nitrogen (Eff. N), phosphorus (Eff. P);
- References.

  Operative data such as mesh size, centrifugal force or settling time were not used since none or few were available.

Table 3. Description of the 8 groups used for the elaborations.

Group	Animal species	Separation technique	Separator type
1	Cattle	Gravity filtration	Inclined screen Vibrating screen Rotating screen
2	Cattle	Pressurised filtration	Screw press Roller press Belt press
3	Cattle	Settling	Sedimentation Settling
4	Cattle	Centrifugation	Decanting centrifuge
5	Swine	Gravity filtration	Inclined screen Vibrating screen Rotating screen
6	Swine	Pressurised filtration	Screw press Roller press Belt press
7	Swine	Settling	Sedimentation Settling
8	Swine	Centrifugation	Decanting centrifuge

Data collection

The database is composed of data found through a bibliographical search. We collected 98 papers, published in the last decade. These mainly consisted of scientific papers, but also included proceedings from conferences, chapters from books, graduation theses and publications by universities and public institutions.

Hence, it is worth noting that data concerning experiments were gathered for a different purpose, so the studies are rather heterogeneous and not completely comparable. Furthermore, the separation efficiencies are calculated using different equations, affecting data elaboration. Most studies contained information about the DM concentration of input slurry but few had information about the considered separation efficiencies. In fact, some papers did not report the separation indexes, but did report the DM and nutrient concentrations in the solid and liquid fractions. Other papers did not give any information about the separation efficiencies, but provided nutrient concentrations of the input slurry and of the final products. Since there are different equations to calculate separation efficiency, we did not calculate separation efficiencies and, therefore, the data were not used in the analysis. In some cases, articles by the same authors referred to the same experiments. After this further selection, 60 publications were used (Table 2). The collected data were revised, if necessary, so as to be expressed in the same units of measurement. Finally, they were uploaded onto the database (n=482 observations).

Data processing

The SPSS 18.0 statistical package (IBM Corp., Armonk, NY, USA) was used to analyse the collected data.

Mean efficiency and variability for different categorical variables (animal species, effluent type, use of flocculants, separator type) were analysed by mean of error and bar plots were then produced. In this case, error bars represent the double standard error mean of separation efficiencies for DM, N and P. This analysis allowed us to identify the variables, which mainly affect separation efficiency, and to indicate if their means differed.

Definition of relationships and model validation

To define the correlations of the separation efficiencies with the physical and chemical characteristics of the inlet slurries, a regression analysis was performed using DM, N, P and K of the raw slurries as independent variables.

Model definition and validation was carried out on each of the groups using two methods:

- Random: using the SPSS 18.0 statistical package (IBM Corp.), the database was first divided into the identified groups. Each dataset was then randomly split into two fractions of 70% and 30% of observations, respectively (Preece *et al.*, 2009). The first observations were used to define linear regressions that allowed us to model the relationships between the separation efficiencies and the DM concentration, distinguishing data through the presence or absence of chemical additives. Data sets containing 30% of the observations were used for model validation.
- Crossvalidation*:* the *leave-one-out* crossvalidation was performed using Unscrambler© *X 10.0.1* software (CAMO Software, Oslo, Norway) (Soriano-Disla *et al.*, 2010) that was applied to each group.

For every regression, we calculated the coefficient of determination (r^2) and the significance values. For crossvalidation, the coefficients of determination for calibration (r^2 cal) and validation (r^2 val) were calculated.

Finally, for every validation method, the reliability of predictions and their deviation from observed values were analysed both graphically and by means of error calculations. In particular, we calculated the root mean squared error (RMSE) and the relative root mean squared error (RRMSE):

$$RMSE = [n^{-1} \textstyle\sum_{i=1}^{n}(P_i - O_i)^2]^{1/2} \qquad \text{(Eq. 3)}$$

$$RRMSE = \left({}^{RMSE}/_{\bar{O}}\right) \cdot 100 \qquad \text{(Eq. 4)}$$

where n is the number of data used, P_i are the predicted values, O_i are the observed values and $\bar{O}$ is the mean of the observed data.

RMSE evaluates the model's accuracy as the difference between predicted and measured values, and it indicates the fitting's absolute mean error, while RRMSE shows the magnitude of the error. They were used to quantify model accuracy and to compare between them.

Table 4. Descriptive statistics of each group for the entire database divided by the use of chemicals.

Group	Additive	Efficiency (%)	N.	Min	Max	Mean	Std. Dev.
1 Cattle gravity filtration	Without	DM	35	6.00	71.70	32.26	16.43
		N	11	8.30	49.20	28.21	14.26
		P	11	12.10	62.80	35.46	16.56
	With	DM	31	63.00	95.70	81.99	11.52
		N	41	14.00	86.00	51.97	16.00
		P	41	16.30	99.00	66.86	26.22
2 Cattle pressurised filtration	Without	DM	36	4.34	77.80	40.17	16.69
		N	22	3.97	39.28	17.25	10.48
		P	22	5.72	73.70	31.44	20.57
3 Cattle settling	Without	DM	11	18.10	64.90	44.58	17.51
		N	11	1.60	40.00	20.25	11.59
		P	11	13.50	61.40	40.24	16.45
	With	DM	44	29.30	92.80	78.38	11.59
		N	60	3.71	74.00	40.25	14.39
		P	61	16.30	91.70	66.05	20.17
4 Cattle centrifugation	Without	DM	11	53.50	69.10	59.84	5.61
		N	11	20.30	49.12	28.64	7.42
		P	11	45.50	93.80	71.84	16.64
5 Swine gravity filtration	Without	DM	21	3.00	58.70	26.75	16.86
		N	15	3.50	42.00	16.34	11.67
		P	12	3.00	46.50	17.55	14.11
	With	DM	0				
		N	7	13.00	35.00	25.71	8.24
		P	15	21.00	80.30	60.37	18.16
6 Swine pressurised filtration	Without	DM	28	5.50	68.25	31.01	18.94
		N	25	0.83	33.50	9.34	8.47
		P	27	7.00	73.70	25.33	18.37
	With	DM	4	38.10	79.37	54.40	18.50
		N	6	13.11	79.50	38.16	29.61
		P	6	53.97	90.48	75.94	14.26
7 Swine settling	Without	DM	3	49.00	64.00	57.33	7.64
		N	0				
		P	0				
	With	DM	11	34.00	87.00	65.57	16.15
		N	15	16.10	58.30	37.77	14.76
		P	14	70.00	91.30	81.44	8.53
8 Swine centrifugation	Without	DM	46	8.00	70.40	48.53	15.29
		N	45	7.00	35.50	20.84	7.22
		P	45	26.00	90.95	66.57	13.34
	With	DM	12	47.00	76.00	57.83	11.19
		N	12	17.00	48.00	32.83	11.65
		P	12	54.00	88.00	71.00	11.82

DM, dry matter; N, nitrogen; P, phosphorous; Std. Dev, standard deviation.

Results and discussion

Data analysis

Factors influencing separation efficiency

This analysis aimed to identify the categorical variables mainly affecting the separation efficiencies. In particular, we considered the separation efficiencies for DM, N and P, expressed as functions of animal species, effluent type, use of additives and separator type. When the separation efficiencies are grouped according to species (Figure 1A), mean values have significantly different variations for all the separation efficiencies considered. Specifically, the separation efficiencies for cattle slurries are higher, meaning more DM, N and P are in the solid fraction at separation of cattle slurry rather than in swine slurry. This result agrees with previous findings (Peters *et al.*, 2011).

The mean values also present different variations when separation efficiencies are classified by the use of chemical additives (Figure 1B).

Table 5. Correlation equations, r^2 and significance (F) values of regressions achieved by the random method. For each group, values are distinguished by the use of chemical additives.

Group	Additive	N.	Random Separation efficiency (%)	Correlation equation°	r^2	F
1 Cattle gravity filtration	Without	9	DM	0.483*DM+24.39	0.35	***
		6	N	0.16*DM+27.5	0.2	n.s.
		6	P	-0.02*DM+35.1	0	n.s.
	With	22	DM	0.32*DM+81.6	0.012	n.s.
		27	N	-0.5*DM+52.5	0.05	n.s.
		27	P	-2.034*DM+109.05	0.88	***
2 Cattle pressurised filtration	Without	26	DM	0.506*DM+8.966	0.69	***
		18	N	0.30*DM-3.49	0.34	*
		18	P	0.51*DM-2.48	0.25	n.s.
3 Cattle settling	Without	7	DM	1.104*DM+18.33	0.43	n.s
		7	N	0.556*DM+6.907	0.17	n.s.
		7	P	0.62*DM+17.235	0.23	n.s.
	With	31	DM	-0.77*DM+89.23	0.48	***
		40	N	0.067*DM+36.1	0.004	n.s.
		41	P	-1.13*DM+91.53	0.58	***
4 Cattle centrifugation	Without	7	DM	0.044*DM+57.923	0.05	n.s.
		7	N	0.181*DM+22.556	0.33	n.s.
		7	P	-0.4*DM+86.1	0.5	*
5 Swine gravity filtration	Without	8	DM	-0.2*DM+25.77	0.06	n.s.
		5	N	0.37*DM+6.11	0.4	n.s.
		5	P	0.57*DM+1.2	0.15	n.s.
	With	0	DM	n.a	n.a	n.a.
		5	N	n.a	n.a	n.a.
		5	P	n.a	n.a	n.a.
6 Swine pressurised filtration	Without	15	DM	0.55*DM+11.44	0.32	*
		15	N	0.34*DM-1.89	0.42	*
		15	P	0.15*DM+16.5	0.04	n.s.
7 Swine settling	Without	2	DM	-0.9*DM+70.8	0.99	n.s.
		0	N	n.a	n.a	n.a
		0	P	n.a.	n.a	n.a.
	With	6	DM	1.33*DM+38.89	0.68	*
		6	N	0.763*DM+18.434	0.48	n.s.
		5	P	0.3*DM+77.976	0.21	n.s.
8 Swine centrifugation	Without	32	DM	0.5*DM+28.97	0.64	***
		31	N	0.15*DM+16.14	0.26	**
		31	P	0.34*DM+54.12	0.45	***
	With	8	DM	0.46*DM+29.55	0.05	n.s.
		8	N	0.13*DM+16.15	0.05	n.s.
		8	P	0.30*DM+53.44	0.07	n.s.

DM, dry matter; N, nitrogen; P, phosphorous; n.s., not significant; n.a., not available. °DM, DM concentration in the input slurry (gL^{-1}); *,**,***, significant correlations at $P<0.05$, 0.01, 0.001, respectively.

As expected, flocculants improve the separation efficiencies and it is a relevant predictive variable. Digestion and removal of solids with separation reduce the DM content of the liquid fraction and increase relative content of the dissolved total ammoniacal nitrogen in the nitrogen pool. Therefore, effects on the separation index could be expected. However, considering separation efficiency for DM (Figure 1C), means having different variations only for separated slurry, whereas the three effluent types (digested, raw and liquid from separation) do not present different variations in the means for the separation efficiency of N and P. Therefore, we could not confirm that the effluent type statistically affects the separation efficiencies. This absence of a significant statistical difference could be due to the fact that manures from different origins are included in the different pool; they are not, therefore, suitable for definitively ruling out a correlation/ variation. In conclusion, from this analysis, the categorical variables, which mainly affect separation efficiencies, are animal species, use of chemical additives and separator type.

Table 6. Correlation equations, r^2 and significance (F) values of regressions achieved by the cross-validation method. For each group, values are distinguished by the use of chemical additives.

Group	Additive	N.	Cross-validation Separation efficiency (%)	Correlation equation°	r^2	F
1						
Cattle gravity filtration	Without	17	DM	0.392*DM+23.41	0.27	**
		11	N	0.251*DM+16.855	0.15	n.s.
		11	P	0.085*DM+31.605	0.09	n.s.
	With	31	DM	0.004*DM+81.9	0.0	n.s.
		41	N	-0.4*DM+59.84	0.09	*
		41	P	-1.99*DM+104.97	0.86	***
2						
Cattle pressurised filtration	Without	38	DM	0.45*DM+10.27	0.47	***
		22	N	0.28*DM-2.13	0.29	**
		22	P	0.34*DM+7.48	0.11	n.s.
3						
Cattle settling	Without	9	DM	0.31*DM+41.3	0.05	n.s.
		9	N	0.4*DM+13.5	0.13	n.s.
		9	P	-0.3*DM+44.2	0.04	n.s.
	With	44	DM	n.a	n.a	n.a
		60	N	n.a.	n.a	n.a
		61	P	n.a	n.a.	n.a.
4						
Cattle centrifugation	Without	11	DM	0.04*DM+58.30	0.04	n.s.
		11	N	0.12*DM+24.10	0.21	n.s.
		11	P	-0.36*DM+85.35	0.6	*
5						
Swine gravity filtration	Without	21	DM	0.22*DM+21.73	0.04	n.s.
		14	N	0.25*DM+2.28	0.29	n.s.
		9	P	0.88*DM-8.08	0.54	n.s.
	With	0	DM	n.a.	n.a.	n.a
		7	N	n.a.	n.a.	n.a.
		7	P	n.a.	n.a.	n.a.
6						
Swine pressurised filtration	Without	26	DM	0.62*DM+8.04	0.32	**
		23	N	0.33*DM-2.75	0.42	**
		25	P	0.30*DM+13.55	0.08	n.s.
7						
Swine settling	Without	3	DM	n.a.	n.a.	n.a.
		2	N	n.a.	n.a.	n.a.
		0	P	n.a.	n.a.	n.a.
	With	11	DM	0.91*DM+50.95	0.42	*
		8	N	0.3 *DM+29.9	0.0	n.s.
		7	P	n.a.	n.a.	n.a.
8						
Swine centrifugation	Without	46	DM	0.48*DM+29.28	0.61	**
		45	N	0.14*DM+15.40	0.21	**
		45	P	0.33*DM+53.39	0.37	**
	With	12	DM	0.49*DM+49.67	0.07	n.s.
		12	N	-0.05*DM+33.71	0.05	n.s.
		12	P	0.65*DM+60.13	0.12	n.s.

DM, dry matter; N, nitrogen; P, phosphorous; n.s., not significant; n.a., not available. °DM, DM concentration in the input slurry (gL^{-}); *,**,***, significant correlations at $P<0.05$, 0.01, 0.001, respectively.

Separator grouping

Some separator types behave similarly in accordance with their functioning characteristics, as described above (Table 1). Therefore, separator types were grouped according to their construction and operating characteristics (gravity filtration, pressurised filtration, settling and centrifugation), taking into account the results of dispersion and error bar plots. Thus, separation devices were divided in 8 groups: 4 for cattle slurry and 4 for swine slurry (Table 3).

Finally, for every group, data were distinguished by the presence or absence of chemical additives. Since some separator types are not used with chemical additives in the collected experiments (groups 2 and 4), 14 subgroups were obtained.

For each identified group, descriptive statistics were calculated (Table 4). It is clear in Table 4 that, for some groups, more data are available (*e.g.* groups 2 and 8). For every group, each variable has a different number of observations; there were more observations for separation efficiencies achieved without chemical additives, except for sedimentation (groups 3 and 7). Considering all groups, some separation efficiencies present few data. Furthermore, for each cluster, the data present a high range of variation, particularly without flocculants.

The order of the separation efficiencies for DM, N and P within swine and cattle slurry are equivalent, *i.e.* pressurised filtration < gravity filtration < centrifugation (with additive) < settling (with additive). Hence, sedimentation techniques are superior to filtration. Applying filtration without chemical additives is the least effective technique. Application of additives causes the most efficient separation. Without chemical additives, sedimentation techniques are superior to filtration, as also indicated in the error bar plots. Gravity filtration without chemical additives requires large mesh so only large particles are retained in the solid fraction. Settling under optimal conditions, *i.e.* high force applied and long retention time, also cause retention of small particles in the solid fraction. This is supported by previous findings (Møller *et al.*, 2002).

The order of efficiency of the separator types for N and P separation efficiencies was similar to DM separation efficiency. This is supported by the fact that N, and particularly P, are associated with the particles (Christensen *et al.*, 2009).

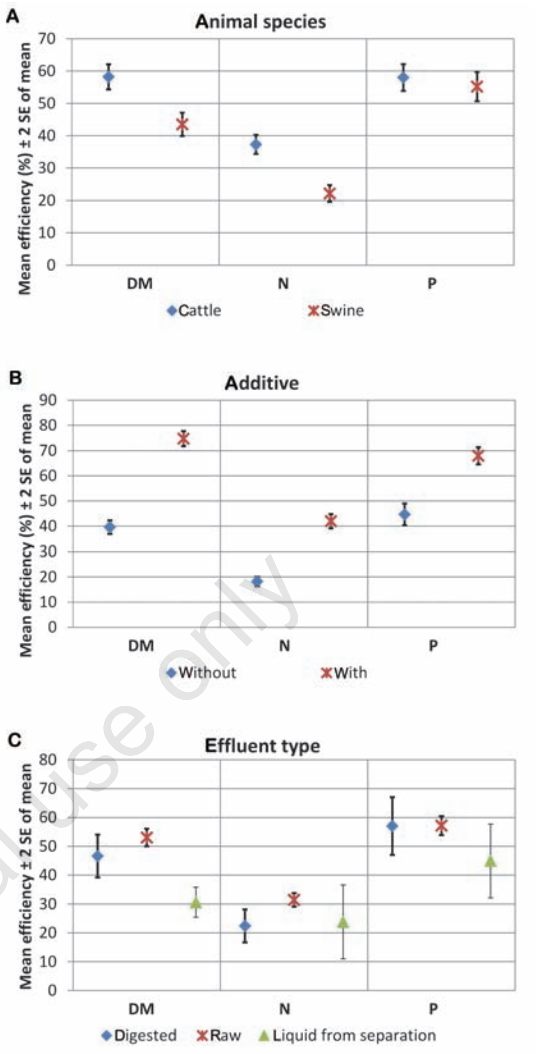

Figure 1. Error bar plots of separation efficiencies for dry matter, nitrogen and phosphorous grouped by species (A), use of chemical additives (B) and effluent type (C).

Table 7. Root mean squared error and relative root mean squared error values for significant equations.

Group	Additive	Efficiency (%)	RMSE		RRMSE (%)	
			Random	Cross-validation	Random	Cross-validation
1 Cattle gravity filtration	Without	DM	17.29	14.26	53.60	44.20
	With	P	17.73	12.19	26.52	18.23
2 Cattle pressurised filtration	Without	DM	15.66	12.38	38.98	30.82
		N	8.65	9.06	50.14	52.52
4 Cattle centrifugation	Without	P	15.93	14.00	24.38	19.49
6 Swine pressurised filtration	Without	DM	15.60	15.22	50.31	49.08
		N	4.87	6.94	52.14	74.30
7 Swine settling	With	DM	22.02	15.68	33.13	23.91
8 Swine centrifugation	Without	DM	7.67	9.69	15.80	19.97
		N	5.83	6.47	27.98	31.05
		P	8.52	10.73	12.80	16.12

DM, dry matter; N, nitrogen; P, phosphorous; RMSE, root mean squared error; RRMSE, relative root mean squared error.

Correlation definition

Using the methods described above, we carried out the regressions for model definition (random and crossvalidation). In particular, we defined regressions that identify the relationships between the separation efficiencies for DM, N and P with the DM, N, P and K concentration of the slurry. DM was the only parameter included in the regression model used and, therefore, results are shown using only this parameter as independent variable.

As shown in Table 3, some separator types, corresponding to groups 2 (cattle slurry/pressurised filtration) and 4 (cattle slurry/centrifugation), are not used with chemical additives. Furthermore, for group 6 (swine slurry/pressurised filtration), data for separation indexes achieved with chemicals refer only to belt presses and are highly variable. For this reason, only regressions for separation efficiencies of swine manure treated by pressurised filtration without additives were calculated.

Tables 5 and 6 present the correlation equations, and their r^2 and significance (F) values obtained applying the random and crossvalidation methods, respectively. In some cases, the methods used did not achieve significant regressions for all the separation efficiencies because of the lack of data or because of the presence of some anomalous values for the DM concentration of the input slurry.

After model definition, regressions were validated using plots and error calculation. In particular, we calculated the RMSE error and the RRMSE only for regressions that resulted significant for both random and crossvalidation methods (Table 7). In most cases, the RRMSE values are below 50% for both random and crossvalidation methods.

For solid-liquid separation of cattle slurry by gravity filtration (group 1) without using chemical additives, only the correlations for the DM separation efficiencies were significant. However, the separation efficiency for DM is not entirely correlated to the input DM concentration; in this case, the measured values are highly variable and, therefore, the RRMSEs are large for both random and crossvalidation models. Hence, a larger amount of experimental data could allow us to achieve multiple linear regression lines depending not only on the DM concentration of the input slurry, but also on other criteria that affect the separation efficiency, such as mesh size.

Using additives, only the regressions for the separation efficiency of P were significant. The random and the crossvalidation models showed a decreasing trend, matching that of the data.

Overall, for cattle manure treated by pressurised filtration without chemical additives, the random and the crossvalidation regressions were significant only for DM and N separation indexes. However, RRMSE for N separation efficiency was high (Table 7).

There are few and variable measured data related to the P separation efficiency for the separation of cattle slurry by centrifugation without chemical additives.

As for cattle slurry, only the separation efficiencies for DM and N present significant regressions for swine slurry separated with pressurised filtration without additives. Separation efficiencies of DM data are very variable and so, even though the random and crossvalidation models are similar, the regression error is greater. Generally, the separation efficiency of DM and N for pressurised filtration of cattle and swine slurry (groups 2 and 6) are both correlated to the DM content of the input slurry. Of all the separator types, these pressurised filtration separators result in the fewest of the minor particles being retained in the solid fraction, which may be why this correlation is so simple and, therefore, reaches significance.

The separation efficiency for DM of the solid-liquid separation of swine manures by sedimentation using flocculants presents few data showing a clear tendency and has a good fit in both of the two models. For the separation of swine slurry by centrifugation, only the separation efficiencies for DM, N and P without the addition of flocculants present significant regressions. Separation efficiencies for DM, N and P were very similar.

Generally, we did not find significant correlations for separation efficiencies obtained using flocculants, except for groups 1 and 7. In general, correlations may be complicated by the applied flocculation treatments, which vary greatly between the different experiments. Therefore, it is necessary to take into account the chemical applied and the added dose relative to the optimal chemical dose.

Conclusions

The analysis allowed us to distinguish several technological and operational conditions that affect separation efficiency. The most relevant characteristic of the input slurry is DM. The main variables affecting separation efficiency are species, use of additives and separator type.

For 7 of the 14 subgroups, it was possible to define and validate the predictive models. These present RRMSEs that are less than 50% and could, therefore, be implemented in a decision support tool to identify the most effective treatment option according to the farmer's needs. For the remaining separation technologies and operative conditions, most of which include the use of flocculants, more data are needed to define and validate empirical predictive models.

Except for settling, most of the correlations related to the use of additives were not significant. This is due to the wide variety of additives used in the different experiments. In fact, the different types of chemicals and their dosages affect the separation efficiencies in different ways and to different degrees. Therefore, experiments concerning the use of flocculants are often not comparable.

With regard to N separation efficiency, only pressurised filtration was significantly correlated for both cattle and pig slurry, while centrifugation was significant only for pig manure.

More detailed predictive models might be defined only if uniform and complete sets of data are available. In fact, bibliographic data derive from different kinds of experiments that often had different aims and could not be compared. Furthermore, they seldom include all the relevant information required to evaluate efficiency variations (pressure, mesh size, flow rate).

Therefore, more precise and physically-based models should be defined with the support of specific studies in order to predict separation efficiencies in practical conditions.

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