

1 **Yagüe\*, M.R., Bosch-Serra, A.D., Boixadera, J. 2012. Measurement and**  
2 **estimation of the fertiliser value of pig slurry by physicochemical models:**  
3 **Usefulness and constraints. *Biosystems Engineering*, 111 (2): 206-216**  
4 ***DOI::10.1016/j.biosystemseng.2011.11.013***

5  
6  
7  
8  
9  
10 MR. Yagüe, Unidad de Suelos y Riegos (Unidad asociada al EEAD-CSIC), Centro de  
11 Investigación y Tecnología Agroalimentaria de Aragón (CITA), Gobierno de Aragón.  
12 Avda. Montañana 930, 50059, Zaragoza, España. Phone: +34 976 713833. Fax: +34  
13 976 716335.

14 AD. Bosch-Serra, Department of Environment and Soil Sciences. University of Lleida.  
15 Avda. Alcalde Rovira Roure 191, E-25198, Lleida, Spain.

16 J. Boixadera, Departament d'Agricultura, Ramaderia, Pesca, Alimentació i Medi  
17 Natural. Generalitat de Catalunya, Avda Alcalde Rovira Roure 191, E-25198, Lleida,  
18 Spain.

19 E-mail of corresponding author: [mryaguue@aragon.es](mailto:mryaguue@aragon.es)

20 Received 30 June. 2010

21 Posted *on line* 12 Dic. 2011

1 **Abstract**

2 Pig (*Sus scrofa domestica*) slurries (PS) are widely applied to soil as fertilisers.  
3 Compositional variability, as shown in this study, is the main constraint on their  
4 efficient use. Slurry samples, collected from 126 commercial pig farms were analysed  
5 and organic nitrogen (ON), ammoniacal nitrogen (AN), total nitrogen (TN), total  
6 potassium (TK), total phosphorus (TP) content, pH, EC (electrical conductivity), DM  
7 (dry matter) and OM (organic matter) quantified. Relationships between major nutrient  
8 contents of PS and its physical and chemical properties were analyzed. Ammoniacal-N  
9 and TK were linearly related to EC ( $p < 0.0001$ ) for values lower than  $5.6 \text{ kg [AN] m}^{-3}$   
10 and  $5 \text{ kg [TK] m}^{-3}$  with coefficients of determination ( $R^2$ ) of 0.86 and 0.58 respectively,  
11 in agreement with previous linear models. At higher AN values (which means  $\text{EC} > 40$   
12  $\text{dS m}^{-1}$ ) linearity cannot be maintained, which has important consequences for direct  
13 slurry EC measurements. Organic N and TP in slurries were closely related ( $p < 0.0001$ )  
14 to DM with  $R^2$  of 0.90 and 0.68 respectively.

15 **Keywords:** compositional-variability; fertilizer-value; nutrients, physicochemical  
16 models; pig slurry.

1 **Nomenclature**

2 **Abbreviations:**

3	AN	Ammoniacal nitrogen
4	ANOVA	Analysis of variance
5	<i>d</i>	Index of agreement
6	DM	Dry matter
7	DMRT	Duncan's multiple range test
8	EC	Electrical conductivity
9	ICP AES	Inductively coupled plasma atomic emission spectrometry
10	IS	Ionic strength
11	MAE	Mean absolute error
12	MEF	Modeling efficiency statistic
13	NIRS	Near infrared reflectance spectroscopy
14	NS	Non-significant
15	OM	Organic matter
16	ON	Organic nitrogen
17	PS	Pig slurry
18	RMSE	Root mean square error
19	SD	Standard deviation
20	TK	Total potassium
21	TN	Total nitrogen
22	TP	Total phosphorus

23 **Symbols:**

24	<i>n</i>	Number of observed values
----	----------	---------------------------

1	$\hat{O}$	Average of the observed values
2	$O_i$	Observed values for the $i$ th data
3	$P_i$	Predicted values for the $i$ th data
4	$r$	Pearson correlation
5	$R^2$	Coefficient of determination
6		

## 1 **1. Introduction**

2 Livestock produce large amounts of manures which contain a wide range of plant  
3 nutrients as nitrogen (N), phosphorus (P), potassium (K) or micronutrients, which are  
4 recycled in agricultural systems for the production of food and fibre for humans and  
5 feeds for livestock. If they are used properly, they can replace significant amounts of  
6 chemical fertilisers. Crop nutrient requirements and available soil nutrient  
7 concentrations determine the amount of nutrients to be applied.

8 Pig production in Spain was 26 million head in 2009 which represents 17% of total  
9 European Union (FAO, 2011). The autonomous regions of Aragon and Catalonia  
10 contain around 42% of Spanish pig production. In Spain, it is a common practice to  
11 apply slurries as fertiliser in agricultural systems and N, P, and K in slurries should be  
12 quantified in order to avoid nutrient losses and to achieve maximum efficiency in crop  
13 nutrition. Furthermore, during recent years, laws and directives in Europe have been  
14 enforced, in order to reduce environmental impacts, by limiting N application to 170 kg  
15 N ha<sup>-1</sup>, according to the Nitrate Directive (European Union, 1991). Pig slurry is  
16 characterised by its low dry matter content and the predominance of the ammoniacal-N  
17 (AN) in total N (TN) content. Once added to the soil, slurry AN quickly transforms into  
18 nitric-N, and it may be fully assimilated by crops if not leached. Also, its K and P  
19 content are available to crops in a similar way to those from mineral fertilisers (Irañeta  
20 et al., 1999; Eghball et al., 2005). As reported in the literature, the composition of pig  
21 slurries vary to a great extent due to factors such as farm management, animal diet,  
22 water management and storage duration. For instance, slurry composition can be related  
23 to the length of the storage period in the pit (Ndegwa et al., 2002; Ndegwa & Zhu,  
24 2003; Balsari et al., 2006; Yagüe et al., 2011). Manure application rates are generally

1 designed to meet crop growth requirements for N. However, the ratio of N to P, using  
2 an N-based system, can supply the soil with much more P than the crop requires, a  
3 consideration which is of environmental concern (Sharpley et al., 2006).

4 To allow the efficient use of slurry as a fertiliser, characterisation of its nutrient content  
5 (N, P and K) before application must be implemented. Traditional analyses in  
6 laboratories provide great precision, but their cost and the time needed to obtain results  
7 have not been attractive to many farmers. Therefore, farm-level methods to estimate the  
8 nutrient concentration of livestock manure are required. Rapid and low cost estimation  
9 methods can be divided into two types: indirect methods (i.e. physicochemical models)  
10 and direct methods (i.e. rapid methods of nutrient measurement).

11 Physicochemical models relate slurry nutrient content with physicochemical properties  
12 such as specific gravity, dry matter content (DM), pH or electrical conductivity (EC), as  
13 reported by many researchers (Tunney, 1979; Scotford et al., 1998; Zhu et al., 2003;  
14 Moral et al., 2005; Yang et al., 2006b; Martínez-Suller et al., 2008; Suresh et al., 2009;  
15 Chen et al., 2009a). Near-infrared reflectance spectroscopy (NIRS) has been also used  
16 for quantifying nutrient content in animal manures: from pigs (Malley et al., 2002; Yang  
17 et al., 2006a), dairy cows (Reeves & Van Kessel, 2000; Van Kessel and Reeves, 2000)  
18 or poultry (Reeves, 2001; Xing et al., 2008) but implementation for farmers, compared  
19 with other available methods (i.e. densitometry or conductivity measurement) is  
20 expensive and its use is quite tedious at a field level. Determination of specific gravity,  
21 DM, pH or EC can help to quantify available nutrient content (N, P and K) in slurries,  
22 in order to establish their fertiliser value and promote their use in agriculture, thus  
23 saving mineral fertilisers at the farm level and reducing undesired negative  
24 environmental side-effects.

1 The objectives of our research were: (i) to evaluate nutrient variability in pig slurries by  
2 determining N, P and K according to farm type in the northeast of Spain; (ii) to generate  
3 physicochemical models for predicting pig slurry nutrient content using information  
4 from a wide range of samples from different type of farms; (iii) to validate  
5 physicochemical models obtained from references from the literature using our slurry  
6 samples in order to predict their usefulness and constraints in TN, AN, TK and TP  
7 determinations.

## 8 **2. Materials and methods**

### 9 **2.1. Slurry source**

10 Slurry samples were collected from 126 different pig farms in Aragon and Catalonia  
11 (NE Spain). The pits were in static conditions. Slurry samples were directly obtained  
12 from pits and each one was stored in a closed bottle immediately after their aspiration.  
13 Approximately 2-3 l of PS were sampled, kept as cool as possible upon arrival at the  
14 laboratory and stored at low temperature (3-5°C). Samples were classified in three  
15 types: from fattening farms ( $n=57$ ; pigs from 12-16 kg up to 90-110 kg); from maternity  
16 farms ( $n=36$ ; including pregnant sows, lactating sows and piglets up to 12-16 kg) and  
17 closed cycle farms ( $n=17$ ) which include sows and fattening production systems (with  
18 slurries being stored in the same pit).

### 19 **2.2. Sample analysis**

20 The parameters and the analytical methods done in the laboratory were: AN by the  
21 modified Kjeldhal method (Devarda without digestion), gravimetric DM content at  
22 105°C, pH by potentiometry (1:5 dilution), EC at 25°C by conductivity measurement,  
23 organic matter (OM) by calcination at 550°C and organic nitrogen (ON) by the Kjeldahl  
24 method using conventional laboratory analysis (APHA, 1998). Total phosphorous (TP)

1 and total potassium (TK) were analysed by acid digestion (wet) and further determined  
2 with inductively coupled plasma-atomic emission spectrometry (ICP AES, USEPA,  
3 1992).

### 4 **2.3. Physicochemical models**

5 Several physicochemical models of PS nutrient content have been developed and are  
6 available in the research literature (Table 1). They were selected for validation  
7 according the information on the range of nutrients used for the tests and their date of  
8 publication.

### 9 **2.4. Statistical Analysis**

10 The following criteria were used to assess the performance of the different  
11 physicochemical models found in the literature review (Table 1): intercept (*a*) and slope  
12 (*b*) values of linear regression between simulated and observed data for each model; the  
13 root mean square error (*RMSE*; Eq. 1); the modeling efficiency statistic (*MEF*; Eq.2;  
14 Tedeschi, 2006); mean absolute error (*MAE*; Eq. 3) and the *d*-index of agreement (Eq.  
15 4; Wilmott, 1982) that is an aggregate overall indicator that is a better criterion than  $R^2$ .

16 *RMSE*, *MEF*, and *d* were computed as follows:

$$17 \quad RMSE = \left[ \frac{\sum_{i=1}^n (P_i - O_i)}{n} \right]^{-0.5} \quad [Eq. 1]$$

$$18 \quad MEF = 1 - \left[ \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i)^2} \right] \quad [Eq. 2]$$



$$1 \quad MAE = \left[ \frac{\sum_{i=1}^n |P_i - O_i|}{n} \right] \quad [Eq. 3]$$

$$2 \quad d = 1 - \left[ \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i'| + |O_i'|)^2} \right] \quad [Eq. 4]$$

3 Where  $n$  is the number of observed values,  $O_i$  and  $P_i$  are observed and predicted values  
 4 for the  $i$ th data pair,  $P_i' = P_i - \hat{O}$  ( $\hat{O}$ : average of the observed) and  $O_i' = O_i - \hat{O}$ .

5 According to Willmott (1982), the model fit improves as index approaches unity and  
 6  $RMSE$  approaches zero. In a perfect fit,  $MEF$  would result in a value equal to one. If  
 7  $MEF$  is lower than zero, the model-predicted values are worse than the observed mean.  
 8 The  $MEF$  statistic may be used as a good indicator of goodness of fit (Mayer and Butler,  
 9 1993).

10 In the statistical analysis, analysis of variance (ANOVA), correlations and regressions,  
 11 significance levels were indicated using the following probability ( $p$ ) levels: \*  $0.05 \leq p$   
 12  $< 0.01$ ; \*\*  $0.01 \leq p < 0.001$ , \*\*\*  $0.001 \leq p < 0.0001$ . Values of  $p$ , higher than 0.05, are  
 13 considered non-significant (NS). Duncan's Multiple Range Test (DMRT) was  
 14 computed for comparing all possible pairs of means. If the regression between variables  
 15 is significant and the size of the coefficient of determination ( $R^2$ ) is  $\geq 0.70$ , we consider  
 16 that fits are acceptable. The statistical analysis was performed using the statistical  
 17 package SAS V8 (SAS Institute, 1999-2001).

### 18 **3. Results and discussion**

#### 19 **3.1. Physicochemical composition: variability in nutrient fertiliser value**

1 The main component of PS is water. In this study ( $n=126$ ) average DM content was  
2  $63.6 \text{ kg m}^{-3}$  (Table 2) which means an average water content close to 94%. The low  
3 nutrient to volume ratio implies that large volumes of slurry need to be transported, this  
4 being the limiting factor on the distance that slurry can be economically used as  
5 fertiliser. This distance can be roughly doubled if slurry from a fattening farm is used  
6 compared with a sow farm, due to its much higher nutrient content (Yagüe et al., 2006).  
7 The trend is to reduce slurry volume production in a farm, which is a powerful tool in  
8 waste-nutrient management planning (Teira-Esmatges & Flotats, 2003) because it  
9 increases nutrient concentration in PS and reduces transportation costs.

10 The statistics for all datasets and for each type of farm are given in Table 2. Most of the  
11 slurries analysed had a neutral-basic pH up to a maximum value of 9.1. Only 8 samples  
12 of the total 126 analysed in the present study had a pH lower than 7.

13 Electrical conductivity (EC) varied over a range from 8.7 to  $45.0 \text{ dS m}^{-1}$  and the mean  
14 value was  $26.8 \text{ dS m}^{-1}$  (Table 2). This range is somewhat higher than that of the data  
15 obtained by Moral et al. (2005) and Martínez-Suller et al. (2008) where it ranged from  
16  $12.8$  to  $25.2 \text{ dS m}^{-1}$  and  $3.6$  to  $38.1 \text{ dS m}^{-1}$ , respectively. Also, it is lower than data from  
17 Sánchez & González (2005) and Suresh et al. (2009) where it ranged from 2.0 to  $75.2$   
18  $\text{dS m}^{-1}$  and 0.5 to  $58.0 \text{ dS m}^{-1}$  respectively, probably linked to the dietary intake of salts.

19 The variability for DM and OM content was high, from 6.9 to  $238.2 \text{ kg m}^{-3}$  and from  
20  $4.3$  to  $182.2 \text{ kg m}^{-3}$  respectively. This variability, according to Leiros et al. (1983), can  
21 be explained by the rainfall received during storage in open pits while, in closed pits,  
22 the most important dilution factor is the different amount of cleaning water used in  
23 farms. In addition, stratification in the pits when no mixing takes place, increases

1 variability in parameters associated with the solid slurry fraction (Ndegwa et al., 2002;  
2 Ndegwa & Zhu, 2003; Yagüe et al., 2011).

3 The nutrients NPK varied over a wide range; 1.3 to 10.1 kg [TN] m<sup>-3</sup>, 0.9 to 7.5 kg  
4 [AN] m<sup>-3</sup>, 0.3 to 6.0 kg [ON] m<sup>-3</sup>, 0.2 to 8.1 kg [TP] m<sup>-3</sup> and 0.8 to 20.1 kg [TK] m<sup>-3</sup>. As  
5 far as the TP dataset is concerned, 79% of samples had < 2 kg [TP] m<sup>-3</sup>; also, 55% of  
6 values fell into the range 0.09 - 0.99 kg [TP] m<sup>-3</sup> and 45% into 1.00 - 1.99 kg [TP] m<sup>-3</sup>.

7 Similar ranges were found by Chen et al., (2009a) in their recompilation dataset of  
8 different experiments, where more than 70% of samples had a TP content < 2 kg [TP]  
9 m<sup>-3</sup>. In relation to ON dataset, 64% of samples had less than 2 kg [ON] m<sup>-3</sup>, with 45% of  
10 values in the range of 0.09 - 0.99 kg [ON] m<sup>-3</sup> and 55% in the range 1.00 - 1.99 kg ON  
11 m<sup>-3</sup>. This can be explained since the greater part of the samples were taken from lagoon  
12 slurry and only a few from the sediment, in the deeper layer of the pit, where TP  
13 concentration increases in association with total solids accumulation (Ndegwa et al.,  
14 2002), and a similar trend occurs for ON. The rest of the nutrients (TN, AN, and TK)  
15 show a more uniform average distribution along the obtained range of values (Fig. 1a)  
16 although they are influenced by the number of samples taken for each group and by the  
17 nutrient content according to farm type which differs (Table 3).

18 Ammoniacal-N represents, on average, 69%, 72% and 62% of TN for fattening,  
19 maternity and closed cycle farms, respectively. The range of the AN/TN ratio was 0.36-  
20 0.89 (Table 2) which includes the 0.60-0.70 ratio mentioned by Bertrand (1993), the  
21 0.66-0.73 ratio found by Ferrer et al. (2000) and also the 0.70 ratio described by  
22 Christensen et al. (2009) in PS. Ammoniacal-N content is closely related to animal  
23 physiological state and feeding; as adults have a higher catabolism than growing pigs  
24 the proportion of ureic N is higher (Sánchez & González, 2005). Nevertheless, lowest

1 ratio values indicate that important Ammoniacal-N losses can exist in open pits of  
2 Mediterranean farms with high slurry pH which favours ammonium losses as ammonia  
3 (Balsari et al. 2006; Yagüe et al., 2011).

4 The average ratio of major nutrients N:P:K (1:0.3:0.8), remains almost constant in the  
5 total dataset and in the data from the three different farm types (Table 3), No  
6 correlations between TN, AN, TP, and TK contents were observed. Similar mean values  
7 of N:P:K ratios were reported by Levasseur (2002) for pig fattening farms (1:0.3:0.9).  
8 However, the values reported here were somewhat different from the values reported by  
9 Sánchez & González (2005) which were 1:0.3:0.4 (N:P:K). Although the agreements in  
10 N:P ratios, in this last reported papers, with our data, an important dispersion exists. In  
11 our data (Table 2), TP content ranged from 0.1 up to 1.5 times higher and coefficients of  
12 variance were 71%, 67%, 108% for fattening, maternity and closed cycles respectively,  
13 while TK content ranged between 0.2 up to 4.0 times higher than TN content. This  
14 means than N:P:K ratio must be established for each slurry sample and a general value  
15 provided by previous authors (Levasseur, 2002; Sánchez & Gonzalez, 2005) is regarded  
16 as not being useful.

17 According to data presented in Table 2, farm type has an influence in the main  
18 physicochemical parameters of PS, except for TP. This can be explained because the  
19 samples come from farms where slurries are not mixed in the pits before being spread  
20 over land. Total P concentration changes with pit depth, associated with stratification or  
21 sedimentation of solids, as it is mainly found in the solid fraction (Duthion et al., 1979)  
22 also, according to Sánchez & González (2005), around 90% of TP is excreted in the  
23 faeces in the solid fraction, the rest is dissolved mainly in inorganic form. Thus, in static  
24 pits, part of P in the liquid phase is dissolved in urine and other part is suspended, linked

1 to small solid particles (some particle size stratification in the pit profiles exists), which  
2 explains that 78% of PS samples had a TP concentration lower than  $2 \text{ kg P m}^{-3}$ . Ndegwa  
3 et al. (2002) found that TP concentrations in liquid slurry fractions were between 0.5  
4 and  $2.0 \text{ kg [TP] m}^{-3}$  and concentrations increased up to  $3\text{-}5 \text{ kg m}^{-3}$  P values in the  
5 bottom or in the top (crust formation) of pits, associated with an important accumulation  
6 of total solids. Higgins et al. (2004) evaluated TP concentrations as a function of PS  
7 loads pumped from different depths in the pit and showed relatively constant numbers  
8 in the liquid fraction but dramatic changes in TP from the last loads removed at the  
9 deeper pit layers, which illustrates the positive correlation between total solids and TP.  
10 This research indicates the need to quantify TP data content for individual loads, to  
11 avoid excess of soil P content when applying over land. The TP concentration  
12 behaviour in static pits may need to condition phosphorus fertilisation strategies in the  
13 long term for each field receiving slurries.

14 When other nutrients are compared between types of farms, fattening slurries have  
15 around 53% AN, 71% TK and 46% TN higher nutrient content than other farm types.

16 In fattening farms (Table 3), the average DM content of slurries ( $74.0 \text{ kg m}^{-3}$ ) was 56%  
17 and 31% higher than values from maternity or closed cycle respectively. Also, average  
18 EC ( $30.6 \text{ dS m}^{-1}$ ) is 42% and 34% higher than values from maternity and closed cycle,  
19 respectively. Nevertheless, average nutrient values from different types of farms can be  
20 double the values obtained from other areas of Spain (Moral et al., 2005) which also  
21 indicates differences in animal diets and in farm water management.

### 22 **3.2. Correlations to estimate nutrients in pig slurries and regression equations**

23 Correlations between nutrient content of slurries and easily analysed parameters (EC  
24 and DM) were highly significant ( $p < 0.001$ , Table 4).

1 Electrical conductivity was well correlated to ionic species in slurries; AN (0.90) and  
2 TK (0.78). It can be also correlated to TN (0.79) probably because Pearson correlation  
3 value (r) was 0.88 between AN and TN. Dry matter was well correlated to OM (r =  
4 0.99), ON (r = 0.95) and TN (r = 0.78). Both parameters, DM and EC, are frequently  
5 used to estimate the fertiliser value of manures (Stevens et al., 1995, Zhu et al., 2003;  
6 Moral et al., 2005; Martínez-Suller et al., 2008). On the other hand, Higgins et al.  
7 (2004) suggest that TN may be more dependent on the animal growth stage/storage  
8 facility than total solids content, which agrees with the AN/TN ranges found (Table 2).  
9 However, PS undergoes changes during pit storage that could change the relationship  
10 between nitrogen forms because of the ON association with the solid fraction (i.e.  
11 changes due to sedimentation process) and the AN association with liquid fraction (i.e.  
12 changes due to ammonia volatilisation).

13 Phosphorus, as an organic-dependent parameter which is also associated to the solid  
14 fraction, was correlated (Table 4) to DM (r = 0.78), OM (r = 0.76) and ON (r = 0.74).  
15 The average TP/ON ratio was  $0.90 \pm 0.5$  ( $\pm$  SD) for all datasets, but although both  
16 nutrients are linked to the solid fraction of slurry they did not show a constant ratio  
17 (Table 2).

18 Pearson coefficient between AN and TK free ions was 0.51 probably because their ratio  
19 can also change during pit storage (Table 4). Ammoniacal-N can be lost from open  
20 storage facilities to the atmosphere at different rates under the influence of different  
21 environmental factors, such as temperature, wind speed or solar radiation (Portejoie et  
22 al., 2003). Potassium concentration in slurry is a constant or can increase if time-lag in  
23 pit is long enough to have significant water evaporation losses. As water evaporates,  
24 volume reduces and salt concentration increases (Yagüe et al., 2011). This fact

1 (ammonia volatilisation losses and potassium concentration increment in the slurry)  
2 shows an AN/TK ratio with an important variability (Table 2), average value including  
3 all data was  $0.96 \pm 0.4$  ( $\pm$  SD). The semiarid Mediterranean climate in the area provides  
4 favourable conditions for ammonia volatilisation from pits and also favours increments  
5 in TK concentration of the stored slurries.

6 Linear regressions were derived, including all data sets, and acceptable fits were  
7 obtained between the analysed physicochemical parameters (EC and DM) and the main  
8 nutrients in PS (Fig. 2 and 3). Nevertheless, although the observed AN and TK  
9 correlation with  $EC < 40 \text{ dS m}^{-1}$  has a consistent linear relationship beyond the  $40 \text{ dS m}^{-1}$   
10 linear relationship cannot be maintained. Previous studies (Moral et al., 2005; Provolo  
11 & Martínez-Suller, 2007; Martínez-Suller et al., 2008) had EC values lower than  $40 \text{ dS}$   
12  $\text{m}^{-1}$ ; only Sánchez & González (2005) had values up to  $40 \text{ dS m}^{-1}$  but they did not focus  
13 on nutrient-EC relationships. Suresh et al. (2009) measured EC up to  $58 \text{ dS m}^{-1}$  and the  
14 best fit for AN and TN versus EC was an exponential equation ( $R^2 = 0.91$  and  $0.74$   
15 respectively, Table 1) and for TK versus EC, best fit was a quadratic equation ( $R^2 =$   
16  $0.69$ , Table 1).

17 Electrical conductivity in slurries is governed by the concentrations of the major cations  
18 dissolved in the liquid phase ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ ,  $\text{NH}_4^+$ ) balanced by anions with the  
19 same total negative charge. As most monovalent salts are almost completely dissociated  
20 in water, and  $\text{K}^+$  and  $\text{NH}_4^+$  are the dominant cations in slurries, they can be correlated to  
21 EC (Stevens et al., 1995). The EC is a measure of effective ionic strength (IS) but  
22 according to Sposito (2008) and experiments with soil solutions, the Marion and  
23 Babcock (1976) equation:  $\log \text{IS} = 1.159 + 1.009 \log \text{EC}$  is only accurate for IS up to  $300$   
24  $\text{mol m}^{-3}$ , which means for EC up to  $37.86 \text{ dS m}^{-1}$  because the ion-pairing effect alters

1 the linear relationship. The principal factors that influence EC in aqueous solutions are  
2 the nature and concentration of solutes, the degree to which the solutes are dissociated  
3 into ions, the charge on each ion, the mobility of each ion, and temperature of the  
4 solution (Hem, 1982). This boundary agrees with the EC limit value found in this study  
5 for linear relationships; AN vs. EC and TK vs. EC. An increasing IS of the liquid will  
6 affect flocculation processes due to a reduced electrostatic repulsion (Hjorth et al.,  
7 2010). We detected this fact for EC values  $> 40 \text{ dS m}^{-1}$  which adjust to AN values  $> 5.6$   
8  $\text{kg m}^{-3}$  and TK values  $> 5 \text{ kg m}^{-3}$ .

9 Dry matter (Fig. 3) was the best significant parameter ( $p < 0.001$ ) for fitting ON ( $R^2 =$   
10  $0.90$ ) and TP ( $R^2 = 0.68$ ) which can be explained as they are related to the slurry solid  
11 fraction (Ndegwa et al., 2002; Yagüe et al., 2011) and also because of the strong  
12 correlation ( $r = 0.99$ ) between DM and OM. However, for TP a more significant  
13 relationship can be found for samples with  $\text{DM} < 125 \text{ kg m}^{-3}$ , which includes 79% of the  
14 dataset, and also relates to maximum TP concentration in pit storage solution under  
15 static conditions ( $< 2 \text{ kg m}^{-3}$ ). This new relationship has the same  $R^2$  value.

16 Thus, in the case of slurries with low DM content, such as pig slurry, separation into 2  
17 fractions  $> 2000 \mu\text{m}$  and  $< 2000 \mu\text{m}$  would allow the removal of most of the solids and  
18 phosphorus from the liquid phase (Fangueiro et al., 2010), which has important  
19 agronomic implications (i.e. requiring fertilisation adjustments) when the different  
20 fractions are applied in the field. This could be also the case when flocculating additives  
21 for slurry are used (Hjorth et al., 2010), because additives flocculates the solid fraction  
22 which mainly contains the TP amount and, as the solid fraction separates from the liquid  
23 fraction, two different products for fertiliser use are obtained.



1 If DM vs. TP models are compared with those which have  $R^2$  values higher than 0.68,  
2 their TP values are lower than  $2 \text{ kg [TP] m}^{-3}$  (Scotford et al., 1998; Moral et al., 2005),  
3 which suggests that they were calculated from samples associated with the slurry liquid  
4 fraction or from diluted slurries. The models with higher TP content (4 or  $9.1 \text{ kg [TP]}$   
5  $\text{m}^{-3}$ ) had lower  $R^2$  values, between 0.37 to 0.43 (Martínez-Suller et al., 2008 and Zhu et  
6 al., 2003). Our model includes a wide range of TP contents (up to  $6.0 \text{ kg m}^{-3}$ ;  $R^2 = 0.68$ ),  
7 which allows it to be used in pits under static conditions, where sedimentation takes  
8 place.

### 9 **3.3. Evaluation of physicochemical models: model comparisons**

10 Our measured data was compared with nutrient contents predictions by various  
11 physicochemical models (Table 1) as shown in Fig. 4. The TN physicochemical models  
12 (Fig. 4a) were significant ( $p < 0.0001$ ) with an  $R^2 = 0.63$ , and  $d$  index between 0.69 and  
13 0.89 (Table 5) but the model proposed by Suresh et al. (2009) gave the best predictions  
14 (RMSE= 1.37; MAE= 0.95; MEF= 0.59;  $d = 0.89$ ), probably because it was the only one  
15 that included, in its development, EC values higher than  $40 \text{ dS m}^{-1}$ .

16 For AN content Suresh et al. (2009) also gave the best fit (RMSE= 0.64; MAE= 0.46;  
17 MEF= 0.78;  $d = 0.95$ ). Two models (Moral et al., 2005; Martínez-Suller et al., 2008; Fig.  
18 4b) had good fit up to  $5.6 \text{ kg [NH}_4\text{-N] m}^{-3}$  content (which is also the maximum value  
19 used) but above this value only Suresh et al. (2009) gave good results. It was observed  
20 that at higher EC ( $> 40 \text{ dS m}^{-1}$ ) the behaviour was not linear, as also observed by Suresh  
21 et al. (2009). When considering all our data (values higher than  $5.6 \text{ kg [NH}_4\text{-N] m}^{-3}$  are  
22 included) a linear regression fitted just as well as exponential ( $\text{AN} = 0.14 \text{ EC} - 0.32$  and  
23  $\text{AN} = 0.10 \text{ EC}^{1.09}$ ; both with an  $R^2 = 0.86$  and significance:  $p < 0.0001$ , Fig. 2a), but for  
24 values higher than  $5.6 \text{ kg [NH}_4\text{-N] m}^{-3}$ , when the exponential equation was used,

1 differences between measured and predicted values were reduced (data not shown)  
2 when compared to the linear regression equation. The accurate prediction of AN content  
3 was acceptable for all three models when AN values  $< 5.6 \text{ kg m}^{-3}$  or  $\text{CE} < 40 \text{ dS m}^{-1}$  are  
4 included (Fig. 4b).

5 Figure 4c shows the relationship between measured and predicted TK content by three  
6 models. The regression three models had similar indexes: RMSE, MAE, MEF and d-  
7 index (Table 5) using all data. However, although the trends in the models were similar  
8 they did not fit acceptably. The upper limit content in Moral et al. (2005) and Martínez-  
9 Suller et al. (2008) studies was  $6 \text{ kg [TK] m}^{-3}$  and in both of these references they just  
10 present two values inside the  $30 - 40 \text{ dS m}^{-1}$  range. In Suresh et al. (2009) the upper  
11 limit was  $7.3 \text{ kg [TK] m}^{-3}$  (with only two values between  $40 - 58 \text{ dS m}^{-1}$ ) and a  
12 quadratic model was used. Chen et al. (2009a and 2009b) compiled datasets from  
13 different authors and countries for cattle and pig slurry and, from their findings, it  
14 appears to have an upper limit close to  $5 \text{ kg [TK] m}^{-3}$  (and  $\text{EC} < 40 \text{ dS m}^{-1}$ ) using the  
15 linear relationships established.

16 The use of EC as tool to prediction for AN in concentrations  $> 5.6 \text{ kg [AN] m}^{-3}$   
17 indicates an important underestimation of this nutrient by linear physicochemical  
18 models. It would be also the case for  $\text{TK} > 5 \text{ kg m}^{-3}$  (Fig. 4b and 4c). This fact has  
19 important environmental (i.e. N leaching or P accumulation in soil) and agronomic  
20 consequences (i.e. excess N, lodging of crops) if they are not taken into account.  
21 Furthermore, in the context of a general trend towards the minimisation of PS volume at  
22 farm level, in order to reduce transport costs, when this slurry is applied in the field,  
23 these concentration boundaries have other practical implications as the number of  
24 samples exceeding these limits will increase in Mediterranean areas.

1 The significant number of cases with high potassium concentration values in PS could  
2 be due to an excess in the diet of this nutrient or a relative concentration during storage  
3 in open pits. As observed by Scotford et al. (1998) and Martínez-Suller & Provolo  
4 (2007), the content of TK and the degree of its correlation with EC varies a lot between  
5 geographical locations, and probably because of differences in feeding and management  
6 strategies. As an example, soybeans can supply most of the crude proteins needed by  
7 pigs, while at the same time soybeans contain high concentrations of K that increase the  
8 pH and TK content of urine slurry when excreted (Portejoie et al., 2004).

9 Physicochemical models for TP based on DM (Zhu et al., 2003;  $R^2 = 0.46$  and  
10 Martínez-Suller et al., 2008;  $R^2 = 0.37$ , Fig. 4d), when data from our study are used, had  
11 a coefficient of determination of 0.61, similar to that obtained when TP was correlated  
12 to DM ( $R^2 = 0.68$ ; Table 5). The main inconvenience of this estimator is that DM  
13 analysis cannot be as easily carried out “in situ” unlike the EC determination.

#### 14 **4. Conclusions**

15 Slurry nutrient content and N:P:K ratios vary between type of farms to a great extent.  
16 Pig slurries from fattening farms exhibit higher nutrient content than slurries from  
17 maternity and closed cycle farms. Physicochemical linear models are good tools for  
18 nitrogen nutrient estimation (the main nutrient where fertilisation restrictions are  
19 established) and also they are good for phosphorous estimation but, in both cases, some  
20 limitations exist. AN ( $< 5.6 \text{ kg m}^{-3}$ ) can be indirectly measured by EC ( $< 40 \text{ dS m}^{-1}$ ) and  
21 ON and TP can be indirectly quantified from DM. Our model for TP is consistent for a  
22 wider range of values ( $< 6 \text{ kg [TP] m}^{-3}$ ) than other models found in the literature. Total  
23 K shows high variability when it is related to EC ( $R^2 = 0.58$ ) thus, the estimated  
24 regression equation would not be sufficiently useful.

1 **Acknowledgements**

2 The authors thank farmers, Miguel Izquierdo, Jesús Gaudó and Francisco Iguácel for  
3 their invaluable field management assistance; also the assistance of Carmen Herrero and  
4 Jordi Coromines is fully acknowledged. We would also like to acknowledge the  
5 anonymous reviewers for their useful comments. This study was funded by the National  
6 Institute for Agricultural and Food Scientific Research and Technology of Spain  
7 (INIA), projects SC00-061, RTA04-114 and RTA10-126.

## 1 **References**

- 2 APHA, (1998). Standards methods for the examination of water and wastewater. 20<sup>th</sup>  
3 edn (Eds L.S. Clesceri, A.E., Greenberg, & A.D. Eaton). American Public Health  
4 Association. Washington, D.C.
- 5 Balsari, P., Dinuccio, E., & Gioelli, F. (2006). A low cost solution for ammonia  
6 emissions from covered slurry compared with uncover during storage. *Agriculture*  
7 *Ecosystems and Environment*. 112, 129-134.
- 8 Bertrand, M. (1993). Caracterización y gestión de los estiércoles sólidos y licuados.  
9 *Residuos ganaderos*. Fundación “La Caixa”. Barcelona. pp 177-190.
- 10 Chen, L., Xing, L., Han, L., & Yang, Z. (2009a). Evaluation of physicochemical models  
11 for rapidly estimating pig manure nutrient content. *Biosystems Engineering*, 103(3),  
12 313-320.
- 13 Chen, L., Xing, L., Han, L., & Yang, Z. (2009b). Evaluation of physicochemical models  
14 for rapidly estimating cattle manure nutrient content. *Biosystems Engineering*, 104(1),  
15 143-151.
- 16 Christensen, M.L., Hjorth, M., & Keiding, K. (2009). Characterization of pig slurry  
17 with reference to flocculation separation. *Water Resources*, 43(3), 773-783.
- 18 Duthion, C., Catroux, G., & Germon, J.C. (1979). Land spreading of liquid pig manure:  
19 II. Nutrient balances and effects on drainage water. In: Grassier J.K.R (Ed.), *Effluents*  
20 *from livestock*. Applied Science Publish Ltd, London, pp 59-79.
- 21 Eghball, B., Whienhold, B.J., Woodbury, B.L., & Eigenberg, R.A. (2005). Plant  
22 availability of phosphorus in swine slurry and cattle feedlot manure. *Agronomy*  
23 *Journal*, 97(2), 542-548.

1 European Union. 1991. Council directive 91/676/EEC of 12 December concerning the  
2 protection of waters against pollution caused by nitrates from agricultural sources.  
3 Off. J. Eur. Communities: L375. Brussels, Belgium. Available at [http://eur-](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1991:375:0001:0008:EN:PDF)  
4 [lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1991:375:0001:0008:EN:PDF](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1991:375:0001:0008:EN:PDF)  
5 (verified 14 Nov. 2011). European Communities, Brussels.

6 Fangueiro, D., Gusmao, M., Grilo, J., Porfirio, G., Vasconcelos, E., & Cabral, F. (2010).  
7 Proportion, composition and potential N mineralization of particle size fractions  
8 obtained by mechanical separation animal slurry. *Biosystems Engineering*, 106(4),  
9 333-337.

10 FAO. 2011. FAOSTAT. [Online]. Available at:  
11 <http://faostat.fao.org/site/573/DesktopDefault.aspx?PageID=573#ancor> (verified 14  
12 Nov. 2011). FAO. Rome.

13 Ferrer, M., Orús, F., & Monge, E. (2000). Determinación de formas nitrogenadas en  
14 estiércol fluido porcino (EFP) por distintos métodos analíticos. *Anaporc*, 205, 86-101.

15 Hem, J.D. (1982). Conductance: a collective measure of dissolved ions. In: Minear,  
16 R.A., Lawrance, H.K (Eds.) *Water analysis, Vol 1, Inorganic species Part 1*, London.  
17 Academic Press, pp 137-161.

18 Higgins, S.F., Shearer, S.A., Coyne, M.S., & Fulton, J.P. (2004). Relationship of total N  
19 and total phosphorus concentration to solids content in animal waste slurries. *Applied*  
20 *Engineering in Agriculture*, 20(3), 355-364.

21 Hjorth, M., Christensen, K.V., Christensen, M.L., & Sommer, S.G. (2010). Solid-liquid  
22 separation of animal slurry in theory and practice. A review. *Agronomy for*  
23 *Sustainable Development*, 30(1),153-180.

- 1 Irañeta, I., Pérez de Ciriza, J.J., Santos, A., Amézqueta, J., Carro, P., Iñigo, J.A., &  
2 Abaigar, A. (1999). Purín porcino (I): Valor agronómico. Navarra Agraria. Julio-  
3 Agosto-Septiembre, pp 14-25.
- 4 Leirós, M.C., Villar, M.C., Cabaneiro, A., Carballas, T., Díaz-Fierros, F., Gil, F., &  
5 Gómez, C. (1983). Caracterización y valor fertilizante de los purines de vacuno en  
6 Galicia. Anales de Edafología y Agrobiología, 42, 752-768.
- 7 Levasseur, P. (2002). Composition chimique détaillée des aliments des lisiers de porc.  
8 Techniporc, 25(1), 19-25.
- 9 Malley, D.F., Yesmin, L., & Eilers, R.G. (2002). Rapid analysis of hog manure and  
10 manure amended soils using near-infrared spectroscopy. Soil Science Society of  
11 America Journal, 66, 1677-1686.
- 12 Marion, G.N., & Babcock, K.L. (1976). Predicting specific conductance and salt  
13 concentration of dilute aqueous solution. Soil Science 122(4), 181-187.
- 14 Martínez-Suller, L., Azzelino A., & Provolo, G. (2008). Analysis of livestock slurries  
15 from farms across Northern Italy: relationship between indicators and nutrient  
16 content. Biosystems Engineering, 94(4), 540-552.
- 17 Mayer, D.G., & Butler, D.G. (1993). Statistical validation. Ecological Modelling, 68,  
18 21-32.
- 19 Moral, R., Pérez-Murcia M.D., Pérez.-Espinosa, A., Moreno-Caselles, J., & Paredes C.,  
20 (2005). Estimation of nutrient values of pig slurries in Southeast Spain easily  
21 determined properties. Waste Management, 25(7), 719-725.
- 22 Ndegwa, P.M., & Zhu, J. (2003). Sampling procedures for piggery in deep pits for  
23 estimation of nutrient content. Biosystems Engineering, 85(2), 239-248.

1 Ndegwa, P.M., Zhu, J., & Luo, A. (2002). Stratification of solids, nitrogen and  
2 phosphorus in swine manure in deep pits under slatted floors. *Bioresource*  
3 *Technology*, 83(3), 203-211.

4 Portejoie, S., Martínez, J., Guiziou, F., & Coste, C.N. (2003). Effect of covering pig  
5 slurry stores on the ammonia emissions processes. *Bioresource Technology*, 87(3),  
6 199-207.

7 Portejoie, S., Dourmad, J.Y., Martinez, J., & Lebreton, Y. (2004). Effect of lowering  
8 dietary crude protein on nitrogen secretion composition and ammonia emissions from  
9 fattening pigs. *Livestock Production Science*, 91(1), 45-55.

10 Provolo, G., & Martínez-Suller, L. (2007). In situ determination of slurry nutrient  
11 content by electrical conductivity. *Bioresource Technology*, 98(17), 3235-3242.

12 Reeves, III, J.B. (2001). Near- versus mid-infrared diffuse reflectance spectroscopy for  
13 determination of minerals in dried poultry manure. *Poultry Science*, 80, 1437-1443.

14 Reeves III, J.B., & Van Kessel, J.S. (2000). Near-infrared spectroscopic determination  
15 of carbon, total nitrogen, and ammonium-N in dairy manure. *Journal of Dairy*  
16 *Science*, 83, 1829-1836.

17 Sánchez, M., & González, J.L. (2005). The fertilizer value of pig slurry. I Values  
18 depending on the type of operation. *Bioresource Technology*, 96(10), 1117-1123.

19 SAS. 1999-2001. SAS Institute Inc 1999-2001 SAS/TAT. Software V 8.2. Cary . NC.  
20 USA.

21 Scotford, I.M., Cumby, T.R., White, R.P., Carton, O.T., Lorenz, F., Hatterman, U., &  
22 Provolo, G. (1998). Estimation of the nutrient value of agricultural slurries by  
23 measurements of physical and chemical properties. *Journal of Agricultural*  
24 *Engineering Research*, 71(3), 291-305.



1 Sharpley, A.N., Daniel, T., Gibson, G., Bundy, L., Cabrera, M., Sims, T., Stevens, R.,  
2 Lemunyon, J., Kleinman, P., & Parry, R. (2006). Best management practices to  
3 minimize agricultural phosphorus impacts on water quality [Online]. Available at:  
4 [http://www.ars.usda.gov/is/np/BestMgmtPractices/Best%20Management%20Practic](http://www.ars.usda.gov/is/np/BestMgmtPractices/Best%20Management%20Practices.pdf)  
5 [es.pdf](http://www.ars.usda.gov/is/np/BestMgmtPractices/Best%20Management%20Practices.pdf) (verified 14 Nov. 2011) USDA-ARS Report No. 163, U.S. Govt. Printing  
6 Office, Washington, DC.

7 Sposito, G. (2008). Chemistry of soils. (2<sup>nd</sup> edition, electronic version). Cary: Oxford  
8 University Press.

9 Stevens, R.J., O’Bric, C.J., & Carton, O.T. (1995) Estimating nutrient content of animal  
10 slurries using electrical conductivity. *Journal of Agricultural Science*, 125, 233-238.

11 Suresh, A., Choi, H.L., Oh, D.I., & Moon, O.K. (2009). Prediction of the nutrients value  
12 and biochemical characteristics of swine slurry by measurement of EC- Electrical  
13 conductivity. *Bioresource Technology*, 100(20), 4683-4689.

14 Tedeschi, L.O. (2006). Assessment of the adequacy of mathematical models.  
15 *Agricultural Systems*, 89, 225-247.

16 Teira-Esmatges, M.R., & Flotats, X. (2003). A method for livestock waste management  
17 planning in NE Spain. *Waste Management*, 23(10), 917-932.

18 Tunney, H. (1979). Dry matter, specific gravity, and nutrient relationships of cattle and  
19 pig slurry. In: Hawking, J.C (Ed.) *Engineering Problems from livestock*, Proceedings.  
20 C.E.C. Seminar, Cambridge, England. Luxembourg, pp 430-447.

21 USEPA. (1992). United States Environmental protection Agency. Method 6010A.  
22 Inductively coupled plasma-atomic emission spectroscopy. Kovar. J.K. Chapter 6.  
23 methods of determination of P, K, Ca, Mg and others trace elements. In: J. Peters (ed.)  
24 Recommended methods of manure analysis. Publ. A3769. Univ. of Wisconsin-

1 Extension. [Online]. Available at: <http://uwlab.soils.wisc.edu/pubs/A3769.pdf>.  
2 (verified 14 Nov. 2011). Madison, WI.

3 Van Kessel, J.S., Reeves III, J.B. (2000). On farm quick tests for estimating nitrogen in  
4 dairy manure. *Journal of Dairy Science*, 83, 1837-1844.

5 Willmott, C.J. (1982). Some comments on the evaluation of model performance.  
6 *Bulletin of the American Meteorological Society*, 63(11), 1309-1313.

7 Xing, L., Chen, L.J., & Han, J. (2008). Rapid analysis of layer manure using near-  
8 infrared reflectance spectroscopy. *Poultry Science*, 87, 1281-1286.

9 Yagüe M.R., Guillén, M., & Quílez, D. (2011). Effect of covers on swine slurry  
10 nitrogen conservation during storage in Mediterranean conditions. *Nutrient Cycling in*  
11 *Agroecosystems*, 90(1), 121-132.

12 Yagüe, MR., Iguácel, F., Orús, F., & Quílez, D. (2006). Evaluación de costes de equipo  
13 de aplicación de purín. In: Magrí, A., Prenafeta-Boldú, F.X., Flotats, X. (Ed.), *Libro*  
14 *de actas del I Congreso Español de Gestión Integral de Deyecciones Ganaderas*, 249-  
15 253.

16 Yang, Z., Han, L.J., & Fan, X (2006a). Rapidly estimating nutrient contents of fattening  
17 pig manure from floor scrapings by near infrared reflectance spectroscopy. *Journal of*  
18 *Near Infrared Spectroscopy*, 14 (1), 261-268.

19 Yang, Z., Han, L., Li, Q., & Piao, X. (2006b). Estimating nutrient contents of pig  
20 slurries rapidly by measurement of physical and chemical properties. *Journal of*  
21 *Agricultural Science*, 144(3), 261-267.

22 Zhu, J., Zhang, Z., & Ndegwa, P.M. (2003). Using a soil hydrometer to measure the  
23 nitrogen and phosphorus contents in pig slurries. *Biosystems Engineering*, 85(1), 121-  
24 128.

1 **Legend figures**

2 **Fig. 1.** Sample distribution (a) (%) of total compiled datasets (*n*: number of total  
3 analysed samples and for each type of farm) and also according to each type of farm:  
4 fattening (b), maternity (c) and closed cycle (d), for total nitrogen (TN), ammoniacal-N  
5 (AN), total phosphorus (TP) and total potassium (TK)

6 **Fig. 2.** Relationship between (a) ammoniacal-N and (b) potassium versus electrical  
7 conductivity for slurry (\*\*\*)  $p < 0.001$ )

8 **Fig. 3.** Relationship between (a) organic-N, (b) total phosphorus and dry matter (DM)  
9 for all different types of farms slurry data (\*\*\*)  $p < 0.0001$ )

10 **Fig. 4.** Comparison of measured and predicted nutrient content by different  
11 physicochemical models: Martínez- Suller et al. 2008 (Mtz); Moral et al. 2005 (Moral);  
12 Suresh et al. 2009 (Suresh) and Zhu et al. 2003 (Zhu)

13

14

15

16

17

18

19

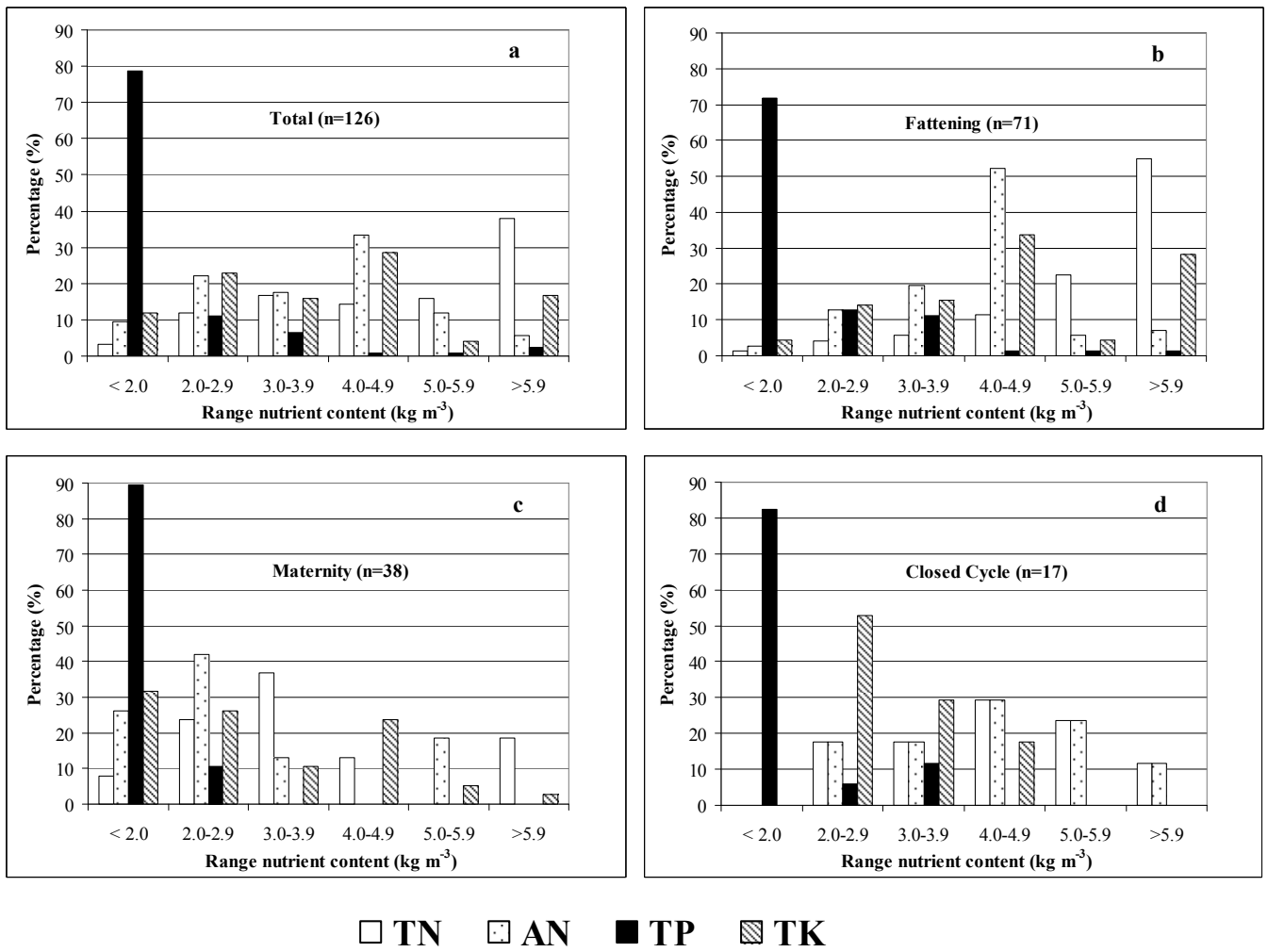
20

21

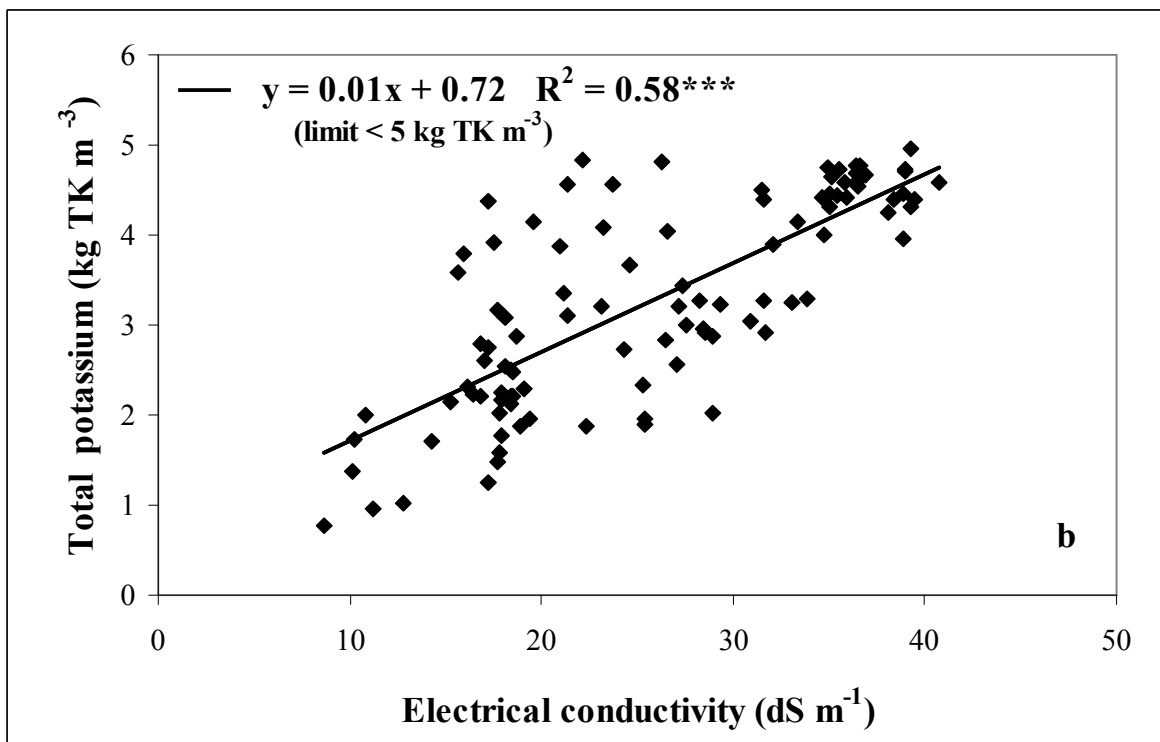
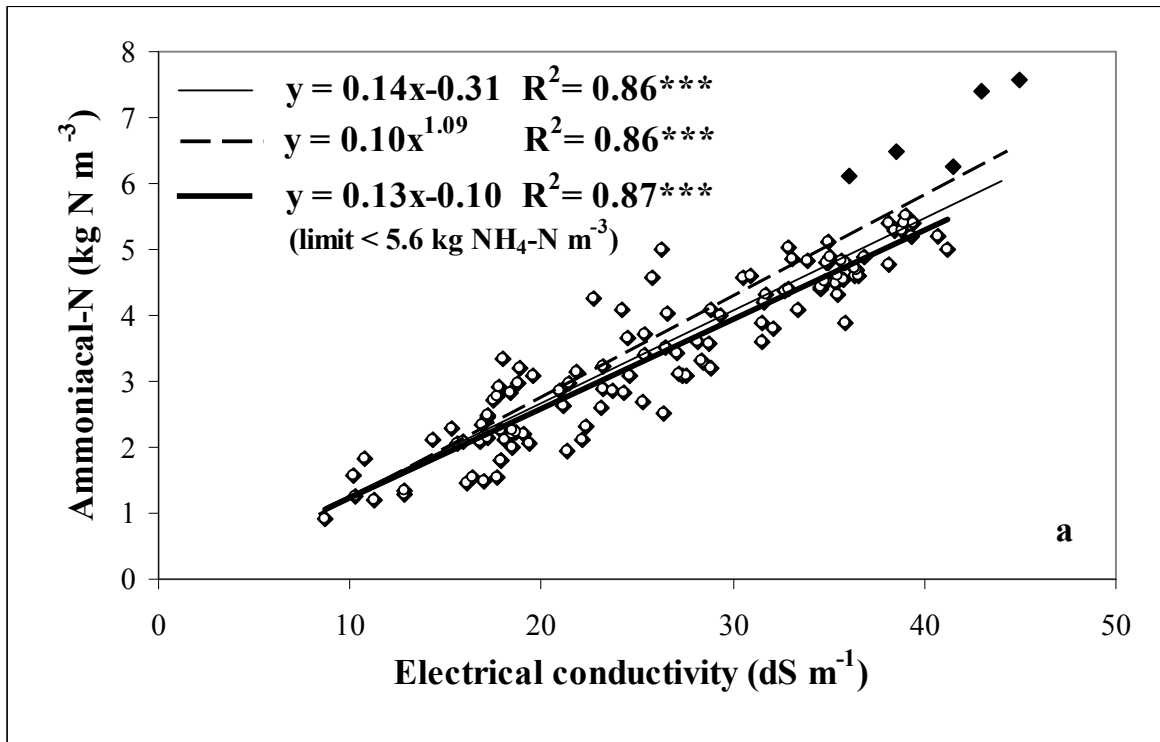
22

23

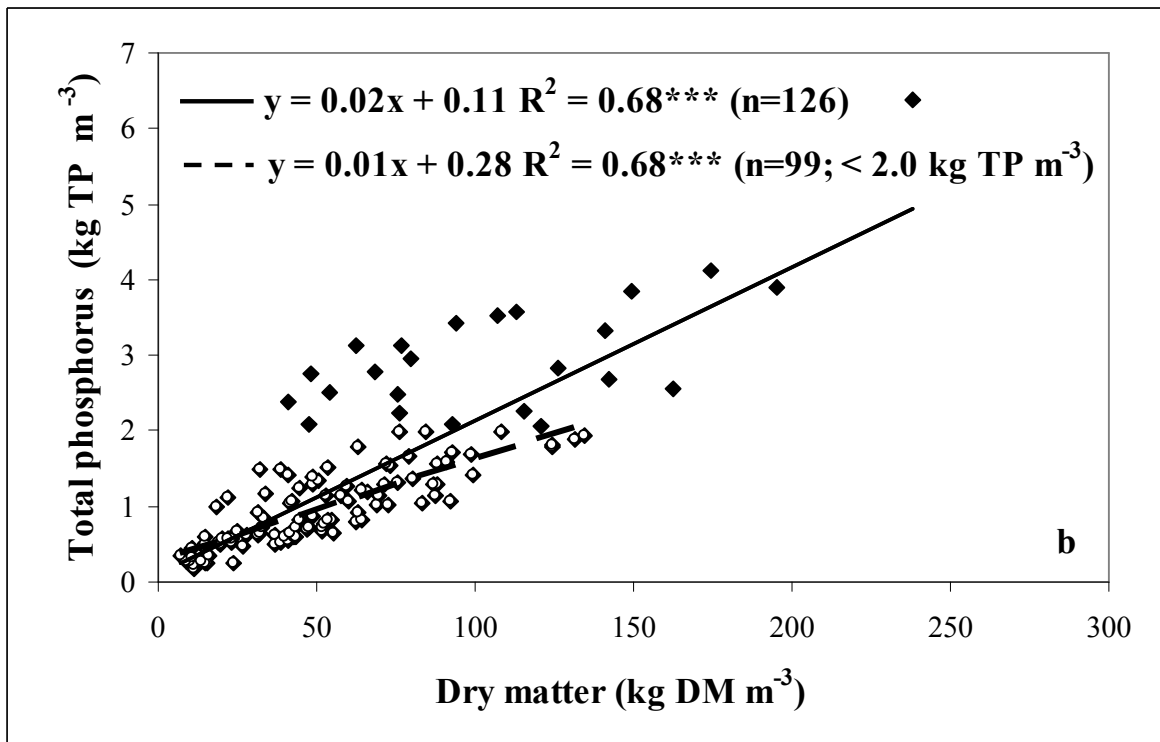
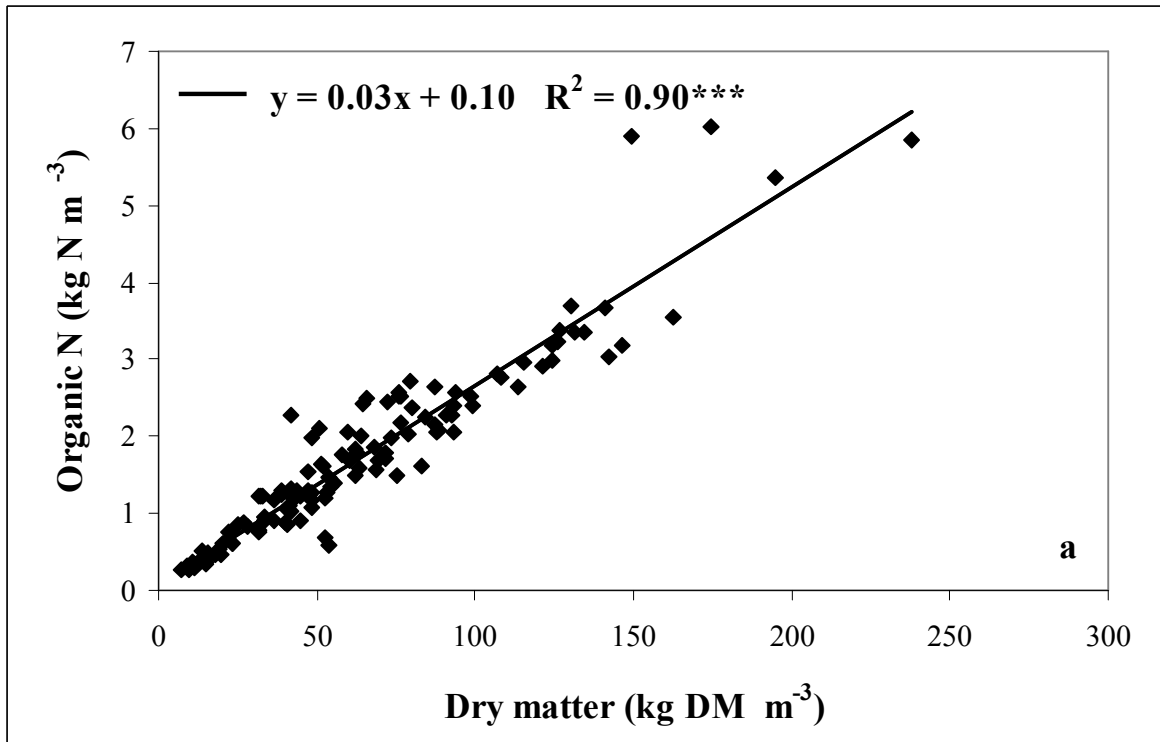
24



**Fig. 1.** Sample distribution (a) (%) of total compiled datasets (n: number of total analysed samples and for each type of farm) and also according to each type of farm: fattening (b), maternity (c) and closed cycle (d), for total nitrogen (TN), ammoniacal-N (AN), total phosphorus (TP) and total potassium (TK)

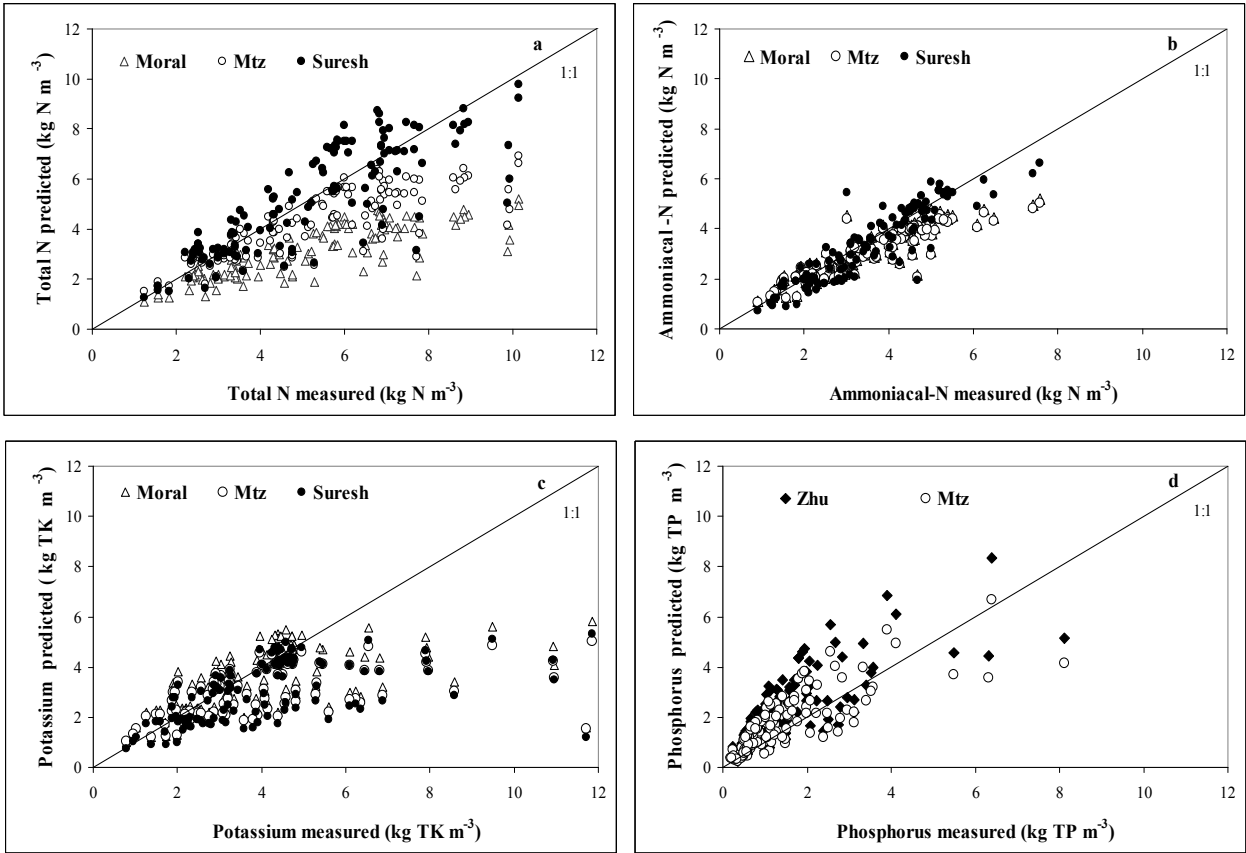


**Fig. 2.** Relationship between (a) ammoniacal-N and (b) total potassium versus electrical conductivity for slurry (\*\*\*)  $p < 0.001$ )



**Fig. 3.** Relationship between (a) organic-N, (b) total phosphorus and dry matter (DM) for all different types of farms slurry data (\*\*\*)  $p < 0.0001$

1



**Fig. 4.** Comparison of measured and predicted nutrient content by different physicochemical models: Martínez- Suller et al. 2008 (Mtz); Moral et al. 2005 (Moral); Suresh et al. 2009 (Suresh) and Zhu et al. 2003 (Zhu)

2

1 **Table 1.** Published physicochemical models for predicting pig slurry nutrient content,  
 2 regression equations and coefficients of determination ( $R^2$ )

Nutrient	Reference	Country	Equation <sup>a</sup>	Range of nutrient content	$R^2$
Total Nitrogen (TN)	Moral et al. 2005	Spain	TN= 0.13EC+0.24	0.5-5.8	0.78
	Martínez–Suller et al. 2008	Italy	TN= 0.15EC+0.19	0.2-5.6	0.78
	Suresh et al. 2009	Korea	TN= 83.79EC <sup>1.25</sup>	0.5-13.0	0.74
Ammoniacal N (AN)	Moral et al. 2005	Spain	AN=0.11EC+0.10	0.2-4.5	0.83
	Martínez–Suller et al. 2008	Italy	AN=0.11EC+0.09	0.2-5.0	0.82
	Suresh et al. 2009	Korea	AN <sup>b</sup> = 39.89EC <sup>1.343</sup>	0.5-7.5	0.91
Total Potassium (TK) <sup>c</sup>	Moral et al. 2005	Spain	TK=0.14EC-0.21	0.2-6.0	0.82
	Martínez–Suller et al. 2008	Italy	TK=0.11EC+0.04	0.3-6.0	0.52
	Suresh et al. 2009	Korea	TK <sup>b</sup> =0.60EC+102.6EC-196.3	0.5-7.3	0.69
Total Phosphorus (TP) <sup>c</sup>	Zhu et al. 2003	USA	TP=0.035DM+0.01	0.1-4.0	0.46
	Martínez–Suller et al. 2008	Italy	TP=0.03DM+0.05	0.1-9.1	0.37

3 <sup>a</sup> Electrical Conductivity (EC) expressed as dS m<sup>-1</sup>; DM (dry matter), total nitrogen  
 4 (TN), ammoniacal-nitrogen (AN), total potassium (TK) and total phosphorus (TP)  
 5 expressed as kg m<sup>-3</sup>

6 <sup>b</sup> It was expressed in mg l<sup>-1</sup>, it was transformed to kg m<sup>-3</sup> dividing by 1000 the value  
 7 obtained in equation

8 <sup>c</sup> Conversion of P to P<sub>2</sub>O<sub>5</sub> is done by multiplying by 2.29 and conversion of K to K<sub>2</sub>O  
 9 by multiplying by 1.20



1 **Table 2.** Average composition (Mean), standard deviation (SD), maximum (Max.) and minimum (Min.) values of the analysed  
 2 physicochemical parameters<sup>a</sup> according to type of farm

	<b>Total (n=126)<sup>b</sup></b>				<b>Fattening (n=71)</b>				<b>Maternity (n=38)</b>				<b>Closed Cycle(n=17)</b>			
	<b>Med.</b>	<b>Max.</b>	<b>Min.</b>	<b>SD</b>	<b>Med.</b>	<b>Max.</b>	<b>Min.</b>	<b>SD</b>	<b>Med.</b>	<b>Max.</b>	<b>Min.</b>	<b>SD</b>	<b>Med.</b>	<b>Max.</b>	<b>Min.</b>	<b>SD</b>
<b>pH (1:5)</b>	8.20	9.10	6.11	0.7	8.39	9.10	7.54	0.4	8.29	9.10	7.56	0.4	7.21	8.70	6.11	1.1
<b>EC (dS m<sup>-1</sup>)</b>	26.84	45.00	8.67	8.5	30.59	45.00	10.28	7.5	21.61	40.70	8.67	9.0	22.84	31.70	15.30	5.7
<b>DM (kg m<sup>-3</sup>)</b>	63.60	238.12	6.89	42.5	73.97	238.12	8.96	44.5	47.37	134.60	6.89	33.8	56.55	146.40	11.48	40.3
<b>OM (kg m<sup>-3</sup>)</b>	42.61	182.16	4.31	31.2	49.61	182.16	5.44	33.7	31.09	95.38	4.31	23.9	39.10	96.03	6.12	28.1
<b>TN (kg m<sup>-3</sup>)</b>	5.30	10.14	1.24	2.1	6.22	10.14	1.58	1.9	3.97	8.85	1.24	2.0	4.48	7.26	2.37	1.4
<b>AN (kg m<sup>-3</sup>)</b>	3.57	7.57	0.91	1.4	4.20	7.57	1.25	1.2	2.81	5.51	0.91	1.3	2.69	4.30	1.46	0.7
<b>ON kg m<sup>-3</sup>)</b>	1.73	6.02	0.26	1.2	2.03	6.02	0.32	1.2	1.16	3.37	0.26	0.8	1.78	3.37	0.29	1.0
<b>TP (kg m<sup>-3</sup>)</b>	1.44	6.38	0.18	1.2	1.68	6.38	0.24	1.2	1.05	2.79	0.22	0.7	1.29	6.31	0.18	1.4
<b>TK (kg m<sup>-3</sup>)</b>	4.38	20.07	0.77	2.9	5.35	20.07	1.73	3.3	3.12	11.71	0.77	2.0	3.16	4.83	2.02	0.8
<b>AN/TN</b>	0.69	0.89	0.36	0.1	0.69	0.89	0.36	0.1	0.72	0.89	0.46	0.1	0.62	0.89	0.40	0.1
<b>AN/TK</b>	0.96	2.02	0.12	0.4	0.94	2.02	0.19	0.4	1.03	1.98	0.12	0.4	0.89	1.47	0.44	0.3
<b>TP/ON</b>	0.90	4.28	0.32	0.5	0.84	4.28	0.32	0.5	1.04	2.82	0.41	0.6	0.75	1.87	0.34	0.4

- 1 <sup>a</sup> EC: Electrical Conductivity; DM: Dry matter; OM: Organic matter; TN: Total N; AN: Ammoniacal N; ON: Organic nitrogen; TP: Total
- 2 phosphorus; TK: Total potassium
- 3 <sup>b</sup> n: number of samples analyzed for each type of farm
- 4

1 **Table 3.** Electrical conductivity (EC), dry matter (DM) and major nutrients content in  
 2 pig slurry (TN: Total N; AN: Ammoniacal N; ON: Organic nitrogen; TP: Total  
 3 phosphorus; TK: Total potassium) in the three types of farms (n=126)

	EC	DM	TN	AN	ON	TP	TK	N/P/K
	dS m <sup>-1</sup>	----- kg m <sup>-3</sup> -----						
<b>Fattening</b>	30.6A <sup>a</sup>	74.0A	6.2A	4.2A	2.0A	1.7	5.4A	1/0.3/0.9
<b>Maternity</b>	21.6B	47.4B	4.0B	2.8B	1.2B	1.1	3.1B	1/0.3/0.9
<b>Closed cycle</b>	22.8B	56.6AB	4.5B	2.7B	1.8A	1.3	3.2B	1/0.3/0.8
<b>Type farm</b>	***	**	***	***	***	NS	***	-

4 <sup>a</sup> Within columns, means followed by the same letter are not significantly different

5 according to Tukey multiple range test (0.05)

6 NS: not significant; \*\* 0.01 ≤ p < 0.001; 0.001 ≤ p < 0.0001

1 **Table 4.** Correlation matrix between the different slurry properties and nutrients in total  
 2 pig slurry samples (n=126), numbers are the values of the Pearson correlation (r)

	<b>pH</b>	<b>EC<sup>a</sup></b>	<b>DM</b>	<b>OM</b>	<b>TN</b>	<b>AN</b>	<b>ON</b>	<b>TP</b>	<b>TK</b>
<b>pH</b>		0.14	0.02	0.03	0.05	0.15	0.09	0.16	0.26
<b>EC</b>	NS		0.37	0.34	0.79 <sup>b</sup>	0.90	0.40	0.08	0.78
<b>DM</b>	NS	NS		0.99	0.78	0.42	0.95	0.78	0.38
<b>OM</b>	NS	NS	***		0.76	0.40	0.94	0.76	0.32
<b>TN</b>	NS	***	***	***		0.88	0.82	0.55	0.56
<b>AN</b>	NS	***	***	***	***		0.44	0.24	0.51
<b>ON</b>	NS	***	***	***	***	***		0.74	0.44
<b>TP</b>	NS	NS	***	***	***	**	***		0.35
<b>TK</b>	**	***	***	***	***	***	***	***	

3 <sup>a</sup> EC: Electrical Conductivity; DM: Dry Matter; OM: Organic Matter; TN: Total  
 4 Nitrogen; AN: Ammoniacal Nitrogen; ON: Organic Nitrogen; TP: Total phosphorus;  
 5 TK: Total potassium

6 <sup>b</sup> Dark colour means r values higher than 0.70

7 NS: not significant; \*\* 0.01 ≤ p <0.001; \*\*\* 0.001 ≤ p <0.0001

1 **Table 5.** Statistical performance<sup>a</sup> of different physicochemical models, using data from this study (n=126), for predicting slurry nutrient  
 2 content (NT, total N; AN, Ammoniacal N; TK, total potassium; TP, total phosphorus)

Nutrient	Reference	Equation <sup>b</sup>	RMSE	MAE	MEF	d-index	a	b	R <sup>2</sup>	p
			----- kg m <sup>-3</sup> -----							
TN	Moral et al. 2005	TN= 0.13EC+0.24	2.13	1.62	0.01	0.69	-0.18	1.48	0.63	<0.0001
	Martínez –Suller et al.2008	TN= 0.15EC+0.19	1.74	1.21	0.34	0.77	0.00	1.28		<0.0001
	Suresh et al. 2009	TN= 83.79EC <sup>1.250</sup>	1.37	0.95	0.59	0.89	1.09	0.81		<0.0001
AN	Moral et al. 2005	AN=0.11EC+0.10	0.77	0.58	0.68	0.90	-0.31	1.24	0.82	<0.0001
	Martínez–Suller et al.2008	AN=0.11EC+0.09	0.83	0.64	0.63	0.88	-0.30	1.27		<0.0001
	Suresh et al. 2009	AN <sup>c</sup> = 39.89EC <sup>1.343</sup>	0.64	0.46	0.78	0.95	0.03	1.00		<0.0001
TK <sup>d</sup>	Moral et al. 2005	TK=0.14EC-0.21	0.82	0.65	0.43	0.86	0.88	0.70	0.57	<0.0001
	Martínez–Suller et al.2008	TK=0.11EC+0.04	0.78	0.58	0.48	0.85	0.70	0.85		<0.0001
	Suresh et al. 2009	TK <sup>c</sup> =0.60EC <sup>2</sup> +102.6EC-196.3	0.88	0.65	0.34	0.84	1.15	0.73		<0.0001
TP	Zhu et al. 2003	TP=0.035DM+0.01	1.20	0.94	0.15	0.82	-0.04	0.68	0.61	<0.0001
	Martínez–Suller et al.2008	TP=0.03DM+0.05	0.91	0.70	0.50	0.86	-0.07	0.84		<0.0001

- 1 <sup>a</sup> RMSE: root mean square error. MAE: mean absolute error. MEF: modeling efficiency. d-index: index of agreement
- 2 <sup>b</sup> EC expressed in dS m<sup>-1</sup> and DM expressed in kg m<sup>-3</sup>
- 3 <sup>c</sup> It is expressed in mg L<sup>-1</sup>. Can be transformed to kg m<sup>-3</sup> by dividing by 1000 the value obtained in the equation
- 4 <sup>d</sup> TK values <5 kg TK m<sup>-3</sup> (n=99)
- 5 In linear regressions between simulated and observed values: intercept (a), slope (b), coefficient of determination (R<sup>2</sup>) and signification (p)
- 6