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# Effects of Solids Separation and Time on the Production of Odorous Compounds in Stored Pig Slurry

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Fresh pig faeces were separated into seven different liquid portions with particle size ranges $<2{\cdot}0$, $<1{\cdot}4$, $<1{\cdot}0$, $<0{\cdot}5$, $<0{\cdot}25$, $<0{\cdot}15$, and $<0{\cdot}075$ mm, respectively. Separation was achieved by consecutive sieving of the fresh pig manure through a series of seven American Society for Testing Materials (ASTM) standard wire screen sieves with openings of 2·0, 1·4, 1·0, 0·5, 0·25, 0·15 and 0·075 mm. The separated manure fractions were stored at an ambient temperature of approximately 20°C in Plexiglas columns (91 cm deep and 15 cm in diameter) to simulate storage in under-floor or in other types of holding pits. The results indicated that although solid–liquid separation was found to reduce production of volatile fatty acids (VFAs) and 5-day biochemical oxygen demand ($BOD_5$) regarded as odour precursors, this technique might not significantly reduce odour nuisances from swine facilities unless particles smaller than 0·075 mm are separated from the liquids. Inverse linear correlations were observed between total solids (TS) and total volatile solids (TVS) with both $BOD_5$ and VFAs and therefore their respective levels could also be used to quantify the potential of odour nuisances in stored pig manure.

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## 1. Introduction

One of the most critical environmental issues facing the swine industry today is odour. In contrast to other environmental challenges, technologies for the elimination of odour from swine production facilities are not readily apparent. The odours from animal wastes are complex mixtures of malodorous gases. Powerful organic odorants such as aliphatic amines, mercaptans, sulphides, organic acids and skatole are invariably components of the odour from animal wastes (Burnett & Dondero, 1970; Rainville & Morin, 1985).

It is generally accepted that most of the odour-generating organic substances are produced from manure solids and therefore separating solids from manure liquid can theoretically reduce generating emissions from the manure. The impact of liquid separation on odour reduction is largely determined by the amount of biodegradable organic solids and nutrient elements removed from the manure. Kroodsma (1985) reported successful reduction of odour from a pig facility after solids were separated from the liquids immediately after the faeces and the urine were voided. A review of previous work on this subject by Zhang and Westerman (1997) concluded that finer particles in the manure decompose faster and to a greater extent than coarse particles. Moreover, most of the reduced carbon compounds, protein and nutrient elements (especially nitrogen and phosphorus) are contained in the fine particles. Since these compounds are the precursors for odour generation and the carriers of organic nitrogen and phosphorus, it can be inferred that the more easily biodegradable fine fractions would perhaps have more contribution to odour problems than coarse fractions during storage. A study focused on the effect of solid–liquid separation on the potential of odour generation by the separated fractions is therefore critical in the development of solid–liquid separation technologies.

Inabilities to measure odour, quantify thresholds, or clearly define the problem make it even more difficult to develop strategies toward odour solutions (Coffey, 1996).

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Some remarkable studies have been conducted to relate chemical characteristics to odour intensities and offensiveness of excreta. Bell (1970) found a close relationship between volatile fatty acids (VFAs) and odour offensiveness of anaerobically and aerobically stored poultry manure. Barth *et al.* (1974) correlated concentrations of VFAs, hydrogen sulphide and ammonia in dairy cattle manure, stored aerobically and anaerobically, with odour intensity and found that VFAs concentrations correlated best with odour intensity. A review paper by Spoelstra (1980) indicates that for manure slurry stored anaerobically, VFAs, indoles and phenols are suitable indicators of odours. Other studies by Williams (1984) found good correlations between odour offensiveness and both VFAs and the 5-day biochemical oxygen demand ($BOD_5$). The studies by Williams (1984) further established that not only were better correlations obtained with supernatant's VFAs and $BOD_5$ contents of the manure, but also that $BOD_5$ appeared to be a better indicator of odour offensiveness. From the above studies, it appears that the VFAs and $BOD_5$ contents can be used as valid indicators of odour and their concentrations as valid quantifiers of odour intensities. Therefore, in the present study, $BOD_5$ and VFAs contents were used as odour indicators and also to quantify odour intensities during the storage of separated swine manure.

The objectives of the present study were to investigate: (i) the effects of particle size on the potential of odour production during the storage of pig manure in under-slat pits, or in other types of manure-holding pits; and (ii) the potential use of total solids (TS) and total volatile solids (TVS) of pig manure in quantification of odour intensity. The latter objective was based on a study by Sobel (1972), in which the offensiveness of poultry manure in various conditions of storage was found to have an inverse logarithmic relationship with TS. The VFAs and $BOD_5$ of the supernatants were used as odour indicators and their concentrations were used to determine levels of odour nuisances at various stages of storage.

## 2. Materials and methods

### 2.1. *Manure collection and experimental procedure*

Fresh pig faeces were collected from the floor of a pig fattening hoop building and diluted with tap water to approximately 8% total solids content. The pigs in this operation were on a regular maize and soya bean ration. The diluted faeces were separated into seven different liquid portions with particle size ranges $< 2{\cdot}0$, $< 1{\cdot}4$, $< 1{\cdot}0$, $< 0{\cdot}5$, $< 0{\cdot}25$, $< 0{\cdot}15$ and $< 0{\cdot}075$ mm, respectively. Separation was effected by consecutive sieving of the fresh swine manure through a series of seven American Society for Testing Materials (ASTM) standard wire screen sieves with openings of 2·0, 1·4, 1·0, 0·5, 0·25, 0·15 and 0·075 mm. At each stage of separation, one of the seven simulation Plexiglas columns (91 cm deep and 15 cm diameter) was filled up leaving approximately 10 cm headspace. Once all the columns had been filled, each column was thoroughly stirred using a motorized paddle-stirrer (Tline Laboratory Stirrer, Model 102, Talboys Engineering Corp., Montrose, PA) and a sample drawn from the homogenized slurry from approximately the mid-depth of each column. This sampling technique was continued for the first 30 days of storage at 5 day intervals. The columns were stored in a dark room to simulate the conditions in the storage pits. The room's ambient temperature was maintained between 18 and 22°C.

### 2.2. *Laboratory Analyses*

Using standard laboratory methods (APHA, 1998), the following parameters were determined for each collected sample: total solids (TS), total volatile solids (TVS), total suspended solids (TSS) and total volatile suspended solids (TVSS). For the VFAs and the $BOD_5$ determinations, a well-mixed sample was diluted and then centrifuged at $4000\ \mathrm{min}^{-1}$ for 30 min. The VFAs were determined using an esterification method, which is based on esterification of the carboxylic acids present in the sample and then determining the esters by a ferric hydroxamate reaction. All volatile acids are reported as their equivalent $\mathrm{mg}\ l^{-1}$ acetic acid (Hach Company, 1993). To determine $BOD_5$, a 300 m*l* airtight BOD bottle was half-filled with aerated dilution water, 2 m*l* of the supernatant was pipetted into the bottle and the bottle filled to overflowing with the aerated dilution water. Initial dissolved oxygen ($DO_1$) was determined using a dissolved oxygen (DO) meter (Orion Model 810, Orion Research Inc., USA), the samples were then incubated for 5 days at 20°C and dissolved oxygen remaining in day five ($DO_5$) determined. The $BOD_5$ was computed as the difference between $DO_1$ and $DO_5$ after correcting for the dilution.

### 2.3. *Experimental design and statistical analysis*

The manure was separated into seven different size ranges and the change with time of storage in the manure investigated in terms of VFAs, $BOD_5$, TS, TVS, TSS and TVSS. This fits the classical two-factor (solids particle size ranges and time) experimental design with responses being VFAs, BOD$_5$, TS, TVS, TSS and TVSS. Two-way analyses of variances were therefore performed on the responses to determine their respective variation with time and with particle size ranges in the respective manure fractions. Pair-wise comparisons were performed using the least-significant difference method (lsd) whenever necessary. All the analyses were performed using a standard Statistical Analyses Software (SAS). A probability level $\alpha$ of 0·05 is implied whenever significant difference is mentioned in the text or elsewhere, unless otherwise stated.

## 3. Results and discussion

The effect of storage time on the following parameters of swine manure TS, TVS, TSS and TVSS, is presented in *Figs 1–4*, respectively, while their respective net changes, expressed as a percentage of the initial quantities over the first 30 days, are presented in Table 1. The overlaps in some of the curves are probably because of the inherent problems in obtaining truly representative samples of non-homogenous materials like manure. In general, however, the contents of TS, TVS, TSS and TVSS in all particle size ranges decrease with an increase in storage time presumably because of the natural anaerobic microbial degradation. The percentage reductions (Table 1) of these parameters also indicate that the smaller the particle size of the separated liquid fraction, the greater was the reduction achieved during the period of this study.

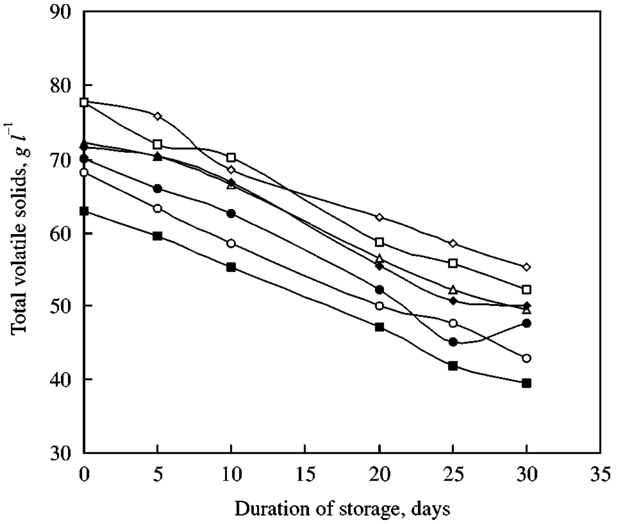

*Fig. 2. Effect of time on total volatile solids (TVS) during the first 30 days of manure storage for different particle sizes* $P_s$: ◇, $P_s < 2{\cdot}0$ *mm*; □, $P_s < 1{\cdot}4$ *mm*; △, $P_s < 1{\cdot}0$ *mm*; ◆, $P_s < 0{\cdot}5$ *mm*; ●, $P_s < 0{\cdot}25$ *mm*; ○, $P_s < 0{\cdot}15$ *mm*, ■, $P_s < 0{\cdot}075$ *mm*

This observation is consistent with the discussion presented by Zhang and Westerman (1997).

The total volatile solids fraction represents the organic component of the solids while the TVSS represents that fraction of the TVS that is in suspension, *i.e.* the separable part. The trends of the TVSS (*Fig. 4*) indicate that all separated liquid fractions with less than 0·25 mm particle size were degraded significantly in approximately 10

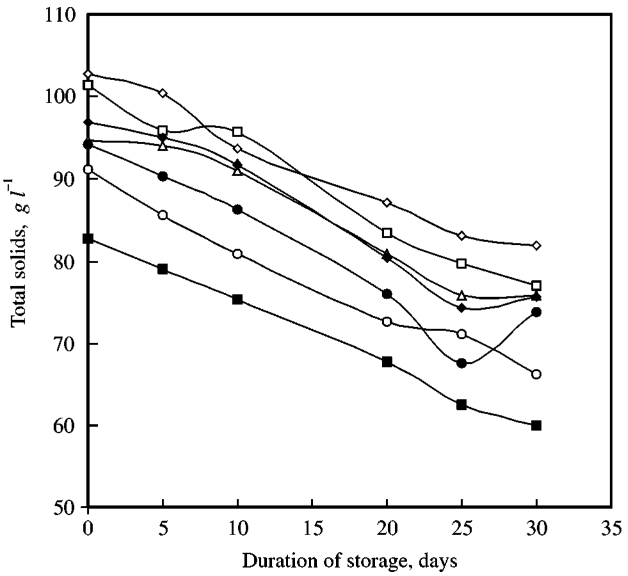

*Fig. 1. Effect of time on total solids (TS) during the first 30 days of manure storage for different particle sizes* $P_s$: ◇, $P_s < 2{\cdot}0$ *mm*; □, $P_s < 1{\cdot}4$ *mm*; △, $P_s < 1{\cdot}0$ *mm*; ◆, $P_s < 0{\cdot}5$ *mm*; ●, $P_s < 0{\cdot}25$ *mm*; ○, $P_s < 0{\cdot}15$ *mm*, ■, $P_s < 0{\cdot}075$ *mm*

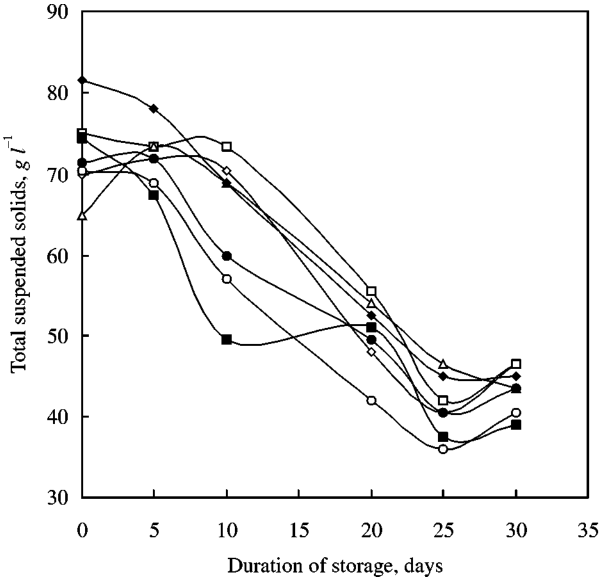

*Fig. 3. Effect of time on total suspended solids (TSS) during the first 30 days of manure storage for different particle sizes* $P_s$: ◇, $P_s < 2{\cdot}0$ *mm*; □, $P_s < 1{\cdot}4$ *mm*; △, $P_s < 1{\cdot}0$ *mm*; ◆, $P_s < 0{\cdot}5$ *mm*; ●, $P_s < 0{\cdot}25$ *mm*; ○, $P_s < 0{\cdot}15$ *mm*, ■, $P_s < 0{\cdot}075$ *mm*

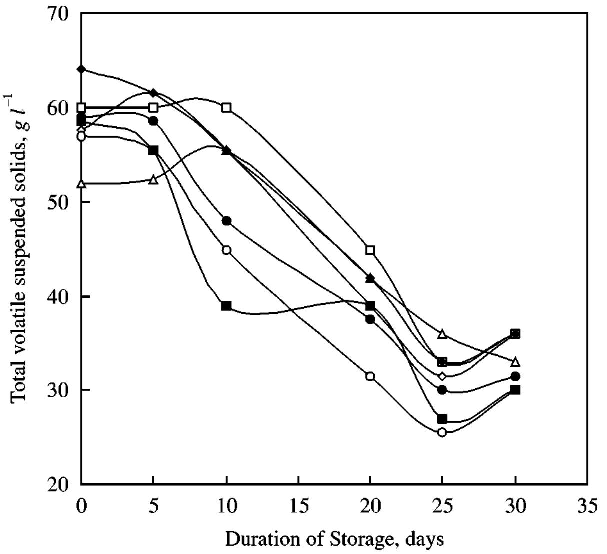

*Fig. 4. Effect of time on total volatile solids (TVSS) during the first 30 days of manure storage for different particle sizes $P_s$: ◇, $P_s$ < 2·0 mm; □, $P_s$ < 1·4 mm; △, $P_s$ < 1·0 mm; ◆, $P_s$ < 0·5 mm; ●, $P_s$ < 0·25 mm; ○, $P_s$ < 0·15 mm, ■, $P_s$ < 0·075 mm*

days. On the other hand, the reduction in the TVSS in the manure fractions with < 2·0, < 1·4 and < 1·0 mm particle sizes were gradual throughout the storage period. This observation suggests that since anaerobic decomposition results in the production of compounds considered as odour precursors in the stored manure, the finer fractions released most of the odour within the first 10 days while the other fractions released the odorous compounds gradually over the entire storage period in which this study was conducted. Although this gradual/slow release may seem desirable because of reduced odour intensity over the storage period, it may mean persisting odour nuisances. However, high releases of odour in the first 10 days from these finely separated manure fractions may imply decreased odour nuisances in the latter days of storage.

The relationships of the TVS to both the BOD$_5$ and the VFAs are shown in *Figs 5* and *6*, respectively, while the respective linear correlations are given in Table 2. Within each of the seven particle size ranges examined in this study, both the BOD$_5$ and the VFAs display strong linear relationships with the TVS. The values of the coefficients of determination $R^2$ for these relationships ranged between 0·82 and 0·97 for BOD$_5$ against TVS. The VFAs *versus* TVS linear relationships are marked by equally strong values of $R^2$ ranging between 0·80 and 0·92. In both cases, the results are similar, within 95% confidence interval, and provide collaborating information. The higher the TVS in the stored manure, the lower the BOD$_5$ and the VFAs. Since TVS decreased with storage for the first 30 days of storage, it follows that both VFAs and BOD$_5$ increased with storage at least in the first 30 days of storage. This observation is similar to that reported by Williams (1983) where VFAs, BOD$_5$ and chemical oxygen demand (COD) were observed to increase during the on-farm storage of piggery slurry. Another study by Williams and Evans (1981) showed that BOD$_5$, and VFAs of separated liquor of swine manure increased during storage. The increase in BOD$_5$ was attributed mostly to the increase in the levels of VFAs, although other intermediate simple compounds of microbial degradation could also have been responsible. Since both VFAs and BOD$_5$ are linearly correlated with odour offensiveness (Barth *et al.*, 1974; Williams, 1983, 1984), this result suggests that over the first 30 days of storage of swine manure, odour increased throughout this period. An inverse relationship between TS and odour offensiveness reported by Sobel (1972) support this finding. Since TS decreased with storage time in our study, this implies that odour nuisances increased concomitantly.

Considering the relationship between particle sizes and odour intensities, it is evident that the odour intensities decreased with the increase in separation of solids from the liquid, *i.e.* the BOD$_5$, at a given level of TVS, increased from the more separated manure to the less

**Table 1**

**Percentage reduction of total solids (TS), total volatile solids (TVS), total suspended solids (TSS) and total volatile suspended solids (TVSS) in each fraction over the first 30 days of fresh pig manure storage**

| | *Percentage reductions* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *Particle size fraction, mm* | | | | | | |
| *Parameter* | *< 2·0* | *< 1·4* | *< 1·0* | *< 0·5* | *< 0·25* | *< 0·15* | *< 0·075* |
| TS | 20·2 | 24·0 | 19·8 | 21·8 | 21·6 | 27·4 | 27·7 |
| TVS | 28·7 | 32·6 | 31·2 | 30·0 | 32·1 | 37·1 | 37·0 |
| TSS | 33·6 | 38·0 | 33·1 | 44·8 | 39·2 | 42·6 | 47·7 |
| TVSS | 37·4 | 40·0 | 36·5 | 43·8 | 46·6 | 47·4 | 48·7 |

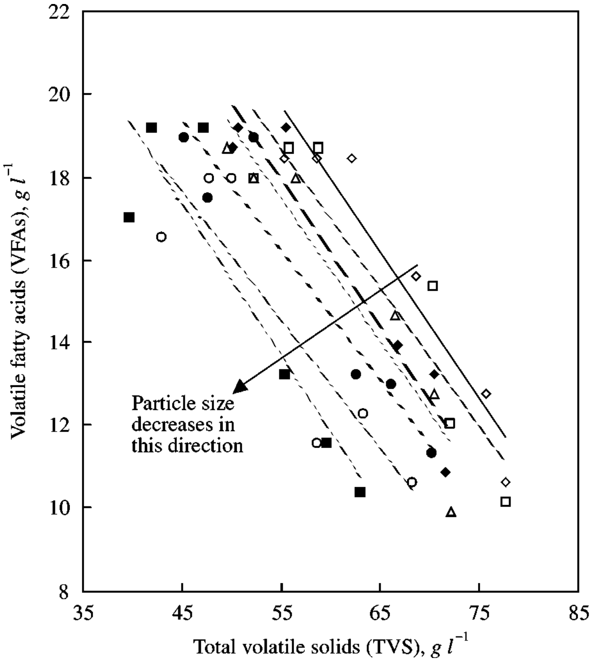

*Fig. 5. Relationship between total volatile solids (TVS) and 5-day biochemical oxygen demand ($BOD_5$) during the first 30 days of manure for different particle sizes $P_s$: ◇—, $P_s < 2{\cdot}0$ mm; □---, $P_s < 1{\cdot}4$ mm; △----, $P_s < 1{\cdot}0$ mm; ◆—–, $P_s < 0{\cdot}5$ mm; ●---, $P_s < 0{\cdot}25$ mm; ○-----, $P_s < 0{\cdot}15$ mm, ■-------, $P_s < 0{\cdot}075$ mm*

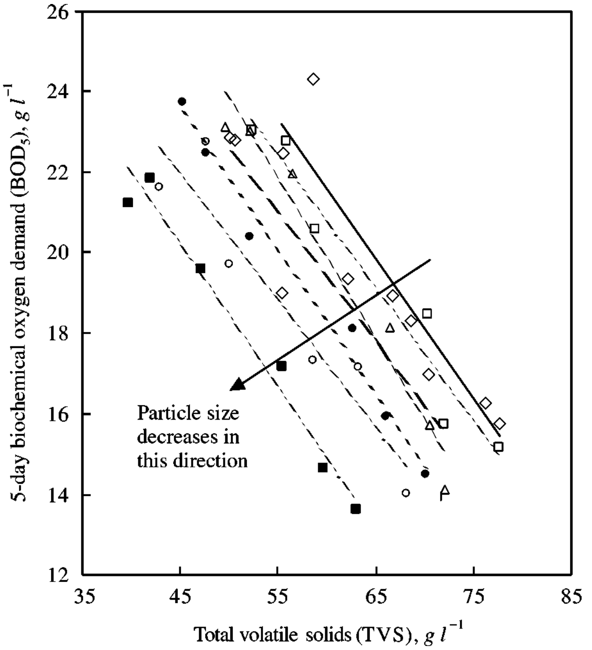

*Fig. 6. Relationship between total volatile solids (TVS) and odorous volatile fatty acids (VFAs) during the first 30 days of manure storage for different particle sizes $P_s$: ◇—, $P_s < 2{\cdot}0$ mm; □---, $P_s < 1{\cdot}4$ mm; △----, $P_s < 1{\cdot}0$ mm; ◆—–, $P_s < 0{\cdot}5$ mm; ●---, $P_s < 0.25$ mm; ○-----, $P_s < 0{\cdot}15$ mm, ■-------, $P_s < 0{\cdot}075$ mm*

separated manure. The same phenomenon was observed between TVS and VFAs (*Fig. 6*). Clearly, the preceding results show that solid–liquid separation of the manure resulted in reduced production of $BOD_5$ and VFAs in the remaining slurry during the period that this test was conducted. Sneath (1988) reports a similar decrease in the production of VFAs in stored slurry when solid materials were physically removed.

Analysis of variance in VFAs and $BOD_5$ during the storage period of manure amongst the test particle size ranges indicated that both parameters significantly ($\alpha$ of 0·05) changed with time and with particle size ranges. A pair-wise comparison [least-significant difference (lsd) method] of the means of VFAs and $BOD_5$ of each particle size range over the entire period of this study is presented in Tables 3 and 4. On the basis of these comparisons, solids removal between 2·00 and 0·15 mm sieves did not seem to have a significant effect on the overall $BOD_5$ reduction. Similarly, the cumulative production of VFAs did not significantly seem to depend on solids removal between 2·00 and 0·15 mm sieves. However, separating solids between 0·15 and 0·075 mm significantly reduced the levels of VFAs and $BOD_5$ during storage. Both $BOD_5$ and VFAs changes with time of storage had

**Table 2**

**Values for the coefficients of determinations $R^2$ for linear relationships between: total volatile solids (TVS) and 5-day biochemical oxygen demand ($BOD_5$), and TVS and volatile fatty acids (VFAs), at each respective size fraction over the 30 days of pig manure storage**

| | *Coefficients of determination ($R^2$)* | | | | | | |
|---|---|---|---|---|---|---|---|
| | *Particle size fraction, mm* | | | | | | |
| *Relationship* | *< 2·0* | *< 1·0* | *< 1·0* | *< 0·5* | *< 0·25* | *< 0·15* | *< 0·025* |
| TVS *vs* $BOD_5$* | 0·87 | 0·96 | 0·95 | 0·98 | 0·89 | 0·82 | 0·97 |
| TVS *vs* VFAs* | 0·92 | 0·86 | 0·90 | 0·92 | 0·91 | 0·80 | 0·83 |

*All $R^2$ values were significant at a probability $\alpha$ of 0·05.

**Table 3**
**Pair-wise comparisons of mean 5-day biochemical oxygen demand ($BOD_5$) in the separated pig manure by particle size fractions and time of storage**

| *Fraction, mm* | **Means of $BOD_5$ content, $g\,l^{-1}$* | *Storage period, day* | *Means of $BOD_5$ Content, $g\,l^{-1}$* |
|---|---|---|---|
| < 2.00 | 19·40a | 0 | 14·44a |
| < 1·40 | 19·35a | 5 | 16·07b |
| < 1·00 | 19·30a | 10 | 18·06c |
| < 0·50 | 19·19a | 20 | 20·08d |
| < 0·25 | 19·07a | 25 | 23·04e |
| < 0·15 | 18·77a,b | 30 | 22·41e |
| < 0·075 | 18·03b | | |

*Means with the same letter are not significantly different at the probability level $\alpha$ of 0·05.

**Table 4**
**Pair-wise comparisons of mean volatile fatty acids (VFAs) in the separated pig manure by particle size fractions and time of storage**

| *Fraction, mm* | **Means of $VFA_s$ content, $g\,l^{-1}$* | *Storage period, day* | *Means of $VFA_s$ content, $g\,l^{-1}$* |
|---|---|---|---|
| < 2·00 | 15·72a | 0 | 10·54a |
| < 1·40 | 15·48a | 5 | 12·51b |
| < 1·00 | 15·32a,b | 10 | 13·94c |
| < 0·50 | 15·84a | 20 | 18·62d |
| < 0·25 | 15·48a | 25 | 18·62d |
| < 0·15 | 14·49b | 30 | 17·84d |
| < 0·075 | 15·08a, b | | |

* Means with the same letter are not significantly different at the probability level $\alpha$ of 0·05.

basically the same trends. Both changed significantly between day 0 and day 20 but remained more or less the same afterwards. Although the results presented in the preceding paragraph seem to suggest that any level of solid–liquid separation can mitigate situations of odour problems, the statistical data did weaken this postulation since there were no significant differences in the levels of VFAs and $BOD_5$ upon removing solids larger than 0·15 mm during the storage period of manure in this study. The data nevertheless seem to suggest that most of the VFAs and $BOD_5$ is contained in particles smaller or equal to 0·075 mm and therefore abatement of odour nuisances can possibly be expected by the removal of these fine particles.

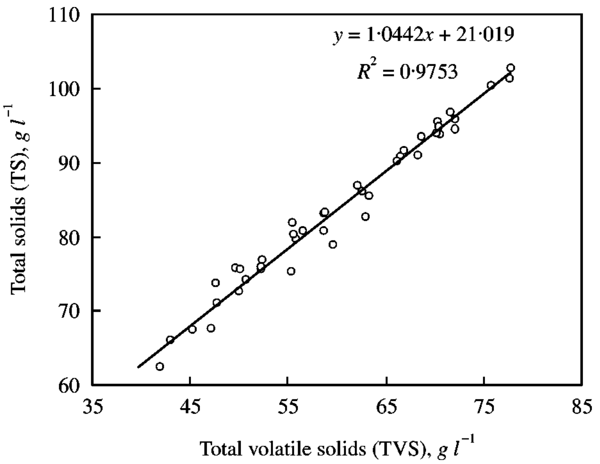

*Fig. 7. Relationship between total volatile solids (TVS) and total solids (TS) in pig manure: ——, linear regression line; $R^2$, coefficient of determination*

*Figure 7* displays the relationship between the TS and the TVS for the pig manure during the same period of storage. This relationship, which was obtained by consolidating together all the TVS and TS data in this study, indicates a linear relationship with a correlation coefficient $R$ of 0·98 (within 99% confidence interval), indicating a statistically strong linear relationship. This result suggests that either TS or TVS could be used to quantify odour levels emanating from stored manure. However, due to the limited data, more research is needed to further verify this observation before widespread adoption can be recommended for the use of these parameters in the quantification of odour offensiveness.

## 4. Conclusions

1. Solid–liquid separation resulted in reduced production of both volatile fatty acids (VFAs) and 5-day biochemical oxygen demand ($BOD_5$) in stored pig manure during the first 30 days of storage. However, removal of solids larger than 0·015 mm did not have significant reductions in the levels of either $BOD_5$ or VFAs during the 30 days of storage in this study. Most of the VFAs and $BOD_5$ therefore appeared to be contained in particles smaller than 0·075 mm. Based on the results of this study, it appears that solid–liquid separation may only significantly mitigate odour problems in separated manure if the separation process can remove this fine fraction of the solid manure.

2. On the basis of the foregoing conclusion, it is unlikely that screening as a solid–liquid separation technique for odour control is a candidate since it is extremely difficult to remove fine particles solely by screening, at least from the type of manure used in this study. Research is, however, needed using manure from diverse sources for verification of the findings of this study. More work is also needed using further separated slurries before discarding the idea of using solid–liquid separation for purposes of controlling odour.

3. A linear correlation was observed between total solids (TS) and the total volatile solids (TVS). Similarly, linear correlations were found between TVS and both $BOD_5$ and VFAs levels in stored manure. It appears that either TV or TVS may be used for quantification of odour intensities in stored manure. More work is suggested using manure from different sources for the validation of this relationship. TS and TVS in manure are both easy to measure since they do not require complex apparatus and their use would naturally simplify the quantification of odour nuisances in stored pig slurries.

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## References

**APHA** (1998). Standard methods for the examination of water and wastewater. (Lenore S C; Greenberg A E; Eaton A D, eds), (20th Edn.). American Public Health Association, 1015 Fifteenth Street, NW, Washington DC 20005

**Barth C L; Hill D T; Polkowski L B** (1974). Correlating odor intensity index and odorous components in stored dairy manure. Transactions of the ASAE, **17**(4), 742–744, 747

**Bell R G** (1970). Fatty acid content as a measure of the odor potential of stored liquid poultry manure. Poultry Science, **49,** 1126–1129

**Burnett W E; Dondero N C** (1970). Control of odors from animal waste. Transactions of the ASAE, **13,** 221–231

**Coffey M T** (1996). Environmental challenges as related to animal agriculture—swine. In: Nutrient Management of Food Animals to Enhance and Protect the Environment (Kornegay E T, ed). CRC Press Inc., 2000 Corporate Blvd., N. W., Boca Raton, FL 33431

**Hach Company** (1993). Procedure Manual. PO Box 389, Loveland, CO 80539-9987

**Kroodsma W** (1985). Separation as a method of manure handling and odors reduction in pig buildings. In: Odor Prevention and Control of Organic Sludge and Livestock Farming (Nielson V C; Voorburg J J; L'Hermite P, eds), pp 213–221. Elsevier Applied Science Publishers, London and New York

**Rainville N; Morin A** (1985). Change in the volatile fatty acids content of laboratory stored sterilized and non-sterilized swine wastes. Microbios, **42,** 175–182

**Sobel A T** (1972). Olfactory measurements of animal manure odors. Transactions of the ASAE, **15**(4), 696–699, 703

**Sneath R W** (1988). The effects of removing solids from aerobically treated piggery slurry on the VFA levels during storage. Biological Wastes, **26,** 175–188

**Spoelstra S F** (1980). Origin of objectionable odorous components in piggery wastes and the possibility of applying indicator components for studying dour development. Agriculture and Environment, **5**(3), 241–260

**Williams A G** (1984). Indicators of piggery slurry odor offensiveness. Agricultural Wastes, **10,** 15–36

**Williams A G** (1983). Organic acids, biochemical oxygen demand and chemical oxygen demand in the soluble fraction of piggery slurry. Journal of Science of Food and Agriculture, **34,** 212–220

**Williams A G; Evans M R** (1981). Storage of piggery slurry. Agricultural Wastes, **3,** 311–321

**Zhang R H; Westerman P W** (1997). Solid–liquid separation of animal manure for odor control and nutrient management. Transactions of the ASAE, **13**(3), 385–393