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# Applied and Environmental Chemistry of Animal Manure: A Review

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## ABSTRACT

Animal manure consists of predominantly urine and feces, but also may contain bedding materials, dropped feed, scurf, and other farming wastes. Manure is typically applied to soils as fertilizer for agricultural production. The estimated amount of manure produced in 12 major livestock-producing countries is $9 \times 10^9$ Mg of manure annually. Manure is rich in plant nutrients. However, manure is also considered as an environmental pollutant when it is over-applied to cropland or following runoff into surface water. Manure can also influence global climate change *via* emissions of methane ($CH_4$) and nitrous oxide ($N_2O$). Thus, increased and updated knowledge of applied and environmental chemistry of animal manure is needed to shed light on the research and development of animal manure utilization and minimization of its adverse environmental concerns. The advances in basic and applied studies of manure major components, organic matter, phosphorus, and nitrogen, primarily related to US livestock production are summarized in this review. Detailed focus was placed on three notable challenges for future manure research: 1) soil application of animal manure, 2) manure phytate phosphorus, and 3) manure nitrogen availability. This review may contribute to the global effort in sustainable and environmentally sound agriculture by stimulating new ideas and directions in animal manure research, and promoting application of knowledge and insight derived from manure research into improved manure management strategies.

*Key Words*: environmental pollutant, fertilizer, nitrogen availability, organic matter, phosphorus, phytate, plant nutrients

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## INTRODUCTION

By definition, animal manure is animal excreta (urine and feces) and bedding materials, which is usually applied to soils as a fertilizer for agricultural production (He *et al.*, 2012a). Animal manure may also contain dropped feed, scurf, water, and soil, depending upon specific livestock management practices. Since the beginning of human agricultural activities over 8 000 years ago in Neolithic Europe, manure has been an integrated part of sustainable crop production (Bogaard *et al.*, 2013). Before the extensive manufacturing of synthetic fertilizer, the majority of out-sourced crop nutrient inputs were from animal manure. However, the current environmental impact of manure generation and disposal extends beyond that of simple organic fertilizers, as more manure is produced in large confined animal feeding operations (CAFO) than can be cost-effectively transported to cropland beyond the feeding farms. More animal products (*i.e.*, meat, milk, and eggs) are required to meet the food demands of an increasing world population with higher expectations of life quality (Tilman *et al.*, 2002). Table I lists the number of cattle (*Bos taurus* and *Bos indicus*), pigs (*Sus scrofa domesticus*), chickens (*Gallus gallus domesticus*), sheep (*Ovis aries*), and goats (*Capra aegagrus hircus*) in 12 countries in 2013 (FAO, 2015). It is estimated that these high animal numbers would produce a total of $9 \times 10^9$ Mg of manure annually.

Increases in the number of CAFO, such as beef cattle feedyards that house more than 100 000 cattle at a time, result in far more manure than needed by local cropland, thus creating environmental concerns in recycling and disposing of manure surplus (Zhang and Schroder, 2014). Manure is rich in nitrogen (N), phosphorus (P), and carbon (C) (Pagliari and Laboski, 2012) and can increase global climate change *via* emissions of methane ($CH_4$) and nitrous oxide ($N_2O$) (Leytem *et al.*, 2011). Ammonia ($NH_3$) emission from manure can impair air, soil, and water quality (Jongb-

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TABLE I

Number of animals by animal type in selected countries in 2013[a] and estimated amount of manure produced[b]

| Country | Cattle | | Pigs | | Chickens | | Sheep and goats | |
|---|---|---|---|---|---|---|---|---|
| | Number | Manure produced | Number | Manure produced | Number | Manure produced | Number | Manure produced |
| | $\times 10^3$ heads | $\times 10^6$ Mg | $\times 10^3$ heads | $\times 10^6$ Mg | $\times 10^3$ heads | $\times 10^6$ Mg | $\times 10^3$ heads | $\times 10^6$ Mg |
| Argentina | 51 095 | 474.00 | 2 440 | 2.04 | 107 | 9.14 | 18 950 | 8.06 |
| Australia | 29 291 | 382.57 | 2 098 | 2.92 | 99 | 8.41 | 79 098 | 50.24 |
| Brazil | 211 764 | 1 964.53 | 36 744 | 31.58 | 1 249 | 107.05 | 26 070 | 11.03 |
| Canada | 12 215 | 159.58 | 12 879 | 18.18 | 167 | 14.23 | 922 | 0.57 |
| China | 113 645 | 1 000.51 | 482 398 | 414.10 | 4 835 | 414.52 | 357 871 | 151.55 |
| Germany | 12 587 | 168.70 | 27 690 | 42.43 | 161 | 13.76 | 2 024 | 1.25 |
| India | 189 000 | 958.61 | 10 130 | 8.71 | 709 | 60.72 | 197 800 | 83.77 |
| Mexico | 32 402 | 300.59 | 16 202 | 13.89 | 524 | 44.97 | 17 162 | 7.32 |
| Pakistan | 38 299 | 194.23 | – | – | 413 | 35.44 | 93 613 | 39.65 |
| Russia | 19 930 | 246.69 | 18 816 | 28.87 | 448 | 38.40 | 24 180 | 10.22 |
| UK | 9 844 | 131.94 | 4 885 | 7.54 | 152 | 13.05 | 32 954 | 20.92 |
| USA | 89 300 | 1 166.40 | 64 775 | 91.35 | 1 917 | 164.33 | 8 146 | 5.17 |
| Sum | 809 372 | 7 148.36 | 679 057 | 661.61 | 10 780 | 924.02 | 858 789 | 389.74 |

[a]From the FAOSTAT database (FAO, 2015).
[b]Converted from the parameters in Monreal and Schnitzer (2012).

loed and Lenis, 1998). Runoff or leaching of N or P can impair both ground- and surface waters (Hooda *et al.*, 2000). Another aspect to consider is the effect of changing dietary feedstuff composition on the resulting manure. Modern understanding of animal nutrition, improved feed processing technologies, and increased availability of distillers byproducts and other alternative feedstuffs results in diets containing more readily-available nutrients and more synthetic additives for disease prevention and growth promotion than traditional animal feed, which ultimately end up in manure (Schroder *et al.*, 2011; Tazisong *et al.*, 2011; He *et al.*, 2014c; Song and Guo, 2014). Thus, updated knowledge of the applied and environmental chemistry of animal manure is needed to effectively utilize animal manure while reducing its adverse environmental impacts.

Considerable research has been conducted on animal manure and researchers often apply knowledge and trusted techniques of soil chemistry into their manure research. However, such application may be misguided in a manure study, as soil is usually mineral-based, whereas manure is more organic matter (OM)-based. One vivid example is that no organic P ($P_o$) was measured or accounted for in the HCl fraction (*i.e.*, no $P_o$ considered to be associated with calcium cations ($Ca^{2+}$)) of manure extracted with a sequential fractionation procedure developed for soils (Ajiboye *et al.*, 2004; McDowell and Stewart, 2005). However, more recently developed manure characterization approaches, such as phosphatase hydrolysis and solution $^{31}P$ nuclear magnetic resonance (NMR) spectroscopy, revealed the presence of $P_o$ in the Ca-associated HCl fraction (HCl-$P_o$) of manure, particularly in poultry litter (He *et al.*, 2006a, c, 2008). Furthermore, these approaches have shown accumulation of Ca-associated $P_o$ in calcareous soils that received repeated applications of poultry litter (Waldrip *et al.*, 2015c). Thus, measurement of $P_o$ in sequentially extracted fractions improves not only the knowledge of manure P composition (Godlinski *et al.*, 2011; Kumaragamage *et al.*, 2012), but also accuracy of modeling P transformation and predicting runoff losses (Vadas *et al.*, 2007; Vadas and White, 2010; Vadas, 2011). Indeed, the inclusion of HCl-$P_o$ measurement into the traditional sequential fractionation procedure may also improve soil P studies (Sales *et al.*, 2015; Shi *et al.*, 2015). Linquist and Ruark (2011) evaluated various soil P tests to determine relationships with rice (*Oryzae sativa* L.) growth and the annual input/output P budget of a rice cropping system. These researchers found that HCl-$P_o$ was correlated with both P content of the Y-leaf (*i.e.*, the most recently expanded leaf of a plant) and the annual P budget.

Increased and updated knowledge of modern techniques in applied and environmental chemistry of animal manure are needed to improve utilization of animal manure and minimize adverse environmental concerns. To meet these challenges and opportunities, He (2011, 2012) initialized and organized a team of internationally accomplished scientists to compile two volumes on applied and environmental research of animal manure. Topics in applied manure and nutrient recycling for sustainable agriculture and environment were further explored in another collection (He and Zhang,