Current Pollution Reports (2018) 4:162–174
https://doi.org/10.1007/s40726-018-0084-x

LAND POLLUTION (GM HETTIARACHCHI, SECTION EDITOR)

Manure Phosphorus: Mobility in Soils and Management Strategies to Minimize Losses

D. Kumaragamage [1] · O. O. Akinremi [2]

Published online: 27 February 2018

Abstract
Manure is a valuable source of plant nutrients; however, continuous application to soils may lead to accumulation of phosphorus (P), increasing the risk of P loss into waterways triggering freshwater eutrophication. This review paper summarizes and critically evaluates relevant research findings published within the last 5 years on manure P mobility in soils and management strategies to mitigate losses identifying future research needs. Past and recent research evidence on manure P mobilization and losses from soils have yielded inconsistent and often confounding results, because of the interactive effects of source factors and the existence of concurrent transport pathways. Although far from being conclusive, a few general trends are worth noting; P losses were greater with (a) increasing soluble P applied with manure, (b) vulnerable soils with limited P sorption capacity and/or susceptible to preferential flow/erosion, (c) conditions conducive to P release and transport, and (d) reduced soil-manure P interaction following application. Effective mitigating strategies included (a) generating low-P manure, (b) processing manure to reduce total and/or soluble P, and (c) adopting best management practices (BMPs) during and post-manure application. Future research should focus on a better understanding of the interactive effects of source factors on short- and long-term manure P loss via different transport pathways. Existing mitigation efforts and new directions should focus on reducing P buildup in soil by employing a combination of strategies during generation, processing, and application of manure, coupled with site- and time-specific BMPs selected based on the dominant pathway of P loss.

Keywords Manure phosphorus · Mitigation · Phosphorous losses · Soil · Source factors · Transport factors

Introduction

Global livestock production has rapidly expanded and intensified over the last century, generating large quantities of livestock manure, annually. Livestock sector is estimated to occupy 30% of the world's ice-free terrestrial surface area using large areas of rangelands and arable croplands that provide livestock feed [1]. The estimated stocks of livestock in 2014 was 21.3 billion chicken (*Gallus gallus domesticus*), 1.48 billion cattle (*Bos Taurus*), 1 billion pigs (*Sus scrofa domesticus*), and 1.21 billion sheep (*Ovis aries*) globally, with a global manure production rate of about 15 million tons of dry matter/day [2]. Cattle contribute the most to the global manure production (~ 60%), while pigs and poultry contribute ~ 9 and ~ 10%, respectively [3].

Livestock manures are intrinsically heterogeneous organic material containing animal feces and urine, often mixed with bedding material such as straw, sawdust, and/or other foreign matter such as lime, sand, and soil, depending on the collection method. Based on the total solid (TS) content, animal manure can be categorized as solid (> 20% TS), slurry (4–20% TS), or liquid (< 4% TS). Since livestock manures are valuable sources of plant macro- and micronutrients [4], they can be recycled by application to croplands and grasslands [5•], thus serving as a low-cost source of plant nutrients replacing significant amounts of commercial fertilizers. Besides being a valuable source of plant nutrients, manure application improves soil physical, chemical, and biological properties mainly through increasing soil organic carbon [6], which in

This article is part of the Topical Collection on *Land Pollution*

✉ D. Kumaragamage
d.kumaragamage@uwinnipeg.ca

[1] Department of Environmental Studies and Sciences, The University of Winnipeg, Winnipeg, MB R3B 2E9, Canada

[2] Department of Soil Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada

turn improves water infiltration, enhances nutrient retention, promotes microbial activity, and reduces soil erosion [4, 7].

Despite the many benefits of livestock manure applications to soils, there are some concerns over the potential negative impacts on the environment and human health. Phosphorus (P) accumulation in soils with continuous manure applications [5•, 8•, 9, 10] is a serious environmental concern because of the potential P transport to freshwater bodies [11, 12••] that may lead to eutrophication, a process that is primarily controlled by concentrations of dissolved P in fresh water [13, 14]. Ratio of N/P of most livestock manures are much lower relative to plant uptake; thus, manure application rates based on crop N requirements often lead to an excess application of P [15, 16•], leading to a P buildup in soils. Moreover, large amounts of livestock manure is generated in localized areas with manure disposal mainly via on-farm applications in excess of crop nutrient needs, which aggravates the P buildup in localized areas.

Phosphorus accumulation in soil and losses from soils to waterways with the land application of manure had been extensively reviewed and documented [11, 14], and possible management strategies to mitigate P loadings to water bodies have been identified and evaluated [17–19]. The goal of the current review paper is to summarize and critically evaluate recent advances on mobilization of manure P in soils focusing mostly on research published within the last 5 years, and to present an overview on recent management efforts to mitigate P losses from manure-amended soils and their implications. The term “P losses” in this review paper refers to mass loss of P from soils in kilograms per hectare.

Mobility of Manure Phosphorus

Agricultural soils receiving continuous applications of manure have a greater potential for P transfer to water bodies, thus becoming a non-point source of P if not properly managed. The concept of critical source area, defined as the overlap of land area with a high P source and high P transport potential, has been widely used in assessing the risk of P loss from agricultural soils, and planning management strategies [20•]. In the following section, we summarize recent research findings that have focused objectively on the influence of source and transport factors on P mobility in manure-amended soils with an attempt to place recent findings in context with earlier published work.

Source Factors

Soluble and Total P in Manure

Recent research corroborates previous findings that dissolved reactive P (DRP) losses through surface and subsurface pathways from manured soils are closely related to the water extractable P (WEP) rather than total P (TP) in manure, irrespective of animal species generating manure [21, 22•, 23]. This trend was observed mostly for freshly applied manure where runoff or leaching event occurred immediately after or within a few days of manure application. In situations where runoff or leaching event occurred a few weeks after manure application, WEP in some studies was poorly related to DRP loss with runoff and leaching [24, 25]; whereas, labile–P concentrations in manure measured as water + $NaHCO_3$ extractable P [25] was better related to dissolved P losses. The WEP may not be a good predictor of P loss when contribution from particulate P (PP) loss to TP loss is high as in preferential flow, tile drainage, and surface erosion, since analytical procedure of WEP involves measuring dissolved P in filtered (0.45 μ) extracts, thus excluding the P bound to large (> 0.45 μ) suspended particulates [26]. Although WEP, by itself, may not be a good predictor of potential P transport from a manure source, WEP combined with other factors is widely used in P indices to evaluate risk of P runoff loss from manure-amended soils [27, 28].

Total carbon (C), TP, and ratio of C/P in manure can influence the amount of P loss from manured soils; however, the effect of manure TP and the ratio of C/P in manure on P losses is inconsistent. In a field lysimeter study, greater P leaching was observed with dairy and poultry manure containing low P than high P, when surface applied to provide the same amount of TP [22•]. This effect was attributed to the higher quantity of manure, and thus, greater C added with low-P manure, which may improve soil structure, promotes the activity of microorganisms and earthworms, and thereby maintain macropore flow paths through which unreactive P can leach [22•]. Increased dissolve C with application of high C-containing manures or applying at higher rates significantly reduced P sorption capacity and thereby increased the mobility of P, posing greater risks of P losses [29, 30]. In contrast, leaching losses of soluble P decreased when more C was added (e.g., with manures of high C/P compared with low C/P manure compost). This may be attributed to enhanced decomposition and mineralization with application of low C/P composts releasing soluble P [31••].

Manures from Different Animal Species

Estimated potential risk of P loss and actual P loss from manure-applied soils reported by various researchers for manures from different animal species show inconsistencies when ranked. For example, liquid swine > liquid dairy > solid poultry > solid beef (based on P source coefficient calculated using extractable P after incubation) [32]; ruminant + horse species > non-ruminant species (based on inorganic P extracted by water + $NaHCO_3$) [33]; dairy manure > boiler litter > swine manure (based on water + $NaHCO_3$ extractable P concentrations) [34]; liquid swine manure > solid cattle manure (based on water + $NaHCO_3$ extractable concentrations and actual runoff P loss with simulated rain) [25]; and solid fraction of swine manure > cattle manure compost (based on actual total P loss with runoff and sediments) [35]. Somewhat contradicting findings confirm that making generalized comparisons on the potential risk of manure P loss based on the animal species can be misleading, since manure P composition within an animal species is highly variable depending on factors such as the diet, manure collection, processing, and storage [34, 36, 37]. For example, supplementing P in dairy heifer diet increased WEP in manure by 100% [37]. Other studies showed that increasing dietary P supplementation with diets containing wheat dried distillers' grain with solubles (DDGS) increased not only manure TP but also the proportion of WEP [31••, 38]. Manure processing techniques such as composting, increased TP content by about 10–55%, with a corresponding decrease in WEP by about 5–17% [34].

Comparison of actual or potential P loss from liquid manure/manure slurries with solid manure however, showed a consistent trend; greater and more rapid losses from liquids and slurries than solids [25, 32, 39]. With high TS and less water contents, solids require a large amount of rain or irrigation water to be absorbed prior to P release, during which mixing and dilution occurs [26], which slow down the P losses as well as reduces P concentration in runoff or leachate generated.

Manure Rate, Timing and Placement

Results of recent research investigating the effects of manure application rates, time, and placement methods more or less confirm and reiterate previous findings; (a) actual and potential runoff and leaching losses of manure P are greater at higher rates of manure P added to soil [40–42]; (b) with surface applications, the risk of P losses are high when manure application is immediately followed by a runoff event [43], and decrease with increasing time duration between manure application and the first runoff event [43–46]; (c) high risk of P losses with runoff when manure is surface-applied to frozen and/or snow-covered ground particularly when runoff occurred soon after manure application [39, 47]; and (d) total and dissolved P loads in runoff and leaching is less with manure injection or incorporation as compared with surface application without incorporation [37, 46, 48•, 49•]. Some exceptions to these general trends do exist; for example, while runoff dissolved P losses were greatest at the first runoff event after application of dairy manure [44], the leachate-dissolved P losses were greatest when the soils had the highest P saturation which coincided with leaching at 4 weeks after surface application of poultry manure [50]. A study comparing tillage and liquid swine manure application method showed reduced overland runoff PP with minimum tillage and injected manure compared with conventional tillage and broadcast manure but not the DRP load [51]. Inconsistent and often confounding effects of source factors on manure P losses arises because of their cumulative interactive effects as well as the existence of concurrent transport pathways that are influenced differently by source factors.

Transport Pathways

Manure P can be transported from soils in two forms, particulate P or dissolved P, via a number of surface and subsurface flow pathways namely, soil erosion, surface runoff, matrix leaching, and preferential flow [11, 20•, 27, 41, 51]. The dominant mechanism/s under a given situation depends on soil, climate, topography and management factors. Significant correlations have been observed between total P loads in runoff with storm intensity, runoff/leachate duration and volumes, snow water equivalent, and sediment losses [12••, 26, 43, 46, 52].

Contrary with the traditional misconception that surface runoff of particulate and dissolved P is the major pathway of P loss from soils, the significance of leaching and preferential flow has been clearly demonstrated and documented [11, 19, 48•, 53]. Greater P leaching was observed in soils with preferential flow pathways [22•], compared with soils lacking preferential flow pathways that allowed dissolved P to diffuse into the soil matrix. In tile-drained field, mobilization of P with leaching contributed to more than 40% of total P loss [54], where P transfer to tile drains mostly occur through preferential flow [48•, 54, 55••, 56]. While the vast majority of documented research focused predominantly on rainwater- and irrigation-driven mobilization of particulate or dissolved P from manure [41, 43, 48•, 57], recent efforts included manure P mobilization via snowmelt-driven overland runoff and drainage [51, 57, 58, 59•], two major pathways of P loss under colder climates. Estimated contribution of snowmelt-driven P loss from soils could be > 50% of the runoff and dissolved P load over the year [58]. Using SurPhos computer model with over 100 site-years of weather and runoff data, the estimated P loss with winter application of manure was 2.5 to 3.6 times greater than with non-winter applications [12••]. Complexity of manure P mobility is further compounded in soils prone to prolonged seasonal flooding during snowmelt or storm events, since anaerobic conditions often result in greater P mobilization from soils, thus enhancing the risk of runoff and leaching losses [60]. Research on P release from manured soils under prolonged flooding is limited to a few laboratory scale studies [60] and showed substantial increases in P release from manured soils to pore water and floodwater, with the magnitude of increase varying depending on soil properties. More research on redox-induced losses of manure P under flooded conditions is needed to assess the risks and identify mitigation measures for soils prone to flooding with snowmelt and precipitation.

Transport Factors

Phosphorus losses from manure are influenced by factors that influences transport pathways such as soil characteristics, drainage, land use, hydrology, and climatic conditions. Dissolved P and PP behave differently with regard to the means of their transport [61] and thus on their response to changes in source and transport factors influencing manure P loss. For example, manure P losses though preferential flow was greater from fine-textured, well-structured soils than coarse-textured soils [62], while manure P mobility through matrix leaching was greater in a coarse-textured than a fine-textured soil [63]. Thus, there is a need for long-term field scale research adopting a holistic approach to understand the interactive effects of multiple source and transport factors on manure P loss via various pathways that occur concurrently. Since field scale research evaluating multiple factors on P loss from soils is expensive and time consuming, mathematical models are increasingly being used to evaluate the potential impact of different management options in reducing P loss from soils, of which some models (e.g., SurPhos, APLE, SWAT) are designed to include P loss from manure applications [12••, 64, 65]. The use of models can complement long-term field studies in evaluating the interactive effects of source and transport factors on manure P losses via different pathways and identify alternative management options to reduce P losses.

Management Strategies to Mitigate Losses

Manipulation of source and transport factors has been extensively researched as means of mitigating manure P losses from soils through different pathways [19, 37, 44, 49•, 55••, 66•, 67, 68••, 69], with greater emphasis on control at the source level which is more effective and less complex than controlling transport factors. Management efforts that have been evaluated at different scales to manipulate source and transport factors to mitigate manure P losses are summarized in Fig. 1. Transport of manure P at a given time occurs through both particulate and dissolved forms via concurrent pathways; thus, attempts to minimize P loss through one pathway may enhance losses through another. It has been noted that some of the best management practices (BMPs) effective in reducing erosion and particulate P (PP) transport such as minimum or zero tillage, buffer strips, etc. can inadvertently increase DRP export via surface runoff and subsurface drainage [70, 71]. Research into mitigating manure P losses from manure-amended soils should therefore, address both dissolved and particulate P forms and also take into account the lower bioavailability of PP in aquatic ecosystems [61], posing a different level of environmental threat to water quality than dissolved P.

Controlling Source Factors

Reducing the rate of P applied with manure undoubtedly, is the most cost-effective approach to mitigate P losses from manured soils. Many countries have established strict regulations regarding manure P application rates to agricultural fields based on soil P thresholds [48•, 72] where STP is often used to establish an upper limit to P application. Various approaches to reduce the rate of manure P loading to soils include, but not limited to, (a) generating manure with low TP and/or WEP (b) processing manure to reduce TP and/or WEP, (c) converting soluble P in manure to less available forms prior to or during application, and (d) decreasing manure application rates and transporting excess manure elsewhere. Based on data reported in recent literature, the relative change in TP and WEP of manure that were generated and/or processed through various P-reducing techniques, as compared with unprocessed manure or manure generated under conventional methods, are summarized in Table 1. The amount of WEP added with the same rate of TP was calculated and compared among different techniques tested with various manure types (Table 1).

Generating Low P Manure

Reducing TP concentration in manure and thereby increasing N/P in manure is an attractive option to effectively control soil P buildup even with an N-based manure application rates. Various approaches such as livestock diet manipulation, manure separation and processing, and amendment treatments have been used with varying success in reducing TP and/or WEP concentrations in manure (Table 1). Reduced P supplementation in feed [82], increasing fiber content in diet [83], and supplementing monogastric animal diets with phytase to increase the bioavailability of phytate-P and thereby reduce inorganic P supplementation, have resulted in manure with lower TP and/or WEP [84, 85].

Manure Processing to Reduce P Content

A number of manure processing techniques have been evaluated and are presently being used [86•] while emerging technologies continue to develop to process manure with the target of reducing TP and/or WEP contents. For manure slurries such as swine and dairy slurries, solid-liquid separation is an option to reduce the rate of P applied, since separation usually result in an N-rich liquid separate (LS) with less TP, which can be used on-farm as a N fertilizer, while P-rich solid separate could be transported elsewhere [77–79, 87–89]. Average N/P

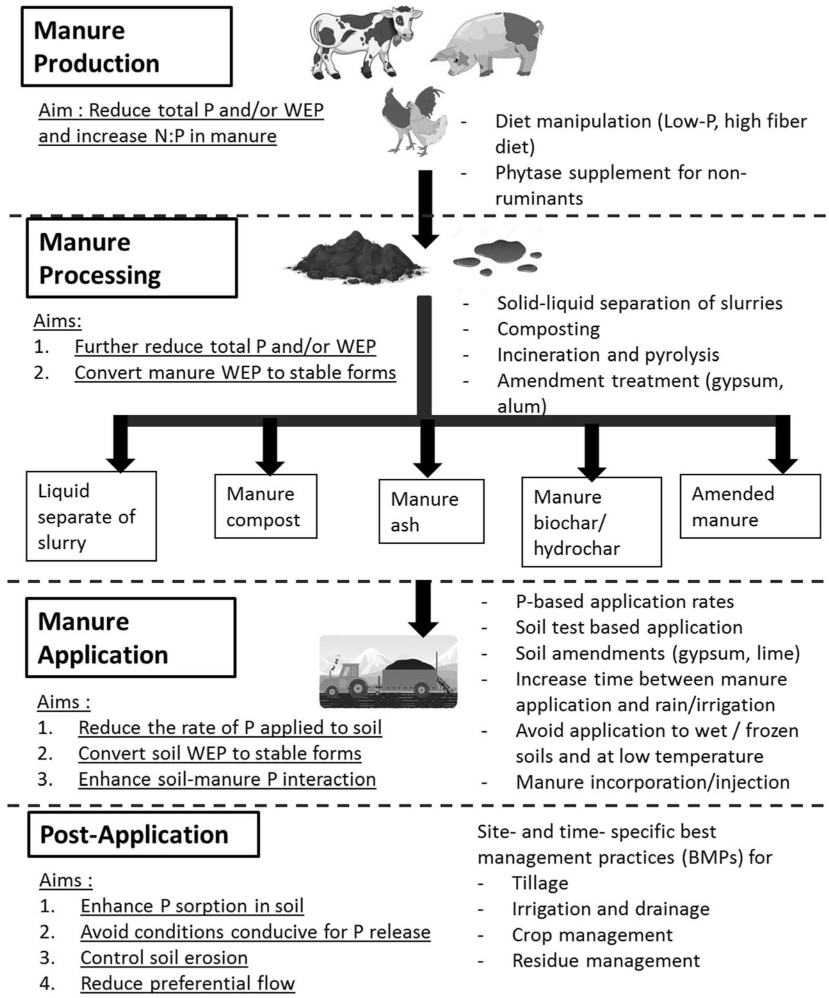

Fig. 1 Schematic illustration of mitigation strategies for controlling P accumulation in soils with manure application at various levels

ratio increased by 1.5- to 6-fold in LS compared with raw slurry (RS) of swine manure depending on the separation technique [77–79], an advantage since more N is provided per unit P than unseparated RS. Estimated TP loadings with the application of LS of swine slurry were only 50 to 70% of that of RS at equivalent rates of total N applied [88], which may or may not result in a reduction in WEP loading, since WEP/TP in LS can be more than RS depending on the separation technique (Table 1). Moreover, for manure slurries with a larger proportion of dissolved inorganic P, solid-liquid separation may result in LS with even greater TP than RS [90].

Composting of manure mixed with high C materials may result in a stable product with lower TP and higher C/P ratio and a lower risk of runoff and leaching losses when applied to soils [73•, 80, 91, 92]. Depending on the materials used in composting, TP may increase [31••, 73•] or decrease [92], resulting in a wide variation of C/P [31••, 73•, 80]. Composting often resulted in a significant reduction in water-extractable P [31••, 73•, 74] via the formation of recalcitrant P forms [74]. Thus, when added to provide the same rate of TP, composted manure resulted in about 26–52% reduction in WEP added than uncomposted manure (Table 1). Greater TP leaching losses with composted versus uncomposted cattle manure had been observed [31••] despite lower WEP in composted manure, which was attributed to the relatively lower C/P ratio in composted manure used. The contradicting results emphasize the need for careful selection of composting material that will reduce C/P while decreasing TP and WEP during composting. It has also been documented that P losses with runoff could be high during the early stages of composting which has to be contained [93].

Manure incineration (direct combustion in the presence of air) is a process that converts fresh manure to a P-rich ash [94•], which essentially contain zero nitrogen because of gaseous losses of nitrogen during the incineration process [86•], thus reducing its value as a nutrient source. Compared with fresh manure, manure ash releases P slowly [95]; thus P release with cattle manure ash-amended soil was found to be significantly lower than compost amended soil at the same P application rate [96].

Producing biochar from manure through incomplete combustion under anaerobic conditions (pyrolysis) immobilizes P

Table 1 Total P (TP) and water extractable P (WEP) in manure generated/processed through various P-reducing techniques and in corresponding manure generated under conventional methods/unprocessed raw manure, with calculated relative change in TP and WEP and the percentage reduction in WEP for same rate of TP added (based on data reported in recent literature)

Process	Manure type	Description	TP[a] ($g\ kg^{-1}$)	Relative change in TP	WEP[a] ($g\ kg^{-1}$)	Relative change in WEP	Reduction in WEP for same TP rate (%)	Reference
Diet manipulation	Dairy manure	P supplemented	3.9	–	0.99	–		[37]
		P not supplemented	3.1	0.79	0.63	0.64	19.9	
	Dairy manure	P supplemented	5.1	–	0.94	–	–	
		P not supplemented	4.3	0.84	0.42	0.45	47.0	
Composting	Broiler litter	Uncomposted	8.9	–	2.27	–	–	[73•]
		Composted	9.8	1.10	1.21	0.53	51.5	
	Beef cattle	Uncomposted	5.2	–	1.29	–	–	[31••]
		Composted	5.8	1.12	1.06	0.82	26.4	
	Cattle manure fed with DDGS	Uncomposted	8.8	–	2.57	–	–	[31••]
		Composted	13.7	1.56	2.44	0.95	39.0	
	Poultry litter	0 day of composting	49.4	–	12.4	–	–	[74]
		7th day of composting	53.2	1.08	5.53	0.45	58.6	
Pyrolysis	Dairy manure	Raw manure	5.6	–	1.47	–	–	[75]
		Biochar (350 °C)	10.0	1.78	0.38	0.26	85.6	
		Biochar (700 °C)	16.9	3.01	0.10	0.07	97.8	
	Paved feedlot	Raw manure	7.1	–	3.07	–	–	[75]
		Biochar (350 °C)	11.4	1.61	0.46	0.15	90.7	
		Biochar (700 °C)	17.6	2.49	0.18	0.06	97.6	
	Poultry litter	Raw manure	13.9	–	2.90	–	–	[75]
		Biochar (350 °C)	20.8	1.50	0.43	0.15	90.1	
		Biochar (700 °C)	31.2	2.24	0.90	0.31	86.2	
	Swine solids	Raw manure	24.7	–	11.0	–	–	[75]
		Biochar (350 °C)	38.9	1.57	0.39	0.04	97.7	
		Biochar (700 °C)	59.0	2.39	0.06	0.01	99.8	
	Turkey litter	Raw manure	16.1	–	9.11	–	–	[75]
		Biochar (350 °C)	26.2	1.63	1.06	0.12	92.8	
		Biochar (700 °C)	36.6	2.27	1.75	0.19	91.5	
	Dairy manure	Raw manure	8.6	–	0.76	–	–	[67]
		Biochar	25.2	2.93	0.04	0.05	98.2	
	Poultry litter	Raw manure	13.7	–	2.95	–	–	[76•]
		Biochar	27.1	1.98	0.17	0.06	97.1	
Hydrothermal carbonization	Cattle manure	Raw manure	~ 14	–	6.80	–	–	[66•]
		Hydrochar	~ 19	~1.35	< 2.0	~0.29	~78.3	
Solid-liquid separation	Swine slurry	Raw slurry	30.1[b]	–	2.11[b]	–	–	[77]
		Liquid separate (CN)	27.9[b]	0.93	1.77[b]	0.84	9.1	
		Raw slurry	22.1[b]	–	3.32[b]	–	–	[77]
		Liquid separate (CF)	31.0[b]	1.41	4.79[b]	1.44	−2.8	
		Raw slurry	26.4[b]	–	3.49[b]	–	–	[77]
		Liquid separate (RF)	28.9[b]	1.10	5.07[b]	1.45	−32.7	
	Swine slurry	Raw slurry	20.9[b]	–	12.2[b]	–	–	[78]
		Liquid separate (SP)	8.3[b]	0.46	8.08[b]	0.76	−66.8	
	Swine slurry	Raw slurry	2.1[b]	–	0.23[b]			[79]
		Liquid separate (SP)	3.0[b]	1.42	0.30[b]	1.35	5.1	

Table 1 (continued)

Process	Manure type	Description	TP[a] ($g\ kg^{-1}$)	Relative change in TP	WEP[a] ($g\ kg^{-1}$)	Relative change in WEP	Reduction in WEP for same TP rate (%)	Reference
		Liquid separate (FD)	2.2[b]	1.04	1.11[b]	4.93	−374	
		Liquid separate (CN)	1.2[b]	0.54	0.23[b]	1.02	−88	
Amendments	Chicken manure compost	Compost alone	16.1	–	0.09[b]	–	–	[80]
		Biochar-blended compost	15.0	0.93	0.06[b]	0.65	29.8	
	Dairy slurry	Dairy slurry	10.9[b]	–	2.86	–	–	[81]
		Alum amendment	11.1[b]	1.02	0.003	0.001	99.9	
		Lime amendment	6.81[b]	0.63	0.03	0.009	98.6	
		PAC amendment	12.9[b]	1.19	0.003	0.001	99.9	
		$FeCl_3$ amendment	10.4[b]	0.95	0.02	0.0071	99.3	

CN, separated using centrifuge, without a flocculant [79]; CF, separated using centrifuge, with a flocculant; RF, separated using rotary press, with a flocculant [77]; SP, screwpress [78]; FD, flocculate and drain

[a] Dry weight basis

[b] Converted to dry weight basis using wet weight basis concentrations and total solids (or moisture) contents

and consequently reduces the risk of runoff and leaching losses [67, 76•, 94•, 97]. Pyrolysis of various manures resulted in an increase in TP, with increment ranging from ~24 to > 200% depending on pyrolysis temperature [67, 75, 76•, 94•, 98], with greater TP at higher temperatures of up to 1000 °C [75, 94•]. Despite the increase in TP, pyrolysis reduced the WEP dramatically [67, 75, 76•, 94•, 98] by transforming labile P in manure to more stable forms such as Mg/Ca phosphate minerals [67, 99]. The decrease in WEP with manure pyrolysis in different studies ranged from 68 to 99% and is influenced by manure type [67, 75, 76•]. Based on the TP and WEP of biochars reported in recent literature, application of biochar may result in a reduction of > 85% of WEP for the same rate of TP added compared with raw manures (Table 1). When applied to soils, P release rate was slower and steadier over a longer time period with biochar than from raw manure; thus biochar could potentially be a slow-release P source that may result in more efficient uptake by plants and reduced losses from soils [76•, 95].

Compared with manure biochar, much less is known about manure hydrochar produced through direct pyrolysis of wet manures through hydrothermal carbonization. Since this relatively new technology avoids the step of evaporating water, and uses a relatively low temperature (180–350 °C), the energy requirement is much less than pyrolysis for wet manures [86•]. Hydrothermal carbonization of cow manure increased the TP content substantially by ~30% with a significant decrease in WEP by > 70% [66•]. More research on P release characteristics and P speciation of hydrochars produced through this emerging technology is needed for different manures under varying conditions.

Converting Manure P to less Soluble Forms

Various amendments can be added to manure prior to or during manure application to convert the soluble manure P to more stable, recalcitrant forms. Use of industrial by-products as amendments to reduce soluble P concentrations in animal manure, and thereby minimize the potential for P transport to surface waters after land application of the manure was recently reviewed [18]. Flue gas desulfurization (FGD) gypsum is one of the most evaluated industrial by product as a manure amendment as well as a soil amendment. The FGD gypsum was effective in reducing P concentration of dairy liquid manure in the settling tanks within about 4 h of reactions, thus could be used prior to field application of manure [100]. This amendment showed a reduction of 53–91% in leachate P compared with unamended poultry litter [73•, 91], a 54% reduction in runoff P during initial runoff event compared with unamended poultry litter [101•], and 47–81% reduction in leachate when amended to composted manure [73•]. Reduction in runoff P loss with FGD gypsum continued over successive runoff events indicating a persistent effect over the growing season [101•]. Other amendments that were evaluated recently showing significant reductions in P losses from soils include alum and alum mud with a 29–84% decrease in DRP loss with runoff compared with unamended poultry manure and swine slurry [23, 69, 102], liquid ferric chloride and liquid poly-aluminum chloride, both with a 84% reduction in DRP runoff losses compared with unamended swine slurry [69] and combined amendments of zeolite with polyaluminum chloride with an 87 and 81% reduction in runoff TP losses compared with unamended dairy and pig slurries, respectively [103]. Other amendments such as activated red mud [104], mine drainage residue [105], lime [81], bauxite [68••, 106], and sulfuric acid mixed with alum and bauxite [68••] were effective in reducing WEP in various manures (Table 1) and warrants field scale evaluation in reducing P losses from manured soils. Enhanced reduction of P losses through combined amendments compared with single amendment [68••, 103] indicate the possible synergies among different amendments, which needs to be better understood and utilized.

Reducing Manure Application Rates

Repeated land applications of manure based on plant N needs results in excessive P concentrations in soils because of low N/P ratio of manure compared with crop requirement [107, 108]; thus, shifting from N-based to P removal-based manure application has been recognized as a potential alternative to reduce P buildup in soils with continuous manure applications [16•, 109•, 110]. Recent research evidenced approximately 40% less P accumulation in soil from P-based compared with N-based application of dairy manure compost [15, 110], while the reduction in P accumulation with liquid dairy manure with P-based manure application was about 7% [110].

Manure rates should also be adjusted based on soil properties, adding less to high runoff-prone and leaky soils. Both leaching and runoff losses of manure P are enhanced when soils have low P sorption capacity with high degree of P saturation [23]. While low application rates of manure P can reduce P buildup in soils with repeated manure application, it may involve hauling excess manure generated from livestock farms elsewhere. Granulating and pelletizing of manure can enhance the ease of transporting [86•]. Solid-liquid separation of manure slurries is also effective since N-rich liquid can be applied on-farm, while P-rich solid which is about one-tenth of the total mass of slurry [77] could be easily transported off-site to be used as a P fertilizer.

Comparing different processing techniques, P availability was shown to decrease in the order of drying > composting > pyrolysis > combustion with increasing degree of processing, with negligible WEP with pyrolysis above 700 °C or combustion above 400 °C [94•]. Based on proportion of WEP to TP calculated using recent data from various processing techniques and manures, P bioavailability generally decrease in the order solid-liquid separation > composting > pyrolysis (Table 1).

Controlling Transport Factors

While manipulating at source level is the more effective approach to minimize P accumulation in soils with manure applications, controlling transport factors is effective in reducing P mobility from manure-amended soils to sensitive locations such as fresh water bodies. Past and recent approaches to regulate manure P transport from soils to waterways focused mainly on enhancing manure P-soil interaction (e.g., proper timing, placement, and methods of manure application), and controlling soil erosion, surface runoff, and preferential leaching (e.g., minimum tillage, terracing, controlled drainage, etc.) [17–19, 20•].

Enhancing Manure P Interaction with Soils

Soil particles can retain manure P; therefore, enhancing manure P interaction with soils can reduce P mobility. Manure application to wet soils, frozen ground, and during late fall and winter seasons when temperatures are low, can significantly increase manure P losses because of low P retention, and thus, should be avoided [12••, 111, 112]. Incorporation and injection of manure enhances soil-manure contact and facilitates P retention. When compared with surface application of pig slurry, incorporation and injection resulted in a > 50% reduction in TP and dissolved P loads with runoff and leaching [46, 48•] and is usually a recommended practice to reduce manure P losses.

Controlling Soil Erosion, Surface Runoff, and Preferential Leaching

Loss of PP from manured soils is highly correlated with sediment loss [41] and can be greatly reduced through controlling soil erosion and preferential flow. While strategies commonly used for erosion control such as conservation tillage, terracing, contour tillage, and cover crops were often effective in reducing PP loss from soils via surface runoff, they are less effective in reducing dissolved P losses and may increase the total dissolved P in losses over time [19, 20•]. For example, a study analyzing a database of drainage-associated nutrient loads indicated that conservation tillage, an effective measure for reducing PP losses with surface runoff, can increase DRP loss with rain water- and snowmelt- driven surface and subsurface pathways [53], largely due to P accumulation in surface soils with conservation tillage leading to vertical stratification in relation to STP.

Controlled drainage reduced manure P loss to tile drainage, with a 40-fold reduction in leachate DRP concentration compared with free drainage 1 week after manure application

[55••]. This was attributed to a reduction of preferential flow through macropores allowing more time for P sorption to occur. A significant redox-induced DRP release was not observed during 3-week subsurface water retention; however, other studies reported significant increase in P release from manured soils with longer periods of water retention [60]. Lack of redox-induced P release in the former study [55••] could be soil specific; thus, more research is needed using soils with a wide range of properties. While controlled drainage decreased DRP losses in leachate through preferential flow [55••], how it influences P loss from other pathways is uncertain; and authors cautioned that the impact of controlled drainage on surface water hydrology, erosion potential, and overall P loss risk, need to be evaluated.

Increasing time between manure application and runoff event can reduce both particulate and dissolved P losses, particularly with surface-applied manures as shown by actual P loss from manured fields and predicted P loss using different models [12••, 44–46, 113]. Predictions using SurPhos model suggest that enhanced soil-manure P interactions is not the dominant mechanism that decreased available P for runoff as thought earlier; rather, decreased runoff P loss was primarily caused due to less runoff generated from drier soils with increasing time after manure application [46], which may also result in more manure P infiltration into soil. Thus, it is clear that storm hydrology is the driver of manure P loss when manure is applied on soil surface, rather than the time gap between manure application and runoff event.

The complexity of concurrent processes of manure P transport clearly indicates that effectiveness of BMPs tested for a particular scenario may not be transferable to a different location, or moment of time. Selection of appropriate BMPs therefore should be site and time specific based on the dominant mechanism/s by which manure P is transported.

Conclusions

Manure is a rich source of plant nutrients that can significantly reduce the use of mineral fertilizers in crop production; however, proper management is crucial to avoid non-point pollution of freshwater with P. Manures differ in their P content and forms of P present, and when applied to soils with varying properties under a range of environmental conditions, a large number of interactive factors influences manure P accumulation and mobility in soils. Based on research findings, P losses from manure-applied soils in general, is greater with (a) increasing soluble P applied with manure, (b) vulnerable soils with limited P sorption capacity and/or susceptible to preferential flow/erosion, (c) physical/chemical conditions conducive to P release and transport (e.g., water-logged conditions), and (d) reduced soil-manure P interaction following application (e.g., manure application when rainfall is imminent). Since manure P can be transported as particulate P or dissolved P from soils, via a number of surface and subsurface flow pathways which occur concurrently, attempts to minimize P loss through one pathway may enhance losses through another. Future research therefore, should focus on a better understanding of the interactive effects of source factors on short- and long-term manure P loss via different transport pathways that occur concurrently. Special attention should be paid to vulnerable conditions such as water-logged and frozen soils, with more research on snow-melt driven P losses to better understand the factors controlling manure P loss under such conditions.

Mitigating strategies to reduce P transport from amended soil to waterways can be achieved at multiple stages; during manure generation, processing, application and post-application. Future research should continue to hone existing techniques to reduce P buildup in soils with manure applications while developing novel cost-effective and environmentally friendly options. Mitigation efforts should focus on reducing P buildup in soil by employing a combination of strategies during generation, processing, and application of manure, coupled with site- and time-specific BMPs selected based on the dominant pathway of P loss.

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Papers of particular interest, published recently, have been highlighted as:
• of importance
•• of major importance

1. Herrero M, Havlík P, Valin H, Notenbaert A, Rufino MC, Thornton PK, et al. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc Natl Acad Sci. 2013;110(52):20888–93.
2. FAOSTAT. FAOSTAT database. Food and Agriculture Organization of the United Nations, Rome, Italy. 2013.
3. Herrero M, Thornton PK, Gerber P, Reid RS. Livestock, livelihoods and the environment: understanding the trade-offs. Curr Opin Environ Sustain. 2009;1(2):111–20.
4. Zhang H, Schroder J. Animal manure production and utilization in the US. In: Zhongqi H, Zhang H, editors. Applied manure and nutrient chemistry for sustainable agriculture and environment. Dordrecht: Springer; 2014. p. 1–21.
5.• Penha HGV, Menezes JFS, Silva CA, Lopes G, de Andrade Carvalho C, Ramos SJ, et al. Nutrient accumulation and availability and crop yields following long-term application of pig slurry in a Brazilian Cerrado soil. Nutrient Cycling in Agroecosystems. 2015;101(2):259–69. **This article evaluates effects of long-term applications of pig slurry without incorporation on soil phosphorus at different soil depths. Results indicate increased**

P availability following pig slurry application; however, this increase occurred only in soil surface.

6. Nest TV, Vandecasteele B, Ruysschaert G, Cougnon M, Merckx R, Reheul D. Effect of organic and mineral fertilizers on soil P and C levels, crop yield and P leaching in a long term trial on a silt loam soil. Agric Ecosyst Environ. 2014;197:309–17.
7. D'Hose T, Ruysschaert G, Viaene N, Debode J, Nest TV, Van Vaerenbergh J, et al. Farm compost amendment and non-inversion tillage improve soil quality without increasing the risk for N and P leaching. Agric Ecosyst Environ. 2016;225:126–39.
8.• Pizzeghello D, Berti A, Nardi S, Morari F. Relationship between soil test phosphorus and phosphorus release to solution in three soils after long-term mineral and manure application. Agriculture, Ecosystems & Environment. 2016;233:214–23. **This article compared P accumulation following long-term (44 years) farmyard manure and mineral applications with untreated. Farmyard manure increased soil P by 7.7-fold that of untreated, down to 50 cm in clay and peaty soil and 28-fold untreated, down to 90 cm in sandy soil, thus indicating both accumulation and leaching of P.**
9. Waldrip HM, Pagliari PH, He Z, Harmel RD, Cole NA, Zhang M. Legacy phosphorus in calcareous soils: effects of long-term poultry litter application. Soil Sci Soc Am J. 2015;79(6):1601–14.
10. Omara P, Macnack N, Aula L, Raun B. Effect of long-term beef manure application on soil test phosphorus, organic carbon, and winter wheat yield. J Plant Nutr. 2017;40(8):1143–51.
11. King KW, Williams MR, Macrae ML, Fausey NR, Frankenberger J, Smith DR, et al. Phosphorus transport in agricultural subsurface drainage: a review. J Environ Qual. 2015;44(2):467–85.
12.•• Vadas PA, Good LW, Jokela WE, Karthikeyan KG, Arriaga FJ, Stock M. Quantifying the impact of seasonal and short-term manure application decisions on phosphorus loss in surface runoff. J Environ Qual. 2017. **The article discusses the predicted risk of P loss using the SurPhos computer model and 108 site–years of weather and runoff data with dairy manure application in winter or when runoff is imminent. Model predicted increased P loss for manure applied from late November through early March, with a maximum P loss from application in late January and early February.**
13. Schindler DW, Hecky RE, McCullough GK. The rapid eutrophication of Lake Winnipeg: greening under global change. J Great Lakes Res. 2012;38:6–13.
14. Darch T, Blackwell MSA, Hawkins JMB, Haygarth PM, Chadwick D. A meta-analysis of organic and inorganic phosphorus in organic fertilizers, soils, and water: implications for water quality. Crit Rev Environ Sci Technol. 2014;44(19):2172–202.
15. Komiyama T, Ito T, Saigusa M. Effects of phosphorus-based application of animal manure compost on the yield of silage corn and on soil phosphorus accumulation in an upland andosol in Japan. Soil Sci Plant Nutr. 2014;60(6):863–73.
16.• Sadeghpour A, Ketterings QM, Godwin GS, Czymmek KJ. Shifting from N-based to P-based manure management maintains soil test phosphorus dynamics in a long-term corn and alfalfa rotation. Agronomy for Sustainable Development. 2017;37(2):8. **The article examines soil test P dynamics in a 10-year corn-alfalfa rotation annual spring applications of N-based versus P removal based compost, liquid dairy manure and two control treatments with and without fertilizer N. Results show, for the first time in dairy forage rotations, the benefits of P-based manure management on long-term sustainability emphasizing the importance of rotation fertility management rather than single-year P management.**
17. McDowell RW. Estimating the mitigation of anthropogenic loss of phosphorus in New Zealand grassland catchments. Sci Total Environ. 2014;468:1178–86.
18. Penn CJ, McGrath JM. Chemistry and application of industrial by-products to animal manure for reducing phosphorus losses to surface waters. In: He Z, Zhang H, editors. Applied manure and nutrient chemistry for sustainable agriculture and environment. Dordrecht: Springer; 2014. p. 211–38.
19. Schoumans OF, Chardon WJ, Bechmann ME, Gascuel-Odoux C, Hofman G, Kronvang B, et al. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: a review. Sci Total Environ. 2014;468:1255–66.
20.• Tayyab U, McLean FA. Phosphorus losses and on-farm mitigation options for dairy farming systems: a review. JAPS J Anim Plant Sci. 2015;25(2). **The article reviews P losses and on-farm mitigation options for dairy farms. Following strategies are identified as important: quantification of potential P losses, riparian buffer strips, conservation tillage, precise feeding, animal health, exogenous enzymes and rotational grazing, with efficient manure storage, management and transport.**
21. García-Albacete M, Requejo MI, Cartagena MC. Phosphorus runoff losses after application of organic waste. CLEAN: Soil, Air, Water. 2016;44(12):1628–35.
22.• Toor GS, Sims JT. Phosphorus leaching in soils amended with animal manures generated from modified diets. J Environ Qual. 2016;45(4):1385–91. **In this article the effectiveness of dietary changes in reducing P leaching loss on land application of manures was investigated using a lysimeter study. Results indicated greater P leaching when preferential flow pathways exist in soils. Application of manure at similar P rate resulted in adding higher amount of low-P dairy manure and phytase-amended broiler litter, which controlled P leaching from soils.**
23. Roberts J, Israel DW. Influence of soil properties and manure sources on phosphorus in runoff during simulated rainfall. Commun Soil Sci Plant Anal. 2017;48(2):222–35.
24. García-Albacete M, Tarquis AM, Cartagena MC. Risk of leaching in soils amended by compost and digestate from municipal solid waste. Sci World J. 2014;2014:1–8.
25. Kumaragamage D, Flaten DN, Akinremi OO, Sawka CA, Ige D, Zvomuya F. Impact of manure phosphorus fractions on phosphorus loss from manured soils after incubation. J Environ Qual. 2012;41(3):845–54.
26. Blaustein RA, Dao TH, Pachepsky YA, Shelton DR. Differential release of manure-borne bioactive phosphorus forms to runoff and leachate under simulated rain. J Environ Manag. 2017;192:309–18.
27. Vadas PA, Busch DL, Powell JM, Brink GE. Monitoring runoff from cattle-grazed pastures for a phosphorus loss quantification tool. Agric Ecosyst Environ. 2015;199:124–31.
28. Vadas PA, Good LW, Panuska JC, Busch DL, Larson RA. A new model for phosphorus loss in runoff from outdoor cattle lots. Trans ASABE. 2015;58(4):1035–46.
29. Weyers E, Strawn DG, Peak D, Baker LL. Inhibition of phosphorus sorption on calcite by dairy manure-sourced DOC. Chemosphere. 2017;184:99–105.
30. Nest TV, Ruysschaert G, Vandecasteele B, Houot S, Baken S, Smolders E, et al. The long term use of farmyard manure and compost: effects on P availability, orthophosphate sorption strength and P leaching. Agric Ecosyst Environ. 2016;216:23–33.
31.•• Li P, Lang M, Li C, Thomas BW, Hao X. Nutrient leaching from soil amended with manure and compost from cattle fed diets containing wheat dried distillers' grains with solubles. Water, Air, & Soil Pollution. 2016;227(10):393. **This article compares potential P leaching losses from soils amended with beef manure, beef manure compost, manure from cattle fed a typical finishing diet, and composted and uncomposted manure from cattle fed with a diet containing dried distillers' grains with solubles (DDGS). Cumulative leaching losses of P were significantly higher, from compost-amended than manure-amended**

soil. Total P leached was greater from soil amended with manure or composted manure from cattle fed with DDGS compared to beef manure.

32. Wang YT, Zhang TQ, Hu QC, Tan CS. Phosphorus source coefficient determination for quantifying phosphorus loss risk of various animal manures. Geoderma. 2016;278:23–31.
33. Pagliari PH, Laboski CAM. Investigation of the inorganic and organic phosphorus forms in animal manure. J Environ Qual. 2012;41(3):901–10.
34. Li G, Li H, Leffelaar PA, Shen J, Zhang F. Characterization of phosphorus in animal manures collected from three (dairy, swine, and broiler) farms in China. PLoS One. 2014;9(7):e102698.
35. Horta C, Roboredo M, Carneiro JP, Duarte AC, Torrent J, Sharpley A. Organic amendments as a source of phosphorus: agronomic and environmental impact of different animal manures applied to an acid soil. Arch Agron Soil Sci 2017:1–15.
36. Kebreab E, Hansen AV, Leytem AB. Feed management practices to reduce manure phosphorus excretion in dairy cattle. Adv Anim Biosci. 2013;4(s1):37–41.
37. Jokela WE, Coblentz WK, Hoffman PC. Dairy heifer manure management, dietary phosphorus, and soil test P effects on runoff phosphorus. J Environ Qual. 2012;41(5):1600–11.
38. Bernier JN, Undi M, Ominski KH, Donohoe G, Tenuta M, Flaten D, et al. Nitrogen and phosphorus utilization and excretion by beef cows fed a low quality forage diet supplemented with dried distillers grains with solubles under thermal neutral and prolonged cold conditions. Anim Feed Sci Technol. 2014;193:9–20.
39. Komiskey MJ, Stuntebeck TD, Frame DR, Madison FW. Nutrients and sediment in frozen-ground runoff from no-till fields receiving liquid-dairy and solid-beef manures. J Soil Water Conserv. 2011;66(5):303–12.
40. Ciapparelli IC, de Iorio AF, García AR. Phosphorus downward movement in soil highly charged with cattle manure. Environ Earth Sci. 2016;75(7):568.
41. Lehrsch GA, Lentz RD, Westermann DT, Kincaid DC. Nutrient loads and sediment losses in sprinkler irrigation runoff affected by compost and manure. J Soil Water Conserv. 2014;69(5):456–67.
42. Yang Y, Zhang H, Qian X, Duan J, Wang G. Excessive application of pig manure increases the risk of P loss in calcic cinnamon soil in China. Sci Total Environ. 2017;609:102–8.
43. Tomer MD, Moorman TB, Kovar JL, Cole KJ, Nichols DJ. Eleven years of runoff and phosphorus losses from two fields with and without manure application, Iowa, USA. Agric Water Manag. 2016;168:104–11.
44. Cherobim VF, Huang C-H, Favaretto N. Tillage system and time post-liquid dairy manure: effects on runoff, sediment and nutrients losses. Agric Water Manag. 2017;184:96–103.
45. Laurenson S, Houlbrooke DJ. Nutrient and microbial loss in relation to timing of rainfall following surface application of dairy farm manure slurries to pasture. Soil Res. 2014;52(5):513–20.
46. Schuster NR, Bartelt-Hunt SL, Durso LM, Gilley JE, Li X, Marx DB, et al. Runoff water quality characteristics following swine slurry application under broadcast and injected conditions. Trans ASABE. 2017;60(1):53–66.
47. Owens LB, Bonta JV, Shipitalo MJ, Rogers S. Effects of winter manure application in Ohio on the quality of surface runoff. J Environ Qual. 2011;40(1):153–65.
48.• Bergström L, Kirchmann H, Djodjic F, Kyllmar K, Ulén B, Liu J, et al. Turnover and losses of phosphorus in Swedish agricultural soils: long-term changes, leaching trends, and mitigation measures. J Environ Qual. 2015;44(2):512–23. **This review article examined effectiveness of BMPs used in ten Swedish long-term soil fertility trials on subsurface losses of P. Incorporation of pig slurry into a clay soil instead of surface application reduces P leaching by 50%. Effectiveness of BMPs showed no clear trend while weather conditions and soil type, have profound effects on P losses, masking the effects of BMPs.**
49.• Jokela W, Sherman J, Cavadini J. Nutrient runoff losses from liquid dairy manure applied with low-disturbance methods. J Environ Qual. 2016;45(5):1672–9. **This article evaluates tillage immediately after application to incorporate manure into the soil on runoff losses. Highest losses of total P and dissolved reactive P in post-manure application runoff were from surface-applied manure. Dissolved P loss was reduced 98.53. And 80% by strip-till injection, aerator band method and disk incorporation, respectively.**
50. Giles CD, Cade-Menun BJ, Liu CW, Hill JE. The short-term transport and transformation of phosphorus species in a saturated soil following poultry manure amendment and leaching. Geoderma. 2015;257:134–41.
51. Coelho BB, Murray R, Lapen D, Topp E, Bruin A. Phosphorus and sediment loading to surface waters from liquid swine manure application under different drainage and tillage practices. Agric Water Manag. 2012;104:51–61.
52. Xue QY, Dai PB, Sun DS, Sun CL, Qi LY, Ostermann A, et al. Effects of rainfall and manure application on phosphorus leaching in field lysimeters during fallow season. J Soils Sediments. 2013;13(9):1527–37.
53. Christianson LE, Harmel RD, Smith D, Williams MR, King K. Assessment and synthesis of 50 years of published drainage phosphorus losses. J Environ Qual. 2016;45(5):1467–77.
54. Smith DR, King KW, Johnson L, Francesconi W, Richards P, Baker D, et al. Surface runoff and tile drainage transport of phosphorus in the midwestern United States. J Environ Qual. 2015;44(2):495–502.
55.•• Young EO, Geibel JR, Ross DS. Influence of controlled drainage and liquid dairy manure application on phosphorus leaching from intact soil cores. J Environ Qual. 2017;46(1):80–7. **This article evaluated the effectiveness of controlled drainage in reducing manure P loss to tile drainage. Results showed a 40-fold reduction in leachate DRP concentration compared to free drainage one week after manure application attributed to a reduction of preferential flow through macropores allowing more time for P sorption to occur. A significant redox-induced DRP release was not observed during 3-wk subsurface water retention.**
56. Ulén B, Wesström I, Johansson G, Forsberg LS. Recession of phosphorus and nitrogen concentrations in tile drainage water after high poultry manure applications in two consecutive years. Agric Water Manag. 2014;146:208–17.
57. Mina O, Gall HE, Saporito LS, Elliott HA, Kleinman PJA. Relative role of transport and source-limited controls for estrogen, TDP, and DOC export for two manure application methods. Agric Ecosyst Environ. 2017;247:308–18.
58. Jokela WE, Casler MD. Transport of phosphorus and nitrogen in surface runoff in a corn silage system: paired watershed methodology and calibration period results. Can J Soil Sci. 2011;91(3):479–91.
59.• King T, Schoenau J, Elliott J. Relationship between manure management application practices and phosphorus and nitrogen export in snowmelt run-off water from a Black Chernozem Saskatchewan soil. Sustain Agric Res. 2017;6(2):93. **This article describes effect of surface and subsurface application of solid cattle manure (SCM) and liquid hog manure (LHM) on soluble reactive P (SRP) loss with simulated snowmelt runoff using a novel methodology to simulate melting snow conditions generating runoff using soil monoliths. Export of SRP was less in LHM treatments than SCM treatments, while manure placement had not significant effect on SRP loss.**
60. Amarawansha E, Kumaragamage D, Flaten D, Zvomuya F, Tenuta M. Phosphorus mobilization from manure-amended and

unamended alkaline soils to overlying water during simulated flooding. J Environ Qual. 2015;44(4):1252–62.
61. Penn CJ, Bowen JM. Reducing phosphorus transport: an overview of best management practices. In: Design and construction of phosphorus removal structures for improving water quality. Cham: Springer; 2018. p. 13–33.
62. Kleinman PJA, Church C, Saporito LS, McGrath JM, Reiter MS, Allen AL, et al. Phosphorus leaching from agricultural soils of the Delmarva Peninsula, USA. J Environ Qual. 2015;44(2):524–34.
63. Abboud FY, Motta ACV, Barth G, Goularte GD, Favaretto N. Mobility and degree of phosphorus saturation in oxisol under no-tillage after long-term application of dairy liquid manure. Agric Ecosyst Environ. 2017.
64. Bolster CH, Vadas PA. Sensitivity and uncertainty analysis for the annual phosphorus loss estimator model. J Environ Qual. 2013;42(4):1109–18.
65. Collick AS, Veith TL, Fuka DR, Kleinman PJA, Buda AR, Weld JL, et al. Improved simulation of edaphic and manure phosphorus loss in SWAT. J Environ Qual. 2016;45(4):1215–25.
66.• Dai L, Tan F, Wu B, He M, Wang W, Tang X, et al. Immobilization of phosphorus in cow manure during hydrothermal carbonization. J Environ Manag. 2015;157:49–53. **This article describes hydrothermal carbonization, a relatively new technology in producing hydrochar from wet manure, avoiding the step of evaporating water, and using a relatively low temperature (180 – 350°C) for pyrolysis. Results showed that hydrothermal carbonization of cow manure increased the total P content by ~20% with a significant decrease in water extractable P by >80%.**
67. Liang Y, Cao X, Zhao L, Xu X, Harris W. Phosphorus release from dairy manure, the manure-derived biochar, and their amended soil: effects of phosphorus nature and soil property. J Environ Qual. 2014;43(4):1504–9.
68.•• Moore PA. Development of a new manure amendment for reducing ammonia volatilization and phosphorus runoff from poultry litter. J Environ Qual. 2016;45(4):1421–9. **This article investigates 16 different manure amendments developed using mixtures of alum mud, bauxite ore, sulfuric acid, liquid alum, and water that are as effective as alum in reducing P runoff from manure amended soils. Water-extractable P was significantly reduced by all of the amendments while mixtures of alum mud, bauxite, and sulfuric acid were more promising.**
69. O'Flynn CJ, Healy MG, Wilson P, Hoekstra NJ, Troy SM, Fenton O. Chemical amendment of pig slurry: control of runoff related risks due to episodic rainfall events up to 48 h after application. Environ Sci Pollut Res. 2013;20(9):6019–27.
70. Baker DB, Confesor R, Ewing DE, Johnson LT, Kramer JW, Merryfield BJ. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: the importance of bioavailability. J Great Lakes Res. 2014;40(3):502–17.
71. Daloglu I, Cho KH, Scavia D. Evaluating causes of trends in long-term dissolved reactive phosphorus loads to Lake Erie. Environ Sci Technol. 2012;46(19):10660–6.
72. Withers PJA, Hodgkinson RA, Rollett A, Dyer C, Dils R, Collins AL, et al. Reducing soil phosphorus fertility brings potential long-term environmental gains: a UK analysis. Environ Res Lett. 2017;12(6):063001.
73.• Adeli A, Sheng J, Jenkins JN, Feng G. Composting and gypsum amendment of broiler litter to reduce nutrient leaching loss. J Environ Qual. 2015;44(2):676–83. **This article compared composted and fresh broiler litter with and without flue gas desulfurization (FGD) gypsum on P leaching. Results revealed less P leaching with composted litter compared to fresh broiler litter. When gypsum was mixed with fresh broiler litter P leaching was significantly reduced.**
74. Hashimoto Y, Takamoto A, Kikkawa R, Murakami K, Yamaguchi N. Formations of hydroxyapatite and inositol hexakisphosphate in poultry litter during the composting period: sequential fractionation, P K-edge XANES and solution 31P NMR investigations. Environ Sci Technol. 2014;48(10):5486–92.
75. Cantrell KB, Hunt PG, Uchimiya M, Novak JM, Ro KS. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresour Technol. 2012;107:419–28.
76.• Wang Y, Lin Y, Chiu PC, Imhoff PT, Guo M. Phosphorus release behaviors of poultry litter biochar as a soil amendment. Sci Total Environ. 2015;512:454–63. **This article examined water extractability of P in poultry litter biochar and its release kinetics in amended soils. Results showed that P in poultry litter biochar is predominantly water insoluble while release of P from biochar was slower and steadier than from raw poultry litter.**
77. Kumaragamage D, Akinremi OO, Grieger L. Phosphorus fractions in solid and liquid separates of swine slurry separated using different technologies. J Environ Qual. 2013;42(6):1863–71.
78. Riaño B, García-González MC. On-farm treatment of swine manure based on solid–liquid separation and biological nitrification–denitrification of the liquid fraction. J Environ Manag. 2014;132:87–93.
79. Sommer SG, Hjorth M, Leahy JJ, Zhu K, Christel W, Sørensen CG. Pig slurry characteristics, nutrient balance and biogas production as affected by separation and acidification. J Agric Sci. 2015;153(1):177–91.
80. Vandecasteele B, Reubens B, Willekens K, De Neve S. Composting for increasing the fertilizer value of chicken manure: effects of feedstock on P availability. Waste Biomass Valoriz. 2014;5(3):491–503.
81. Brennan RB, Wall DP, Fenton O, Grant J, Sharpley AN, Healy MG. Impact of chemical amendment of dairy cattle slurry on soil phosphorus dynamics following application to five soils. Commun Soil Sci Plant Anal. 2014;45(16):2215–33.
82. Zhang B, Wang C, Wei ZH, Sun HZ, Xu GZ, Liu JX, et al. The effects of dietary phosphorus on the growth performance and phosphorus excretion of dairy heifers. Asian Australas J Anim Sci. 2016;29(7):960–4.
83. Huang Q, Ackerman J, Cicek N. Effect of dietary fiber on phosphorus distribution in fresh and stored liquid hog manure. Can J Civ Eng. 2013;40(9):869–74.
84. Kumar V, Singh D, Sangwan P, Gill PK. Management of environmental phosphorus pollution using phytases: current challenges and future prospects. In: Kaushik G, editor. Applied environmental biotechnology: present scenario and future trends. India: Springer; 2015. p. 97–114.
85. Yitbarek A, López S, Tenuta M, Asgedom H, France J, Nyachoti CM, et al. Effect of dietary phytase supplementation on greenhouse gas emissions from soil after swine manure application. J Clean Prod. 2017;166:1122–30.
86.• Szogi AA, Vanotti MB, Ro KS. Methods for treatment of animal manures to reduce nutrient pollution prior to soil application. Curr Pollut Rep. 2015;1(1):47–56. **The review article summarize existing technologies for animal waste treatment and emerging new technologies for recycling manure phosphorus.**
87. Garcia MC, Szogi AA, Vanotti MB, Chastain JP, Millner PD. Enhanced solid–liquid separation of dairy manure with natural flocculants. Bioresour Technol. 2009;100(22):5417–23.
88. Kumaragamage D, Akinremi OO, Racz GJ. Comparison of nutrient and metal loadings with the application of swine manure slurries and their liquid separates to soils. J Environ Qual. 2016;45(5):1769–75.
89. Popovic O, Hjorth M, Stoumann Jensen L. Phosphorus, copper and zinc in solid and liquid fractions from full-scale and

laboratory-separated pig slurry. Environ Technol. 2012;33(18):2119–31.

90. Pagliari PH, Laboski CAM. Dairy manure treatment effects on manure phosphorus fractionation and changes in soil test phosphorus. Biol Fertil Soils. 2013;49(8):987–99.

91. Adeli A, Read J, Feng G, McGrew R, Jenkins J. Organic amendments and nutrient leaching in soil columns. Agron J 2017.

92. Dere AL, Stehouwer RC, Aboukila E, McDonald KE. Nutrient leaching and soil retention in mined land reclaimed with stabilized manure. J Environ Qual. 2012;41(6):2001–8.

93. Larney FJ, Olson AF, Miller JJ, Tovell BC. Nitrogen and phosphorus in runoff from cattle manure compost windrows of different maturities. J Environ Qual. 2014;43(2):671–80.

94.• Christel W, Bruun S, Magid J, Jensen LS. Phosphorus availability from the solid fraction of pig slurry is altered by composting or thermal treatment. Bioresour Technol. 2014;169:543–51. **This article evaluated slurry acidification, separation technology and thermal processing on P availability in soil amended with solid fraction of pig slurry. Separated solids increased soil P availability initially, which declined with time, whereas slurry chars and ashes showed less P availability, which remained constant or increased slightly over 12 weeks.**

95. Christel W, Bruun S, Magid J, Kwapinski W, Jensen LS. Pig slurry acidification, separation technology and thermal conversion affect phosphorus availability in soil amended with the derived solid fractions, chars or ashes. Plant Soil. 2016;401(1–2):93–107.

96. Tran QT, Maeda M, Oshita K, Takaoka M. Phosphorus release from cattle manure ash as soil amendment in laboratory-scale tests. Soil Sci Plant Nutr 2017:1–8.

97. Dai L, Li H, Tan F, Zhu N, He M, Hu G. Biochar: a potential route for recycling of phosphorus in agricultural residues. GCB Bioenergy. 2016;8(5):852–8.

98. Wang T, Camps-Arbestain M, Hedley M, Bishop P. Predicting phosphorus bioavailability from high-ash biochars. Plant Soil. 2012;357(1–2):173–87.

99. Uchimiya M. Changes in nutrient content and availability during the slow pyrolysis of animal wastes. In: He Z, Zhang H, editors. Applied manure and nutrient chemistry for sustainable agriculture and environment. Berlin: Springer; 2014. p. 53–68.

100. Michalovicz L, Michalovicz L, Dick WA, Dick WA, Cervi EC, Cervi EC, et al. Flue gas desulfurization gypsum as a chemical amendment to reduce the concentrations of phosphorus and suspended solids in liquid manure. Manag Environ Quali Int J. 2017;28(5):624–31.

101.• Watts DB, Torbert HA. Influence of flue gas desulfurization gypsum on reducing soluble phosphorus in successive runoff events from a coastal plain bermudagrass pasture. J Environ Qual. 2016;45(3):1071–9. **This article evaluated the effect of flue gas desulfurization (FGD) gypsum to reduce P concentrations immediately, 5 wk, and 6 mo (i.e., at the end of growing season) after poultry litter application to determine gypsum's effectiveness at controlling P loss over successive runoff events. Results revealed that FGD gypsum can reduce runoff dissolved P losses, and effective in succeeding runoff events during a growing season.**

102. Huang L, Moore PA, Kleinman PJA, Elkin KR, Savin MC, Pote DH, et al. Reducing phosphorus runoff and leaching from poultry litter with alum: twenty-year small plot and paired-watershed studies. J Environ Qual. 2016;45(4):1413–20.

103. Murnane JG, Brennan RB, Healy MG, Fenton O. Use of zeolite with alum and polyaluminum chloride amendments to mitigate runoff losses of phosphorus, nitrogen, and suspended solids from agricultural wastes applied to grassed soils. J Environ Qual. 2015;44(5):1674–83.

104. Peng X, Liang C, Shi L. Immobilization of phosphorus, copper, zinc and arsenic in swine manure by activated red mud. Environ Earth Sci. 2014;71(5):2005–14.

105. Sibrell PL, Penn CJ, Hedin RS. Reducing soluble phosphorus in dairy effluents through application of mine drainage residuals. Commun Soil Sci Plant Anal. 2015;46(5):545–63.

106. Wang JJ, Gaston LA. Nutrient chemistry of manure and manure-impacted soils as influenced by application of bauxite residue. In: He Z, Zhang H, editors. Applied manure and nutrient chemistry for sustainable agriculture and environment. Dordrecht: Springer; 2014. p. 239–66.

107. Maguire RO, Mullins GL, Brosius M. Evaluating long-term nitrogen-versus phosphorus-based nutrient management of poultry litter. J Environ Qual. 2008;37(5):1810–6.

108. Olson BM, McKenzie RH, Larney FJ, Bremer E. Nitrogen-and phosphorus-based applications of cattle manure and compost for irrigated cereal silage. Can J Soil Sci. 2010;90(4):619–35.

109.• Sadeghpour A, Ketterings QM, Godwin GS, Czymmek KJ. Nitrogen-vs. phosphorus-based manure and compost management of corn. Agron J. 2016;108(1):185–95. **This article evaluated soil test P changes with a change from N-based applications of manure and compost without incorporation to a P-based management system with immediate incorporation. After 5 yr, STP increased four- and six-fold for N- and P-based manure, respectively and by two- and four- fold for N- and P-based compost, respectively.**

110. Sadeghpour A, Ketterings QM, Vermeylen F, Godwin GS, Czymmek KJ. Soil properties under nitrogen-vs. phosphorus-based manure and compost Management of Corn. Soil Sci Soc Am J. 2016;80(5):1272–82.

111. Aronsson H, Liu J, Ekre E, Torstensson G, Salomon E. Effects of pig and dairy slurry application on N and P leaching from crop rotations with spring cereals and forage leys. Nutr Cycl Agroecosyst. 2014;98(3):281–93.

112. Ahmed SI, Mickelson SK, Pederson CH, Baker JL, Kanwar RS, Lorimor JC, et al. Swine manure rate, timing, and application method effects on post-harvest soil nutrients, crop yield, and potential water quality implications in a corn-soybean rotation. Trans ASABE. 2013;56(2):395–408.

113. Vadas PA, Jokela WE, Franklin DH, Endale DM. The effect of rain and runoff when assessing timing of manure application and dissolved phosphorus loss in runoff. JAWRA J Am Water Res Assoc. 2011;47(4):877–86.