soil systems

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Review

Livestock Manure and the Impacts on Soil Health: A Review

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Abstract: Soil health is the capacity of the soil to provide an environment for optimum growth and development of plants, while also ensuring the health of animals and humans. Animal manure has been used for centuries as a source of nutrients in agriculture. However, many other soil properties that contribute to soil health are affected when manure is applied. Bulk density, aggregate stability, infiltration, water holding capacity, soil fertility, and biological properties are impacted to various degrees with manure application. The goal of this paper was to compile the research findings on the effects of various livestock manure types on soil fertility, soil physical properties, soil biology and the yield of various cereal crops. Specifically, this paper summarizes results for poultry, cattle, and swine manure used in various cropping systems. Although there are conflicting results in the literature with regards to the effect of manure on various soil properties, the literature offers convincing evidence of beneficial impacts of manure on soil and the growth of crops. The degree to which manure affects soil depends on the physical and chemical properties of the manure itself and various management and environmental factors including rate and timing of application, soil type, and climate.

Keywords: manure; soil fertility; nutrients; soil organic carbon

1. Introduction

Manure was applied to crops as a slow release fertilizer by European farmers as early as 6000 B.C. [1]. Since the early years of agricultural development in the United States (U.S.), the 16th through the 19th century, manure has been considered an agricultural resource of significance [2]. Early publications from the United States Department of Agriculture (USDA) showed that it was believed that the neglect of this resource would lead to significant losses for the farm [3]. In these records, the fertilizing value of manure produced by the number of cattle in the U.S. at that time was estimated to be over 1 billion U.S. dollars [3]. These early records indicate that the USDA worked to increase the awareness of the nutrient value of manure among farmers. It also sought to encourage farmers to use manure rather than completely replacing it with commercial fertilizers. Economic and demographic developments after the second world war brought about an increase in agricultural production efficiency which resulted in the rise of large concentrations of livestock operations at the same time that commercial fertilizer production was also increasing [2]. In today's world, land degradation as a result of erosion, desertification, tillage, and unsustainable agricultural practices have caused a significant decline in productivity on some land [4]. On the other hand, the growth in world population has increased food demand, which requires an increase in agricultural production. These developments necessitate the implementation of practices that improve or restore the quality of agricultural land. Manure has been known to have beneficial effects on soil fertility and many other soil properties, contributing to the overall soil health. The Natural Resources Conservation Service (NRCS) defined soil health or soil quality as the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans [5]. One of the reasons that there has been an increasing interest in the use of organic nutrient sources and soil amendments is the fact that they are a source of carbon (C) which plays a role in improving soil quality and climate change mitigation. Heightened public and consumer's interest in organically produced crops and sustainable agriculture have also contributed to an increasing demand in organic soil amendments [6,7]. Sources of animal manure that are most used in the U.S. are cattle and chicken manure [8]. However, the use of other livestock manure such as horse, sheep, goat, turkey, and rabbit among others are not uncommon around the world. The USEPA (2013) [9] estimated that 900 million Mg of manure was generated from 2.2 billion livestock in 2007. In 2012, manure was applied to 275,000 farms translating to roughly 8.9 million hectares of cropland in the U.S. [10]. In an analysis of global data, Zhang et al. [11] showed a steady increase in manure nitrogen (N) production, globally, between 1998 and 2014 to 131 Tg N yr^{-1}. This study also showed that on a global scale, cattle contributed the most to global manure N production, contributing 43.7% to the total manure N production in 2014, while goats and sheep together produced one third of the global manure N in that same year [12]. More recent statistics published by the FAO [8] show that globally, most manure N applied to cropland came from poultry (chicken, duck, and turkey); contributing 7132 × 10^3 Mg of N to cropland (Figure 1). From these data we can infer that manure remains an important source of nutrients in agricultural production. Ultimately, the amount of manure applied to fields depends on different factors including the composition of the manure, the soil available nutrients, the crop to be grown, and environmental conditions [13]. The objective of this paper is to compile the existing research related to the effects of poultry, cattle, and swine manure on overall soil health. In this paper we approach soil health as consisting of a set of independent indicators, what Kibblewhite et al. [14] calls the "reductionist" approach. We consider various chemical, physical, and biological properties of the soil which all contribute to overall soil health. In addition, we evaluate the effect of these manure types on the yields in various grain cropping systems.

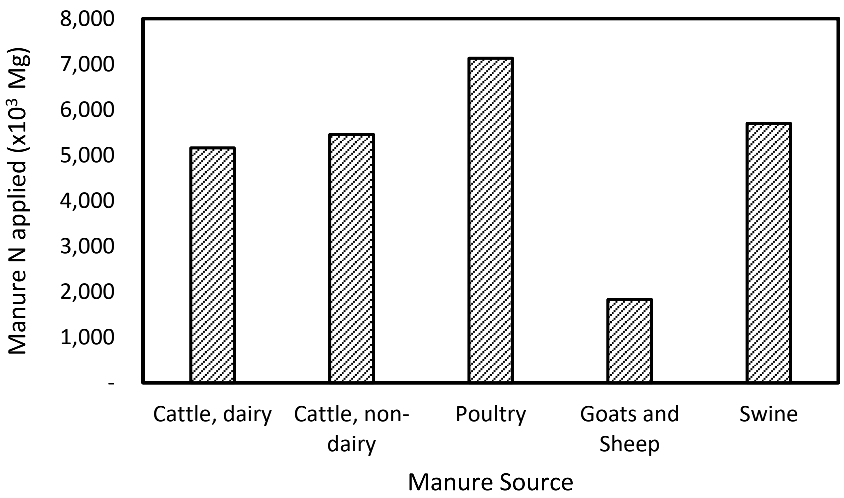

Figure 1. The nitrogen (N) applied to global land as manure coming from different livestock (Source: Food and Agriculture Organization (FAO, [8]).

2. Methodology

Several procedures and criteria were followed to put together this comprehensive review of literature. Firstly, the manure types that are most used on a global scale were identified. These manure types included cattle, poultry, and swine manure. Web search engines such as Google and Google Scholar™ were then used to find peer reviewed journal articles related to these manure types. Soil health indicators as defined by the NRCS [5] were listed and used to further narrow down the search and organize the studies in four main categories: soil chemical properties, soil physical properties, soil biological properties, and grain yield. When considering yield, this work focused solely on yield components in cereal grain crops, as these are the most widely grown crops globally [8]. These web searches were supplemented by studies accessed through the academic databases Agricola and Web of Science. Publications were also accessed through organizational websites such as USDA-NRCS, FAO, and the Soil Science Society of America. A wide range of studies were included in this review, including field, greenhouse, and laboratory studies. The studies were selected based on the following criteria: (1) they evaluated the effect of poultry, cattle manure, or swine manure on one or various soil properties; studies where the animal source of the manure was not clearly defined were not included; (2) they evaluated raw or composted manure; (3) they included at least two growth cycles or cropping seasons, or multiple study sites; (4) they reported numerical results and statistical analysis of the data.

Data from a total of 130 studies were included in this review. Data organization and visualization for this review was done using Microsoft® Excel.

3. Soil Nutrient Status

Soil fertility is defined as the available nutrient status of the soil and its ability to provide nutrients inherently and from external sources [15]. Various studies have reported an increase in macro- and micronutrients as a result of manure application [16–18], which in turn positively affects the growth and productivity of crops. Various chemical properties influence the overall fertility of soils including soil pH, cation exchange capacity (CEC), organic matter, and organic carbon (C). Manure application affects these different soil properties in addition to releasing nutrients through mineralization. The nutrient content of manure depends on several factors including animal type (Table 1), feed intake and water consumption by the animals [7], manure storage and management, and whether the manure is liquid or solid [19]. This section of the paper explores the effect of land applied manure on soil chemical properties, including selected nutrients and their availability.

Table 1. Total nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) concentrations in various manure types as reported in literature.

Manure Type	Total N	P_2O_5	K_2O	Reference
	g kg^{-1}			
Beef	3.7 (liquid) †	0.8	2.3	[20]
	5.5 (solid) † §	9	5	[21]
	10.5 (solid) † ¶	9	13	
	3.8 (1000- lbs. cow) †	2.0	3.2	[22]
	22.8 ‡	5.2	21.5	[23]
Dairy	3.9 (liquid) †	0.9	2.5	[20]
	5.5 (solid)	2.5	5.5	[24]
	4.5 (solid) †§	2	5	[21]
	12 (liquid) †	9	14.5	
	5.9 (1000-lbs dry cow)†	2.2	4.7	[22]
	3.3-8.8 (solid)	1.1–8.8	1.1–17.6	[25]
Swine	3.9 (solid) †	1.2	1.3	[20]
	5 (solid) † §	4.5	4	[21]
	4 (solid) † §	3.5	3.5	
	11.5 (300 lbs. finishing)	4.1	6.1	[22]
	2.2–15.4	1.1–34.2	1.1–9.9	[25]
Poultry	8.1 †	2.8	3.0	[20]
	16.5 (solid) † §	24	17	[21]
	28 (solid) † ¶	22.5	17	
	11.0 (broiler)	7.4	5.3	[22]
	19.3	28.9	14.7	[26]

† As-is basis, ‡ Dry weight; § No bedding or litter; ¶ Bedding or litter.

4. Total Nitrogen and Nitrate

Various studies have evaluated the effect of manure on total N [26,27] and nitrate [28] in the soil. The studies evaluated for this review show a general increase in soil total N, as the rate of manure increased (Table 2). However, work by Ferreras et al. [29] showed that an increase in the rate of manure from 10 to 20 Mg ha^{-1} did not increase soil N. In a study, investigating the effect of dairy manure and tillage in maize, Khan et al. [30] reported that the addition of 10 Mg ha^{-1} and 20 Mg ha^{-1} of dairy manure in addition to inorganic fertilizer increased soil N by 24% and 27%, respectively, compared to inorganic fertilizer alone. The release of N or any other nutrient from manure depends on the rate of mineralization. In general, the amount of a nutrient that is mineralized in manure is a function of manure characteristics, environmental factors, soil properties, and microbial activity [13]. Eghball et al. [13] also noted that manures containing large amounts of organic N release less plant-available N, since the organic N needs to be converted to inorganic N first. A study conducted by Hou et al. [31] showed that the application of chicken manure in combination with inorganic fertilizer significantly increased the N content in plant parts. Conversely, manure application has been associated with increased nitrate (NO_3) leaching from soils [32]. Application of manure at a time when the plant does not absorb N can cause significant losses of nitrate, especially during high rainfall events. Various studies have evaluated nitrate leaching from manure [32,33]. Van Es et al. [33] confirmed that timing of manure application and soil type affected the amount of nitrate concentration in drainage waters; manure applications made in late fall reduced the concentration of nitrate N concentration by 4 mg L^{-1} relative to early fall applications made in maize. This study showed that the lowest nitrate N concentrations were achieved with spring applications. The dependence on environmental factors such as moisture and temperature and the potential losses make the availability of N from manure highly variable and unpredictable. As a result, producers often over apply manure to land which in turn becomes a potential problem to the environment. The studies that were reviewed showed a general increase in total N with increase in the rate of manure applied (Table 2), however, this increase was not consistent across all studies. A study by Mokgolo [34] showed that the addition of 20 Mg per ha produced a slight reduction or no change in total N. A study by Adeli et al. [35] however, showed that the application of 2.2 Mg of manure per ha increased the total soil N by 110 mg kg^{-1}; doubling the application to about 4.5 Mg ha^{-1} increased soil N by an additional 30 mg kg^{-1} relative to the control. Another study showed that increasing the poultry manure application rate from 5 to 10 Mg per ha did not cause a significant increase in total soil N [26] (Table 2). These findings confirm the unpredictability of the release of nutrients from manure.

Table 2. A review of total nitrogen (N), soil test P, and exchangeable potassium (K), relative to the control treatments (no manure and no fertilizer) as a function of manure application.

Study Site	Nutrient		Total N	Soil Test P	Exchangeable K	References
	Source	Quantity Mg ha^{-1}		mg kg^{-1}		
South Africa	-	0	450, 570 †	7.6, 2.0	156, 163.8	[34]
	Poultry	20	420, 570	9.3, 2.7	252.3, 417.3	
	Cattle	20	500, 650	31.0, 30,3	250.8, 265.2	
	Poultry + Cattle	20 + 20	370, 780	8.5, 29.4	223.1, 553.8	
United States	-	0	650, 600 †	22, 55		[35]
	Poultry	2.2	860, 700	38, 97		
	Poultry	4.5	890, 770	64, 119		
	Poultry	6.7	980, 890	97, 146		
China	-	0	980	5.8	144	[36]
	Cattle	75	1220	12.7	193	

Table 2. *Cont.*

Study Site	Nutrient		Total N	Soil Test P	Exchangeable K	References
	Source	Quantity Mg ha^{-1}		mg kg^{-1}		
Nigeria	-	0	900,1100 ‡	8.3, 9.9	44.9, 163.8	[37]
	Poultry	7.5	3100, 3600 ‡	13.5, 15.4	232.1, 368.6	
Nigeria		0	600	9.1, 6.9	50.4, 68.4	[26]
	Poultry	5	800,700 †	12.5, 14.2	82.8, 140.4	
	Poultry	10	900,800	13.2, 17.8	111.6, 151.2	
Nigeria	-	0	900, 1200 †	10.6, 9.0		[38]
	Poultry	10	1700, 3500	18.2, 18.9		
	Poultry	25	5100, 4800	30.9, 37.1		
	Poultry	40	2800, 5200	33.0, 44.3		
	Poultry	50	3100, 5600	32.6, 45.6		
Argentina	-	0	950, 1240 †			[29]
	Poultry	10	1050, 1550			
	Poultry	20	1080, 1490			
United States	-	0		51.8, 65.3 §	19.5, 29.4	[23]
	Cattle	10		93.6, 101.3	45.9, 44.6	
	Cattle	20		153.6, 162.8	59.9,65.4	
	Cattle	30		205.7, 155.4	75.6, 91.9	
	Cattle	40		236.1, 209.3	96.7, 126.4	
Canada	-	0	1300			[39]
	Cattle	20	1400			
	Cattle	40	1500			
	Cattle	60	1600			

† numbers separated by a comma indicate the numbers in different years or seasons at a single location; ‡ numbers separated by a comma indicate the numbers at two different locations averaged over multiple years; § numbers separated by a comma indicate the soil nutrient content immediately after manure application and 8 weeks after incubation.

5. Phosphorus

Repeated manure applications can lead to excessive P levels in soil [40]. One of the additional challenges this brings, is the potential for phosphorus (P) runoff causing eutrophication in surface waters. Manure contains both organic and inorganic P. The inorganic orthophosphates are the form in which P is taken up by plants and it generally constitutes 45% to 90% of the P in manure [41], making manure an important source of P. However, the problem of excessive P in soils to which manure has been applied is caused by the narrow N: P ratios in manure relative to the N: P ratio in plants [41]. This means that manure needs be applied in large amounts to supply the N required by plants. As the crop removes more N than P from the manure, P build-up is inevitable [40]. A study conducted by Butler et al. [42] showed a 10-fold increase in soil-P with the addition of 70 Mg ha^{-1} of composted dairy manure relative to the treatment with no compost application. The literature generally shows a linear increase in available phosphorus (P) with an increase in the amount of manure applied to soil (Table 2). The increase in available P after manure application to soil is a function of various soil characteristics including soil pH, organic matter content, and clay type [43]. The nutrient content and thus the P content of manure can be highly variable and depends on animal species, diet composition, manure storage, type of bedding, and moisture content [44]. Barnett [45] noted the importance of not just knowing the total P content, because the value of manure for use as a fertilizer hinges on P that is plant available. In addition to soil properties, manure characteristics also affect the portion of P that becomes plant available. There are various forms of extractable P in manure, herein arranged in decreasing order of plant availability: (1) water soluble, (2) bicarbonate-extractable P, (3) sorbed P that is soluble in sodium hydroxide, and (4) acid extractable P [31]. Swine and poultry manure have been shown to have higher concentrations of total P, while dairy manure contains the highest amount of water-soluble P. Fuentes et al. [44] noted that the factor that affects the manure P content the most is the form in which P is provided in feed. Phytic acid is the main form of P in cereal grains [46]. Swine and poultry manure generally contain more phytic P than cattle manure. The reason is that chicken and swine contain less phytase to break down phytic acid than cattle does [41,44]. Phytic P, unlike phosphate, easily forms insoluble complexes in soil, making it less plant available and susceptible to loss through runoff [46].

6. Trace Elements and Micronutrients

Various works have reported on the effect of applied manure on trace elements in soil [47–49]. Trace elements are defined as microelements with a concentration of less than 100 mg kg^{-1} on average [50]. Some of these trace elements are essential for the growth and productivity of plants and animals; these are called micronutrients [51]. Work by Nikoli and Matsi [48] has shown that micronutrient availability increases with manure application. In this study, it was shown that after nine years of manure application, extractable Cu, Zn, Mn, and B significantly increased relative to the control and inorganic nutrient treatments. Japenga et al. [52] postulated that adding liquid manure to soil aids in solubilization of metal micronutrients. This can be attributed to the formation of water-soluble complexes between organic ligands and the metal micronutrients [53,54]. A study conducted by Sheppard and Sanipelli [49], in which various manure types were tested for approximately 60 different elements, showed an accumulation of trace elements, but primarily Zn, in manured soils. The accumulation of trace elements was correlated with P accumulation in those soils. Similarly, work by Benke et al. [47] found that long-term manure application increased total Cu and Zn in the soil, with significantly elevated levels for Zn in the topsoil after application of 180 Mg ha^{-1} manure. In a study conducted by Sager [55] the highest concentrations of Zn were found in pig manure relative to cattle manure, pig dung, poultry dung, biogas manure, compost, and sewage sludge at nearly 1200 mg kg^{-1}. These levels of Zn in manure would qualify this as hazardous waste based on Austrian standards [55]. Research has established that as with other nutrients, trace elements in manure are strongly related to the trace elements in animal feed [49,56]. These findings are further confirmed by Chaudhary and Narpal [57] who found that DTPA extractable Zn, Fe, Mn, and Cu increased with increasing rate of farmyard manure. The increase of these elements with increasing rates of manure is likely due to the formation of complexes with organic ligands, preventing them from being adsorbed to the soil complex or precipitating out of soil solution [57].

7. Soil Acidity

The literature shows an inconsistent relationship between manure and the soil pH. The literature is replete with works that show an increase in pH as a function manure application [58–60]. Ano and Ubochi [59] reported a consistent increase in soil pH with the application of 10, 20, 30, and 40 Mg ha^{-1} of rabbit, swine, goat, chicken, and cow manures. The increase in the pH as a function of manure application has been attributed to the calcium carbonate and bicarbonate found in manure [23,61], the addition of cations such as Ca and Mg [62], and the presence of organic anions in the manure which can neutralize H^+ ions [63]. The presence of these substances in the manure depends on the animal diet. Narambuye and Haynes [64] found that manure types with elevated levels of $CaCO_3$ increased the pH to a greater degree in comparison to manure with lower levels of $CaCO_3$; poultry and pig manure had higher levels of $CaCO_3$ relative to cattle manure because of their $CaCO_3$ rich diet in comparison to an all grass diet for the cattle. This study also showed that increasing $CaCO_3$ resulted in increasing proton consumption capacity for the different manure types tested and that as pH increased Al^{3+} in solution decreased. In contrast, Hao and Chang [65] found a steady decrease in the soil pH with increasing rate of cattle manure application under irrigated and non-irrigated growing conditions. In a study evaluating chemical changes in soil as a result of cattle feedlot manure applications, Chang et al. [66] found a decrease of 0.3–0.7 in the soil pH over an 11-year period of manure application. Similarly, O'Hallorans et al. [58] found a linear decrease with an increasing rate of chicken manure. The decrease in soil pH is explained by the acidifying effect of nitrification and the concomitant increase in electrical conductivity; the increase in cations replace H^+ ions on the exchange sites [58]. Tang and Yu [67] found that the concentration of organic anions, the initial soil pH, and the degree of residue composition effect the degree of acidification of soil by organic residues. A long-term study by N'dayegamiye and Cote [39] showed that there was no increase or decrease in the soil pH as a function of farmyard manure or pig slurry. This was attributed to the fact that this soil had been limed before the experiment. The variability in results show that the effect of manure on soil acidity depends on the properties of the manure type and the soil conditions [60].

8. Cation Exchange Capacity and Ca, Mg Saturation

Cation exchange capacity (CEC) is a measure of the retention of positively charged ions on the surface of soil particles [68]. The CEC of soil generally increases with the increase of clay content and organic matter. Studies have shown that there is an increasing trend in the CEC with an increase in the rate of applied manure (Table 3). This trend can be attributed to the organic matter in manure and the increasing pH with manure application [69]. A study by Steiner et al. [27] showed that the application of chicken manure at 47 Mg ha^{-1} organic matter content increased the CEC by more than 10 cmol kg^{-1}, with significantly higher concentrations of base cations in comparison to the control plots. Furthermore, Miller et al. [70] found a significant linear relationship between the rate of manure application and the CEC after 13 years of application, while no significant relationship was found after just one year of application. However, this increase is not consistent across all the studies evaluated for this review. Mokgolo [34] found a decrease of 4.67 cmol kg^{-1} in the CEC with the application of 20 Mg ha^{-1} of manure relative to the control, which was consistent with a decrease in the exchangeable Ca and Mg (Table 3). Another study, evaluating the effect of long-term manure application on CEC, found that applying cattle manure at 90 Mg ha^{-1} increased the CEC by 5.6 cmol kg^{-1} under non-irrigated conditions. Under irrigation the application of the same rate of manure increased the CEC from 19.6 cmol kg^{-1} to 33.5 cmol kg^{-1} [65]. The concentration of extractable Ca, Mg, and Na were lower in the poultry manure treated plots relative to the control treatment. In addition, this study showed an increase of the CEC with the application of cow manure. A possible explanation is that the chicken manure had a higher C/N ratio relative to the cow manure. The higher C/N ratio reduced the rate of decomposition and therefore the CEC. Miller et al. [70] postulated that decomposition of organic matter increases the CEC due to an increase in the negatively charged sites on carboxyl and phenolic groups. Similarly, Muller [71] noted that the CEC of plant residue is closely related to the degree of decomposition of organic residue.

Table 3. A review of cation exchange capacity (CEC), exchangeable potassium (K), calcium (Ca), and magnesium (Mg) relative to the control treatment as a function of manure application.

Study Site	Nutrient		CEC	Ca	Mg	References
	Source	Quantity Mg ha^{-1}	Cmol kg^{-1}			
South Africa	-	0	18.2, 17.7 †	6.7, 7.2 †	2.2, 2.4 †	[34]
	Poultry	20	13.5, 15.6	5.5,6.3	1.9, 2.2	
	Cattle	20	19.1, 21.0	8.5, 8.7	2.7, 3.0	
	Poultry + Cattle	20 + 20	16.1, 17.2	5.6, 7.5	2.1, 3.1	

Table 3. *Cont.*

Study Site	Nutrient		CEC	Ca	Mg	References
	Source	Quantity Mg ha^{-1}	Cmol kg^{-1}			
Canada	-	0	25.2, 25.0, 27.3 †			[70]
	Cattle ¶	13	25.9, 26.6, 28.7			
	Cattle	39	26.7, 26.7, 29.8			
	Cattle	77	26.8, 28.4, 31.6			
	Cattle ¶¶	13	26.5, 25.5, 28.5			
		39	25.4, 27.2, 29.1			
		77	27.2, 25.9, 30.2			
Nigeria	-	0		2.0, 1.2 ‡	0.9, 1.3 ‡	[37]
	Poultry	7.5		3.7, 3.5 ‡	2.5, 2.1 ‡	
Nigeria	-	0	2.8, 3.6 †	2.1, 2.1 †	0.5, 0.9 †	[26]
	Poultry	5	4.0, 4.9	2.8, 3.0	0.7, 1.3	
	Poultry	10	4.5, 6.6	2.6, 4.2	0.7, 1.7	
Canada	-	0	19.5, 19.6 §	15.4, 15.8 §	2.2, 2.3 §	[65]
	Cattle	30	20.7, 23.7	13.7, 16.1	2.7, 3.7	
	Cattle	60	24.2, 28.4	15.0, 19.0	3.6, 4.7	
	Cattle	90	25.1, 33.5	14.5, 21.3	4.2, 6.0	
Canada	-	0		16.1	6.5	[72]
	Cattle	100 £		16.5	6.6	
	Cattle	400 £		18.0	6.7	
Puerto Rico	-	0		1.7	0.5	[58]
	Poultry	5		1.8	0.5	
	Poultry	10		2.0	0.5	
	Poultry	15		2.4	0.6	

† numbers separated by a comma indicate the numbers in different years or seasons at a single location; ‡ numbers separated by a comma indicate the numbers at different locations averaged over multiple years; § numbers separated by a comma indicate the numbers under two different growing conditions non-irrigated and irrigated, respectively. ¶ composted manure with straw; ¶¶ stockpiled manure with straw; £ Presented as kg N ha^{-1}.

9. Electrical Conductivity

Electrical conductivity (EC) is the ability of a substance to conduct an electrical current [73]. When the effect of manure on soil EC was considered, literature showed that increasing manure application increases EC. Soil EC is related to various soil properties such as organic matter content, texture, moisture content, salinity, and CEC [74]. Electrical conductivity in soil has been primarily linked to exchangeable K^+ [58,75,76]. Work by O'Hallorans et al. [58] showed a linear increase in the EC with the increase in the rate of manure applied. This work reported an increase of 1.73 mmho cm^{-1} with the application of 15 Mg ha^{-1} of chicken manure relative to the treatment without any manure. The experimental design of this study, conducted in Puerto Rico, was a randomized complete block design in a split plot arrangement. Main plots consisted of 4 N rates and subplots contained 4 chicken manure rates: 0, 5, 10, and 15 Mg ha^{-1}. The increasing EC with increasing manure application makes sense as it can be related to increasing organic matter, which supplies a pool of nutrients and ions that can be released in the soil solution [77]. Similar to the findings by O'Hallorans et al. [58], Miller et al. [78] found an increase in EC with increasing rate of beef manure. The study showed that treatments where 77 Mg ha^{-1} of stockpiled manure with straw had been applied, the EC increased to 7 mmho cm^{-1}, while the unamended treatment had an EC of 0.8 mmho cm^{-1}. The study compared manure with straw bedding to manure with woodchips and found that woodchips were better for keeping the EC below levels that would inhibit growth of the most common crops (<4 mmho cm^{-1}). It is interesting to note that straw as bedding also produced higher concentrations of soluble cations and anions in the surface soil, which correlates to the higher EC with manure containing straw bedding. These results imply that the effect of manure on EC is highly dependent on the rate and type of manure and the type of bedding used.

10. Soil Organic Matter and Carbon

One of the biggest challenges in soil health is the depletion of soil organic matter (SOM) as a result of long-term cultivation of land [79]. Studies have shown, however, that the addition of animal manures to soil increases SOM or retards the process of SOM depletion [80,81]. The studies used in this review consistently show an increase in SOM with manure application. In a tomato study, Ewulo et al. [38] found that with the application of 10, 25, 40, and 50 Mg chicken manure per hectare (ha), SOM levels respectively increased by 0.85, 1.50, 1.72, and 1.95 percentage points relative to the control treatment with no addition of manure. These findings agree with work by Deryqe et al. [82] who found that applying chicken manure at rates of 5, 10, and 15 Mg ha^{-1} increased SOM by 0.44, 0.96, and 1.68 percentage points, respectively. Similar results are found with the addition of cow manure to soil. In one year of a three-year study conducted by Butler et al. [42], the addition of 35 Mg ha^{-1} dairy manure compost significantly increased SOM by 8.7 g kg^{-1} which represented an increase of 73% relative to the untreated check (Table 4). There was no difference in the SOM content with the higher rates of applied compost. The study was conducted over 3 years and evaluated the effect of dairy manure compost on silage quality and soil properties. Manure compost was applied only in the first year of the study, as a result SOM kept decreasing in consecutive years. This shows that the addition of manure slows down the depletion of SOM.

Table 4. Effects of Dairy Manure on Organic Matter (Adapted from (Butler et al. [42]).

Treatment	Organic Matter (g kg^{-1})
Untreated check	12.0
Inorganic fertilizer (336N-49P-93K kg ha^{-1})	14.8
Dairy Compost (Mg ha^{-1})	
0	15.6
35	20.7
70	29.3
105	29.3

The buildup of SOM as a function of manure application depends greatly on the manure type and the type of manure bedding [83,84]. Manure that contains bedding high in organic matter will produce a greater increase in SOM compared to manure with low organic matter bedding [84]. The benefits of building or maintaining SOM are many; some of which are reduced erosion and runoff [85], improved infiltration [86], improved soil structure [87]. One aspect that is receiving much attention is the contribution of organic amendments to the carbon (C) cycle [88,89]. Various works have stressed the importance of soil organic carbon (SOC) in mitigating the impacts of climate change [90,91]. There is great disparity in what has been reported in the literature on the relationship between manure and SOC. In an evaluation and analysis of the cattle manure studies included in this review that reported on SOC, no significant relationship was found between the cattle manure rate and SOC (Figure 2). The poor relationship illustrates the conflicting results found in literature when it comes to the relationship between manure and SOC. In a report by the World Bank [92] it was estimated that in Africa, Asia, and Latin America, carbon sequestration rates were, respectively, 23%, 109%, and 267% higher on soils where manure had been applied compared to soils treated with inorganic fertilizer. Liu et al. [36] found that in comparison to the control and inorganic fertilizer treatments, the addition of farmyard manure to soil alone and in combination with N and P resulted in higher SOC contents of 9.98 g kg^{-1} and 10.52 g kg^{-1}, respectively. A study by Wang et al. [93] showed that over a 23-year period, pig manure alone and in combination with N, P, and K increased SOC by 25% and 30% relative to the treatment without any additional fertilizer or manure. In contrast, this study showed that where no nutrients had been applied, initial SOC decreased by 9% in the top 20 cm of soil. Consistent with these findings, Manna et al. [94] showed that SOC in unfertilized plots declined by at least 15.5%, whereas SOC was either maintained or increased with the addition of fertilizer and manure relative to initial levels. Other research has shown, however, that the addition of manure to soil over multiple years decreased SOC, but at a slower rate than in unfertilized plots [95]. These results are consistent with work by Ren et al. [96], who reported that the addition of manure did not increase SOC. Tan et al. [97] postulated that the dynamics of SOC can be somewhat explained by studying the way C is allocated in the different fractions of soil organic matter. The light fraction of SOM is defined as a fraction that is sensitive to changes in management practices [97,98] and shows a high correlation with N mineralization [97,99,100]. Microbes decompose organic matter, using the carbon as source of energy, and release nutrients into the soil. Increased microbial respiration because of the addition of organic matter can be indicated as the source of the decrease in SOC [101] as found in some studies.

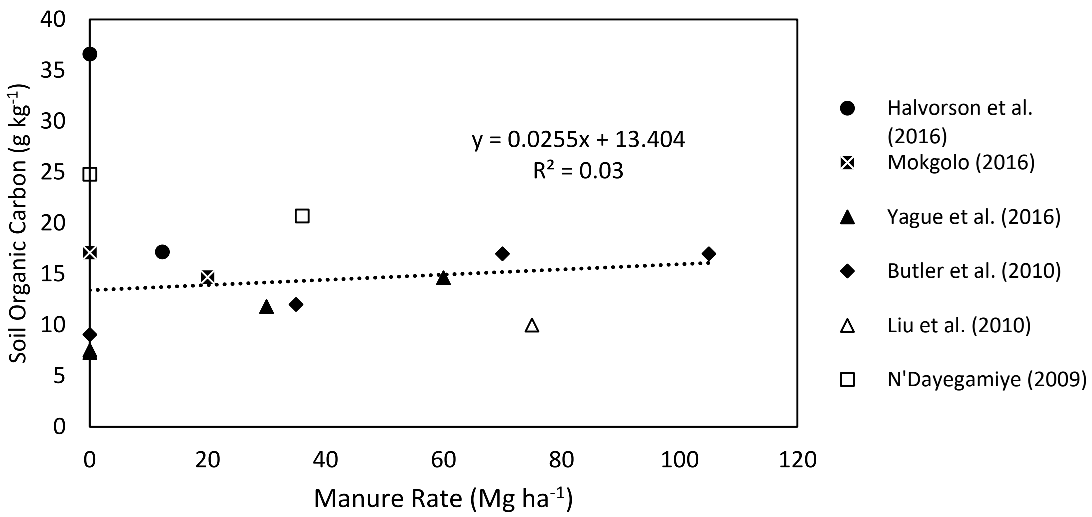

Figure 2. Relationship between cattle manure and soil organic carbon (SOC). Included in this dataset are six different studies evaluating the relationship between cattle manure and soil properties.

11. Manure and Soil Physical Properties

The addition of manure to soils in general does not only impact soil chemical properties but it also greatly impacts soil physical conditions such as soil water [86,102], structure [86], bulk density [102], and resistance against erosion [103,104]. In this section we specifically focus on the effects of manure on soil water, soil temperature, and bulk density.

12. Soil Water and Soil Hydraulic Properties

One of the challenges we face in agriculture is the scarcity of water [105]. According to Mekonnen and Hoekstra [106], an estimated 4 billion people live with severe water scarcity at least one month out of the year. With the growing world population and the increase in food demand, the pressure on this already scarce resource will only increase. One of the ways to mitigate this problem is to increase on-farm water retention which can be accomplished by applying organic soil amendments to land. Various studies have shown a relationship between SOM and water infiltration, soil water holding capacity, or water content [103,107,108]. Organic matter promotes soil aggregation which allows the formation of pores and thus storage of water [109]. The effect of organic matter on soil water retention has been documented extensively and conclusions vary [110–114]. Minasny and

McBratney [111] showed a small increase in soil water with increase in organic C, but they argued that rate of organic C sequestration and the presumed increase in available water did not correspond and was negligible. However, other works have shown a significant effect of organic matter on the retention of water [110,112–114]. Ankenbauer et al. [112] found that the effect of organic matter on water retention was more profound on low clay content soil. Other work has shown that organic matter increases the soil's adsorbing capacity allowing for improved water retention [113]. Various properties of the organic matter itself, however, may contribute to the increase in soil water retention. In a study evaluating hydraulic properties of biochar amended soil, Ni et al. [114] found that field capacity, permanent wilting point, and available water content increased by 38%, 58%, and 14%, respectively, relative to bare soil. In addition, field capacity and permanent wilting point increased by 43% and 57%, respectively, when biochar was added to grass covered soil. This work noted that the pores inside biochar might have acted as additional capillaries allowing for increased water storage. Soil water holding capacity or available water capacity is the amount of water that a soil can hold for use by plants; it is the water that is held between field capacity and permanent wilting point [115]. The water content of a soil is defined as the total amount of water present in the soil and is expressed as gravimetric or volumetric water content [116]. The volumetric water content can be calculated by multiplying the mass water content by the ratio of the bulk density and the density of water [117]. The literature shows varying results pertaining to the effect of manure on soil water content. In a study evaluating the effect of feedlot manure on various soil physical properties, Miller et al. [118] found little to no significant difference in soil volumetric water content based on manure type and bedding in the surface (0–5.5 cm) soil over two years of the study. However, Ahmed et al. [119] found that soil treated with poultry or farmyard manure retained more water than untreated soil. Similarly, Nyamangara et al. [108] found that the addition of cattle manure to soil increased water retention in comparison to the control treatment where no manure had been applied. In a study evaluating the effect of farmyard manure on soil physical and chemical parameters, SchjØnning et al. [103] found a higher water retention for farmyard manure compared to NPK fertilizer and unfertilized treatments at depths of 8–12 cm and 30–35 cm. In an early study by Bouyoucos [107] it was shown that adding 54 Mg of partially decomposed horse-cow manure to a sandy loam increased the percent by volume soil water content by 10.2 percentage points relative to the plots were no manure had been applied. In more recent published work by Wang et al. [120] it was shown that the application of 15 Mg ha^{-1} and 22.5 Mg ha^{-1} significantly increased soil water storage at the tasseling stage of maize in comparison to lower rates of manure and synthetic fertilizer. These findings suggest that manure application affects soil water. The increase in soil water retention as a function of manure application is likely an effect of the organic matter on soil porosity. Infiltration, as a soil physical term, is defined as the process by which water enters the soil by downward flow through the soil surface [117]. When the infiltration capacity of a soil is saturated, ponding or runoff occurs [121]. This means that the more water infiltrates into the soil, the less water is lost through runoff. Yague et al. [122] showed that with manure applications, runoff was reduced by as much as 82% under no till and by 42% in plots that had been chisel plowed. Manure may impact infiltration and hydraulic conductivity due to its effect on soil aggregation [123], especially when the manure is rich in Ca and Mg ions [124].

13. Soil Temperature

Soil temperature and temperature fluctuations affect various soil health indicators. Soil temperature has been shown to affect soil biological activity [125,126], nutrient cycling [127] and nutrient uptake [128]. There are few works that report on the effect of manure on soil temperature. There are some studies, however, that have reported on the relationship between other organic amendments and soil temperature. In a study evaluating the effect of poultry manure on various soil properties, Agbede et al. [37] found that the addition of 7.5 Mg ha^{-1} manure consistently decreased the soil temperature by 2 to 2.3 degrees Celsius. The lower temperatures associated with the application of organic amendments is likely caused by improved water retention and protection of the soil against large temperature fluctuations [129]. In contrast, Deguchi et al. [130] found that soil temperature increased with increasing rates of applied compost. This increase in soil temperature was attributed to the reduced evaporation with the application of compost to the soil [130]. Similarly, Unger and Stewart [131] showed that the addition of farmyard manure resulted in a reduction in evaporation, a direct effect of manure on soil physical properties. Evaporation has a cooling effect on the soil surface, thus a reduction in evaporation suppresses the cooling of the soil surface. On the other hand, improved soil structure, increased porosity and hydraulic conductivity, resulting from manure application [12,108], could cause water to penetrate deeper into the soil causing the soil surface to dry and warm up faster [130]. In addition, the increased soil porosity due to the presence of organic matter, decreases the thermal conductivity of soil, thereby allowing the organic matter to insulate the soil against increasing temperatures during the summer [132] and warm up the soil during the winter, although its effect during the winter would be considered negligible due to the insulating effect of snow on the ground. The complexity of the relationship between manure and soil temperature is further confirmed in a study conducted by Rees et al. [133] who found that the addition of manure on potato hills with a 8% slope reduced the soil temperature by 0.32 °C relative to the control treatment, while manure on the 11% slope increased the soil temperature by 1.03 °C, from 16.16 °C to 17.19 °C. Based on these findings it becomes apparent that the effect of manure on soil temperature would be affected by the time of year, the amount of manure applied, and properties of the manure applied. Although Deguchi et al. [128] found no relationship between chemical characteristics of compost and soil temperature, the literature suggests that varying rates and characteristics of manure affect various soil physical properties including hydraulic properties which may influence soil temperature [134].

14. Bulk Density

Various studies have shown a correlation between organic matter content [135,136] or organic amendments [137,138] and bulk density. Bulk density is an important indicator of soil compaction and depends on the density of mineral particles, organic matter, and their packing arrangement [139]. Bulk density is the weight of dry soil per unit bulk volume of soil, which includes solids plus pore space [115]. The more solids a soil has relative to pore space, the higher the bulk density for that soil [137]. A review by Khaleel et al. [140] showed a consistent decrease in bulk density with the application of various organic waste products in both long-term and short-term studies. Compiled data from chicken manure studies show a negative linear relationship between the rates of manure applied and soil bulk density (Figure 3). Agbede et al. [141] showed a 28% decrease in the bulk density when 30 Mg ha^{-1} of chicken manure was applied to soil. Other studies have shown similar results. A study conducted by Celik et al. [142] showed that the addition of compost or manure at 25 Mg ha^{-1} year^{-1} resulted in the lowest bulk densities in comparison to synthetic fertilizer. This study found that the average bulk density at a depth of 0–15 cm was 1.21 mg m^{-3} in plots where manure had been applied compared to 1.40 mg m^{-3} in plots where synthetic fertilizer, N, P, and K had been applied. Ahmad et al. [7] found that a 4%, 8%, and 9% decrease in bulk density resulted from cow manure applications of 165, 335, and 670 kg N ha^{-1}, respectively. The decrease in bulk density as a result of manure application is primarily caused by the increase in porosity. Soil porosity is the volume of space in-between soil particles that can be filled with water and/or air. In a study conducted by Meng et al. [143] results showed that long-term annual manure applications decreased the bulk density and increased the total porosity of the soil. This study showed that 20 years of manure application increased the total porosity of the soil by 11.9%, while the bulk density decreased by 13.1% relative to the control treatment. Khaleel et al. [140] called the increasing pore space with mixing in of organic waste with the denser mineral fraction of the soil, the dilution effect. Treatment of the soil with organic products such as manure release bacterial gums and polysaccharides that aid in binding soil particles together, thus increasing aggregation and decreasing the bulk density [144].

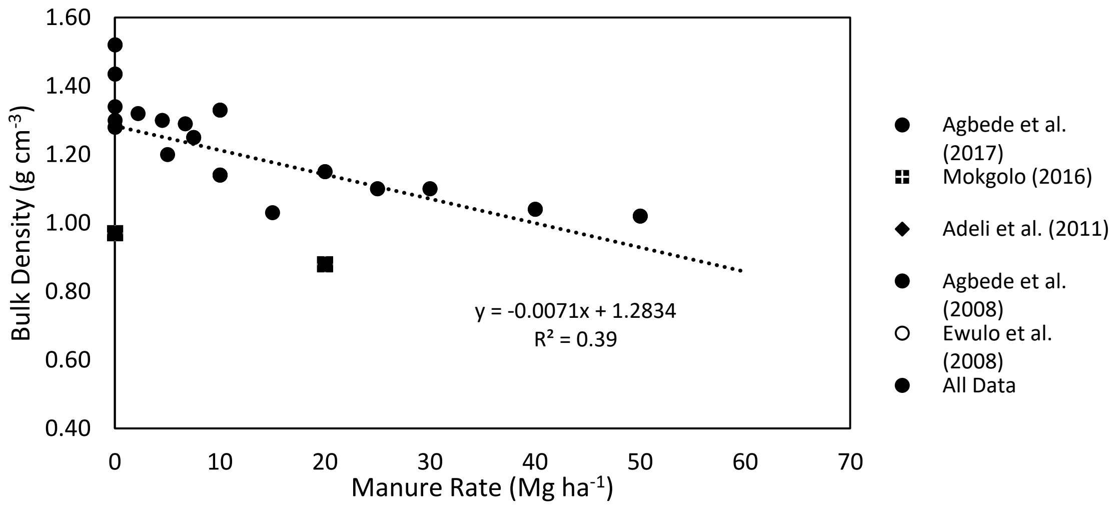

Figure 3. The relationship between the rate of chicken manure and soil bulk density as derived from data from five different studies.

15. Soil Biology

Improving soil health requires a holistic approach that does not only supply nutrients in adequate and balanced amounts but also enhances the soil biological system. In particular, soil microorganisms are a hallmark of soil as a living system that in some instances solely dictates the rate of reactions that takes place during nutrient cycling [145]. In this section, we reviewed the significance of livestock manure in improving soil microbial status and ultimately to improve soil fertility. In studies examining the role of manure in soil fertility, Parham et al. [146] and Hamm et al. [147] demonstrated that manure application enhances the bacterial community in the soil, thus leading to an improvement in soil productivity. Further, manure application also increases fungal diversity in the soil and when applied with inorganic fertilizers, reverses the declining microbial biodiversity trend associated with inorganic nutrients applied alone [148]. In summarizing past studies, we found manure-treated plots to have a large population of microorganisms than the unfertilized check plots (Table 5). These studies found bacteria to thrive well and grow large in population size in the soil treated with livestock manure. Because manure is capable of sustaining or slowing the rate at which soil pH declines over time [149], it is, therefore, not surprising that the bacterial community was richer and more even in manure treated plots [146]. Declining soil pH towards the strongly acidic regions begins to favor fungal population at the expense of bacterial population as their dominance wanes [146]. Regardless of the dominant microorganisms, this review demonstrates that applying manure is invaluable for improving soil fertility by increasing the population of microorganisms that are useful for nutrient transformations in the soil.

Table 5. A review of soil microbial population in manure vs check or inorganic nutrient sources.

Site of Study	Nutrient		Microbial		Reference
	Source	Quantity (Mg ha^{-1})	Type	Population (cfu g^{-1})	
Japan	-	0	Fungi	10^5(2.1–2.7) †	[150]
	Cattle manure	40	Fungi	10^5(2.3–3.2)	
	-	0	Bacteria	10^7(3.0–5.0)	
	Cattle manure	40	Bacteria	10^7(3.0–5.6)	
Israel	-	0	Fungi	1.2×10^4	[151]
	Cattle manure	90	Fungi	1.6×10^4	
	-	0	Bacteria	7.0×10^7	
	Cattle manure	90	Bacteria	8.3×10^7	

Table 5. *Cont.*

Site of Study	Nutrient		Microbial		Reference
	Source	Quantity ($Mg\ ha^{-1}$)	Type	Population ($cfu\ g^{-1}$)	
China	-	0	Bacteria	10^6(0.8, 1.5, 0.8) ‡	[152]
	Cattle manure	80	Bacteria	10^6(1.6, 4.4, 4.5)	
	-	0	Fungi	10^3(4.1, 4.1, 4.9)	
	Cattle manure	80	Fungi	10^3(3.5, 2.7, 1.5)	
	-	0	Actinomycetes	10^5(2.4, 2.0, 1.7)	
	Cattle manure	80	Actinomycetes	10^5(2.7, 6.6, 10.5)	
Canada	-	0	Heterotrophs	10^3(4, 6.2, 6.8)	[153]
	Cattle manure	120 §	Heterotrophs	10^3(1.6, 9.0, 70.0)	
	Cattle manure	240 §	Heterotrophs	10^3(1.6,11.0, 96.0)	
	Cattle manure	480 §	Heterotrophs	10^3(4.9, 11.0, 5.7)	
	Urea	50 §	Heterotrophs	10^3(5.8, 4.7, 5.8)	
	Urea	100 §	Heterotrophs	10^3(5.1, 9.7, 1.1)	
	Urea	200 §	Heterotrophs	10^3 (0.6, 6.1, 71.0)	

† the population presented as a range; ‡ the numbers separated by coma within each parenthesis indicate the microbial colony forming units (cfu) in different years or seasons. The number outside the parenthesis is multiplied by the ones inside to obtain the total population size; § Presented in kg N ha^{-1} of cattle manure.

Further, soil microorganisms contribute to the building of SOC which is an important indicator of soil quality [12]. The strong association between light fraction-C and culturable microbial count provides some evidence that soils with a large microbial population may also have more SOC [154]. This was further reiterated by Zhang et al. [12] who found SOC to be related to soil microbial C. As a result, applying livestock manure to the soil provides a mechanism for improving soil microbial status as well as SOC.

The increase in microbial population due to manure application is also vital for improved nutrient uptake [148,155,156]. N'dayegamiye and Cote [39] indicated that increased microbial population associated with manure application also led to an increase in potentially mineralizable N. In the same study, the authors found potentially mineralizable N to be larger at high manure application rates and that a strong association exists between organic matter and microbial activity and N mineralization potential. Because of this, nutrient availability for crop uptake may be increased due to livestock manure application to agricultural croplands. Further, fungi increase root surface area for extraction and absorption of plant nutrients [157]. This is evidenced by increased mycorrhizal colonization of crop roots in manure treatment [155,158]. This is particularly relevant in the uptake of immobile nutrients such as phosphorus (P). Bolan [159] summarized and stated that improved uptake of immobile P by plants is aided by several mechanisms undertaken together with mycorrhizal fungi including fungal hyphal root extension for nutrient extraction from a large volume of soil, quick movement of P into the fungal hyphae and solubilization of soil P. Clearly, these illustrate that applying livestock manure does not only improve microbial population but also nutrient uptake from the soil. Therefore, creating conditions favorable for increased microbial activities are vital for sustaining and improving soil fertility levels. Manure is one option that makes it possible to improve microbial activities in the soil, a point which was reiterated by Parham et al. [146] in a cattle manure study.

Aggregate stability is another attribute important for the health and productivity of the soil through its ability to hold soil particles together and to provide sites and pores for nutrient exchange. It can be debated whether microorganisms are a critical part of this soil stability. Fungal mycelia help to improve the stability of soil aggregates [160], and any action that increases the fungal population may improve aggregate stability. For example, cattle manure appears to increase the proportion of macroaggregates in the soil [161]. At the same time, the macroaggregate formation is associated with microbial biomass C indicating that applying manure leads to an improvement in microbial population and activities which subsequently improve soil aggregate stability [161]. Noteworthy is that soil microbial activities and biomass C tend to be higher in cattle manure treatments [162]. Plaza et al. [163] corroborated this assertion in a pig slurry study and concluded that adding manure is beneficial in improving soil microbial biomass C. Since SOC serves as a binding agent for aggregate stability [164], applying manure improves this process through several ways including its ability to enhance microbial biomass. Soil that receives manure input is likely to maintain a high population of microorganisms that stabilize the soil. In fact, applying fungicide and bactericide has a reverse effect of lowering the population of bacteria and fungi. This was reported by Tang et al. [165] who observed a lower population of soil fungi and bacteria following the application of fungicide and bactericide. Since bacteria and fungi are vital in soil aggregate stability, their reduced presence due to fungicide or bactericide may lower the formation of stable soil aggregates. Despite all these positive aspects of livestock manure for soil fertility improvement, incorrect use of manure such as excess application can lead to unintended consequences. Phosphorus eutrophication, as well as leaching, denitrification and volatilization of N to water bodies and atmosphere, have all been reported in livestock manure studies [166,167].

Therefore, the use of livestock manure alongside other agronomic practices in a manner that does not negatively impact the environment is critical to improving soil biological properties which directly or indirectly also influence other soil properties.

16. Yield and Yield Components

Healthy soil, by definition, supports increased plant growth and productivity. Plant genetics, climatic factors, soil type and properties, and management are some factors that affect crop yield. The improvement of soil properties due to manure application may also favor crop growth and productivity. Literature is replete with evidence of the positive effect that manure has on grain yield and various yield parameters such as 1000-grain weight, biomass, and harvest index (Table 6). In a study where the effect of poultry manure on maize performance was evaluated, Adeyemo et al. [168] found that relative to the control treatment, the application of 6 Mg ha^{-1} increased dry shoot biomass weight by 36% on a sandy clay loam and by 86% on a clay loam. This study also showed an increase in 1000-grain weight and cob weight with increasing manure application rate [168]. In contrast, Khan et al. [30] found a decrease in total dry matter yield in maize after application of 10 Mg of dairy manure per ha and a decline of 2.7 Mg ha^{-1} dry matter relative to the N,P, and K treatment with an application of 20 Mg ha^{-1}. In addition, this study found that manure application decreased the 1000-grain weight of maize, while no significant difference in grain yield was observed. The lack of a difference in grain yield may have been due to optimum availability of nutrients from the nutrient sources supplied. Mahmood et al. [169] found that 13 Mg of farmyard manure per ha^{-1} decreased maize grain yield by 1.4 Mg ha^{-1} relative to NPK at 250-150-125 kg ha^{-1}. This is likely a result of the lower N, P, and K content in the manure that was used relative to the inorganic NPK source. In addition, manure is a nutrient source that releases nutrients more slowly than inorganic commercial NPK sources. In a study with rice by Rahimabadi et al. [170], a decrease in 1000-grain weight was found with the application of 15 and 30 Mg of cow manure in comparison to the control. However, there was a significant grain yield increase of more than 800 kg ha^{-1} with 30 Mg of manure ha^{-1} in both years of the study. The effect of manure on yield is not only dependent on the manure characteristics, but also on climatic factors. Nikiema et al. [171] found that wheat yield was not affected by liquid hog manure in below average precipitation years. This can be attributed to a low yield potential under low precipitation, affecting the response to nutrients negatively. However, when precipitation was above average, there was a 20%, 30%, and 50% increase in grain yield with 64, 128, and 192 kg of manure N ha^{-1}, respectively [171]. The study also showed an increase in straw yield with increasing manure rate, with the highest yield of 5.1 kg ha^{-1} with the application of 192 kg of N ha^{-1} in manure. Additional yield components of wheat were investigated by Jan et al. [172], who found that 1.5 Mg ha^{-1} of poultry manure increased spike length, 1000-grain weight, and grain yield. None of these yield components significantly increased any further with the application of 2 Mg ha^{-1}. Interesting about this experiment is that the soil of the experimental site was alkaline and low in available N (0.04 g kg^{-1}) and P (4 mg kg^{-1}). The low levels of N and P might explain the response of the wheat to the manure. Koutroubas et al. [173] reported that there was no significant increase in dry matter wheat yield between the control (no manure, no synthetic fertilizer) and 16 Mg ha^{-1} farmyard manure treatment. However, there was a significant increase of more than 2 Mg dry matter with 32 Mg ha^{-1} manure application. The same trend was found with grain yield, however, there was no significant difference in grain weight between treatments. Interestingly, this study found that the high rate of manure gave similar yields as the inorganic N fertilizer treatment of 120 kg N ha^{-1}, implying that the yield response depended on the availability of N. The N in synthetic fertilizer is more directly available in comparison to N in manure because of the slow release of organic N in manure and ammonia loss when manure is surface applied [174]. The results from literature show that the effect of manure on yield and yield components is a function of various external factors including soil and climatic factors.

Table 6. Grain yield in maize, rice, wheat, and sorghum as affected by manure application.

Study Site	Nutrient		Crop	Grain Yield(s)	Source
	Source	Quantity Mg ha^{-1}		Mg ha^{-1}	
United States	Cattle	0 22.5 45 90 180	Sorghum	3.80 4.40 4.30 4.20 3.60	[175]
	Cattle	0 22.5 45 90 180	Wheat	2.50 2.30 2.30 2.20 2.20	[175]
Greece	Cattle	0 16 32	Wheat	3.28 3.49 4.50	[173]
Nigeria	Poultry	0 5 10 15 20	Maize	1.33, 0.81 † 2.76, 1.98 2.87, 1.66 3.63, 0.83 2.82, 2.82	[176]
Nigeria	Poultry	0 5 10	Maize	1.90 3.72 2.95	[26]
India	Cattle	0 40 §	Rice	2.23 3.47	[177]
Germany	Cattle	0 80 § 160 § 240 §	Wheat	5.15; 5.27 † 5.48; 5.84 5.53; 6.19 - - ; 6.34	[178]
United States	Cattle	0 56 § 112 § 168 §	Maize	6.9, 6.5, 6.3 7.2, 7.3, 6.9 7.3, 7.5, 5.9 6.6, 7.8, 7.0	[174]

† numbers separated by a comma indicate the numbers in different years or seasons at a single location; § Presented in kg N ha^{-1} of cattle manure.

17. Summary

Soil health is a broad term that speaks to the capacity of the soil to function as an ecosystem that supports the plant, animal, and human life. This review shows that manure contributes to creating this ecosystem in supplying nutrients and improving various soil properties (Table 7). The extent to which it does, however, can be variable and depends on various factors including chemical and physical properties of the manure itself and external factors including climatic factors and soil characteristics (Table 7). While, the benefits of manure on various soil properties are clear, conclusions about the effect of manure on some soil properties must be approached cautiously. The many benefits to soil must also translate to improved plant and or animal productivity all while reducing the risks to the environment. Improved soil fertility, water movement and retention, and soil temperature regulation do facilitate better growth and higher productivity of crops. The high variability in manure characteristics and thus the unpredictability of the response to the environment pose a challenge to sustainable management of manure. The application of nutrients in excess of what the plant needs can end up in the environment through several pathways of loss such as erosion, runoff, leaching, and volatilization which may lead to deterioration of air, soil, and water quality. Moreover, the large amounts of manure that must be applied to get equal quantities of nutrients as synthetic fertilizers, make its application to land unappealing from a labor and cost perspective. Hauling large quantities of manure lead to increased expenses for transport. Moreover, the surge in availability of fertilizer products with a high percentage of needed nutrients make them cheaper per unit nutrient relative to manure [179]. Because of the potential risk to the environment, the U.S and many other countries have developed restrictions and regulations for storage and spreading of manure. The establishment and implementation of regulation imply that society recognizes the importance of this resource and its benefit to agricultural production and sustainability of the environment. It is evident that the benefits of manure application to overall soil quality are numerous, as shown in the 130 studies evaluated for this paper, and that its application to land is a viable option to improve and perhaps restore the health of degraded land. Although the papers reviewed for this work address many aspects of soil health and yield in relationship to manure, there remain aspects of manure in relationship to soil and plant that may be explored in future research. One of which is the nutrient use efficiency from manure; finding ways to improve the uptake of nutrients from manure may reduce the loss of nutrients from land and the subsequent pollution of the environment. In addition, although various works have looked at long-term application of manure and its effect on soil health indicators [18,36,39,47], there remains a need to better understand manure decomposition and its effect on soil health as a function of time. Finally, if manure is to become an attractive amendment to farmers for soil improvement, the economic sustainability of manure-based cropping systems and opportunities to improve their profitability must be explored.

Table 7. Summary of key findings from this review study.

Variable	Key Findings	References
Soil chemical properties	Applied animal manure resulted in a higher amount of SOM when compared to inorganic fertilizer. This led to the building up of SOM in the soil profile	[42]
	While not consistent, applied livestock manure increased CEC by as much as 10 $cmol_c\ kg^{-1}$ relative to the control treatment. This was due to the presence of organic matter present in manure	[27,69,70]
	Repeated manure application led to the build-up of P in the soil with the potential to cause eutrophication	[39,42]
	Generally, manure application tended to lead to an increase in soil pH due to the presence of $CaCO_3$ and HCO_3^-. Properties of manure type and soil conditions dictate soil acidity	[23,58–60]
	Leaching of NO_3^- was least for manure applied in spring and highest for fall-applied manure	[32,33]
Soil physical properties	Manure was vital for lowering soil bulk density, thus, increasing soil pores to support growth of crop roots	[35,37]
	Increased infiltration rate and water holding capacity of the soil due to increased soil organic matter aggregation of soil particles	[103,107–110,112]
	Depending on the time, rate, and properties of manure applied, soil temperature could increase or decrease	[37,129–131]

Table 7. *Cont.*

Variable	Key Findings	References
Soil biological properties	Applied animal manure improved fungal and bacterial diversity in the soil. This is important for mineralization and root extension to extract nutrients from lower soil layers	[146–148,155,156]
	Increased microbial population improved SOC. Additionally, soil microbial C was associated with SOC	[12,154]
	Increased microbial activities such as mineralization of soil organic matter, colonization of plant root, soil aggregation e.g., via fungal hyphae and microbial C	[162–164]
Yield and Yield Components	Manure application improved grain yield over no fertilization of crops due to supply of macronutrients. Application based on N leads to P overapplication	[26,173,175,176]
	Both manure characteristics and climatic conditions dictate whether crops will respond to applied manure	[171]
	Some studies found 1000-grain weight to reduce and no yield difference between manure treated and control plots due to the slow-release nature of manure	[169,170]

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