Chapter

Use of Swine Manure in Agriculture in Southern Brazil: Fertility or Potential Contamination?

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Abstract

A major challenge in agricultural production systems is the maximization of resources used to promote the development of crops with a minimum of environmental impact. In this sense, the use of fertilizers of animal origin has great potential to promote the improvement of soil properties. In southern Brazil, swine manure (SM) is widely used in agricultural areas, allowing nutrient cycling within pig units and reducing costs for chemical fertilizers. Much of this manure is applied in liquid form (PS), but other strategies are often used, such as PS compost and swine bedding (DL). The use of these SMs improves the chemical, biological, and physical attributes of the soil, contributing to increased fertility and productivity of crops. However, prolonged use or applications with high doses of SM can result in the accumulation of metals and phosphorus in soils, representing a risk of contamination of soils and surface water resources, mainly due to losses by runoff, and subsurface, by leaching. Therefore, the adoption of criteria and the rational use of PMs need to be adopted to avoid dangerous effects on the environment, such as plant toxicity and water contamination. The potentialities and risks of SM applications are discussed in this chapter.

Keywords: pig slurry, pig deep litter, fertilization, copper, zinc, phosphorus

1. Introduction

The southern region of Brazil, represented by the states of Santa Catarina (SC), Paraná (PR) and Rio Grande do Sul (RS), stands out in swine production, having almost 50% of the total Brazilian herd, with a total of 20,594,238 heads [1]. However, due to the intensive production system in the swine units, the volume of waste produced daily is high. In these conditions, the use of swine manure as fertilizer in crop and pasture areas is an established strategy, promoting a targeting use of this material and cycling of nutrients [2].

Due to the large volume of swine manure (SM) produced in these swine units in southern Brazil, much work has been carried out to evaluate its effects on soils, as well as promoting strategies for its use, improving its efficiency [3, 4]. Also, alternatives have been proposed in the transformation of waste that is generated in these swine units, mainly in liquid form. These transformations ranged from anaerobic digestion, composting, and swine production in a deep litter production system. These strategies allow pig slurry (PS) transformation into a more stable material, with a higher concentration of nutrients and in a solid form, such as the PS compound and the deep litter (DL). SM transformation also has the advantage of allowing the waste transport and commercialization, becoming another source of income in the swine units [5–8].

Studies carried out in these Brazilian states have shown that SM are rich sources in macro and micronutrients, and their beneficial use for plant growth and development, serving as an interesting alternative in the partial or total replacement of mineral fertilizers, promoting the maintenance of productivity and decrease in external inputs in agricultural production areas [2, 5, 9, 10]. In addition, SM applications in agricultural areas promotes benefits to different soil properties, increasing soil fertility, improving soil structure and microbiological activity [4, 6, 9, 11, 12].

However, SM also has factors limiting its use, such as its variable concentration of nutrients and unbalanced to the needs of the plants, which can compromise the quality and functionality of the environment when excessive and/or continuous fertilization is carried out in the same areas [13–17]. The main concerns raised by researchers, and according to the publications of international academic society, are related to the phosphorus (P) and heavy metals, such as copper (Cu) and zinc (Zn), accumulation, availability, and losses in areas submitted a long history of applications [3, 18–23]. The results of the studies developed to emphasize the importance of adopting technical criteria for the use of SM in agricultural areas, proposing limits of doses used, applications based on soil attributes and composition of manure, the recommendation for crops, determination of limiting elements for the applied dose (mainly P), supplementation of the application of SM with chemical fertilizers and adequate treatments for the storage and stabilization of waste, for example [10, 17, 24, 25].

This chapter aims to survey studies carried out in the states of Santa Catarina, Paraná and Rio Grande do Sul about the use of swine manure in soils, covering its effects on soil fertility, crop productivity, and also on its potentials effects on the contamination of soils and water resources, mainly related to P, Cu, and Zn. Approximately 92 scientific publications conducted in these states were used to carry out this study.

2. Use of swine manure in agricultural areas: soil fertility and crop yield

The use of swine manure (SM) for grain and pasture production is an alternative to mineral fertilizers and allows the disposal of this residue within agricultural units, promoting nutrient cycling and reducing production costs [9, 10, 26].

Swine manure is used as fertilizer because it is rich in nutrients in readily available forms (mineral) to crops, in addition to increasing nutrients levels in organic forms that tend to have less availability, but which they can become available from their mineralization [4, 27, 28]. While pig slurry (PS) can present amounts close to mineral (49.6%) and organic (50.4%), for example, deep litter (DL) presents much higher proportions of organic N (90.6%) compared to mineral N (9.4%) [27]. Changes in these proportions are also observed in soils fertilized with SM, where applications, mainly with higher doses, increase the P labile forms in the soil. However, a large part of the P present in the soil is in more recalcitrant forms, with emphasis on the mineral forms (Pi), corresponding to up to 80% of the total value in soil superficial layers, mainly associated with Fe oxides. In deeper layers, this percentage is even higher. Additionally, the contribution of P organic forms (Po) can reach up to 20%, decreasing with the increase of soil depth and soil organic matter (SOM) content [29]. This presence of organic and mineral components in organic fertilizers favors, in addition to improving soil fertility, microbiological activity, and subsequent crop nutrition, with organic components mineralization over time (residual effect) [4, 26–28, 30–32].

SM applications promote nutrients added to the soil, increasing its contents and, consequently, its availability to plants [6, 33–38]. Naturally, SM applications allow a more complete nutrients fertilization, not limited to N, K, and P, present in high concentrations in the manure, but also adding other macro and micronutrients, such as Ca, Mg, Cu, Zn, and Mn [7, 9, 12]. In a study conducted by Pessotto et al. [35] in the municipality of Três Passos, RS, in a Entisol, PS applications ($150\ m^3\ ha^{-1}$) for four and 16 years in pasture areas (Cynodon spp.) promoted an increase in Cu, Zn, P, K, Ca, Mg and Na contents compared to mineral fertilization in an area of annual grain cultivation under no-tillage, mainly with the longest application time. A similar result was observed by Lourenzi et al. [6] evaluating the effect of PS compost applications in a no-tillage system with maize (*Zea mays* L.), black beans (*Phaseolus vulgaris* L.), in the off-season, and black oats (*Avena strigosa* L.) succession in a Oxisol, located in Chapecó, SC. The authors determined that the dose of $4\ Mg\ ha^{-1}$ promoted nutrients contents similar to mineral fertilization (NPK), but with an increase in Cu, Zn and Ca contents, besides the SOM, in the soil surface layer.

However, unlike mineral fertilizers, the amounts of nutrients added by SM are difficult to control, as their chemical composition is variable [4, 9, 26]. This was evident in a study conducted by Da Ros et al. [36] in PS samples used for fertilizing sunflower (Oct/2009), canola (May/2010), beans (Jan/2011), and maize (Sep/2011) in Santa Maria, RS. During this period, four applications were carried out, with N, P_2O_5, and K_2O contents ranging from 0.83–2.21 $g\ L^{-1}$, 0.37–1.75 $g\ L^{-1}$, and 0.69–1.25 $g\ L^{-1}$, respectively. The different diets offered, the animal ages, the volume of water used to clean slatted floor stalls, and the shape and time of storage, for example, are components that promote variation in the levels of nutrients present in manure [34]. Additionally, the breeding systems and the SM stabilization processes, such as the deep litter system, composting, and anaerobic digestion, promote changes in the structure and composition of manure and in its soil dynamics [5, 7, 8]. Admittedly, the incorporation of substrates with high lignification, such as rice husks, shavings, and sawdust, in the preparation of deep litter and compost increases its C/N ratio. Also, the stabilization process of these swine fertilizers promotes the degradation of more labile organic compounds, reduces the carbon (C) content, increases the levels of nitrate (from the transformation of ammoniacal N) and other nutrients, producing a more stable material [8]. Consequently, its mineralization in the soil can be delayed, as well as the release of nutrients, also possibly causing greater immobilization of nutrients [4]. This was demonstrated by Giacomini et al. [27] evaluating the dynamics of N in the incubation of an Ultisol with DL, PS, and PS + oat straw application, in Santa Maria, RS. DL and PS additions increased soil mineral N contents during incubation, with DL promoting an increase of 17 $mg\ kg^{-1}$, while PS of 66 $mg\ kg^{-1}$, compared to the control treatment. Due to the nature of these wastes, the amount of mineralized N was differentiated, where 34.9% of the total N of the PS was mineralized, whereas for DL this percentage was only 14.6%. Additionally, the authors observed that the addition of PS to the soil covered with oat straw reduced the amount of mineral N by 30%, compared to the soil with only PS, due to the N microbial immobilization in response to the high C/N ratio of the straw (46.5/1), also to the lower mineralization of organic N from PS that remained on the straw, without making contact with the soil.

In addition to nutrients, SM applications also promote changes in the SOM contents, through the addition of organic compounds present in the manure, but mainly by increasing the crops biomass production [7, 9, 26, 37]. The maintenance of these residues in the soil, along with soil conservation systems, such as no-till system and integrated crop-livestock-forest (ICLF), favors the accumulation of MOS [35, 38]. This positive effect can be seen in **Figure 1**, which shows the number of scientific articles developed with SM in the Southern region of Brazil, starting in 2008, which showed changes in the SOM contents. This compilation reveals that in most studies (n = 21) the addition of SM increases the SOM contents compared to soils without fertilization, corresponding to approximately 60% of the studies. In the other studies (40%) there was no change in the levels. This distribution changes when assessing the effect of manure in comparison to applications with mineral fertilizers, changing to close to 40 those in which the MOS content increased and 60% in those in which there was no effect. The positive effect of SM on SOM was observed by Scheid et al. [12] with an increase in the organic C content of a Hapludox in pasture area (Cynodon spp.) after 15 years of PS applications with the dose of 200 m^3 ha^{-1} $year^{-1}$, in Nova Candelária, RS. The authors attributed these results to the direct effect of the C added by the manures (even in low concentration) and indirectly to the C added to the soil by crop residues and roots, which showed an increase in their biomass due to PS fertilization. The same mechanism was used by Lourenzi et al. [6] to justify the increase in SOM contents after six

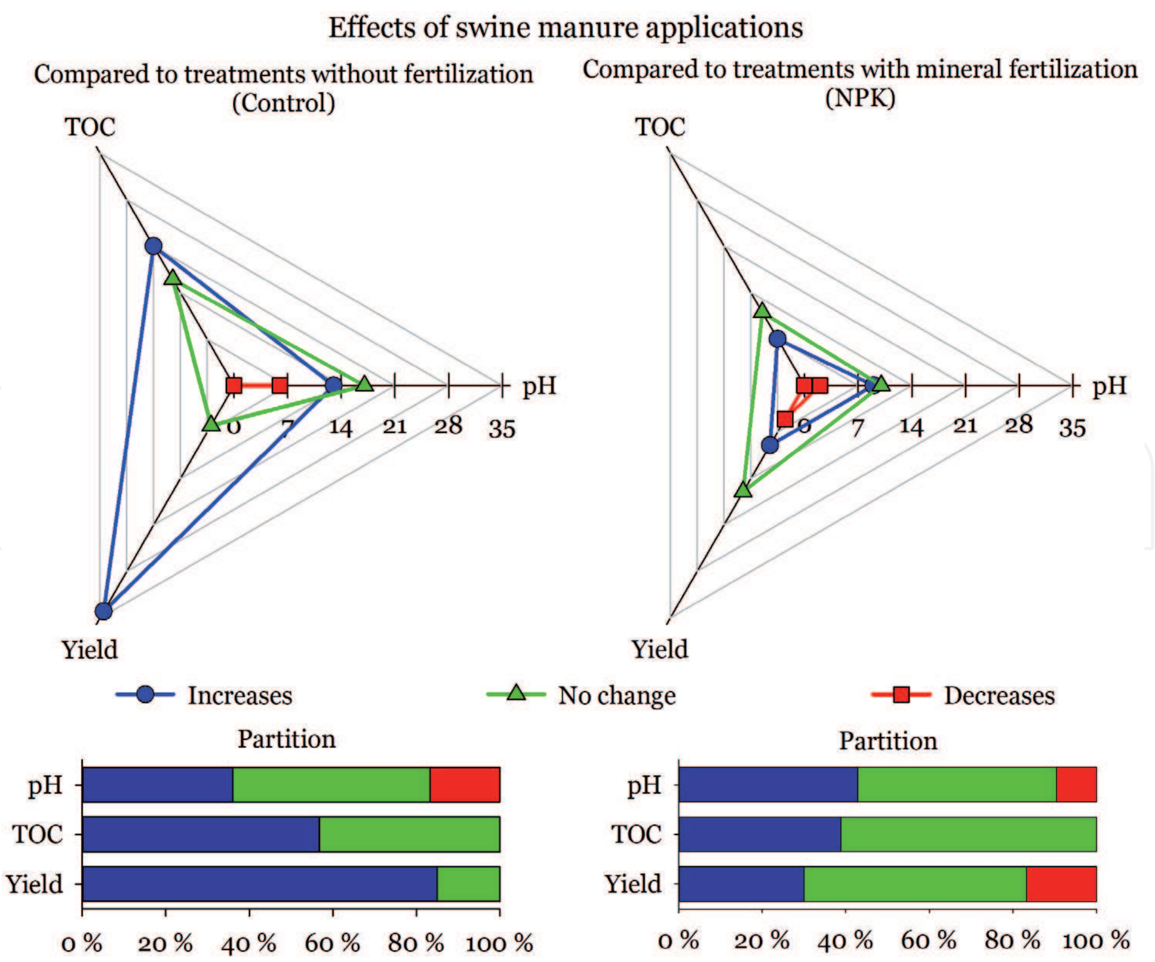

Figure 1.
Number of scientific articles using swine manure that show an increase, reduction, and without change in total organic carbon (TOC) content, pH values, and crop yield compared to treatments without fertilization (control) and with mineral fertilization (NPK).

years of PS composting with shavings applications in a no-till system in Chapecó, SC. The authors observed an increase of 22, 26, and 23% in SOM contents, with the application of 4, 8, and 16 Mg ha^{-1}, respectively. However, it is important to notice that both studies found greater effects on soil superficial layers, promoting changes up to 10 and 4 cm, respectively. Additionally, the addition of solid material, such as PS compost or DL, tends to promote the greater accumulation of organic C than PS applications, due to the higher C content in these solid manures [6, 7]. The increase in SOM contents in soils fertilized by SM is a factor of great importance in increasing soil fertility, contributing to its CEC, microbiological activity, and soil structure, also is an attribute associated with soil quality [11, 12]. However, it is important to notice that some studies have also shown the null effect of SM application on SOM contents [7, 16, 34]. In samples of Entisol, Inceptisol, and Oxisol, obtained from rural units in Western Santa Catarina under a no-tillage system, Scherer et al. [38] observed that SOM contents were similar between areas with PS application and with mineral fertilization, submitted to both managements for 15 and 20–25 years.

Another important component for soil fertility and crop growth influenced by SM fertilization is pH. However, as for SOM, the increase or decrease in pH values depends on the type of manure applied, dose and management used, and also to environmental conditions [26, 36]. However, the positive effect of SM on soil pH tends to be greater compared to mineral fertilization (**Figure 1**). Da Ros et al. [36], for example, observed an increase of 0.3 units in the pH values in the 0–20 cm layer, on average, with the application of 100 m^3 ha^{-1} of PS, being higher than the values observed in treatments without fertilization and with NPK fertilization, in Santa Maria, RS. In the same region, a similar result was found by Lourenzi et al. [37] whose observed an increase in pH values up to 8 cm deep in soil fertilized with PS, mainly with the dose of 80 m^3 ha^{-1}, compared to the treatment without fertilization. According to these authors, the addition of carbonates by the manure and the complexation of Al and H^+ present in soil by organic compounds from SM and crop residues are the main mechanisms responsible for the positive effect of SM on pH, pointed out by these authors. Therefore, the use of soil improvers may not be necessary or reduced. However, the absence of changes in pH values may occur due to the use of liming, as observed by Brunetto et al. [11], when evaluating the effect of DL and PS applications in an Typic Hapludalf in Braço do Norte, SC. Also, NH_4^+ nitrification from SM applications can promote pH values reduction by increasing the H^+ concentration, as observed by Veiga et al. [33] in a Rhodic Hapludox in Campo Novos, SC.

This improvement in soil fertility promoted by SM applications favors the increase of crop productivity, due to the greater supply of nutrients, root growth, and absorption [9, 32]. In comparison to unfertilized soils, SM application has a great effect on crop yield, due to the supply of nutrients in the soil (**Figure 1**). Freitas Alves et al. [28] observed that PS application at a dose of 40 m^3 ha^{-1} promoted an average yield of maize grains from the 2011/12 (Oxisol) and 2012/2013 (Inceptisol) similar to the soil fertilized with NPK (130, 185 and 70 kg ha^{-1} of N, P_2O_5, and K_2O, respectively) and higher than the soil without fertilization, in a study carried out in Lajes, SC. Also, Brugnara et al. [32] also observed the positive effect of PS compost application on the production of passion fruit seedlings, in a study carried out in Chapecó, SC. The authors established PS compost concentrations up to 64% (v/v) (maximum tested dose) and 38.87 to 95.8% (v/v) in mixtures with coconut fiber and conventional substrate, respectively, to obtain the best responses of leaf area, height, dry mass of the aerial part and root and number of leaves. Additionally, Fey et al. [5] observed that doses of 60 and 150 m^3 ha^{-1}, PS applications promoted greater production of maize biomass, and also a higher concentration of N, P, and Mn in the plant tissues, than PS obtained from manure and biodigester, mainly with the highest dose, both in a Oxisol and in an Ultisol, in Marechal Cândido Rondon, PR. The higher concentration of nutrients in the PS without treatment compared to the other wastes promoted this result. These results show that the dose used also needs to consider the nature and composition of the SM to be used and that the amount of nutrients added to the soil can vary considerably according to the type and management adopted about this manure.

However, in studies that compare crops yield with SM fertilization and mineral fertilizers, the results are more controversial (**Figure 1**). Under these conditions, soil natural fertility, manure doses used and the crop type are factors that have great influences on the results. An example is a study by Pandolfo and Veiga [2] on a Hapludox soil, in Campos Novos, SC, with increasing doses of PS in different management systems related to the maintenance of crop residues on the soil surface. First, the authors observed that winter pasture biomass production and maize grain yield in the summer were higher after the second year of evaluation, due to the improvement of soil fertility with PS applications. Second, the effects of PS applications were greater on the management that removed the winter and summer crop residues than on those where these residues were kept (either in winter or in summer). This revealed that in soils with less cycling or greater withdrawal of nutrients, the response in crop yield to PS applications is higher, although higher doses are necessary to maintain soil fertility and crop yield. Additionally, although the use of increasing doses of SM promotes a gradual increase in crop yields, balancing with the results obtained with the mineral fertilizers application, many studies also demonstrate that very high doses of SM are necessary to promote higher yields than those observed in crops with mineral inputs [9, 10, 28]. In a study conducted in Chapecó, SC, for example, Miranda et al. [31] observed that PS applications promoted greater production of dry matter (DM) of giant missionary grass only with the dose of 500 kg of N ha^{-1}, which corresponded to 275 m^3 ha^{-1} $year^{-1}$, in comparison to the application of 200 kg of N with mineral fertilizer. The lower PS doses promoted lower or similar yields to mineral fertilizer treatment. In other cases, some studies have also revealed that after reaching a certain dose, productivity increases are very low or zero [9]. The lower PS doses promoted lower or similar yields to mineral treatment. The lower effect of SM applications on crop yield compared to mineral fertilization is also documented (**Figure 1**). This was observed by Locatelli et al. [10] in maize grain yield in the 2014/15 and 2015/2016 harvests, in Curitibanos, SC. Even with the addition of 140 kg of N ha^{-1}, the yield was lower with PS application (12,778 and 7886 kg ha^{-1}, respectively) compared to the treatment with mineral fertilization (19,348 and 11,411 kg ha^{-1}, respectively) which in total added 122.7 kg of N ha^{-1}.

However, in these conditions with high SM application the fertilizer efficiency index is reduced, promoting greater addition of nutrients in the soil, but with less use by the crops [26]. Consequently, there is a greater accumulation of nutrients in the soil and greater potential for soil pollution and surface and subsurface water resources through losses from runoff and leaching, respectively [5, 23, 39–43]. In terms of runoff losses, the volume of the runoff and the amount of nutrients added to the soil (high doses of manure) are mainly responsible for the increase in losses. Also, the time between the SM application and the first rainfall event has a strong effect on the amount of nutrient lost in the runoff. Therefore, it is recommended that applications are not carried out when there is a risk of rain. On the other hand, the increase in the production of biomass from crops, promoted by its applications can offer a beneficial effect by increasing soil cover, increasing water infiltration, and reducing the volume of runoff [19, 39]. In two parallel studies carried out by Ceretta et al. [3] and Basso et al. [18], the authors assessed the losses by runoff and leaching, respectively, from the application of increasing doses of PS (0, 20 40, and 80 m^3 ha^{-1}). Basso et al. [18] observed that PS applications promoted in the early stages of crop development result in greater N losses by leaching, due to the low root volume and low capacity to absorb nutrients. Also, the greatest losses occur from the greatest addition of nutrients to the soil promoted by high SM doses. These applications, especially in high doses and in the initial stages of plant development, deserved special attention, as they caused concentrations of N in percolated water above 10 mg L^{-1}, considered as a critical level in water for human consumption [44], which can represent a risk to subsurface water quality. However, PS applications promote low changes in P concentrations in the percolated water. This is justified due to the greater interaction between this element and soil mineral components, especially clays [30]. In parallel, Ceretta et al. [3] showed that the P and N concentrations are much higher in runoff waters. The authors calculated that the P and N losses by flow with the doses of 20 40 and 80 m^3 ha^{-1} were 49, 21, and 20 times (available P) and 4.0, 3.7, and 1.5 times (nitrate) greater than those observed by percolation. The highest concentrations of N and P in the runoff waters were obtained after the first dates after the applications and with the highest doses of manure. Furthermore, in many evaluation periods, nitrate concentrations above 10 mg L^{-1} were found mainly with the highest PS doses, which was also observed by Ceretta et al. [19]. This strengthens the greatest concern in areas with a long history of SM application and with more sloping reliefs, which have a greater accumulation of nutrients, especially P, and which are more susceptible to runoff losses. Management systems without carrying out the soil overturning may even present an accumulation of nutrients in the soil's most superficial layers, increasing the risk of losses [40, 41]. As alternatives, the maintenance of vegetation cover, level and/or band cultivation, and the construction of terraces are important strategies to avoid and control these losses and their potential negative effect on the quality of water resources.

In swine units with continuous SM applications, the importance of adopting technical criteria and strategies for the management and application of manure is increasingly emphasized, including the recommendation of nutrients for crops for the choice of dose, application time, manure treatment, soil management, soil moisture, and nutrient concentration in SM. These measures prevent or delay nutrients accumulation in soil and its losses, whether through volatilization (NH_3), percolation, or runoff. The absence of measures and monitoring of applications can compromise the quality of water resources present in the swine units, as observed by the studies by Cadoná et al. [23] and Loss et al. [42]. In the first study, these authors observed in the supply wells of four swine units located in Braço do Norte, SC, an increase in N and P concentrations of in the water. For N, there was the pollution of these water resources with NH_4^+ and NO_3^- in all collections, which were carried out between July 2015 and June 2016. The highest NH_4^+ and NO_3^- concentrations percolated occurred mainly in the month with the highest rainfall, with a greater volume of percolated water and greater transport capacity. These data were worrying, since the concentrations were above the parameters regulated by CONAMA Resolution n° 357/2005 [44] for Total Ammoniacal Nitrogen and NO_3^-, with maximum limits of 3.7 mg L^{-1} and 10 mg L^{-1} for freshwater, respectively. The authors also evidenced that total P concentrations in the water were above that recommended by this Resolution (0.030 mg L^{-1}) in all collections performed, presenting a variation of 0.07 mg L^{-1} to 1.42 mg L^{-1} in collections for the four swine units. Also, a relationship was verified between soil available P contents and total P concentrations in waters. Loss et al. [42] also observed that the water resources (supply well, weir, and spring) of a swine unit (Braço do Norte) showed an increase in NH_4^+ and NO_3^- concentration in all collections, and in certain periods the values were above recommended by CONAMA [44], mainly for NH_4^+. These data strengthen the attention that must be given to the volume of applied manure, favoring the subdivision of applications (mainly in the initial stages of crop development) to reduce the accumulation of nutrients in the soil, especially P.

Therefore, due to the varied positive effects of SM on soil properties and crops yield, the addition of these residues to the soil is no longer considered as disposal, but a recommended direction in the swine production units, since followed by technical criteria [24, 25, 45]. This concern is fundamental for the protection of natural resources and soil functionality maintenance, maintaining attention to the high concentration of nutrients present in SM and its variable composition, being often incompatible with the nutritional requirements of the crops to be fertilized [7, 13, 26].

3. Soil contamination risk from swine manure applications

Although the use of SM contributes considerably to the improvement of soil fertility, its continuous use has been rising concern in academic and environmental society, especially with the use of high doses [22, 46]. Greater attention is paid to P and heavy metals accumulation in soils, which can cause water eutrophication and plant toxicity, respectively, representing risks to the quality and functionality of soils and nearby water resources [7, 14, 15, 17, 24, 25]. For this reason, many studies continue to evaluate the total contents and availability of these elements in different types of soil, applied SM, and management. The main objective is to develop strategies applicable to the management of SM fertilizers that promote soil fertility, without compromising its quality or with the least possible impact. The results obtained by these studies on P and heavy metals accumulations in soils are presented below.

3.1 Phosphorus

In areas subjected to constant application of swine manure, especially at high doses, there may be an increase in the levels of P in the soil. This is justified due to the variable composition of these nutrients in the manure, being predominantly out of balance with the recommendations for different cultures. This makes it difficult to control the quantities added in each application. As noted by **Figure 2**, in studies with SM applications where doses are based on the amount added, that is, by volume (m^3 ha^{-1} for PS) or weight (t ha^{-1} for DL or compost), the higher doses tend to promote greater increases in the availability of P in soils, due to the greater addition of this element. Also, management systems that aim to meet N demands through the exclusive use of SM have resulted in more excessive P and K additions to the soil. In these situations, to reach the recommended N dose, the amount of manure used promotes an addition higher than what will be absorbed by the plants, resulting in accumulation in the soil. And as the number of applications increases, the availability and total P content in the soil also tends to increase (**Figures 2** and **3**) [7, 40, 41]. However, the rate of increase in these levels will depend on the amount of P added in each application, the type of culture and management adopted, and the soil's attributes, such as the type and content of clay, pH, and MOS (**Figure 4**) [15, 46].

In the soil, P has low mobility and is highly reactive to the functional groups of clay minerals and Fe and Al oxides. For this reason, soils with high clay content and mineralogical composition with a greater abundance of hematite, goethite, gibbsite, and some minerals of 1: 1 clay, such as kaolinite, have a greater capacity to adsorb P [30].

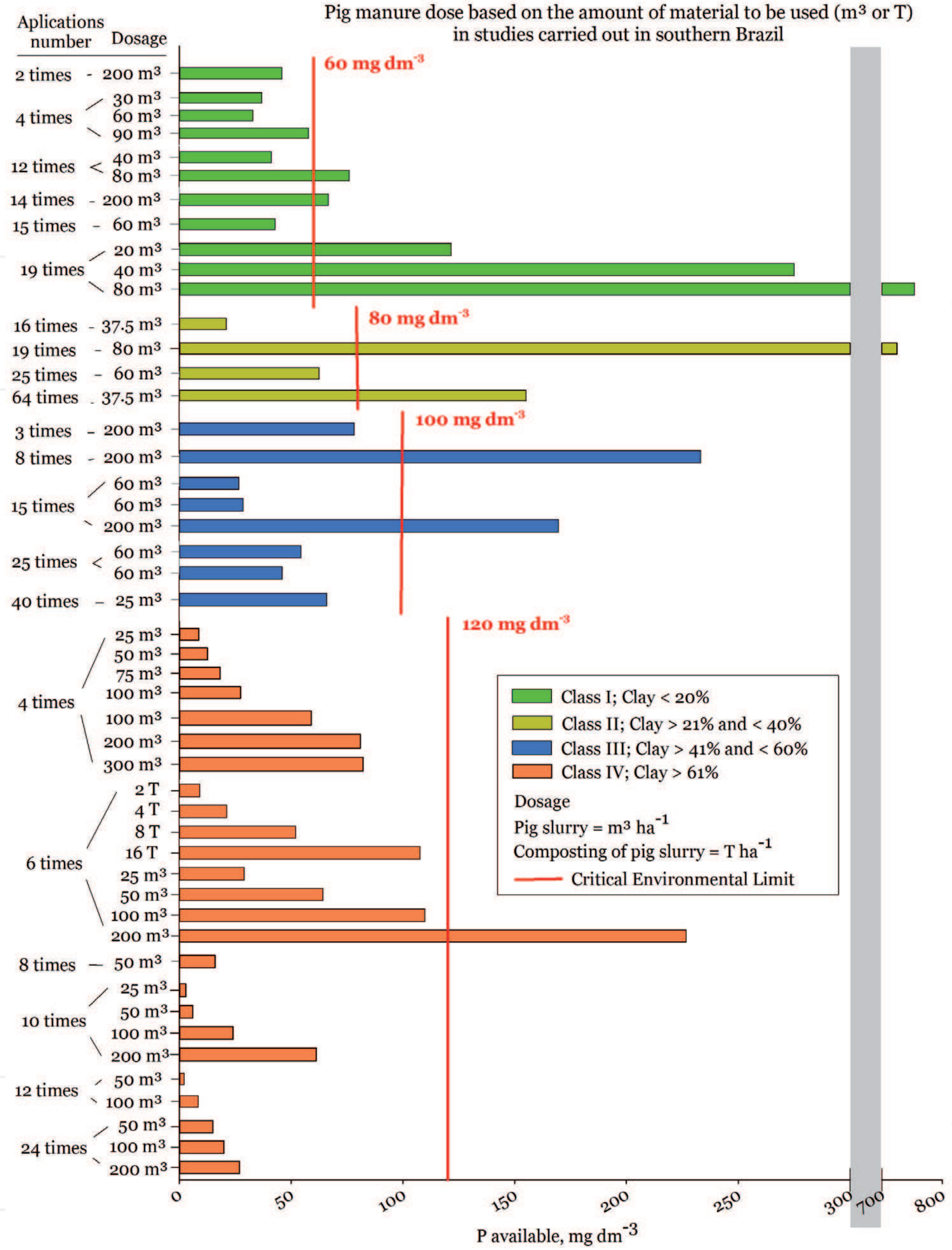

Figure 2.
Available P contents in soils with different clay contents obtained from studies with application of SM conducted in the states of SC, PR, and RS, using the volume (m^3 ha^{-1}) or weight (t ha^{-1}) of the applied waste (PS or PS compost).

Thus, the P that is added by the SM applications tends to be adsorbed, mainly by the more avid adsorption sites, with a greater binding energy of these mineral components [13, 24, 25]. Naturally, the weathering process, the chemical reactions of the soil, and the action of the roots can make available this adsorbed P, as well as releasing the one that is present in the composition of the minerals, but in less quantity and when the available levels are low [39, 47].

Also, the effect of microbiological activity and mineralization of MOS allows P release associated with organic soil components. In this sense, in studies performing P fractionation in the soil with SM applications, it is observed that most of the

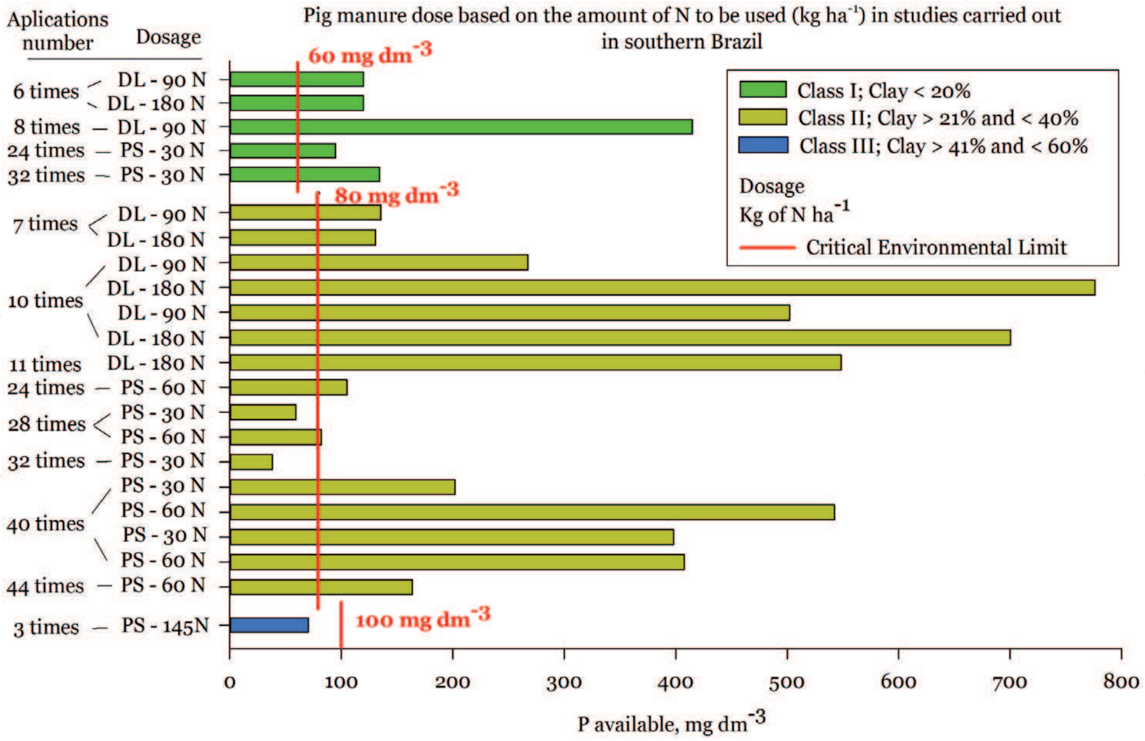

Figure 3.
Available P contents in soils with different clay contents obtained from studies with application of PS and DL conducted in the states of SC, PR, and RS, using as a dose the recommendation for N (kg ha⁻¹).

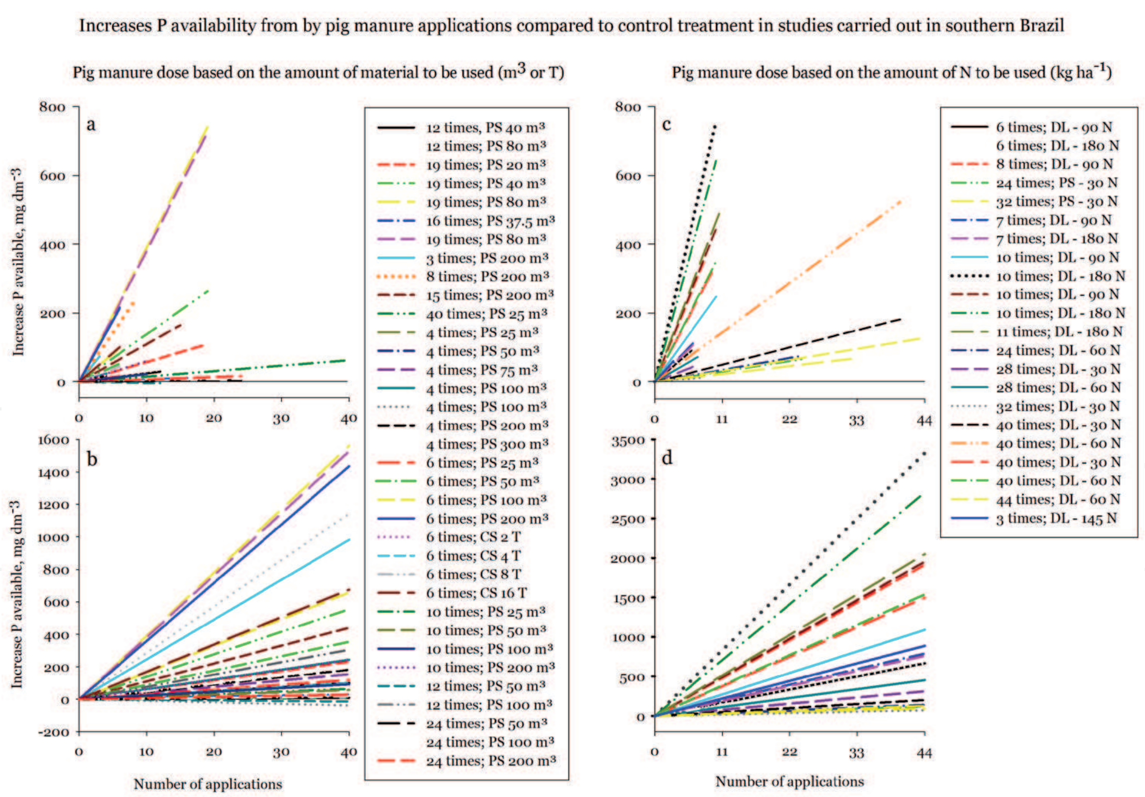

Figure 4.
Increase in soil available P contents based on the number of SM applications used in the studies (a and c) and projected up to 44 applications (b and d) from studies conducted in the states of SC, PR, and RS, using as dose the volume (m³ ha⁻¹) or weight (t ha⁻¹) of the applied manure (a and b) and the recommendation by N (c and d).

added P is in inorganic forms, associated with minerals. However, it is also possible to observe an increase in P organic form, mainly with an increase in SOM promoted by SM application or an increase in cultivated crops DM. The little effect is observed on the P residual contents, a highly recalcitrant form and not available, but there is an increase in the more labile forms, highly related to the applied SM dose [13, 15, 30, 34, 40, 41, 46]. In a study with increasing SM doses in Santa Maria, RS, De Conti et al. [47] also observed that most of the chemical species of P in the soil solution were in the form of orthophosphates ($H_2PO_4^-$ and HPO_4^{2-}). These type of studies, together with the evaluation of the maximum adsorption capacity, demonstrate that the SM applications are saturating the functional groups of the soil colloids, reducing the binding energy, and contributing to the increase of P availability and mobility (migration) in the soil profile (**Figure 4**) [25, 40, 41]. This behavior is observed mainly in the no-tillage system, where applications are made superficially and there is no soil disturbance. This behavior is observed mainly in the no-tillage system, in which applications are carried out superficially and the soil tilling is restricted to the planting lines or seedling cradles. This promotes a marked accumulation of P in the most superficial layers, and a gradual decrease with increasing depth. In the case of systems with overturning, it is expected that P availability will be more evenly distributed over the overturned layer, which may promote a reduction in P contents [13]. Additionally, Gatiboni et al. [34] determined that in samples of ground soil the maximum P adsorption capacity of soils was 1.4 to 14 times greater than samples with preserved structure. The authors pointed out that in samples with the preserved structure, P can migrate through the soil profile through preferential flows, which does not happen with samples with ground soil. Therefore, in samples with the destruction of the soil structure, the area and the contact time between the water containing P that percolates in the soil and the adsorption bands with soil colloids, especially clays, can increase. However, soil losses in systems with tumbling tend to be greater, which can contribute to the losses of P (particulate P) by runoff [14, 15, 39, 46].

The major problem of P accumulation in soils is related to its potential for water resources eutrophication [48]. Although P has low mobility in the soil, the saturation of the adsorption sites by P accumulation can favor its migration in the profile through water infiltration. This migration can occur through preferential flows, through a continuous network of pores and bio pores, and fissures present in the soil structure [18–20, 47]. Additionally, Tiecher et al. [43] also observed that the amount of P added, but mainly the volume of percolated water, highly associated with the intensity of the rain, have the greatest effect on the amount of percolated P. These authors when taking a sample of percolated water at a depth of 0.6 m, observed in many instances the concentration of soluble and available P above 0.15 mg L^{-1}, the maximum limit allowed by Brazilian legislation [44], mainly using the dose of 80 m^3 (the highest dose assessed). However, as previously stated (item, 2), the greatest P loss occurs through its transport through surface runoff water [3, 39, 46]. Soil surface P accumulation, the amount of this element added by the applications, the interval between application, and the occurrence of rain are factors with a high correlation with the amount of P present in the runoff water. Also, the clay content has a great influence on how much the soil can retain P, reducing its losses by the flow. This was evident in the study conducted by Gatiboni et al. [25], who observed that in soils with higher clay content (80%) the increase in the concentration of P in the drained solution only occurs when P availability (determined by Mehlich-1) is very high (147 mg dm^{-3}). On the other hand, soils with lower clay content (20%) already show an increase in P in the drained solution with lower values of available P (74 mg dm^{-3}).

Therefore, the increase in P availability in soils can increase its losses and its direction to nearby watercourses, mainly rivers, springs, dams, and artificial wells, compromising its quality. This is even more worrying due to a large number of watercourses present in the studies of Southern Brazil and the very diversified relief present in this region, with many sloping areas, which favors soils and nutrients loss, especially in the absence of more conservationist soil management [15]. In a study conducted by Boitt et al. [46] in a Typic Hapludox from Campos Novos, Santa Catarina, counting the amount of P added by PS (25, 50, 100 and 200 m^3 ha^{-1} $year^{-1}$) and by the crops residues, the amount accumulated in the soil and extracted by the crops, the authors evaluated that from 6 to 38% of the added P was lost, mainly by runoff. The amount of P that was considered lost was 45 to 1550 kg P ha^{-1}. This study reveals, therefore, that a considerable amount of the added P can be taken from the area of application and, potentially, reach the water resources. However, in a study evaluating the water quality of 13 watercourse points at Taquari Antas Watershed, Rio Grande do Sul State, which featured 861 swine farmers, Schneider et al. [29] determined that the Water Quality Index (WQI) and the trophic state class of the rivers were classified as "good" and "mesotrophic" (P concentration, $137 < P \leq 296$ mg m^{-3}), although they found an increase in the concentration of P at some points. Also, the authors warned about the proximity of swine units to water resources and the flow of rivers, where the closer the facilities are to the rivers, the greater their contaminating potential, and the greater the river's flow should be to promote a dilution effect of polluting agents. The potential of swine units to contaminate water resources was also addressed by Couto et al. [14, 15]. In the first study, the authors used data from estimated soil loss, the distance between the P source and a water body, and soil P concentrations (using P chemical fractionation data) to assess the vulnerability of P contamination in the soils of swine units submitted for different times (years) of PS application in Braço do Norte, SC. In summary, areas with higher levels of P in more labile forms, higher accumulation of P in the soil, lower clay content, and greater erosion caused by water showed greater vulnerability in losing P, which can cause it to be directed to water streams. In parallel, in the same region, Couto et al. [15] separated areas with different years of PS application and different types of land use and used P fractionation data and the universal equation of soil loss (USLE) to create a map representing the vulnerability to P losses for the entire Upper Coruja/Bonito River watershed. The different classes of vulnerability developed by this approach showed an excellent correlation with the P losses assessed in runoff water. For example, areas with the cultivation of black oats and rotating maize showed greater losses of P due to soil tillage and poor surface protection. With these results, the authors recommended the adoption of soil conservationist practices, such as not disturbing with PS incorporation and soil cover.

Therefore, more and more work involving the use of SM as fertilizer reveals that its prolonged and excessive use can pose great risks to environmental quality [48]. From this, strategies for storage, stabilization and application began to be devised in order to facilitate or increase control over what is applied to the soil or to prevent environmental problems in swine areas. In prominence, they became a reference for the assessment of critical P levels in soils, which became known as Environmental Critical Limits (ECL), which are related to the clay content of the soil and the concentration of P in the drained solution and allowed to regulate the amount of SM to be applied in the cultivation areas [24]. These studies were so relevant that they became the basis for the new environmental regulation of the State of Santa Catarina, based on the formulation of Normative Instruction No. 11 [45], which establishes criteria for the implementation of activities related to pig farming, including treatment of swine manure (liquid and solid) and its disposal in the soil. Until that time, Santa Catarina legislation only recommended PS applications in doses of up to 50 m^3 ha^{-1} $year^{-1}$ [49]. Briefly, the new legislation determines that the maximum allowed content (Environmental Critical Limit) of P (ECL-P) extracted by Mehlich-1 in the 0–10 cm layer will be defined by the equation (Eq. (1)) prepared by Gatiboni et al. [24]:

$$ECL - P = 40 + clay(\%) \tag{1}$$

where clay (%) is the soil clay content present in the 0–10 cm layer.

From this equation, it is possible to identify the maximum allowed P content according to soil clay content, being a simple assessment, aided by soil analysis. With the values obtained by Eq. (1), it is then possible to determine the SM dose to be used. In cases where P content is up to 20% above the ECL-P, it is recommended to reduce the recommended maintenance dose by 50% for the crop to be fertilized. And in cases where P content exceeds by more than 20%, the ECL-P is recommended to temporarily suspend any type of fertilization that contains P. Mitigating measures are also recommended in both situations, such as the use of crops with high capacity of extraction and exportation of P and the revolving of the soil aiming at the dilution of P in deeper layers (which must be associated with soil erosion control practices) [45].

Based on this Normative Instruction, the authors of this chapter performed surveyed the scientific articles published in the states of SC, PR, and RS using SM to assess the impact of these applications on the P contents present in the different soils and management. The result of this survey is shown in **Figures 2**–**4**. As can be seen in **Figure 2**, in the studies where the SM applications used their quantity, that is, their volume ($m^3\ ha^{-1}$ for PS) or weight ($t\ ha^{-1}$ for PS compost) to formulate the doses, there are some cases where the levels of available P are already above the ECL-P, especially with the highest doses. At the same time, the increase in the number of applications also tends to contribute to a higher P availability. However, it is also noticeable that in studies with soils with higher clay contents (> 61%) the increase in P availability is more subtle, due to the greater capacity of these soils to adsorb P [24, 25]. Also, in only one case were the available P content was above the ECL-P. On the other hand, when considering the studies that used N as the reference nutrient to determine the dose (**Figure 3**), it is clear that the PS and DL applications promoted an increase in the available P contents above the ECL-P in its vast majority (although the number of studies on soils with clay content>41% is very small). This reveals that the added amount of P in this management system is much higher, increasing its contents in the soil more quickly (**Figure 4**), which tends to cause greater problems in the accumulation and losses of P in the swine units.

The survey of these studies also reveals that if rates of increase in P availability are maintained until 44 applications have been made, approximately 53% of the cases that used the SM volume or weight as the dose will have available P contents above the CEL- P (**Figure 4**). In cases where N is used as a reference element, this number rises to approximately 95%.

Therefore, although SMs are rich and advantageous sources of supplying P to the crops of interest, their use must be carried out with technical criteria, keeping up with P availability in the soil. In swine units, where SM applications were and still are carried out periodically, the choice of dose should take into account the soil fertility, the chemical composition of the manure, and the nutritional requirements of the crops. With these criteria, the application must be carried out until it meets what was recommended for a given nutrient, which is considered the criterion of the critical nutrient. And the other nutrients must be supplemented with mineral fertilizer [45, 50]. Also, the use of N as a reference element in fertilizers should be avoided, as it promotes excessive P addition, especially in richer materials of this element, such as DL. The use of highly demanding plants in P (phytoaccumulators) and the use of conservation practices are also important measures to be taken. These precautions are important to ensure adequate targeting of the SM, avoiding P accumulation in the soil and potential losses, which can affect the quality of water resources present in the swine units or nearby.

3.2 Heavy metals

Continuous SM application and in excessive doses, mainly carried out in swine units also presents the risk of promoting metals accumulation and contamination in soils, which also enhances its transfer to the adjacent water bodies from these areas [51, 52]. Studies carried out in the southern states of Brazil demonstrate this increase in Cu and Zn total and available contents in areas subjected to SM applications, with emphasis on treatments with a greater volume of application or with doses based on the N recommendation (**Figures 5**–7). In parallel, some studies have also shown an increase in Mn, Fe, Ni, Cd, Pb, and Cr contents. However, the greatest focus of studies on metals in the states of SC, PR, and RS was given to Cu and Zn, which tended to have high levels in some studies [57].

SMs present variable but significant concentrations of Cu and Zn in their composition due to the addition of excessive amounts of these elements in the swines' diets about the physiological requirements of these animals [58]. In general, 6.08 to 11.68 mg of Cu kg^{-1}, and from 39.67 to 76.15.0 mg of Zn kg^{-1} of feed is added to the pig's diets between the pre-initial and termination phases [59]. In a study published by the National Research Council (NRC) [60], it was emphasized that Cu requirements can be from 3.0 to 6.0 mg kg^{-1} and Zn from 50.0 to 100.0 mg kg^{-1} during the animals breeding and 5.0 and 50.0 mg kg^{-1} of Cu and Zn, respectively, in the lactation and gestation phases. However, as highlighted by the NRC [60] and Ribeiro et al. [61], it is common to use doses of 100 to 250 mg of Cu kg^{-1} and 1000 to 3000 mg of Zn kg^{-1} of feed to promote pharmacological effects in pigs.

The use of these metals in feed formulations is due to the functions they present in swine metabolism. Copper sulfate ($CuSO_4$) is used as a growth promoter

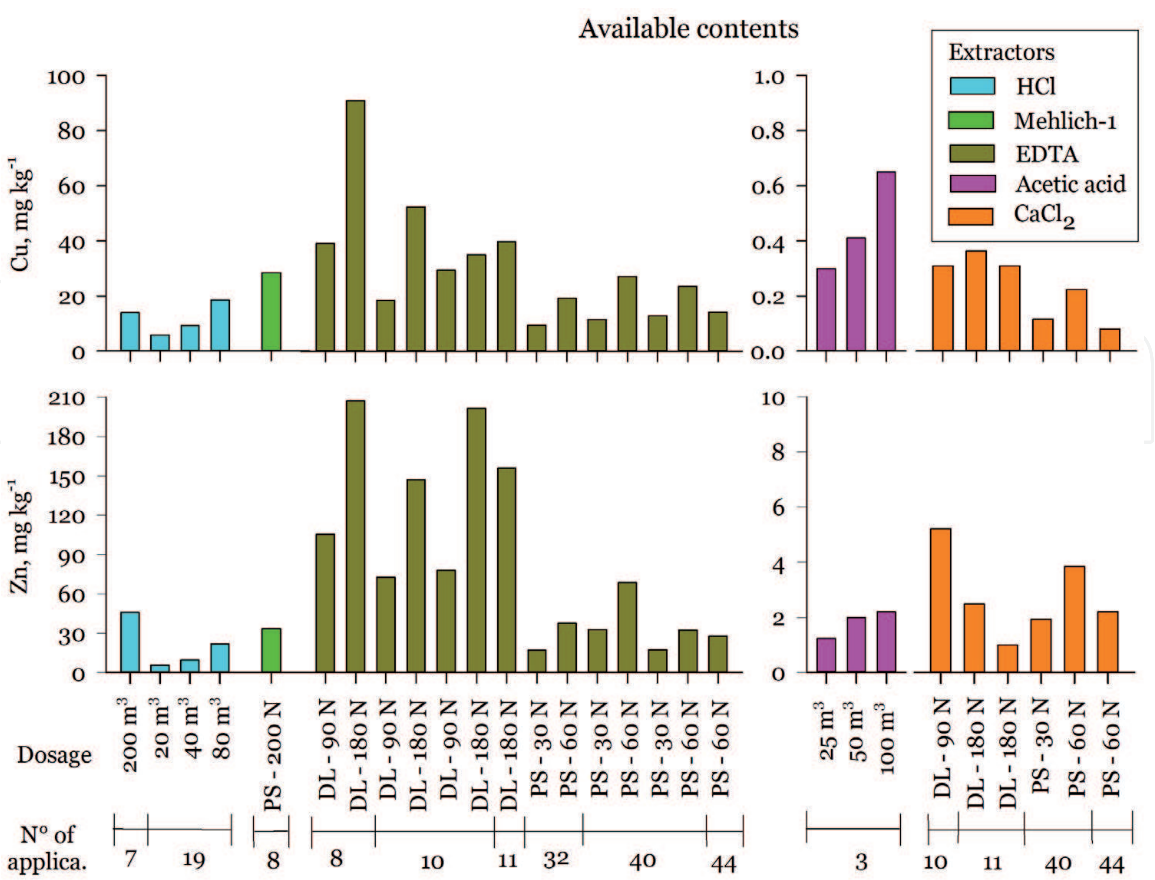

Figure 5.
Available Cu and Zn contents determined by different extractors (HCl, EDTA, Mehlich-1, CaCl2, and acetic acid) in study soils in the states of Santa Catarina, Paraná, and Rio Grande do Sul.

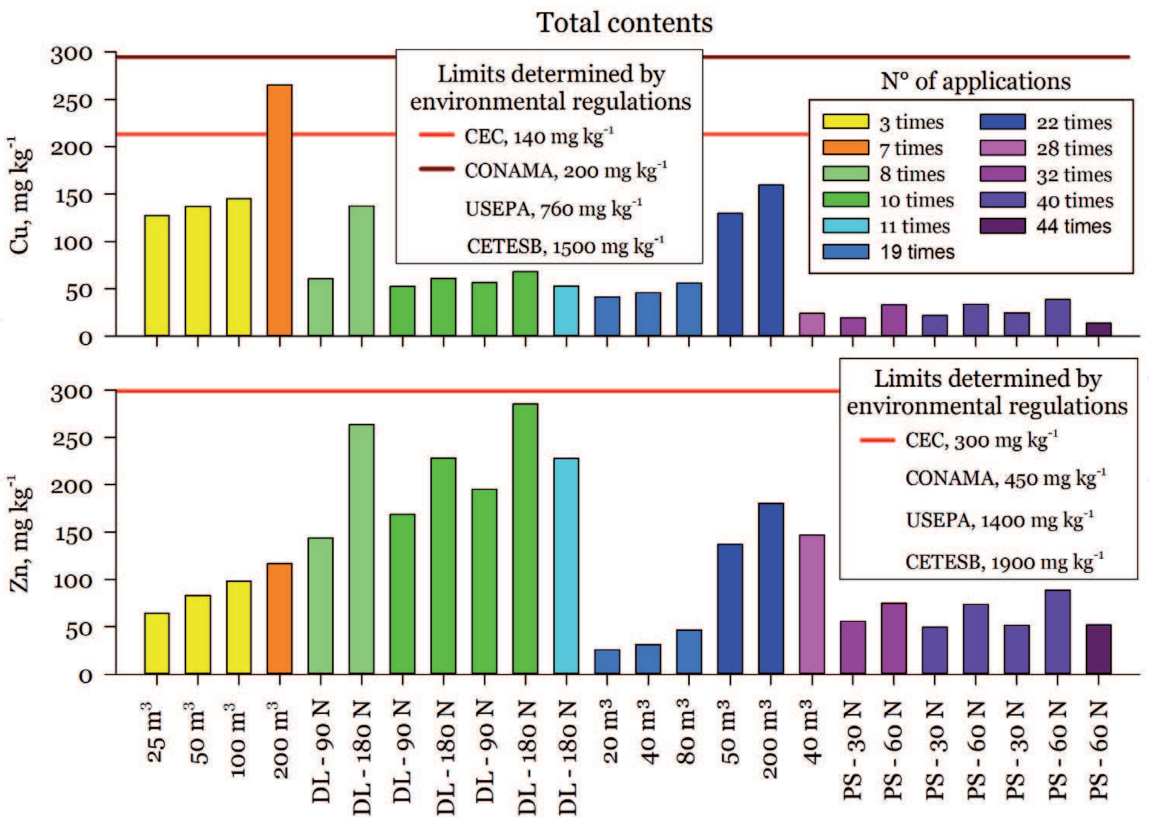

Figure 6.
Total Cu and Zn contents in soils from studies carried out in the states of Santa Catarina, Paraná and Rio Grande do Sul and the values recommended by environmental agencies [53–56].

in animals, while zinc oxide (ZnO) acts as a preventive and curative product for diarrhea [60, 61]. As a result, much of the Cu and Zn added to the feed is eliminated by the animals' feces. At the same time, the adoption of certain manure management systems, such as swine production in a deep litter system and the composting of manure, can increase the proportion of these elements in the final product. The high temperatures during the process of stabilizing the DL or the PS compost and the microbial activity favor the mineralization of OM and the reduction of the C content at the end of this process, increasing the concentration of metals [8].

Cu and Zn when added to the soil via SM are distributed in pre-existing forms in the soil, such as mineral and organic, being adsorbed by the most avid adsorption sites. This ability of soils to adsorb Cu and Zn will depend on the nature of the soil source material, the content, and composition of the clay fraction, the content and composition of the MOS, and the geochemical conditions of the soils, such as pH and ionic strength [17, 57, 62]. However, the continuous addition of Cu and Zn to the soil by SM applications promotes bonds with less adsorption energy and precipitates with greater solubility [57]. In work developed by Girotto et al. [63] in Santa Maria, RS, the authors found that after 17 applications with different doses of DL (0, 20, 40, and 80 m^3 ha^{-1}) Cu and Zn are accumulated in the soil mainly in bioavailable forms, in which the highest levels of Cu were found in organic and mineral form, and Zn, in mineral form. Also, successive manure additions tend to increase the presence of Cu and Zn in more labile forms, such as soluble and exchangeable, due to the saturation of the adsorption sites, reducing the bond stability. Similar results were obtained by other authors in soils in the municipalities of Campos Novos and Braço do Norte, performing the chemical fractionation of Cu and Zn in the soil [21, 57].

Therefore, as Cu and Zn are added to the soil, they are distributed among soil mineral and organic components. However, as the applications are maintained, the bonding groups are saturated, increasing the availability of these metals in the

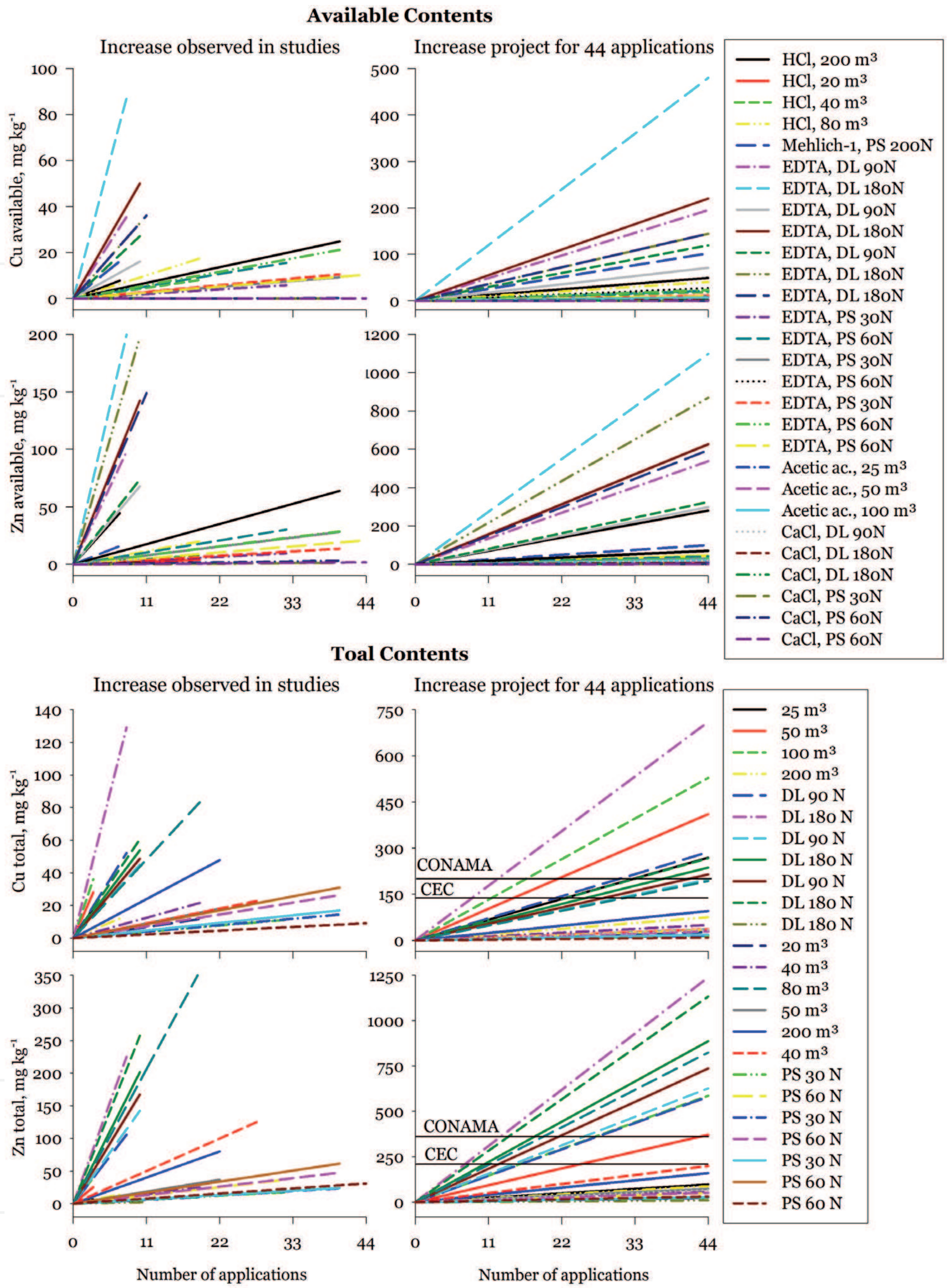

Figure 7.
Increase in available and total Cu and Zn contents in the soil based on the number of SM applications used in the studies and projected up to 44 applications from studies conducted in the states of SC, PR, and RS.

soil. This availability is influenced by pH, redox potential, ionic strength, competing ions, and soil constituents (minerals and organics), in addition to the metal's ionic potential, that is, the ratio of its charge and ionic radius (z^2/r) [62]. Thus, the magnitude in increasing the availability of metals in areas with SM application is not only related to how much is added by the manure, but also by soil attributes. In a studie carried out on swine units in Santa Catarina, Couto et al. [21] observed an increase in Cu and Zn total and available contents, but that this increase was dependent on the type and attributes of the soil, application time and SM composition.

When surveying studies carried out in the southern states of Brazil, we also observed a trend in increasing Cu and Zn availability (determined by HCl, EDTA, Mehlich-1, $CaCl_2$, and Ac. Acetic extractors) and in total contents in the trials, mainly with the highest applied volumes (m^3 of PS ha^{-1}) and with the use of N as a reference element (**Figures 5** and **6**). However, greater attention should be paid to observing that in some cases the Cu total contents are already above the reference values of the Council of the European Communities (CEC) [57] and CONAMA [59]. This represents a risk to the quality of this environment, requiring monitoring and possible mitigating actions in the future. In the case of Zn, no study had levels above the recommended. However, when projecting an increase in the total contents in these areas, up to a number of 44 applications, it is observed that the number of situations where the levels were above that recommended by CEC [57] and CONAMA [59] will be higher (**Figure 7**). Additionally, it is observed that the increase in availability with the 44 applications will provide very high levels, which can represent potential toxic effects in these areas. Therefore, it is important to exercise caution in doses used excessively so as not to compromise the quality of the environment and increase Cu and Zn available contents.

With the increase in Cu and Zn saturation and availability in the soil promoted by SM, consequently, there is an increase in the concentration of these metals in the soil solution, which potentiates their toxic effects on plants and organisms and their movement in the soil profile [7, 16, 17, 20, 63, 64]. The increase in the concentration of these metals in the soil solution after continuous applications of PS was demonstrated by De Conti et al. [65] in soil samples obtained in Santa Maria, RS. In addition to the increased concentration, mainly with the highest dose (80 m^3 ha^{-1}), these authors also observed that the main species of Cu and Zn in the soil solution were free species (Cu^{2+} and Zn^{2+}) and species complexed with dissolved organic compounds (CuDOC and ZnDOC). The increase in free species can pose a risk to crops, as these are forms absorbed by the roots, while the CuDOC and ZnDOC species have greater mobility. However, the authors themselves revealed that the crops could complex these free species with exudates release, which increased the concentrations of CuDOC and ZnDOC in the soil solution. This mobility of Cu and Zn, referring to the soil solution, is dependent on its concentration in the solution, the nature of the association with other soluble ionic species, and the ability of the soil to provide them for the solution [64].

The increase in soil Cu and Zn availability in areas subjected to SM application has raised concerns about the possibility of toxic effects on crop cultivation. This concern is justified because, even though these metals play an important role in many physiological processes in crops, it is expected that in the swine units there may be a steady growth in the contents of these metals in soils, which can reach critical levels, affecting the productive capacity of these areas [22]. In Santa Maria, RS, Girotto et al. [20], when evaluating maize grown in soil samples (deformed and non-deformed) submitted to 19 applications of increasing doses of DL (20, 40, and 80 m^3 ha^{-1}), observed an increase in soil Cu and Zn available contents and physiological changes in the maize, with increased lipid peroxidation, several senescent leaves, and ascorbate peroxidase activity and decreased plant weight and superoxide dismutase activity, especially at higher doses and with the deformed soil sample. In a parallel study, evaluating the maize cultivation in a soil (obtained from Braço do Norte, SC) submitted to nine years of PS and DL applications with doses based on the recommendation of N (90 and 180 kg N ha^{-1}), Benedet et al. [7] observed an increase in Zn concentration in the aerial part and small changes in stomatal density, chlorophyll content and APX and CAT activity in maize grown in the soil with PS 180 kg N ha^{-1}, but this did not affect the crop development. With soil samples obtained in the same area (but with 10 years of application), Benedet et al. [16] observed that black oat plants showed an accumulation of Cu and Zn in the aerial part and Cu in the roots, especially when grown in the treatment with DL 180 kg N ha^{-1}. Additionally, at the beginning of crop development, leaves with chlorosis in DL 180 kg N ha^{-1} were observed. However, no negative effect was observed in the production of DM on plant growth. Although these studies have used high doses of SM, higher than that used in swine units, they indicate a potential negative effect of soil Cu and Zn accumulation of Cu and Zn, their translocation to crop tissues, the need to maintain control on the doses used of SM and monitoring of these areas [21]. Additionally, as presented by Benedet et al. [17], the maintenance of conservationist practices, especially those that favor the maintenance or increase of SOM contents, mainly in the most stable forms, is important to control the availability of metals, mainly Cu, due to their high affinity with the organic groups, increasing the adsorption of these metals and reducing their soluble forms.

In parallel, the accentuated additions of Cu and Zn in the soil by the successive SM applications present a high potential for environmental contamination [21, 61], as they can be submitted losses through runoff and leaching [51, 52, 64]. In an experiment conducted in Santa Maria, Girotto et al. [64] evaluated the Cu losses in the drained and percolated soil solutions submitted to PS applications and found that the greatest Cu losses occurred due to surface runoff. Additionally, the Cu losses in the drained solution, with a dose of 80 m^3 ha^{-1}, were 2.3 times greater than in soil without fertilization, the majority being transferred in particulate form. Smanhotto et al. [53], on the other hand, did not observe changes in the Cu and Zn concentrations in the percolated water collected at a depth of 60 cm in a soil fertilized with PS (100; 200, and 300 m^3 ha^{-1}) in Cascavel, PR. The authors justify the changes in the Cu and Zn concentrations in the percolated solution as dependent on the soil clay content present and the presence of pores and bio pores that favor percolation and alter the interaction between the percolated water and the surface of the clay minerals and Fe oxides and Al. Additionally, Dal Bosco et al. [66] also observed an increase in Cu and Zn concentration in water lost by runoff after application of increasing doses of PS (50, 100, 150, and 200 m^3 ha^{-1}) in Toledo, PR. The authors observed that with the increase of the dose and the first collection of drained water (48 days after sowing) there was a greater loss of Cu. Also, the Zn concentrations in the drained material were close to the maximum concentration of 5.0 mg L^{-1} provided by CONAMA Resolution 357/2005 [44] for the discharge of effluents. These losses due to runoff, although they do not seem significant, can cause contamination of water resources. In parallel studies, Capoane et al. [52] found low Cu and Zn concentrations in the water resources of the hydrographic basin of Arroio Caldeirão, Palmitinho, RS, formed by 124 swine units with the intensive swine production system, dairy cattle, and tobacco production, mainly. However, Capoane [51], when evaluating the Cu and Zn contents in the sediments present in the bottom of the water resources of this basin, observed that Zn concentrations were between the range Threshold Effect Level (TEL) and Probable Effect Level (PEL) (123.1–315.0 mg kg^{-1}), a range that represents the occasional occurrence of adverse effects for organisms. And the Cu concentrations were on average 2.3 times higher than the Canadian Council of Ministers of Environment (CCME) [67] toxicity values (> 197.0 mg kg^{-1}), indicating that adverse effects may already be occurring in the aquatic organisms. The data collected by these studies reinforce the need to use conservationist practices to prevent erosion caused by rains, as described in item 3.1.

Thus, although the use of SM promotes productive gains to agricultural crops and improves soil fertility, its excessive application can promote the accumulation of Cu and Zn above the soil's support capacity, contributing to its mobility in the soil profile and toxicity to plants, in addition to favoring surface and subsurface waters contamination, compromising the functionality of the environment [21, 57, 63, 64].

4. Conclusion

The use of SM as fertilizer in swine units in the states of Santa Catarina, Paraná and Rio Grande do Sul is an advantageous practice for producers, as it allows the use and recycling of a source rich in nutrients, reducing the need for external inputs. The application of SM in soils favors the increase of available contents of macro and micronutrients, but it also tends to promote improvements in various soil attributes. The addition of C by the manure, even in a lower concentration in the PS, and the increase in crops DM production favors the increase of SOM, which consequently contributes to the improvement of soil biological and physical attributes. In addition, many studies carried out in these states demonstrate that SM applications can also favor soil pH values. Reducing the use of limestone or agricultural plaster in these areas. The increase in soil fertility results in enhance crop productivity, and in many cases the gains obtained are equivalent to those promoted by mineral fertilizers. However, it was also common to observe through the studies raised that very high doses of SM are necessary to achieve yields proportional to mineral fertilizers. Therefore, it is important to carefully use the SM in agricultural areas, avoiding excessive applications, higher than what will be absorbed by the crops. In these swine units the formulation of the doses of application of SM must take into account soil fertility, crops recommendations to be cultivated and the chemical composition of the SM. From these criteria, the most limiting element can be determined, that is, the one that first contemplates what was recommended, and the other nutrients will be supplemented with mineral fertilizer. The transformation of PS into solid materials, such as the PS compound and DL, can be an interesting strategy to be used in these swine units, reducing the volume of SM and allowing the transport and commercialization of a product rich in nutrients. However, as these solid manures have a higher concentration of nutrients, their use must present greater care and criteria. Additionally, it was observed by the studies survey that the use of N as a reference element for the recommendations of doses is a practice that should be avoided, as it causes the addition of very high amounts of other elements, such as P, Cu and Zn. Potentializing the accumulation of these nutrients in the soil. In this sense, P is an element of greatest concern in these swine units, as studies already show high levels in the soil and potential losses due to runoff, especially in areas subject to water erosion. Due to the provisions of the new normative instruction in Santa Catarina, the increase in the P content in these areas will make it impossible to continue with SM applications in these areas. And knowing that the extension of the areas of the pig units is limited, this can cause a shortage of options for farmers to target the MPs. Finally, the adoption of conservationist practices is important to maintain the soil structure and avoid losses by erosion and mineralization of the SOM. These practices contribute to increasing the adsorption capacity of these soils, contributing to the retention of P, Cu, and Zn in mineral and organic components.

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