Review

Horticulture and Orchards as New Markets for Manure Valorisation with Less Environmental Impacts

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Abstract: Animal manure management is a real challenge to minimize environmental impacts and ensure that this valuable material is efficiently used in a circular economy context. One of the main limitations for larger use of animal manure as fertilizer is the availability of land to receive it in an area close to the farm. Indeed, animal manure is traditionally used for cereals and animal feed growth, but the soil area occupied with these crops might not be enough to receive all the manure produced and/or part of this soil might have nutrient contents, namely phosphorous, that do not permit further application of manure. Hence, extra land used for other agricultural activities might be an option. The main objective of the present review was to analyse the constraints and solutions to increase the use of manure in horticulture and orchards. Emphasis was given to the legal framework for manure utilization in the EU that might stimulate or restrain such a solution. The main characteristics of manure that might limit or stimulate manure reuse were also described, and the potential of some treatments to valorise manure was analysed. Several examples of alternative uses of manure in horticulture and orchards were examined, and the society and farmers' acceptance of the proposed solution was addressed.

1. Introduction

The increase in the world population of ~33% to 2050 should be followed by a 70% increase in food demand worldwide [1,2]. When considering more specifically meat and dairy products, the increasing demand is also due to the improvement of living conditions in developing countries that will lead to a livestock revolution [3]. In the European Union (EU), a 14% increase in meat consumption per capita is expected between 2017 and 2030 and, simultaneously, milk production is expected to increase 1% per year in the same time interval [4]. To attend to such a demand, the livestock production systems have moved from an extensive to a more intensive activity over the last decades, and the livestock density tended to be very unbalanced between EU regions, ranging from 0.2 livestock units/ha of agriculture area (in Bulgaria) to 3.8 (in The Netherlands) [5]. Furthermore, four countries/regions (Denmark, The Netherlands, Northern Germany, and Western France) host a third of all EU farm animals (especially dairy, pigs, and poultry) [6].

Simultaneously, the size of livestock farms also increased, moving to industrialized farms, concentrated in the same area and, generally, with low soil availability. This is especially the case for pig [7] and poultry [8] productions, while the dairy and beef sector, despite a trend to intensification in some regions, continues to be more extensive [9,10].

One of the main consequences of this intensification is the production of large volumes of manure. Indeed, the total amount of animal manure produced each year in Europe is estimated to be close to 1400 million t (32% cattle slurry, 11% pig slurry and 8% poultry litter) [11]. This amount of manure represents 80–140 million t of nitrogen (N) and

20–30 million t of phosphorus (P) per year, which is equivalent to 1–2 times the amounts of N and P applied annually through mineral fertilizers [12,13].

This large volume of manure is also responsible for a major part of ammonia (NH_3) emissions (1.4 million t $N-NH_3$/year in the EU) [14], and for the emission of 73 million t CO_2 eq/year of greenhouse gases, which represents 50% of the nitrous oxide (N_2O) emissions and 15–25% of the methane (CH_4) emissions from agriculture in the EU [15,16]. Furthermore, manure management in the EU also led to the loading of 4 million t N/year in water bodies [17].

An obvious solution to minimize such environmental impacts, during and after soil application, is to increase the application area and, simultaneously, to decrease the application rate. However, the soil area available to receive animal manure at farm scale might be limited and some productions, as swine and poultry, generally have no soil associated to the farm and have, therefore, to export all the manure. Hence, extra agricultural land, not yet receiving manure, are needed.

Direct application of raw manure in an area close to the farm is the common practice in most EU regions, and it remains the best option (cheaper, lower energy use). Nevertheless, another option to minimize the environmental impacts of animal manure is its treatment, such as solid–liquid separation [18] or acidification [19]. The solid fraction obtained by separation of manure could be more efficiently transported over longer distances, while the liquid fraction might be used directly at the farm, for irrigation.

Till now, in Europe, animal manures and slurries are mainly applied in grassland and arable crops, like cereals [20]. Nevertheless, these materials could be applied in many other crops, and as dressing fertilization, if some constraints to their application are eliminated. Therefore, the solution analysed here is the wider agricultural use of animal manures, like in horticulture and orchards, and with the option of basal and dressing fertilization, in a way to increase their valorisation and nutrients recycling.

The reuse of animal manure in such agricultural activities is also a key solution to minimize the environmental impact of mineral fertilizers production, and to minimize the dependency of EU regarding P fertilizers import. Indeed, the increase in mineral fertilizers prices has led to a growing interest from farmers in the use of organic materials, like manures, as nutrients sources. Moreover, the significant decline of soil organic matter (SOM) in many Mediterranean regions obliges farmers to look at organic fertilizers as attractive products [21], in opposition to the almost exclusive use of mineral fertilizers in the last decades.

The present review aims to analyse the constraints and solutions to increase the use of manure in horticulture and orchards, with special emphasis on the legal framework for its utilization in the EU, the main characteristics of manure that might limit or stimulate its reuse, and the potential of some treatments to its valorisation. An exhaustive presentation of alternative uses of manure in horticulture and orchards is also compiled and, finally, a key parameter for the success of this solution, society and farmers' acceptance, is addressed.

2. Legal Framework to Use Manure in the EU

The legal framework and farmers/society acceptance are the two main drivers to successfully introduce new practices. The main EU regulations dealing with animal manure management were clearly detailed by Sommer et al. [22]. Nevertheless, the interest in organic materials has been growing exponentially and several updates of regulation occurred over the last years. Hence, in this review, the EU legislation will be briefly presented and analysed to understand to which extent it can contribute to stimulate or restrain the use of animal manure as fertilizer for alternative crops and plants.

According to the European Commission [23], animal manures are considered as animal by-products from category 2 and can be directly applied to soil without previous treatment. The transport of manure between EU countries also follows some strict rules, and the receiving country can refuse or impose some specific conditions, for instance, the sterilization of the material.

The Good Agricultural and Environmental Conditions proposed by the EU Council [24] incentives the use of organic materials, namely manures, since it promotes the maintenance of SOM as a way to reach food security and climate change mitigation [25]. However, in most countries, this recommendation has not been included, even though such measure could also contribute to the "4 per Thousand" initiative as a climate change mitigation measure [26,27].

The Directive 2010/75/EU on industrial emissions (the Industrial Emissions Directive or IED) [28] aimed at reducing gaseous emissions by adopting the Best Available Techniques (BAT). Nevertheless, it includes only the intensive pig and poultry farms and, since most of these farms have no associated soil area, it does not consider manure spreading. An increase of agricultural land available to receive slurry would be globally beneficial, not only because it could reduce ammonia emissions by the adoption of BAT for manure application, but also because it would allow a decrease in the application rates. Furthermore, a reduction of application rates would also be beneficial in terms of GHG emissions.

The Groundwater Directive [29], developed in response to the requirements of Article 17 of the Water Framework Directive [30], defines quality criteria regarding nitrates and pesticide concentrations in groundwater, as well as threshold values for other pollutants, namely cadmium (Cd). Regarding the nitrate issue, replacement of N mineral fertilizers by manure should not be a problem, since recent studies indicated that the risk of nitrate leaching can be lower in manure amended soils than in soils receiving mineral fertilizer [31]. Attending that P fertilizers are a significant source of Cd [32,33], replacement of the source of P for plants, from mineral fertilizers to manure, is in line with the Groundwater Directive objectives.

The EU Nitrates Directive [34] is the most impacting measure when dealing with manure application, since it limits the application of N fertilizers to protect waters from nitrate contamination and should therefore be seen as one of the main constraints to the increase of manure receiving agricultural areas, namely to nitrate vulnerable zones. This directive defines the nitrate vulnerable zones (NVZ), where a maximum of 170 kg N ha^{-1} can be applied to soils through animal manures. In countries where the NVZ area could increase, there will be an urgent need to increase the manure receiving surface area and, consequently, it can be said that this directive supports the solution proposed here. Nevertheless, some new areas available to receive manure might also be classified as NVZ. The recent project SAFEMANURE might be seen as a strong opportunity and support to the concept analysed here [35]. Indeed, its main objective is to revise the nitrate directive, allowing the use of N-rich sub-products from animal manure, with the same conditions as those imposed on mineral N fertilizers [35], which are based on soil nutrients status and crop requirements. Even if it implies performing some "heavy" treatment to manure, it will surely open larger markets for animal manure.

The EU climate and energy targets [36] might have an indirect impact on the replacement of mineral fertilizers by animal manure in some regions. Indeed, one of these targets is a 40% decrease in GHG emissions, relative to 1990, and one of the main contributors for GHG emissions is the mineral fertilizers industry [37]. Decreased application of N obtained through the high-energy intensive Haber–Bosch process will drastically reduce the carbon footprint of the agriculture sector. Hence, the replacement of mineral fertilizers by manure should contribute to these targets. Nevertheless, animal production, the main contributor to CH_4 emissions [38], might also need to decrease its emissions to attend to these GHG targets, with a direct impact on the amount of manure available.

The revised National Emission Ceilings Directive (NECD) [39] imposes a strict reduction of gaseous emissions, namely N_2O, CH_4, NH_3, volatile organic compounds and sulphur dioxide that are strongly related to manure management. This might appear as a major constraint to the implementation of the solution proposed here, since a wider handling and soil application of manure might enhance such emissions. However, some manure pre-treatments and balanced soil applications might help to minimize these gaseous emissions.

Other legislation, or recommendations, as the Circular Economy Package [40], New Waste Framework Directive [41], New Landfill Directive [42], and New Fertilizing Products Regulation [43], might also influence the acceptance of the solution proposed here. Indeed, despite the fact of not having a direct impact on manure management and utilization, it will contribute to disseminate/support the use of manure as fertilizer and as an eco-friendly solution.

The CAP 2014–2020 included topics such as climate change mitigation, resource efficiency and soil, water, and land management [44]. More specifically, Rural Development Programmes (RDPs) set up by member states, or regions, on behalf of CAP 2014–2020, must attend almost four of the six EU Rural Development Policy priorities of which Priority 4 (P4) "Restoring, Preserving and Enhancing Ecosystems" and Priority 5 (P5) "Dealing with resource-efficient, climate-resilient economy", can directly influence the use of manure for new cultures. Actually, among other objectives, P4 aimed at "Preventing soil erosion and improving soil management", while another one from P5 deals with "carbon conservation and sequestration in agriculture". Hence, wider use of manure for fertilization and soil enhancement is in line with CAP recommendations. Nevertheless, P5 also includes a focus area on "reduction of greenhouse gases and ammonia emissions from agriculture" that might limit the reuse of manure if no mitigation measures are adopted to minimize NH_3 emissions. Hence, it is important to ensure that mitigation measures to minimize gaseous emissions are adopted in these new application areas. The "greening payments", as part of the CAP direct payments, might also be an important tool to support a larger use of animal manure as an alternative to mineral fertilizers and soil enhancers.

The Post 2020 CAP is being designed attending Good Agricultural and Environmental Conditions that includes several measures to minimize C losses from soil and increase of SOM, as well as the improvement of nutrients management at farm level [45]. It is to believe that the solution proposed in this review is in line with the new CAP policies. Organic farming could be an excellent market to reuse the surplus of manure available in some regions. However, the use of organic fertilizers in these farms is strictly ruled by EU Regulation 2018/848 [46], and only allows the use of manure produced in organic farms, is strictly prohibited the use of manure from intensive animal farms with no associated soil.

Table 1 summarizes the most important EU regulations and policies dealing with animal manure management that may potentiate or restrain the use of manure as a fertilizer for new crops and plants.

Table 1. Main EU regulations and policies dealing with animal manure management and their incentives and constraints to the use of manures as fertilizers for new crops and plants.

	Incentive	Constraint
CAP 2014–2020 and Post 2020 CAP [44,45]	Improvement of soil management and soil erosion prevention (Priority 4) Fostering carbon conservation and sequestration in agriculture and forestry (Priority 5)	Reduction of greenhouse gas and ammonia emissions from agriculture might limit the use of manure or imply the adoption of mitigation techniques (Priority 5)
Groundwater Directive [29]	Decrease of Cd contamination induced by P fertilizers application	Potential risk of nitrate leaching similar or lower than with mineral fertilizer
Nitrates Directive [34]	SAFEMANURE project for nitrate directive (ND) revision: equivalence of N rich sub-products from animal manure relative to mineral fertilizers in terms of ND rules	Limited N application in nitrate vulnerable zones
Climate and Energy targets [36]	Decrease of mineral fertilizers production to decrease GHG emissions and replacement by animal manure	Manure management also leads to GHG emissions and animal production is the main contributor to CH_4 emissions: potential decrease of the amount of manure produced
Revised National Emission Ceilings Directive (NECD) [39]	/	Manure is a strong contributor to most of the gases ruled by the NECD. Manure treatment will be needed.

3. Main Characteristics of Dairy, Pig, and Poultry Manures

Animal manure is a material rich in macro and micronutrients that is suitable to fully, or partially, replace mineral fertilizers. The first limitation of manure, when compared to mineral fertilizers, is the fact that it contains a mixture of several elements and does not allow the application of a single element, e.g., N or P. The second main limitation is the low concentration of nutrients, namely in slurries (liquid manure) and liquid fraction obtained by slurry solid–liquid separation (Figure 1). Indeed, nutrient-exportation in slurry, from livestock farms to arable or horticultural farms, implies larger costs to transport the same amount of nutrients, when comparing to mineral fertilizers.

Last but not least, animal manure is a heterogeneous material with dry matter (DM) content ranging from 10 to 140 g kg^{-1} in liquid manure (slurry), and from 210 to 460 g kg^{-1} in solid manure (~900 g kg^{-1} in poultry manure) [47]. The DM content has a direct influence on the nutrient content in slurries, namely the concentration of available N, P and potassium (K) (Figure 2). The variable composition of manure from different animal production systems and farms is also a serious drawback. In fact, it is highly relevant for farmers, who intend to replace mineral fertilizers with manure, to have a homogenous material between applications, so that they know exactly the amount of nutrients they are applying, and know, for sure, their availability to the plant. Considering N, the mean concentrations in slurries range from 4 to 10 g kg^{-1}, and in solid manure from 7.7 to 34.1 g kg^{-1}, depending on the animal species (Figure 1) [48]. Furthermore, there is also a huge variability between farms, as illustrated by the error bars of Figure 1 with data from more than 1000 samples of manure collected in different farms for each type of manure (except for chicken slurry, where N = 602).

One of the main advantages of using mineral fertilizers is the fact that the whole amount of nutrients is readily available for plants. On the contrary, in animal manure only a fraction of the nutrients content is readily available, while the remaining part can be released later, depending on several factors, such as soil conditions. Nitrogen availability in animal slurry varies between 40 and 60% of the total N, while P and K availability are more homogeneous between animal species, and close to 40 and 90%, respectively [47]. The mineralization and nitrification processes in a soil amended with slurry depend on slurry characteristics, as the C:N ratio or the pH, but the main drivers are the soil characteristics [49].

As occurred with the composition of manure relative to mineral fertilizers (multi elements versus single or selected elements: N, P, K, or others), the ratio between nutrients in manure, namely the N:P ratio, are fixed (against tailor-made ratios in mineral fertilizers) and not always adapted to the crops' requirements. Manure application is usually based on N demand and consequently leads to excessive supply of P [50]. The solution is to base the manure application on P requirements, which will provide an insufficient amount of N to the plant, requiring N supplementation via mineral fertilization. Another option is to use an adequate treatment (see the next section) to modify the manure N:P ratio to the desired value, considering the crops' needs.

As already referred, manure management is responsible for close to 60% of ammonia emissions in Europe [51], and an increase of manure handling and application to a larger area might enhance such emissions. Nevertheless, several solutions were proposed to minimize ammonia emissions associated with manure management (some of them will be detailed in the next section). Furthermore, mineral fertilizers, as urea or ammonium sulphate, also lead to ammonia emissions, and their replacement by manure should not induce an exponential increase in NH$_3$ emissions.
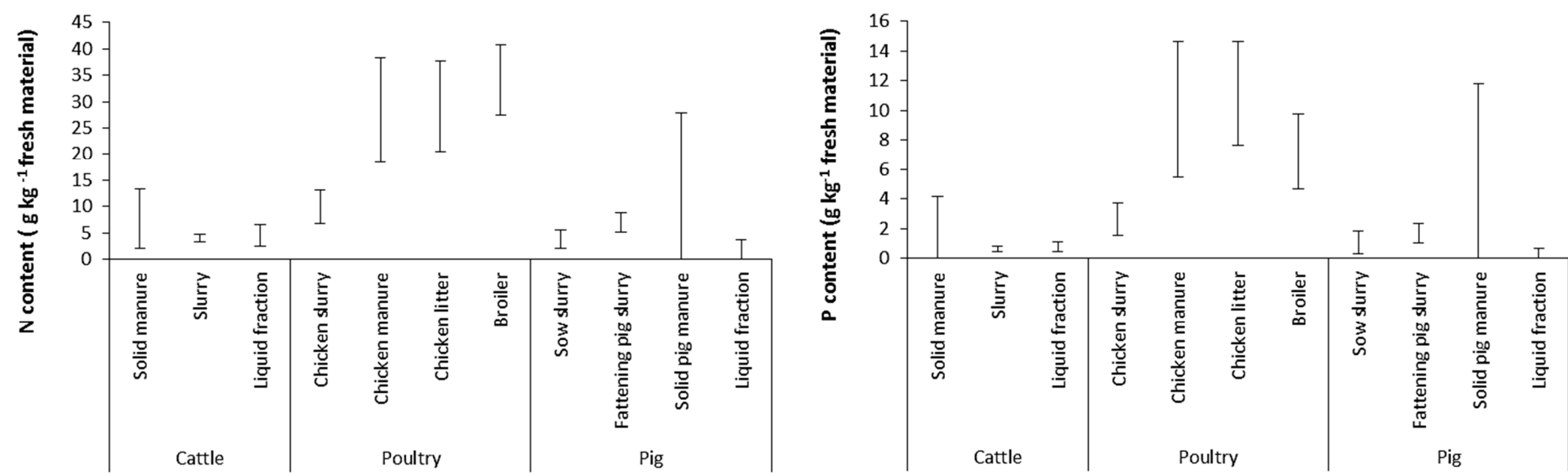
Figure 1. Range of N and P contents in raw and treated manure from cattle, poultry and pig production (adapted from [48]).
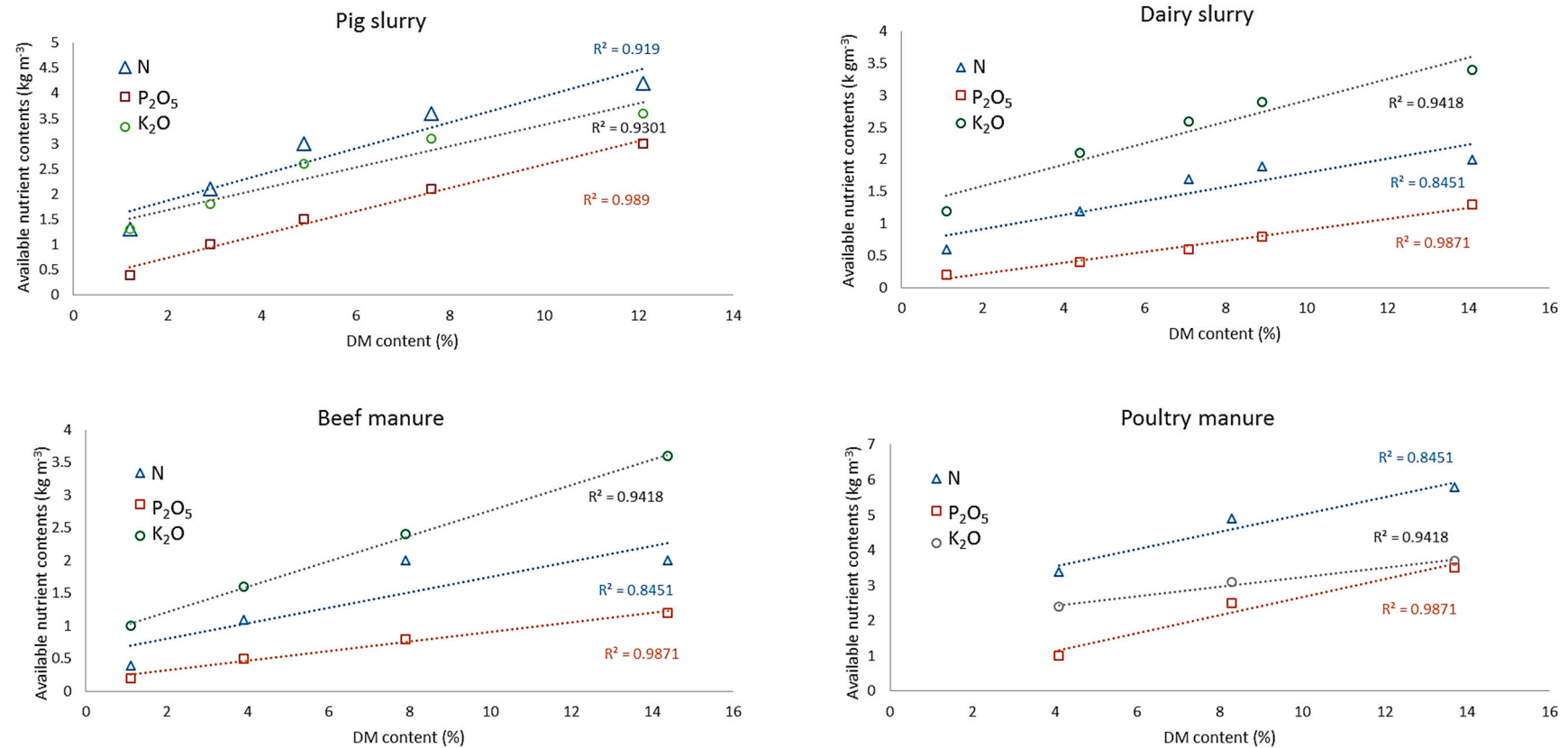
Figure 2. Relationship between the dry matter content and the N, P$_2$O$_5$ and K$_2$O available content in manures (pig, dairy, beef and poultry manure) (adapted from [47]).

One of the issues when dealing with animal manure is related to the odours produced along the whole management chain, especially during the soil application stage [52,53]. As it can be seen in Figure 3, these odours are due to the presence of a larger number of organic compounds with a predominance of acetic and propionic acids, as well as 4-methylphenol [53]. The increasing number of complaints in rural areas due to manure application to soil are mainly related to odours issues. The use of manures in new cultures, and new areas, might lead to more complaints and even produce a negative image of the products fertilized with manure. It is therefore essential to adopt some mitigation measures to minimize odour emission over the whole management chain, like the slurry injection, which proved to be an efficient solution to minimize odour emissions during the application stage (Figure 3).
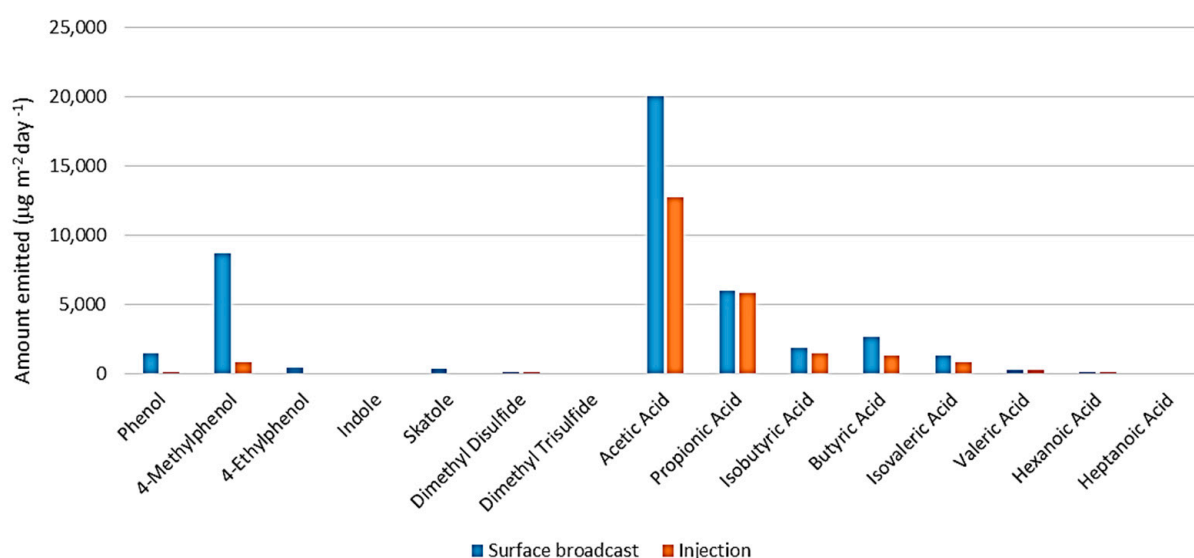

Figure 3. Odorous compounds emission during swine manure application by surface broadcast or injection (adapted from [53]).

Weed seeds are a major concern for agriculture, namely for horticulture, or again for organic farming since no chemical products can be used to fight invasive species [54]. Animal manure might contain a significant amount of weed seeds [55], depending on the animal species and on the stabilization technology adopted (composted or not) (Figure 4). Nevertheless, the impact of manure application to soil on weed growth is not clear, with studies indicating a low impact or no impact at all [55,56] and others reporting a significant impact [57]. This is mainly related to seeds' viability in manure, highly dependent on temperature, with Eghball and Lesoing [58] reporting that at a temperature close to 60 °C, reached during a certain composting time interval, most of the weed seeds were inactivated. Westerman and Gerowitt [59] also indicated that some seeds might also be inactivated during manure storage due to the toxic conditions of the mixture. Composting appears as the best solution to obtain a "weed free" material, even if long-term storage might be sufficient to minimize the risk of weed proliferation [55].

Animal manure contains valuable elements and organic matter that contributes to soil productivity enhancement, but also contains pathogenic microorganisms that can reach humans if appropriate manure management is not secured [60]. Among the pathogenic microorganisms that can potentially be found in animal manure, one can find (1) bacteria, such as *Salmonella* spp., *Campylobacter* spp., *Escherichia coli* or *Listeria monocytogenes*; (2) viruses, such as Polioviruses, Rotavirus, Avian influenza virus or *Hepatitis A and E*; (3) parasites, such as *Cryptosporidium parvum*, *Giardia lamblia*; and (4) fungi [60]. Therefore, animal manure application to agricultural soil represents a potential risk to human health,

both for workers and for consumers, and this issue needs to be addressed properly to broaden the agricultural crops with potential for manure application. Nevertheless, the probability of such contamination is relatively low, since these pathogens are sensitive to several manure properties, like redox potential, temperature, and pH [61], which can be manipulated to adequately hygienize the manures before their use. Indeed, Semenov et al. [62], reported that *E. coli* in manure is much more resistant in anaerobic conditions than in aerobic conditions. For this reason, storage of manure in aerobic conditions is usually pointed out as the most advantageous method of manure hygienization, namely in the case of solid manure [63,64].
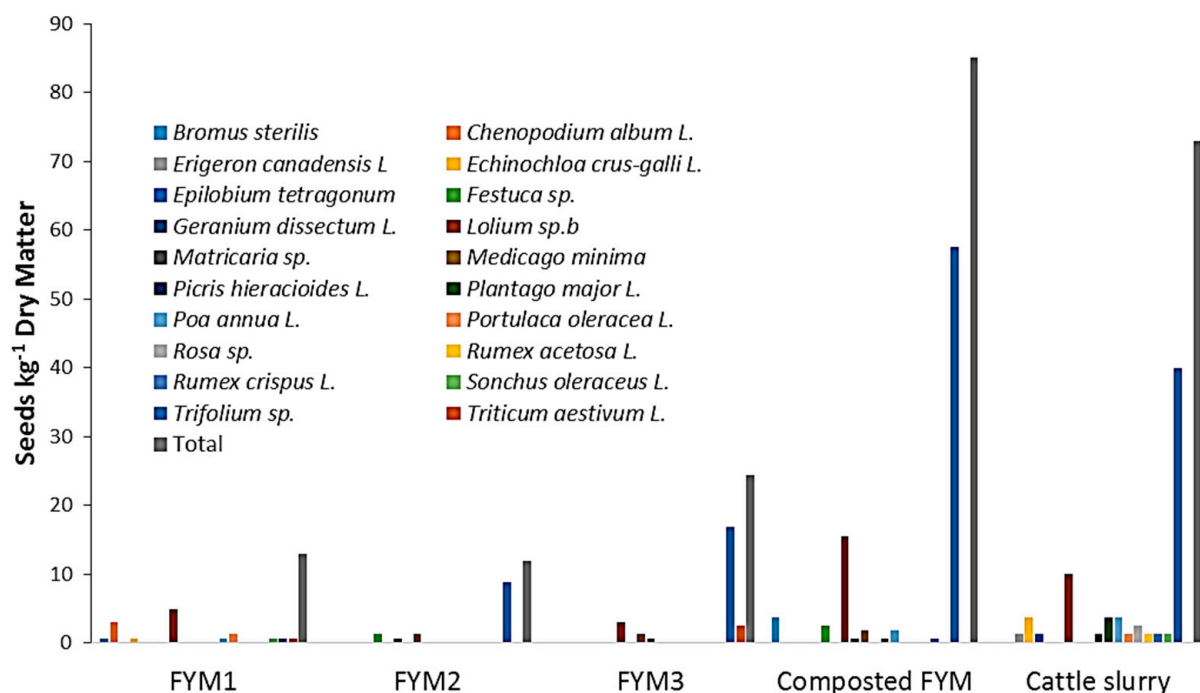

Figure 4. Presence of germinating seeds in animal manure (adapted from [55]).

After manure application to soil, the pathogens will either survive (and replicate) or die, which depends on soil characteristics, weather conditions and other environmental factors [65]. The impact of soil characteristics and conditions on pathogens' survival has been extensively reviewed by Alegbeleye and Sant'ana [60]. The manure-borne pathogens may contaminate agricultural products, which is critical in horticulture, and eventually may be transported along the soil profile and reach the water bodies [66,67].

The dry matter content of manure is also an aspect to be considered when its hygienization is required, since the liquid manure is usually more homogeneous than the solid manure, and consequently more homogeneously contaminated, making it more prone to release and transport pathogenic microorganisms [68,69].

Depending on the plant or crop considered, the pathogens' issue might be relevant, for example for vegetables, usually consumed crude, when manure is applied as dressing fertilization special attention should be given to the time interval between manure application and harvest.

Animal manure is mainly produced in intensive farms with high livestock rates, which implies the need for pharmaceuticals' administration to animals, to prevent diseases and infections, but also to control their hormonal system [70,71]. Recently, a list of antimicrobial agents and other compounds that can be found in animal manure has been published and analysed in a European Commission report [72]. Despite the measures adopted by several countries to ban the use of antibiotics and growth hormones in animal production, it is still a common practice in several world regions [73]. According to Hou et al. [74],

the risk to find sulphonamides, tetracyclines, quinolones and macrolides antibiotics in swine manure is higher than in poultry manure and cattle manure presented the lowest concentrations. The authors explained such differences with the higher and more frequent doses of antibiotics usually administrated to swine, comparatively to cattle, motivated by the growing conditions offered to pigs, that are more prone to develop infections and diseases, sometimes a consequence of poor animal welfare conditions (e.g., poor housing ventilation, small area).

An extensive review of pharmaceuticals, hormones and selected microorganisms that can be potentially found in animal manure has been performed by Ghirardini et al. [73]. According to these authors, the hormones' concentrations in manure are always signifi-cantly lower than antibiotics' concentrations. As an example, the same authors referred that the highest concentrations of hormones were 2.8×10^4 ng/L and 2.1×10^4 ng/L in raw pig and cattle manure, respectively, against values of antibiotics concentrations that can reach 1.1×10^8 ng/L in swine manure and 5.9×10^6 ng/L in cattle manure [73].

4. Treatment Strategies to Increase Manure Acceptance for Farmers and Society

Several strategies were proposed to facilitate manure management and minimize the concomitant environmental impacts [17,18,75–77]. In order to have a holistic perspective of the manure management/treatment schemes, Figure 5 presents the most common treatment pathways, identifies the co-products obtained and shows the possible integration of the different processes: (i) acidification/additives, (ii) separation, (iii) biological, (iv) membrane and (v) thermal.
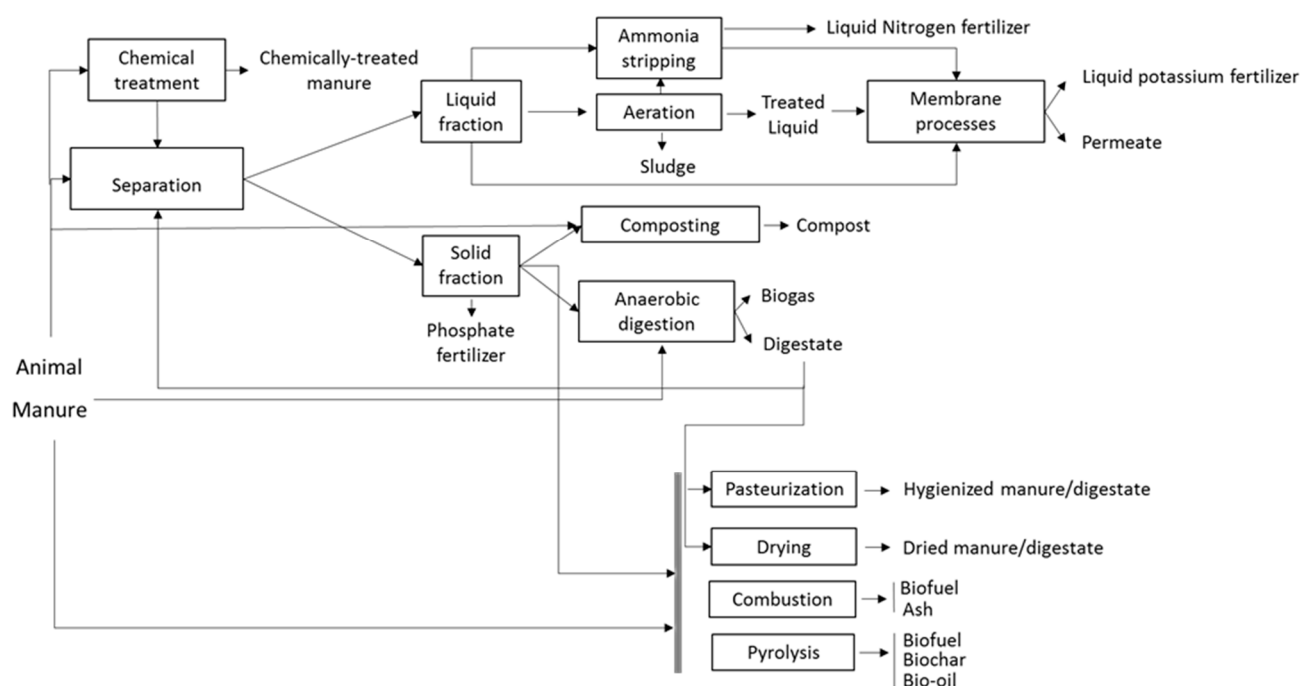

Figure 5. Main strategies for manure management/treatment and resulting co-products.

From Figure 5, it is possible to conclude that manure management/treatment strategies can result in a complex system, sometimes including highly technological solutions. The selection of an appropriate treatment scheme should be based on a fit-for-purpose approach, meaning that depending on the specific case scenario (land availability, odour nuisance, excess of nutrients, risk of water pollution, etc.) the best available strategy can be different. A whole-farm perspective, considering the interactions between processes, nutrient flows and potential drawbacks, is always the best strategy.

As mentioned in the previous section, manure management largely contributes to ammonia emissions in Europe and, therefore, mitigation strategies need to be implemented. The most common practice is chemical treatment, using acids or other additives. Manure acidification was broadly reviewed by Fangueiro et al. [19], who highlighted that beyond minimizing ammonia emissions, it has other positive impacts, such as the improved efficiency of the solid–liquid separation, the increase of nutrients availability in soils, and the disinfection effect. According to Lin et al. [78], acidification is also a highly effective manure management option to reduce antibiotic resistance, as it promotes the degradation of sulphonamide antibiotics and decreases the accumulation of antibiotic resistance genes. This fact is beneficial for its potential use in horticulture, but attention should be given to possible corrosion effects and toxicity to plants due to the presence of strong acids.

Furthermore, acidification can render treatment by biological processes more difficult due to the inhibition of microbial activity and, therefore, its adoption should consider the subsequent treatment processes that will be applied.

Commercially available additives can be used for other purposes than ammonia emission mitigation, such as odour control, prevention of crust formation, foam reduction and nutrient preservation. Duerschner et al. [79] studied the effects of additives (Coban$^{®}$ 90, Manure Magic$^{®}$, MOC-7, More Than Manure$^{®}$, Sludge Away, and Sulfi-Doxx) and disinfectants (Clorox$^{®}$, Pi Quat, Tek-Trol, and Virkon™) on swine slurry characteristics and verified that the use of additives led to a significant increase in DM, TN, P_2O_5, Ca, Mg, Zn, Fe, Mn, and Cu. The authors also found that the disinfectants had an influence on the antibiotic concentrations of swine slurry, e.g., concentrations of chlortetracycline and tiamulin were significantly lower for the treatments containing Tek-Trol [79]. Despite the potential positive effects of additives, their cost and lack of knowledge regarding their cumulative effect on soil and health risks for humans, even more relevant for crops eaten crude, prevent wider adoption of this practice.

Solid–liquid separation of manure is commonly implemented on-farm to obtain fractions that are easier to handle, minimise clogging problems and avoid treating or transporting high amounts of water. Furthermore, it improves homogeneity and facilitates the following processing steps.

The separation process can be achieved using different types of equipment, e.g., rotary screens, static screens, decanter centrifuge, screw press, filter pressing and dissolved air flotation (DAF) [18,80]. The characteristics of the two fractions obtained highly depend on the equipment used, but in all cases, the liquid fraction has a low content of solids and organic matter and contains available N and K; whereas the solid fraction is rich in organic matter and retains organic N and P (organic and mineral) [18,75].

Regarding antibiotic residues, their solubility and sorption properties will dictate their partitioning between the liquid and solid fractions [81], and the separation technique efficiency will also affect that partition, as it influences the total solids content of the resulting fractions.

Biological processes, under aerobic or anaerobic conditions, are widely used to remove the excess nutrients and organic load. Aerobic processes include composting and aeration. Manure composting has been identified as a suitable treatment option [75–77,82,83], which can be applied directly to solid manure or to the solid fraction obtained by separation processes. If well performed, the resulting compost has stabilized organic matter, reduced odour and is free of pathogens and weeds [75,84]. Bernal et al. [84] emphasised that composting can be economically viable, if it produces high-quality compost, and reviewed the factors that affect manure-based composts' quality.

Inactivation of pathogens (e.g., *E. coli*) during composting has been reported on studies using different types of manure, e.g., bovine and chicken [85,86]. The high temperature achieved during the process is the most effective factor for the inactivation of pathogens within a reasonable timeframe [87,88]. Nevertheless, according to Thomas et al. [89], several mechanisms influence *E. coli* reduction. The same authors found that the C/N ratio and moisture content of chicken manure significantly affected the reduction of *E. coli.* during composting, with the ratio of 10:1 showing the faster reduction.

Another aspect worth mentioning is the effect of composting on micro-pollutants present in manure, namely veterinary drugs as antibiotics, hormones, and heavy metals. The use of antibiotics in livestock farming promotes the growth of antibiotic-resistant bacteria in the animals' gastrointestinal tract, leading to their presence in manure [88,90]. Studies have shown that manure composting reduces the concentration of antibiotics and antibiotic-resistant pathogens [91,92].

As mentioned previously, the presence of natural and synthetic hormones in manure is of major concern. Therefore, it is important to study how treatment technologies influence the presence of these compounds. A recent study by Havens et al. [93] observed lower content of progesterone in the runoff from fields where composted manure was applied, which can be the result of its degradation during composting.

Manure can have a significant content of heavy metals (e.g., Cu and Zn in pig manure) and the common practice of solid–liquid separation leads to their concentration in the solid fraction. Nevertheless, there is evidence that composting can minimize heavy metals mobility [94]. Moreover, the integration of additives in the composting process can enhance heavy metals stabilization. Chen et al. [95] observed that integrating bamboo charcoal and bamboo vinegar into pig manure composting piles controlled the mobility of Cu and Zn. Kumar et al. [96] verified that adding wood or wheat–straw biochar and inoculum promoted suitable conditions for the complexation of metal ions reducing their mobility.

A new trend in composting process is integrating black soldier fly larvae (BSFL) as an inoculum, converting manure into larval biomass and compost. The larval biomass can be used in animal feedstock or for bioenergy production [96–98]. According to Liu et al. [98], this practice improved the quality and maturity degree of compost, increased nutrients content and contributed to antimicrobial activity against pathogens.

Aeration is another aerobic biological treatment route, but it is not considered a good option because it promotes nitrification–denitrification, leading to nitrogen gas emission and loss of fertilizer value. Therefore, it is rarely used and can be followed when there is the need to reduce the nitrogen content of slurry or manure liquid fractions, eventually to obtain a lower N:P ratio. Many studies have proven the efficiency of aeration for N removal and more recently have focused on the effect of operational parameters on N_2O emission mitigation (adopting intermittent aeration or acting on aeration flow rates) [99].

Anaerobic digestion (AD) is also a biological treatment process that has the advantage of recovering energy from manure as biogas [100,101]. It can be directly applied to manure or to the solid fraction. The last option enhances biogas production yield, as the substrate fed to the reactor has higher volatile solids' content. Adoption of co-digestion also promotes better bioconversion by synergetic effects between the manure and the other co-substrates, e.g., agricultural or agro-industrial wastes [102–104].

Regarding pathogens inactivation, AD effectiveness is dependent on the operational conditions. A thermophilic regime is necessary to guarantee the inactivation of bacteria, viruses with moderate resistance, and infectious stages of parasites [87]. Hence, when the objective is to use the digestate as dressing fertilization, particularly in horticulture, this operational regime is recommended. Nevertheless, the mesophilic AD also promotes the decrease of pathogens, but a complementary treatment is necessary to achieve hygienization, for example, pasteurization or additives addition [87].

Regarding heavy metals, it should be mentioned that they can have two antagonistic effects on the AD process, either enhancing methane production or causing microbial inhibition [105]. On the other hand, heavy metals speciation is modified during AD (soluble metals are transformed into carbonate, phosphate or sulphide precipitates), influencing their bioavailability, with the operational parameters significantly affecting their speciation [106].

Anaerobic digestion has been reported to remove antibiotic residues, antibiotic-resistant bacteria, and antibiotic resistance genes, with higher degradation rates for the thermophilic regime [60,81]. However, Gurmessa et al. [107], that reviewed several studies on the removal of veterinary antibiotics and antibiotic resistance genes during the AD process, concluded that AD does not guarantee the complete removal of these compounds. To achieve the required efficiency, the authors recommend a thermal pre-treatment (70 to 180 °C) or a post-AD treatment (separation, composting of the solid fraction and phytodepuration of the liquid fraction).

Besides biogas used as an energy source, the AD process produces digestate. The digestate can be processed without previous solid/liquid separation, for example by composting, producing a stable material to be used as fertilizer.

If the solid/liquid separation is implemented, the liquid fraction of the digestate can be handled to obtain liquid fertilizers, an N and K liquid fertilizer, as shown in Figure 5 [108–111]. In fact, in areas where there is an N surplus it is a good strategy to implement N recovery processes (e.g., struvite formation, membrane filtration or NH_3 stripping), producing a mineral fertilizer that is easier to transport and to apply [112–114]. Even if there is no N surplus, processing manure or digestate into an N fertilizer can eliminate, or at least minimize, some of the constraints associated with the direct use of manure.

As seen in Figure 5, thermal processing of manure includes drying, combustion, and pyrolysis. Drying largely reduces the manure volume (facilitating its transport) and produces a stable and hygienized product. However, to minimize the associated costs, it should be applied to manures with high dry matter (above 30%, e.g., poultry manure) [77]. When the adopted treatment strategy includes the AD process, the heat resulting from combined heat and power (CHP) conversion of the biogas can be used to dry the digestate.

One of the objectives of the present review on manure treatment strategies was to access to what extent they would contribute to eliminate or minimize manure characteristics that are considered limitations for its acceptance by farmers and society. In this sense, the authors present a scoring matrix (Table 2) summarizing the effects of the treatment, in their expert opinion and according to the literature reviewed, on the parameters considered as key limitations to broaden manure use.

Table 2. Effects of the described treatment processes on the characteristics considered as limitations for manure acceptance by farmers and society (Legend: ↑—increases, ↓—decreases and → no effect).

Treatment Process	Product	Dry Matter	Organic Matter	Available/Total N	Available/Total P	N:P:K	Active seeds	Pathogens	Micro-Pollutants	Heavy Metals
Acidification	Acidified manure	↑	→	↑	↑	↑	↓	↓	↓	↑
Separation process	Solid fraction	↑	↑	↓	↑	↓	↓	↑	Depends on their solubility and sorption properties; and on separation efficiency	↑
	Liquid fraction	↓	↓	↑	↓	↑	↓	↓		↓
Composting	Compost	↑	↑	↓	→	↓	↓	↓	↓	↑
Anaerobic Digestion	Digestate	↓	↓	↑	↑	↑	↓	↓	↓[1]	↑[2]
Drying	Dried manure	↑	↑	→/↑[3]	→	↓	↓	↓	↓	↑
Pyrolysis	Biochar	↑	→	→/↑[3]	↓	↑	↓	↓	↓	↑[4]

[1] Antibiotics and hormones; The extent depends on the temperature regime, with higher removal for thermophilic process [81]. [2] Increase their availability [106]. [3] The effect depends on the type of manure and pyrolysis temperature, e.g., N is more labile in the cattle manure-based biochar obtained at 300 °C [115]. [4] Increased concentrations of Fe, Zn, Ni and Cu, however bioavailable forms of Zn and Cu decreased [115].

5. Alternative Uses for Manures or Manure-Based Products

In Europe, manure-based fertilizers are applied to soil to supply nutrients to conventional crops, in many cases connected with livestock farms (e.g., grassland, cereals) [20], or other arable crops, like maize [116]. There are few studies on alternative uses of manure-based fertilizers, but good examples were found for horticulture (Table 3), or, less frequently, orchards (Table 4), those being the two systems which appeared more often, as recognized by other authors [20,117].

The main objectives of the first studies were centred in the fertilizing potential of the manure-based fertilizers, relatively to mineral fertilizers or to other biowaste-derived fertilizers (e.g., biosolids, municipal solid waste compost), evaluating the effects on soil nutritional status and on fruit/plant quality and yield [118–122], while recent studies are more concerned about environmental issues, mainly those which have an impact in climate change and its mitigation, like C sequestration [117], gaseous emissions, namely N_2O and CH_4 [123–126], as well as nutrient cycling [126]. Some of these studies have, in fact, pointed to some scenarios where the GHG balance was more negative for organic than for conventional farming [124]. However, it is important to highlight that the use of organic-based fertilizers (namely those based on manures), represent an optimized N fertilizing strategy in a circular economy perspective, contributing to the nutrients loop and to the decrease in the environmental impacts from the overburden use of mineral fertilizers in horticultural systems [126], and from the excessive production of slurries and manures in areas with a high density of livestock systems. Hence, the problems related to emissions should always be seen from a global perspective, and in some cases, the use of treated slurries or manures can obviate some of the problems associated with GHG emissions from the production of chemical fertilizers. Sustainability needs to be seen globally, and organic waste management is considered a sustainable practice, at least when associated with intensive agriculture systems, like in industrial horticulture [127]. Pardo et al. [117] have tried to evidence this, evaluating if there was a real possibility to contribute to C sequestration in orchards and horticulture systems in Spanish Mediterranean coastal areas, with treated (e.g., composted or digested) or non-treated livestock manure (the current scenario), as well as with other conservation agricultural practices. They have observed that manure anaerobic digestion or composting, as a single measure, did not result in significant changes of soil organic C, but if GHG emissions and savings from manure storage and processing management stages were considered, significant reductions in CO_2 emissions could be obtained from anaerobic digestion (4.3 CO_2 eq yr^{-1}) and composting (1.1 CO_2 eq yr^{-1}), which can represent a considerable reduction in agricultural emissions in Spain [117].

The use of manure-based fertilizers in horticultural crops is a very common practice in some Mediterranean countries, like Spain and Italy (Table 3). Sanchez-Martín et al. [123] have highlighted one important potential of this practice, particularly in these semiarid areas with low organic C content, which is the combination of organic fertilizer (applied before or at the time of sowing), with drip-irrigation (DI) systems, only with water, because it is cheaper than fertirigation. The authors have evaluated the combination of anaerobically digested pig slurry, applied before melon plantation, with DI, aiming to reduce N_2O emissions, compared with the more traditional furrow irrigation (FI) [123]. They have managed to prove that the application of organic fertilizers enhances denitrification (and N_2O emissions), however, the water distribution pattern in DI favoured nitrification conditions relatively to FI, decreasing N_2O emissions by 28% from one system to the other, enabling water savings and the re-use of organic amendments [123]. Moreover, at the end of the experiment there were no significant differences in N_2O emissions between the two irrigation systems, which is also very important. The pre-treatment of pig slurry, in this case with anaerobic digestion, was pointed by the authors as very important from the environmental point of view, because it reduces the pathogen load, changes the slurry composition, eliminating a significant proportion of volatile organic compounds, which

minimizes the emissions of odours, homogenizes and reduces the viscosity of the final product, favouring its application and distribution in the soil [123]. This means that the combination of treated slurries, associated with DI, represents a very good option in the context of industrial horticulture in Mediterranean countries [123].

In fact, the major limitation to the use of manure-based fertilizers in horticulture is related to the potential presence of pathogens, which could contaminate the fresh products thereof, endangering human health [128–131]. Actually, even though there are other possible sources of fresh products contamination with microbial pathogens (e.g., irrigation water, wild animal faeces, insects) [132], the manure-based fertilizers are of paramount importance [130,131,133,134] as seen in previous sections. Pathogens identified as of greatest concern were *Salmonella* (found in tomatoes, seed sprouts and spices) and *Escherichia coli* O157:H7 (on leafy greens, like spinach and lettuce) [128], and the major problems identified were associated with the use of untreated manure, like in some African countries, e.g., Rwanda, where 50% of the farms used untreated manures [135]. On the contrary, Denis et al. [136] examined bacterial contamination in fresh fruits and vegetables sold at retail in Canada and found that the prevalence of bacterial contamination was very low, 0–0.08% in tomatoes and 0.79–1.3% in leafy herbs, emphasizing the low bacteriological hazards for vegetables available in Canada. Moreover, higher bacterial contamination rates were confirmed in the summer, and in organic as opposed to conventional products [136]. In fact, due to the more common use of animal manure as fertilizer in organic agriculture, the microbial safety of its products, relatively to conventionally grown products with mineral fertilization only, is sometimes critical, and several studies on this subject found that the fresh products from organic farms, namely vegetables, were more susceptible to faecal contamination [131,136,137].

Therefore, animal slurry hygienization is crucial for its safe use in horticulture, to avoid crop contamination, and the application of treatments for manure hygienization should be considered, broadening the range of possibilities of manure use [60,130,138]. As discussed before, the reduction and control of microorganisms can be carried out by microbiological, chemical, or physical methods [63], because the storage, despite being the most popular and cheapest method to handle certain types of animal manures [64], may be insufficient to ensure their complete hygienization. Julien-Javaux et al. [131] alerted to the fact that the mitigation of the microbiological risk must start at the farm level, and Guidance Manuals are available, like the one from the Food Standards Agency (UK), with practical advice on how to reduce the risk of contamination of ready-to-eat crops when using manures to improve soil fertility [139].

Organic farming is one interesting market for manures and slurries, or their derived products, like the anaerobic digestate of cattle slurry or organic fertilizers based on dried cattle manure or composted manures [140,141]. These authors have been evaluating the application of this type of fertilizers in horticultural organic farming (e.g., lettuce, tomato) in a combination with other agro-ecological techniques (e.g., soil surface shaping, crop rotations, cover crops introduction, and cover crop termination techniques), to adapt to the predicted climatic changes in the Mediterranean area. In fact, the changes in temperature, total seasonal precipitation, potential increase in frequency of droughts and floods, could affect crop growth and lead to a decrease in yield, and the application of organic fertilizers can be a possibility to increase soil fertility to cope with these problems [140–142]. The fact that the organic fertilizers produced with animal manures can be used in organic farming can be a very promising perspective in the coming years, because the European Commission (EC) delivered the "Farm to Fork Strategy", which is at the heart of the European Green Deal aiming to make food systems fair, healthy and environmentally friendly. Organic farming is an environmentally friendly practice that the EC wants to see further developed. The objectives are ambitious: the EC will boost the development of the EU organic farming area with the aim to achieve 25% of the total farmland under organic farming by 2030. This policy will implicate an increase in the consumption of organic fertilizers, which can be seen as an advantage to the valorisation of animal manures.

However, the restrictions for the use of the different animal manures in organic farming should be considered: products from intensive livestock facilities, without associated land, are not allowed in organic farming (see previous Section 2).

Orchards are another important option for animal manure valorisation. In this case, the main constraints to the application of manure-based fertilizers are linked to the feasibility of the process. Gioelli et al. [20] have identified this problem in the Piedmont region (Northwest Italy), where the area occupied by orchards is very extensive (more than 63,000 ha) and, quite often, very close to livestock farms interested in exporting their excess N. However, despite the viability of the transport with high volume slurry tanks, and the application with commonly used spreaders, capable of delivering low application rates of N per ha (<50 kg N ha^{-1}), there are some inconveniences: (i) when higher application rates are needed, that would imply several passages of the tractor, contributing to soil compaction problems; (ii) the slurry would need to be evenly distributed, which is very difficult, giving its heterogeneity; (iii) the number of passages would have to be rigorously calculated, to avoid nutrient losses; and (iv) last but not least, the slurry spreaders would need to fit within the orchard rows, which are usually narrow-wide, with about 4 m, but variable from 3 m in short rotation forestry, to 5–6 m in hazel groves [20,143]. Due to all these constraints, a prototype band spreader with an automatic rate controller was developed, enabling the application of slurry and its solid fraction to different orchards [20,143]. This device could break the negative attitude of the farmers who are not in favour of its use, mainly due to the lack of adequate machinery, and prefer chemical fertilizers [144], leading to an increased depletion of soil organic matter content. The prototype spreader was designed, constructed, and tested to confer to the users the evenness of the distribution, application rate accuracy and working capacity [20,143]. The authors described thoroughly the prototype developed that has the advantage of having a spreader that accommodates a wide range of settings to fit different row spacing and operating conditions, allowing the spread of animal slurries evenly in narrowly space orchards [143]. Moreover, it has an electronic automatic rate controller, with target application rates ranging from 10 to 120 kg N ha^{-1}, which can be controlled from an onboard computer, with simple and clear settings and display [143]. The authors have tested the prototype in a peach orchard and, besides other advantages, mainly operational (which are important to the farmers), they were able to reduce ammonia emissions by 63%, when compared to the common broadcast application systems by splash plate [20].

Another alternative use of animal manure fertilizers is in the plantation of short-rotation intensive cultures, like fast-growing willow [145], or *Eucalyptus globulus* [146], which have high nutritional and water requirements, being good "sinks" for the pig slurry produced in different areas. In this case, the risk to human health from the use of untreated slurries and manures is minimum, at least if the application rates are well balanced to prevent water pollution with nutrients and pathogens.

One other possibility is the old integrated crop–livestock farming. Although this could be an "exotic" solution, it should be considered once a reverse trend in intensification is reaching us rapidly. In fact, extensive rearing systems are considered interesting nowadays, due to their positive effects on meat quality, animal welfare and health [147], and, in this case, the environmental impacts associated with the high-land use demands for grazing would be overcome [147]. These authors have combined free-range livestock and tree crops, to improve sustainability in agriculture. They have used a Life Cycle Assessment (LCA) approach to evaluate the environmental impact of combining free-range poultry with olive orchards. In the past, it was common to rear chickens in fruit orchards, which provides a win–win solution: trees benefit chickens in terms of protection from predators, sun, wind, and extreme temperatures, increasing the time and amount of grazing, while the orchard benefits from a reduced need for fertilization and weed control. From an overall perspective, this system results in less land use, reduced erosion, increases in crop yields, soil biological activity and nutrient recycling [147]. The overall impact reduction of the chickens grazing in orchards was, approximately, 30%, approaching 100% if land use

was not considered, once grazing is associated to the orchards area, without the need of extra pasture area. The results are applicable to other combinations of livestock and crops, turning this into a strategy that should be considered nowadays [147].

Table 3. Examples of manure and animal slurry valorisation in horticulture.

Horticulture	Country	Type of Slurry/Manure	Main Aim of the Study	Main Outcomes Related to Manure Valorisation	Reference
Basil (*Ocimum basilicum* "Dark Opal") and tomato *Lycopersicon esculentum* "Charger F1")	Not referred	Composted swine lagoon sludge with peanut hulls (15:85 v/v) to produce a transplant media (SLC)	Evaluate the use of composted swine lagoon sludge as a nutrient-rich alternative to peat as transplant media	The transplant media produced with composted swine lagoon sludge evidenced as a good substitute for peat, with tomato and basil transplants with similar or higher dry weight than those produced in either the organic matter mixture or the control	[148]
French basil (*Ocimum basilicum* L. cv. Vikas Sudha)	Morocco	Farmyard manure	Effect of organic manures and inorganic fertilizer on growth, herb and oil yield, nutrient accumulation, and oil quality of French Basil	Combined application of manure and inorganic fertilizer helps to increase crops productivity and quality, and maintaining soil fertility	[149]
Tomato (*Solanum lycopersicum* L. cv. Donald) (organic production)	Italy (Southern)	Anaerobic digestate fertilizer based on cattle slurry, and a commercial organic fertilizer based on dried cattle manure	Evaluate the best synergistic combination of agro-ecological techniques to adapt to the predicted changes in temperature and total seasonal precipitation in the Mediterranean area	In the first year of the study, the combination of commercial organic fertilizer and vetch, as cover crop, gave both the highest tomato marketable and total yields	[140]
Lettuce (*Lactuca sativa* var. longifolia Lam.) (organic production)	Italy (Southern)	Anaerobic digestate fertilizer based on cattle slurry, and a commercial organic fertilizer based on dried cattle manure	Evaluate the response of organic lettuce to cover crop management and organic fertilisation (effects on yield, N status and N utilisation efficiency)	Using a vetch cover crop before the lettuce, terminated by the no-till roller-crimper strategy in combination with the use of organic fertilizers assured a satisfactory response to the variability in Mediterranean weather, in terms of both yield stability and preservation of soil fertility	[141]
Spinash (*Spinacia olearacea*)	Spain (Southeast)	Several organic-based stabilized materials (e.g., vermicompost from cow manure, digestate from an anaerobic digestor fed with 30% pig slurry and 70% sludge from tomato processing plant), etc.	Evaluate the use of novel fertilizers that fulfil the N requirements of the crop, but helping to decrease environmental impacts and achieve C-neutral horticulture (enhance soil C stocks and reduce GHG emissions) (mainly animal manure and slurry-based fertilizers)	Some of these materials evidenced multiple positive effects, on crop quality (i.e., N leaf content), and crop yields, with 150 kg N ha^{-1} application rate: similar yields to those of slow-release synthetic fertilizers lower NO_3^- concentration in spinach leaves. Direct N_2O emissions were generally low for manure-based products, helping to achieve circular economy, closing the nutrient loops, and contributing to GHG mitigation potential.	[126]
Cucumber (*Cucumis sativus* L.)	Spain (Segura river valley, South East Spain)	Raw and composted solid fraction of pig slurry	Effect of different application rates of raw and composted solid fraction of pig slurry, versus conventional mineral fertilization, on major nutrients NPK contents in different plant parts of cucumber (stems, leaves and fruits)	Similar or higher yields of fruit and biomass were obtained using raw or composted solid fraction of pig slurry, relatively to the mineral fertilization (300 kg N ha^{-1}), when using the equivalent to 300 kg N ha^{-1} and 450 kg N ha^{-1}, but increasing rates did not result in increased yields.	[121]

Table 3. *Cont.*

Horticulture	Country	Type of Slurry/Manure	Main Aim of the Study	Main Outcomes Related to Manure Valorisation	Reference
Cucumber (*Cucumis sativus* L.) and Milan cabbage (*Brassica oleracea* L. var. capitata)	Spain (Segura river valley, South East Spain)	Raw and composted solid fraction of pig slurry	Study the effect of application of pig manure on the micronutrient (Fe, Cu, Mn, and Zn) concentration in horticultural plants in calcareous soils, which induce the immobilization of these elements.	Micronutrient concentration in both plants was affected by the amendment, with an increase of Mn and Zn uptake and a decrease of Cu, compared to the control. The increasing application rate (300 kg N ha^{-1} and 450 kg N ha^{-1}) did not induce a general increase in the plant uptake of micronutrients, except for the crops grown in soils amended with the composted solid fraction of pig slurry	[119,120]
Melon (*Cucumis melo* L. cv. Sancho)	Spain	Anaerobically digested pig slurry	Evaluate the combination of anaerobically digested pig slurry, applied before melon plantation, with drip-irrigation, aiming to reduce N_2O emissions, compared with the more traditional furrow irrigation	Water distribution pattern in drip-irrigation favoured nitrification conditions, relatively to furrow irrigation, decreasing N_2O emissions by 28% from one system to the other, without a global increase in NO emissions	[123]
Pepper, lettuce and tomato	Spain (South East Spain)	Pig slurry	Evaluate the influence of pig slurry applications on the nutrient composition of three horticultural crops, grown on two calcareous soils, under irrigated conditions	100 m^3 ha^{-1} pig slurry was the optimum dose for N nutrition of the crops, independent of the number of previous applications, while the doses to satisfy the P nutrition decreased with the number of applications. For K, 100–150 m^3 ha^{-1} were required for adequate plant nutrition, but highly dependent on the amount of clay and cation exchange capacity	[150]
Greenhouse lettuce (*Lactuca sativa* L. cv. Esperie)	Portugal	Composts from the solid fraction of dairy cattle slurry	Evaluate the effects of increasing rates of mineral N fertilizer combined with composts from the solid fraction of dairy cattle slurry on lettuce yield and N uptake	Lettuce yield and N uptake increased with compost application (30 t ha^{-1}, maturated and less maturated), relatively to the mineral fertilizer, suggesting other benefits in addition to N availability resulting from its use as a soil amendment	[122]

Table 4. Examples of manure and animal slurry valorisation in orchards.

Orchard Type	Country	Type of Slurry/Manure and Treatment	Main Aim of the Study	Main Outcomes Related to Manure Valorization	Reference
Mango and litchi orchards	China (Guangxi and Hainan provinces)	Manure (unspecified specie)	To determine the effects of organic fertilizer (manure) on arbuscular mycorrhizal fungal (AMF) communities in the rhizospheric soil of litchi and mango orchards affected by manure input	SOC resulting from increased manure input had a direct positive effect on AMF richness, but excessive use of manure is detrimental to AMF occurrence, mainly associated with increased available-P. Manure inputs ranged between 0–0.75 kg plant^{-1} year^{-1} for litchi and 0–0.60 kg plant^{-1} year^{-1} for mango.	[151]
Peach (*Prunus persica* L. Batsch, Springtime and Redhaven cultivars)	Greece	Cattle manure	Response to different fertilizers combinations, including mineral NPK fertilizers and manure (10 years study, from the 5th to the 14th year of the productive life of trees)	The fertilizing combinations which included mineral fertilizers + manure application presented better results (higher productivity). Manure applications tested ranged between 12–60 kg plant^{-1} year^{-1}.	[118]

Table 4. *Cont.*

Orchard Type	Country	Type of Slurry/Manure and Treatment	Main Aim of the Study	Main Outcomes Related to Manure Valorization	Reference
Nectarine (*Prunus persica* L. Batsch, Spring Bright cultivar)	Italy (Cuneo province, Northern)	Swine slurry. Liquid slurry, covered slurry, solid fraction	Possibility of application of swine effluent as fertilizer vs. mineral fertilizer evaluating orchard productivity and fruit quality	No differences were observed in orchard productivity and fruit quality using swine liquid manure as fertilizer (early results)	[144,152]
Apple orchard "Golden Delicious" (*Malus domestica* Bork)	Iran (Zanjan)	Cow and poultry manures (deep litter incorporation)	Evaluate the impact of animal manure application on soil chemistry, mineral nutrients, yield, fruit quality and biological activity	Application of deep litter cow manure at 30 t ha^{-1} or deep litter poultry manure at 10 t ha^{-1} resulted in increased yield and fruit size, but decreased fruit colour; rate of manure application correlated with soil OM; and poultry manure increased soil K, Mg, Ca, ammonium-N, and EC levels	[153]
Almond orchards (*Prunus dulci*)	USA (California)	Composted cattle manure	Evaluate the effects of the composted dairy manure (abundant source of OM for the farmers in the area) and the timing of its application on soil moisture, soil water retention and tree water status of a young orchard	Fall-applied compost dairy manure (CDM) was more effective at enhancing soil moisture retention and reducing the tree water stress compared to Spring applied. Soil water retention (0–100 kPa at 0–10 cm) increased 13%, compared to the control, after 2-years application of 9 t CDM ha^{-1}, in the fall, as surface mulch. Young trees may be protected from periods of limited water supply using organic matter amendments, due to their buffer capacity.	[142]
Peach orchards	Italy (Piedmont region—Northwest)	Solid fraction of pig slurry	Develop a prototype spreader for band application in orchards, electronically controlled, with a wide range of settings, to fit different row spacings and operating conditions	The prototype spreader was designed, constructed, and tested, allowing the spread of solid fraction of animal slurries, evenly in narrowly space orchards, with considerable reductions in ammonia emissions	[20,143]
Peach orchard	China (Taihu region)	Organic manure	Evaluate the effects of chemical fertilizers versus organic manure in soil N_2O and NO emissions	The fertilized peach orchard in this region (converted from a rice–wheat rotation), results in an important source of N_2O emissions. However, the NO emissions, which were enhanced eight-fold by the mineral fertilization, alone or in combination with organic manure, were lower with the organic fertilizer alone	[125]
Citrus orchard (*Citrus sinensis*)	Sorocaba Municipality, São Paulo, Brazil	Organic fertilizer with 78.8% poultry litter	Evaluate gaseous emissions from soils (CO_2, CH_4, N_2O) after the conversion from a forest to orange orchard submitted to organic management versus conventional farming	The results were not positive, apparently: organic management increased N_2O emissions, and the GHG balance was more negative for organic than for conventional farming (N emission factor for organic fertilizer was 3.14, while for inorganic fertilizer was 1.47). However, the only factor in the equation was the gases emissions from soils	[124]
Apple orchard	Shandong Peninsula, China	Rabbit dung and chicken manure	Compare apple production (yields and economic benefits) under organic management relative to the conventional management, with synthetic fertilizers, herbicides, pesticides, etc.	Apple yield in organic management treatment significantly increased by 30%, relative to the conventional management, and the quality of the fruits also increased. Soil physicochemical properties were improved, and the practice is economically advantageous	[154]
Olives grove	Central Italy	Poultry manure (free-range poultry system)	Perform an LCA to evaluate the benefits of combining free-range livestock (e.g., chicken) with orchards (e.g., olives), a common system in the past	The overall impact reduction was approximately 30%, approaching 100% if land use was not considered. The results are applicable to other combinations of livestock and crops.	[147]

6. Farmers and Society Acceptance

When considering the sustainability of activity, besides the economic viability and the environmental soundness, it is very important not to neglect its third dimension, which is social acceptability [127]. De Silva and Forbes [127] evaluated the sustainability of the horticulture industry in New Zeeland and highlighted the need for growers to be better informed about the process of adoption of sustainable practices and the benefits that can be achieved. Several approaches are possible, including the use of education through industry networks and the sharing of best practices. In industrial horticulture in New Zeeland, already 74.5% of the producers voluntarily implemented organic waste management practices [127].

Case et al. [155], in Denmark, have made a thorough survey about the farmers' perceptions on the use of organic waste products as fertilizers. In this study, participants were asked to rank the three most important barriers to the use of organic fertilizers, which were: unpleasant odour for neighbours, uncertainty in nutrient content and difficulty in planning and use. On the other hand, the main advantages pointed out were improved soil structure, followed by low cost to buy or produce, and ease of availability.

Case et al. [155] have mentioned that few studies have specifically considered manure and organic fertilizer adoption or acceptance by farmers [156–158]. In a survey of 111 Dutch dairy farmers, Gebrezgabher et al. [157] found that lower age, lower education level, larger farm size and a positive attitude towards the future of the farm, increased interest in the adoption of manure separation technologies. Núñez and McCann [158] found that transportation costs, odour, awareness of others using manure and low off-farm income, were major factors affecting the willingness of arable farmers to accept manure in a study of 138 American crop farmers. On the other hand, Battel [159] emphasized that extension educators have paramount importance to help farmers reducing nonpoint P loading into surface waters and tried to discover the main factors to encourage farmers to transfer or exchange manure from livestock farms to the fields of neighbouring crop farms. He evaluated farmers' willingness to exchange manure from one farm to another, based on the farmers' age and farm size, in the context of the Michigan State (USA), and found that agronomic considerations were the dominant concerns, separating younger farmers from older ones, and farmers with large properties from those with small properties [159]. Particularly, younger farmers and large landowners were more concerned about (i) using manure containing weed seeds, (ii) the fact that manure application equipment could cause compaction, and (iii) the fact that manure application could interfere with the time schedule of some field activities [159]. On the other hand, older farmers are less willing to accept a neighbouring farmers' manure, more even if they had to pay for it. One opinion was common to all the inquired farmers: irrespective of their age or farm size, they all agreed that their major concern is if the neighbours complain about the odour associated with manure application, being this the most significant barrier to manure use [159].

In Denmark, over half of arable/horticulture farmers used at least one type of organic fertilizer, most frequently unprocessed manures, and there is a high degree of manure export from livestock farms to pure arable farms. However, these numbers are a consequence of the regulatory regime in Denmark, which requires harmony between livestock and available land, forcing farmers with manure in excess to export the surplus to neighbouring arable farms [155]. In the Case et al. study [155], more than 66% of farmers that used organic fertilizer chose unprocessed manures, mainly slurry or farmyard manure, whereas just fewer than 20% used processed manures, mainly anaerobically digested or acidified slurry. However, it is important to refer that only 9% of the overall respondents used urban waste-derived fertilizer, mainly sewage sludge in raw or processed form, and the probable causes that were identified were the limited local access to any manure, either unprocessed or processed, i.e., they would prefer manure-based fertilizers if they had that possibility. Taking this into consideration, one option for increasing the use of animal waste-derived organic fertilizers could be to develop a network between the livestock producers, with surplus production of manure and slurry, and the farmers in areas with no access to manure.

Case et al. [155], among other initiatives, proposes the creation of regional/district virtual "marketplaces" or trading platforms for surplus raw or processed manures.

In most cases, there are no networks developed for the export of nutrients from one livestock farmer to the producers. Bluemling and Wang [160] identified that gap, and presented a paper introducing a cooperative in Sichuan province (China) which connects livestock farms to crop farms that are willing to use imported manure as fertilizer. A framework was developed, based on the "brokerage" concept, helping to close the nutrients cycling in that province. They identified manure processing and manure management issues as the bottlenecks in this framework [160], but this type of structure could be an important solution to the nutrients cycling in the sector, being able to create an organized market associated with animal manures valorisation.

7. Conclusions

Animal manure management must be considered as an opportunity to promote circularity and mitigate NH_3 and GHG emissions. As seen, the legal framework for manure utilization in the EU can help the adoption of manure as fertilizer. However, there is the need to overcome what are considered as the main limitations for its use. For that, several strategies can be used, producing a variety of manure-based fertilizers. It has also been shown that horticulture and orchards can be an alternative market for manure-based fertilizers. Nevertheless, it is still necessary to build up society and farmers' acceptance of this proposed solution.

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