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Sabine Houot, Marie-Noelle Pons, Marilys Pradel, Marc Antoine Caillaud, Isabelle Savini, Anaïs Tibi

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USE OF FERTILIZING WASTE MATERIALS IN AGRICULTURE AND FORESTRY

AGRONOMIC, ENVIRONMENTAL AND SOCIO-ECONOMIC EFFECTS

SHORT SUMMARY OF THE COLLECTIVE SCIENTIFIC EXPERT REPORT - OCTOBER 2014



INRA
SCIENCE & IMPACT

Membre fondateur de



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l'agriculture durables



Organic fertilization of crops and pastures is an ancient practice traditionally based on the spreading of animal manures. Over the course of the 20th century, mineral fertilizers came increasingly to supplement or even replace the use of organic fertilizers, allowing for easier management of the primary fertilizing elements (nitrogen [N], phosphorus [P], and potassium [K]). In more recent years, agricultural use of waste materials from a variety of municipal and industrial waste streams (waste water, household wastes, industrial effluents, etc.) has increased in response to a variety of pressing concerns such as the need to improve waste recycling, rising energy costs for the production of synthetic mineral fertilizers, increased scarcity of mineral resources (notably P), and the loss of soil organic matter.

ADEME (the French Environment and Energy Management Agency) estimated total waste production from domestic and industrial sources in France in 2009 at 355 million metric tons. In the same year, agriculture and forestry generated 374 million metric tons of livestock wastes (solid manure and slurry) and plant residues, the majority of which were utilized on-site. These significant resources in waste-origin fertilizing materials (referred to here as Mafor, for matières fertilisantes d'origine résiduaire) contain nutrients that can reduce or replace synthetic mineral fertilizers.

The application of Mafor on agricultural and forestry soils to improve fertility and other soil properties cannot be undertaken unless the associated environmental and human health risks are acceptable. In order to better understand and, if necessary, regulate the use of these materials, the French ministries of agriculture and ecology requested that INRA (the French National Institute for Agricultural Research), CNRS (the National Center for Scientific Research) and Irstea (the National Research Institute for Science and Technology for Environment and Agriculture) undertake a collective scientific expertise (or ESCo, for Expertise scientifique collective) on the agronomic benefits of Mafor, their potential impacts in terms of ecosystem contamination, and the overall economic and social advantages, disadvantages, and other consequences of their use. This analysis of the scientific literature is intended to contribute to the development of criteria according to which Mafor may be made available to end users as well as to the elaboration of guidelines and regulations for Mafor application.

An evaluation of the potential human health risks associated with Mafor, not included within the scope of this ESCo, is currently the focus of a risk assessment by Anses (the French Agency for Food, Environmental, and Occupational Health and Safety) and should be considered as an extension of the present study.

1. Current use of Mafor in France and associated socio-economic issues

Sectors generating waste materials utilizable for agricultural spreading may be divided into four main groups: livestock production, municipal wastewater treatment, municipal solid waste management, and industry. Mafor flowing from these sectors include a wide variety of materials that may either be spread as-is or subsequent to various biological, physical, or physico-chemical treatments, often including blending with other materials (Table 1). Other materials that may be applied to agricultural soils include wood ash from biomass combustion and dredged sediments from rivers or other waterways.

Table 1. Principal treatment methods applicable to the majority of Mafor

Treatment \ Mafor	animal manures	sewage sludge	urban wastes			industrial wastes
			residual household wastes	pre-sorted organic wastes	green wastes	
no treatment	alone	alone				alone
composting → compost	alone or mixed	mixed	alone	mixed	alone or mixed	alone or mixed
anaerobic digestion (methanization) → digestate	alone or mixed	alone	alone	alone or mixed	mixed	alone or mixed
liming		yes	yes			

1.1. Mafor resources vary by location

An accurate assessment of the quantities of Mafor available in France is difficult to obtain. Data are numerous but are difficult to synthesize and analyze since surveys of available materials tend to employ a variety of different terminologies and units of measure (e.g., raw material vs. dry material).

Livestock wastes are by far the most important Mafor, with 274 million raw metric tons (Mt) generated in 2012. Around 50% of livestock wastes are deposited directly onto pastures. The other 50% are primarily solid manure and slurry from cattle and slurry from pigs, almost all of which are spread without any prior treatment.

Quantities of municipal and industrial Mafor currently applied to agricultural soils are more difficult to estimate, but are believed to

total around 0.7 dry Mt of **municipal sewage sludge**, 2.2 raw Mt of **municipal solid waste composts and digestates**, and 1.8 dry Mt of **industrial effluents**.

Quantities of available Mafor are generally stable and the potential to increase the portion utilizable for agricultural purposes is low. Improvements in the collection of organic wastes (household kitchen wastes, industrial organic wastes and organic wastes from large-scale producers such as cafeterias and supermarkets) could triple the available amount of municipal solid waste composts and digestates, but such an increase would have little impact on the total quantity of available Mafor given the predominance of livestock wastes among Mafor types.

Further development of methanization has the potential to increase the diversity of Mafor without increasing the quantities available: the co-digestion of livestock wastes with other wastes (depending on local industrial activities), for example, leads to an increase in the volume of digestates available while reducing the availability of untreated livestock wastes.

The availability of Mafor in France is spatially heterogeneous. The concentration of such resources within areas dominated by livestock production and around urban centers means that some areas have excess capacity, notably with regard to maximum applications of nitrogen contained in livestock wastes as defined by European Directive 91/676/CEE (also known as “the Nitrates Directive”). The development of regulatory limits for phosphorous is likely to create an additional level of complexity for optimal management of Mafor at the national level.

1.2. Mafor applied to 6.6 million hectares of field crops and pastures in 2011

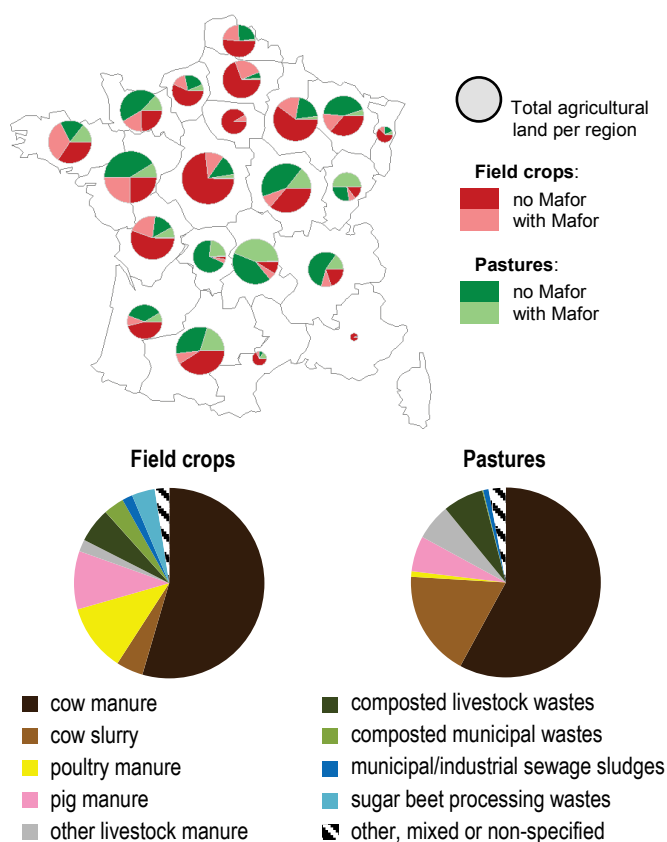
Application of Mafor to agricultural and forestry soils takes place in almost every region of France, although the extent of these practices varies widely by region (Fig. 2). Overall, more than 25% of field crop areas (primarily corn, soft wheat and oilseed rape) and nearly 30% of pastures received Mafor applications in 2011. Ninety-four percent (by quantity) of Mafor applied that year were livestock wastes. The remaining 6% were sugarbeet-processing wastes, municipal composts and municipal or industrial sewage sludges.

Agricultural applications of ash and dredged sediments are not well documented in the scientific literature due to the small volumes of material currently involved. Biochar, a residual product of pyrolysis for energy production, is still only rarely used as a Mafor.

The use of different types of Mafor can respond to specific issues and objectives. For example:

- The spreading of animal wastes is an **ancient practice**. Elimination of this practice is rarely proposed except in areas possessing a structural excess under the Nitrates Directive.
- Agricultural spreading of certain Mafor from the agri-food sector fits perfectly within a logic of **closing loops**. For example, by-products from the sugar beet industry can be applied to fields used for sugar beet production. In keeping with this logic, some agri-food sector Mafor (including sugar beet pulp) are sold as organic fertilizers.
- The spreading of municipal Mafor (sewage sludge, municipal composts) is more likely to be perceived as a **service provided by agriculture to society**, helping municipalities get rid of their wastes. Social perception of new treatment processes for municipal wastes (such as methanization) and use of the “new” Mafor resulting from these processes has not really been studied, however.

Figure 2. Geographic distribution and type of organic Mafor applied in France in 2011



Data: Agreste, "Pratiques culturales" (Agricultural Practices) survey, 2011.

1.3. Legal, economic and social conditions for the replacement of mineral fertilizers by Mafor

Over 95% (by quantity) of applied Mafor are legally classed as either “byproducts” (including livestock manures) or “wastes” (including sewage sludge, industrial wastes and effluents, most digestates, ashes, sediments, etc.). An additional 5 million metric tons of raw materials are applied as approved or standardized “products.” When prices are assigned to Mafor, they are often low relative to the price of mineral fertilizers, a situation that could favor the use of Mafor within a context of escalating prices for synthetic mineral fertilizers.

Reorganizing the spatial distribution of Mafor-generating activities so as to better adapt supply to local demand is a major challenge.

The ESCo “Livestock Production and Nitrogen”¹ underlined the absence of research on the feasibility of options such as the partial relocation of livestock production systems, as well as the need to consider this re-localization on a case-by-case basis, combining it with work on the acceptance of such transfers by residents of the areas concerned.

Few economic studies have been done to establish a cost/benefit analysis of **processing treatments for Mafor that can facilitate transport** and thus help rebalance Mafor applications at the national level. Although they can open the way to commercialization and transport of the transformed material, processing treatments can be expensive. Investing in treatment systems is thus a key consideration for the Mafor producer.

2. Mafor possess significant but variable agronomic value according to their source

An important characteristic of most Mafor is that they contain the three principal fertilizing elements (N, P, and K) in a more or less easily mineralizable organic form. Scheduling Mafor applications thus requires knowing the materials’ total value in N, P, and K as well as the dynamics and crop availability of these nutrients in soils following spreading.

2.1. Agronomic value of Mafor: Fertilizers vs. amendments

Potassium and **phosphorus** are found mostly in mineral form in Mafor. The potassium and phosphorus fertilizing value of Mafor are equivalent to those of mineral fertilizers, with the exception of Mafor containing insoluble phosphate minerals (ashes, for example).

Nitrogen in Mafor is essentially present in organic form, with the notable exception of a few types of Mafor such as slurries, raw liquid digestates and agro-industrial effluents. The proportion of N present in organic and mineral form (primarily ammonia), the stability of these organic forms and the balance of carbon and nitrogen (C/N ratio) are highly variable according to the Mafor in question, and not only between major types (agricultural, urban, industrial) but also within types (manures, for example).

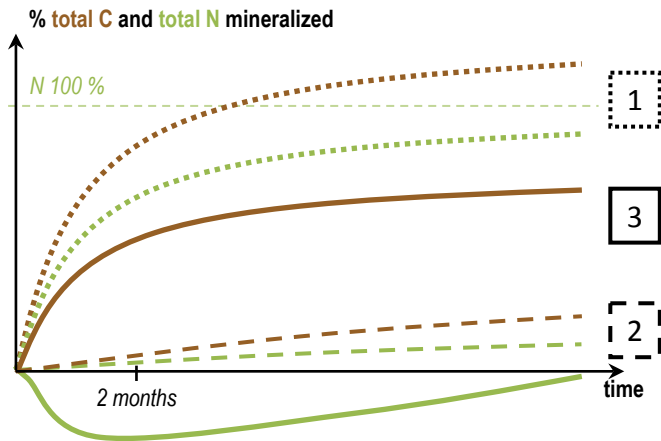
Prior to spreading, the organic and mineral N value of Mafor vary according to the nature of the organic matter (OM) present in the initial waste material and its alteration through the action of microorganisms, during stockpiling or through processing.

Post-spreading, one can distinguish three major patterns of Mafor behavior in the soil (Fig. 3):

- When the speed and intensity of mineralization of the organic fraction are high and the C/N ratio of the Mafor is less than 8-15, the fertilizing N value is high in the year following application (case 1).
- When OM is stable its mineralization is slow; the fertilizing N value in the short term is low or nil, but the amendment value is high since the Mafor will increase the stock of OM in the soil (case 2).
- Finally, when the OM of the Mafor is easily broken down but the C/N ratio is high (above 8-15), soil microorganisms will use mineral N in the soil to break down the OM, leading to a temporary reduction in available N for plants (case 3).

¹ See INRA (2012). *Nitrogen flows in livestock farming systems: Reduce losses, restore balances*. Short summary of the expertise report, 8 pp.

Figure 3. C (in brown) and N (in green) mineralization dynamics following spreading

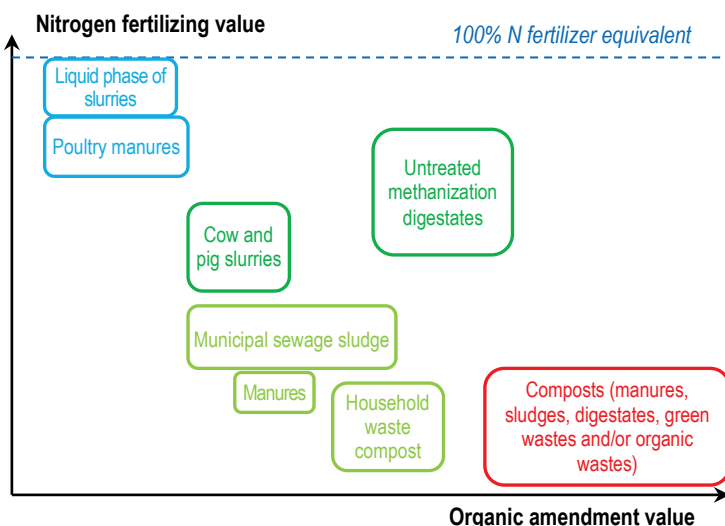


The “nitrogen fertilizing value” and the “organic amendment value” of Mafor are thus closely linked and give rise to variation in Mafor agronomic value. Experimental studies of the nitrogen fertilizing value of different Mafor can be used to rank them with respect to their agronomic value (Fig. 4). The level of detail with which different Mafor have been described in the literature is limited, however, with often only the major types (for example, “manures”) being identified.

Treatments applied to Mafor prior to spreading modify their agronomic value, moving them along the “fertilizer-amendment” gradient:

- composting stabilizes C and N and moves material toward the “amendment” end of the spectrum (to the right in Fig. 4);
- anaerobic digestion mineralizes organic forms of N and raises both the amendment and the fertilizer value of the materials;
- treatments that remove water (drying, dehydration, filtration, phase separation, etc.) are accompanied by a loss of ammoniacal nitrogen, reducing the fertilizer value of Mafor treated in this way (moving material toward the bottom in Fig. 4).

Figure 4. Relative agronomic value of different Mafor



2.2. Potential nitrogen losses

The logistics of Mafor application and the challenge of supplying fertilizing elements in available form at the periods required by crops can result in losses of nitrogen to the atmosphere or to water, leading both to environmental impacts and to reduction in fertilizer value. Principal mechanisms include:

- **Ammonia (NH₃) volatilization**, which takes place primarily in the hours and days after application. Mafor containing the highest

levels of mineral nitrogen (slurry and liquid or raw digestates) are also those most subject to NH₃ volatilization. The application method is the primary factor determining volatilization. For example, soil incorporation immediately following application is effective in limiting volatilization.

- **Emission of nitrous oxide (N₂O)**, resulting from nitrogen transformations undertaken by soil microorganisms. Emissions will be higher with liquid Mafor (slurry, liquid sludges) and lower with solid (manures), composted, or dried (dehydrated sludge, granules) Mafor. Methanization digestates are generally less susceptible to N₂O emissions than the raw materials prior to methanization. Application rates and soil physicochemical conditions appear to be as important as the type of Mafor in determining emissions levels.

- **Nitrate leaching (NO₃⁻)**, when the N supplied by the Mafor is present in the soil at times when crops cannot absorb it and during wet periods. Uncertainty with regard to the amount of N present in the soil during these periods increases the risk of nitrate leaching. In general however, the more mineral N or easily mineralizable N the Mafor contains, the greater the risks of leaching. Planting of cover crops for nitrogen management can help reduce this phenomenon (see the INRA study “CIPAN”²).

Volatilization of NH₃ and leaching of NO₃⁻ can lead to losses on the order of from a few kg to several tens of kg of nitrogen per hectare per year, thus significantly reducing the fertilizer value of the Mafor. By comparison, N₂O emissions involve much smaller quantities of nitrogen, on the order of a kg per hectare per year.

Risks of nitrogen loss by gaseous emissions and leaching also exist for mineral fertilizers, but the latter are easier to apply and may be more precisely calibrated according to meteorological conditions and crop nutrient needs.

2.3. Other risks of losses to the environment

Carbon supplied by Mafor may be partially lost to the atmosphere or transferred into waterways. Determining factors for these mechanisms are not well understood:

- **Methane (CH₄) emissions** linked to the spreading of Mafor are moderate. Mafor whose organic matter undergoes anaerobic decomposition (whether during stockpiling, as a result of processing or once buried in the soil) emit CH₄ during the first few days following application. After this period soils will again become CH₄ sinks.

- Emissions of certain **volatile organic compounds (VOC)** can cause odors. Although Mafor applications are not counted in national inventories of VOC emissions, the amount of carbon present in Mafor in the form of VOC is significant, ranging from a few % to a few dozen %. Emissions of this kind are very rapid, reverting to background levels in just a few hours.

- The formation of **dissolved organic matter (DOM)** after spreading. This form of OM can facilitate the transfer of chemical contaminants into soil and water. The spreading of livestock effluents increases DOM temporarily (from a few days to a few weeks after application). Research is lacking however with regard to the fate of the chemical forms of DOM, which can influence their capacity to bind to contaminants.

Finally, repeated applications of Mafor without sufficient attention to **phosphorus** levels can lead to the accumulation of this element in soils and in turn contribute to risks of phosphorous leaching.

² See INRA (2012). *The use of cover crops to reduce nitrate leaching, Effect on the water and nitrogen balance and other ecosystem services.* Short summary of the study report, 8 pp.

2.4. Improving fertility management with Mafor

Compared to synthetic mineral fertilizers, good use of Mafor involves three challenges:

- N/P/K ratios are not necessarily optimal and are often unknown, notably in the case of application on grasslands (60% of field areas fertilized with Mafor are fertilized without knowledge of N values);
- the long-term availability of nitrogen contained in Mafor is not well understood;
- the available technology for spreading or injecting Mafor does not permit precise application rates.

Mafor offer the agronomic advantage of contributing organic matter to the soil, and are the only renewable source of phosphorus. In France as a whole, the amount of P present in Mafor could supply all the phosphorus required annually for agricultural production.

In theory, the complete replacement of mineral N-P-K fertilizers by Mafor is possible at the farm level, with combinations of different Mafor (composts and digestates, manures and digestates, etc.) used to provide balanced quantities of N, P, and K according to crop requirements. The technical and economic feasibility of such fertility management methods remains to be examined, however. Regulatory requirements associated with most Mafor application situations combined with the technical challenges of Mafor use also make such practices less flexible than the use of mineral fertilizers.

Despite the profusion of decision-making tools to help farmers with fertilizer management (especially with respect to N), use of such tools by farmers is infrequent. Two major reasons for this are:

- such tools are generally designed for use at the individual field level, whereas most farmers manage fertilization at a multi-field level;
- most such tools calibrate the dynamics of Mafor mineralization (farmers' primary concern) on the basis of laboratory results under controlled conditions, which can only approximate actual outcomes in the field. This uncertainty encourages the use of an "insurance factor" leading in some cases to an excess of complementary mineral fertilization.

3. Mafor are associated with manageable levels of biological pathogens

Fecal materials contain large quantities of bacteria, some of which are pathogenic. Viruses, parasites, fungi, yeasts and prions can also be carried by feces. The use of antibiotics in human and veterinary medicine has promoted the development of antibiotic-resistant bacteria. Animal manures and municipal sewage sludge are thus likely to contain biological agents posing two principal health risks:

- the transmission of diseases or parasites from one herd to another (following Mafor application on grasslands or forage crops) or to people (Mafor application on vegetable crops or on field crops consumed raw or only lightly cooked);
- the spread of antibiotic resistance, with a resulting loss of efficacy of antibiotic treatments for humans and animals.

3.1. Possible control of pathogens *via* Mafor treatments

All kinds of pathogenic microorganisms have been detected in untreated Mafor (with the exception of prions, which remain understudied). Pathogenic agents are often found in untreated livestock manures, but their presence is not universal and is difficult to predict given the possibility of healthy carriers. Detection of pathogens in untreated municipal sewage sludge is universal, although concentrations of such pathogens vary.

The issue of dissemination of pathogenic agents into the environment *via* Mafor application relates mainly to bacteria, viruses, and parasites (as well as, in theory, prions). Once in the soil, the persistence of these biological agents ranges from a few days to several months, based primarily on the organisms' intrinsic characteristics as well as on soil temperature and soil moisture (with low temperatures and high humidity levels favoring survival). Contamination of waterways comes primarily from surface runoff, which can transport microorganisms floating freely or attached to soil particles.

Evaluating the contribution of Mafor to soil and water contamination by biological agents is complex, however. The presence of such pathogenic agents in soils independent of Mafor applications has been shown, and techniques to identify the origin of bacterial populations in the soil are extremely difficult to put in place.

Composting, thermophilic anaerobic digestion and liming are all effective treatments to eliminate levels of pathogenic agents in Mafor, although the reestablishment of such populations cannot be excluded. In the case of simple stockpiling, a lengthening of the stockpiling period without new additions of material can limit the presence of pathogens.

No study published to date has documented a case of an animal disease spread by contamination linked to the application of Mafor. The multiple potential pathways of contamination for both animals and people (contaminated irrigation or drinking water, direct contact with infected animals, animal products contaminated during slaughter, etc.) make it difficult to establish a causal link between the spreading of Mafor and the spread of disease.

Although the application of manure and slurry on fields of crops consumed raw have sometimes been suspected in the outbreak of multiple cases of gastrointestinal illness, pathogens are rarely detected on crops at the moment of harvest since their survival decreases over time. Respecting mandated delays between Mafor application and crop harvest or putting animals on treated pastures is thus a key immediate-term measure for limiting contamination of the food chain.

3.2. Spread of antibiotic resistance is insufficiently quantified

The likelihood of finding antibiotic-resistant bacteria is high for untreated animal manures and untreated municipal sewage sludge. Antibiotics ingested by humans and animals are often excreted without being metabolized, and thus municipal sewage sludge and animal manures are likely to contain antibiotic residues potentially exercising unknown levels of selection pressure on soil bacteria. This selection pressure is also influenced by other environmental factors, such as the presence of metallic elements: high levels of copper and zinc in Mafor and/or in soils receiving Mafor applications can favor both the selection of resistant bacteria and their dissemination.

Although little research has been done on the subject, certain treatments (liming, thermophilic anaerobic digestion, and composting) should reduce the prevalence of resistant bacteria in Mafor, although it may not eliminate them entirely.

Bacteria already present in the soil can become resistant to antibiotics through the exchange of resistance genes with bacteria brought in with Mafor. Mafor application is thus likely to favor the spread of antibiotic resistance into the environment.

The existing scientific literature, however, does not make possible an evaluation of the contribution of Mafor to the increase in antibiotic resistance among bacterial species pathogenic for humans and animals.

4. Introduction of chemical contaminants into soils varies depending on the Mafor

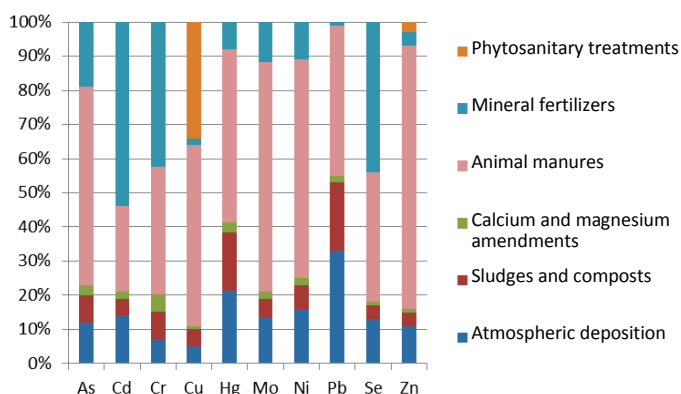
Chemical contaminants likely to be present in Mafor include **trace mineral elements (TME)**³ and **trace organic compounds (TOC)**. TME are naturally present in soils, whereas TOC are mainly of anthropogenic origin. Although some TME are micronutrients necessary for the proper metabolic functioning of living organisms, all TME and TOC may become toxic above certain concentrations.

Currently, 9 TME and 10 TOC are regulated under French legislation applicable to the spreading of Mafor (threshold levels for the Mafor and/or soils receiving Mafor + maximum annual application rates). Most TME and TOC are thus unregulated. Depending on their legal classification, moreover, not all Mafor are regulated according to the same threshold levels.

The heterogeneity of regulated contaminants and established threshold levels in different European countries testifies to the difficulty of arriving at a scientific and political consensus on this topic.

The majority of contaminants likely to be introduced into soils by Mafor may also arrive by other means: atmospheric deposition, phytosanitary treatments, irrigation, etc. Although mineral fertilizers (especially phosphate fertilizers) contain some TME (see Fig. 5), the replacement of mineral fertilizers with Mafor will tend to increase introductions of other chemical contaminants, notably copper, zinc, lead, and pharmaceuticals. Moreover, the specificity of the chemical contaminants introduced by Mafor will depend on the latter's physical composition: most Mafor contain OM, to which certain forms of chemical contaminants can bind. The nature of this binding will affect the **persistence** of contaminants in the soil; their **mobility** from soil into water, plants, and animals; and their **bioavailability** to plants and animals.

Figure 5. % contribution from different sources within total annual movement of 10 TME onto agricultural soils in France



Source: Sogreah 2007

Knowing the range of chemical forms in which contaminants are found in Mafor as well as their fate following Mafor application are two major criteria for evaluating Mafor safety.

4.1. A slow accumulation of TME in soils

Copper and zinc are the TME found in Mafor in the highest amounts. In France, TME concentrations found in municipal sewage sludge, composted domestic waste and/or green wastes are on the whole below regulatory thresholds. TME levels in

animal manures (which are not subject to regulation) are likewise generally below the levels set for municipal sewage sludge and for effluents and wastes from facilities subject to environmental protection restrictions.

Data on contaminants in sediments and biomass ash are harder to come by, but those that exist place these materials within relevant regulatory limits.

The contribution of different sources to total TME movement onto agricultural soils in France is currently well documented for some TME, notably those that are regulated. Livestock manures (whether deposited directly onto pastures or collected and applied) are a major contributor of TME to agricultural soils in France as a whole; for many TME they are the most important single source (see Fig. 5).

At the field level, the relative importance of the various sources of TME varies considerably according to agricultural practices, particularly fertilization decisions (use of mineral or organic fertilizers) and phytosanitary treatments. Composts and municipal sewage sludge, while accounting for just a small percentage of total TME contributions on the national level, can be of much greater significance for specific fields or regions due to their relatively concentrated use near large urban centers (in the regions of Île-de-France, Picardy, Nord-Pas-de-Calais and Provence-Alpes-Côte d'Azur in particular). TME do not break down, and have low mobility within soils due to their binding with organic particles in the Mafor or in the soil. While the impact of Mafor applications (at typical agronomic rates) on total soil TME levels will be small over the space of a few years, all regular applications, even at low amounts, will contribute to the gradual accumulation of TME in the environment. The noticeable increase in copper and zinc levels in certain soils in Brittany, for example, is attributable to regular applications of livestock manures.

Certain chemical forms of TME are known to be more mobile than others, moreover, and are thus more likely to move into waterways or onto primary agricultural products.

How TME mobility changes over the long term following Mafor application is unclear. OM mineralization can increase the mobility of TME that are bound to it, but no massive release of TME has been shown. Such an effect cannot be excluded, however, particularly if certain soil parameters (such as pH) change significantly.

Treatment of materials prior to application can also influence TME concentration and mobility. Any treatment that eliminates a phase (water through drying; organic matter through anaerobic digestion, composting or combustion) will concentrate TME in the Mafor so treated. Conversely, treatments that involve the addition of a second material to the initial waste material (addition of green wastes in the composting of sewage sludge, addition of lime) can result in a dilution of TME provided the additional material is not also contaminated. Composting, anaerobic digestion, liming and pyrolysis tend to reduce TME mobility.

4.2. Large numbers of TOC, difficult to assess and with diverse characteristics

Contrary to TME, TOC are variably degradable. Their breakdown, whether biotic or abiotic, entails the transformation of known parent molecules into metabolites that in many cases have scarcely been studied. Certain TOC, moreover, form strong bonds with organic particles in Mafor or in the soil, forming "bound residues" which cannot be quantified by the chemical extraction methods used to measure contaminant levels. Total TOC levels in Mafor are consequently not always known. A decrease in extractable TOC concentrations is more accurately characterized as being due to "dissipation" rather

³ The 68 metallic or metalloid elements found in the Earth's crust at concentrations less than 0.1%.

than degradation since it could result from diverse mechanisms including export through leaching or volatilization, breakdown, and formation of bound residues.

TOC are divided into two major groups according to their apparent half-life in the soil (the time it takes for 50% of the molecules to dissipate):

- Persistent TOC, the apparent half-lives of which range from one to several years: PCBs, PAHs, dioxins, flame-retardants, etc.
- Non-persistent TOC, the dissipation of which is more rapid (half-lives ranging from a few days to a few months): phthalates, bisphenol A, detergents, etc.

In France, regulations apply to 10 persistent TOC (three PAHs and seven PCBs). Pharmaceutical and pesticide molecules, TOC specific to livestock wastes and Mafor of municipal origin are not regulated.

Data in France on TOC levels in Mafor relate mainly to municipal sewage sludge and livestock wastes:

- For the 10 TOC that are regulated, concentrations in Mafor are below regulatory thresholds. The lowering of regulatory thresholds and the inclusion of additional chemicals to be regulated are currently under discussion by the European Commission. For example, proposed "End of Waste Criteria"⁴, define a single threshold level for a total of 16 PAHs. Some municipal composts and digested sewage sludges approach or even exceed this threshold.
- Among unregulated TOC, pharmaceutical molecules and molecules widely used by households and industry are the most studied. Antibiotics are frequently found in municipal sewage sludge and livestock wastes.

Anaerobic digestion and composting are associated with a dissipation of TOC in Mafor. The underlying mechanisms have only begun to be elucidated, and results are sometimes contradictory according to the TOC in question. Metabolites may also be formed, although the nature and toxicity of these are poorly understood.

Unlike with TME, no study exists estimating the contribution of different sources within the overall movement of TOC into French soils. Studies of Mafor application according to prescribed methods and in normal agronomic quantities do not show TOC accumulation in soils, although low levels of transfer into waterways are likely.

4.3. Accumulation of chemical contaminants in plant and animal products cannot be excluded

Very few studies have examined the potential for transfer of chemical contaminants into crop plants and animal products under real conditions of application. On the other hand, certain transfer mechanisms are known and have been demonstrated under controlled conditions in the laboratory, suggesting that Mafor applications may be at the origin of some chemical contaminants in primary food products.

In plants, roots tend to accumulate TME more than leaves and stems; fruits and seeds are generally the plant parts least affected. Certain plant species are known to accumulate certain TME without suffering phytotoxic effects (e.g. sunflower, lettuce, hard wheats strongly accumulate cadmium), whereas other species are naturally weaker accumulators (maize in the presence of cadmium).

In animals, pathways for exposure to chemical contaminants are multiple: ingestion of forages, of soil, of soil organisms, or of water contaminated by diverse sources. On this point TOC are better documented than TME in the scientific literature. Research has

shown the strong capacity of certain persistent and lipophilic organic contaminants (such as PCBs) to reach the circulatory system during passage through the digestive tract following ingestion, as well as their tendency to accumulate in fatty tissues, milk, and eggs. When TME reach the circulatory system, they are more likely to accumulate in the liver and the kidneys.

5. Possibilities for optimizing Mafor use and future research priorities

The findings of this ESCo suggest possible leverage points for optimizing Mafor use; or in other words for maximizing their agronomic benefits while minimizing the risks of environmental and ecosystem contamination, subject to practical acceptability.

5.1. Importance of "primary" material characteristics and treatment efficacy

This ESCo focused on applied materials, not on handling and treatment practices beginning at the point of collection. In reality, the characteristics of the "primary" materials influence those of the Mafor. For example, current recommendations for pig feeding have led to a reduction of copper and zinc levels in pig manure. The sorting and separating "primary" materials prior to treatment, along with the establishment of selective collection systems, likewise tends to reduce concentrations of TME in household waste composts.

This ESCo did not seek to evaluate the impacts of Mafor treatments on their composition, although these treatments have a strong impact on Mafor characteristics and constitute an important means of optimizing their use. A thorough analysis of the effects of possible Mafor treatments should be made, particularly since these can act both on the agronomic value of Mafor and on their safety, sometimes in conflicting fashion.

A comprehensive comparative evaluation of all production and waste management sector characteristics is required for a better understanding and predictive analysis of the impacts of Mafor application. Such an evaluation would enable improved levels of recycling of nutritive elements while reducing levels of contaminants, from the moment of collection of the "primary" materials to the production of a "ready to spread" Mafor. Establishing a typology of Mafor, along with models identifying their origins (primary material + treatments) so as to better predict their potential effects under given conditions of use, seems essential to overall Mafor optimization.

5.2. Application practices, cropping systems, and field organization

This ESCo points to the importance of Mafor application practices and timing in the outcomes observed, although these issues have not been the focus of much research. Incorporation of Mafor into the soil is key to optimizing their agronomic value and mitigating odor and ammonia emissions. Properly calibrating application rates and timing, practices not thoroughly addressed in the literature, are critical to avoid the creation of localized concentrations of Mafor that can result in excess N or elevated levels of contaminants.

Conducting an overall assessment of the agronomic benefits and environmental risks of Mafor use, *via* life-cycle analysis for example, will require a detailed characterization of the impacts of Mafor application, including indirect effects such as the consequences of increased OM levels in soils, greenhouse-gas emissions associated with Mafor use, etc.

⁴ Criteria allowing certain wastes to cease to be "waste" and legally become a "product."

With regard to the safety of Mafor use, the establishment of waiting periods prior to crop harvesting or placing animals on pasture is an important available measure for limiting food chain contamination. In the longer term, an improved ability to predict the effects of repeated Mafor applications on contaminant levels in soils, their mobility in the environment, and their bioavailability for crops and livestock is needed. Toward that end, long-term field trials can be used to inform models forecasting the long-term dynamics of organic materials and contaminants in soils, as well as testing various Mafor usage scenarios.

5.3. Regional organization and the role of stakeholders

This ESCo has identified a paucity of recent work on the economic effects and acceptability by different stakeholders of Mafor use. No recent economic studies have been published on Mafor markets. Nevertheless, inter-regional trade in Mafor takes place throughout France, and France imports significant amounts of Mafor from other European countries. A few cost-benefit analyses of these movements have been done, but further work could provide insights into the viability of developing processing, transport, and commercialization networks to move Mafor from regions possessing an excess to regions with a deficit of such materials.

The valorization of Mafor from municipal or industrial sources offers a means of replacing or supplementing the use of mineral fertilizers in areas near urban centers and/or in areas with little or no livestock production. The acceptability of these practices by those stakeholders directly concerned raises questions of risk, nuisance and equity.

5.4. Further research on contaminants needed

The potential human and environmental risk of Mafor use varies according to the materials involved and the likelihood of associated contaminants (Table 2). Certain Mafor (for example, industrial effluents and many Mafor “products”) remain poorly documented with regard to their safety. Metabolites resulting from the breakdown of contaminants also require further research. New contaminants such as nanomaterials likely to be present in municipal wastes and other effluents, have only just begun to be studied.

Table 2. Principal contaminants likely to be found in some Mafor

Mafor	Types of contaminants		
	Biological agents	TME	TOC
Animal manures	Pathogens associated with feces	Copper, zinc	Pharmaceuticals (antibiotics, hormones)
Municipal sewage sludge	Antibiotic-resistant bacteria	Copper, zinc, other TME	Wide range, including pharmaceuticals
Municipal composts	Pathogens associated with plants or kitchen wastes	Wide range	Pesticides
		Wide range	Wide range (pesticides for green wastes)
Ashes	Absent	Wide range according to the nature of the combusted material	PAHs produced during incineration
Sediments	Antibiotic-resistant bacteria?	Wide range	PAHs, PCBs found

To ensure the safety of agricultural products, regulations should take into account the full range of potential public health risks associated with the different contaminants that may be present in Mafor. These risks depend primarily on the composition of the Mafor and on the cumulative quantities applied. They are not affected by the legal classification (“waste,” “product,” “by-product”) of different Mafor. Regulatory criteria should thus provide a governance framework adapted to these risks, regardless of Mafor classification. While current criteria establishing maximum regulated contaminant contributions resulting from “normal” agricultural use appear adequate for ensuring the safety of primary agricultural products destined for human consumption, the decision to implement safety criteria for new contaminants or to impose stricter threshold levels will require an evaluation of public health risks based on the information presented in this ESCo.

To learn more:

Houot S., Pons M.N., Pradel M., Caillaud M.A., Savini I., Tibi A. (editors), 2014. *Valorisation des matières fertilisantes d'origine résiduaire sur les sols à usage agricole ou forestier. Impacts agronomiques, environnementaux, socio-économiques*. Expertise scientifique collective, INRA-CNRS-Irstea (France).

The expert report and a synthesis are available on the INRA, CNRS and Irstea websites. A video of the concluding ESCo conference is likewise available online.

Translated by Laura Sayre

Principles and organization of the collective scientific expertise (ESCO)

An ESCo is an institutional expertise activity governed by the national expertise guidelines to which INRA, CNRS, and Irstea formally subscribed in 2011. It is defined as a work of gathering and analyzing scientific knowledge emerging from highly diverse disciplinary fields and relevant for the clarification of public action. This “state of scientific knowledge” is as exhaustive as possible, and its analysis provides neither opinions, recommendations nor specific practical solutions to the commissioning body.

The analysis is conducted by a multi-disciplinary team of research experts from diverse institutional backgrounds. For the “Mafor” ESCo, led by Delegation for Scientific Expertise, Foresight and Advanced Studies of INRA, more than thirty researchers participated from a range of institutions in France and other countries; their disciplinary specialties include agronomy, chemistry, microbiology, ecotoxicology, economics, sociology, and law. The researchers’ work was supported by approximately 3000 bibliographic references, including scientific articles, statistical data, study reports and monographs. The ESCo concludes with the production of a full scientific report presenting the experts’ analysis and conclusions as well as a shorter summary report directed at decision makers.



Delegation for Scientific Expertise,
Foresight and advanced Studies

147, rue de l'Université
75338 Paris Cedex 07
France

Tél. : +33 1 42 75 94 90
Fax : +33 1 42 75 91 72
www.inra.fr



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