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Assessment of Alternative Phosphorus Fertilizers for Organic Farming: Meat and Bone Meal

In the past meat and bone meal was a major source of nutrients for recycling back to agricultural land, either as animal feed or organic nitrogen and phosphorus fertilizer. Nowadays – since the Bovine Spongiform Encephalopathy (BSE) crisis in 1999 – it is only used as fertilizer. Although meat and bone meals are allowed by EU regulation in organic farming, several growers' organisations prohibited them during the BSE crisis. Incineration or melting in a cupola furnace are alternative treatment options to their direct use eliminating any risk on BSE transmission. However, these processes lead to losses of organic matter as well as nitrogen and sulfur and affect the phosphorus availability. The fact sheet shows which actions are needed to ease the statutory restrictions for use as fertilizer and thus to make phosphorus sources in meat and bone meal accessible for organic agriculture again.

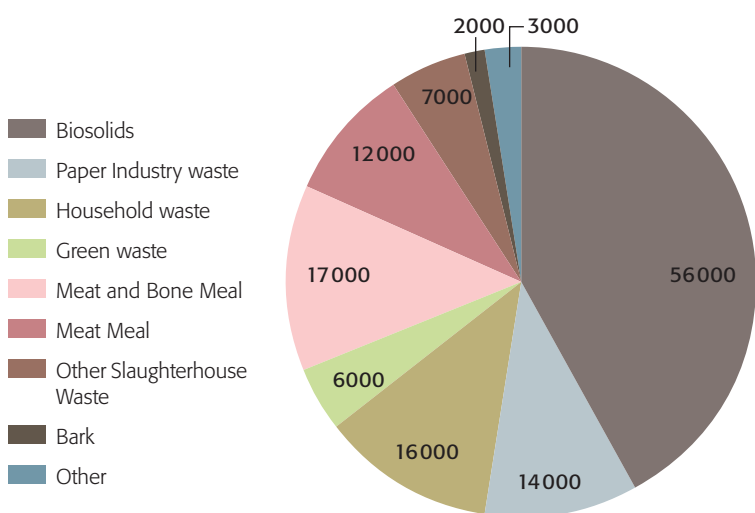
Introduction

Bone meal (BM) and meat meal (MM), as well as meat and bone meal (MBM) are by-products of the rendering industry and made from animal processing offal. Offal consists of those animal parts that are not suited for human consumption. Animal offal contains among others fat, meat, organs, bones, blood and feathers.

Almost 30% of the live weight of an animal ends up as offal. Total production of these by-products in the European Union (EU) exceeds 18 million tonnes per year, including 2.5 million tonnes in

France, 1.5 million tonnes in UK, 350,000 tonnes in Austria, 500,000 tonnes in Denmark and 2.8 million tonnes in Germany ^[1]. The total P potential in the EU from the rendering industry offal ranges between 110,000 and 128,000 tonnes per year. In Germany 20–25% of the total P amounts available – approximately 30,000 tonnes P per year – constitute from recycled P sources ^[2] (Figure 1). Hence, these products are very relevant sources of nutrients for agricultural purposes.

Figure 1: Phosphorus potential in organic residues and by-products in Germany (in Mg year⁻¹) ^[3]



Source: adapted from ^[3]

Meat and bone meals can be used as feed (restricted to a few species), as fertilizers, as energy sources in incineration plants and as feedstock for anaerobic digestion in biogas plants.

In Europe, substrates for the production of meat and bone meal have to be classified with other animal by-products according to the regulation (EC) no. 1069/2009. Three categories are defined (Table 1):

Very often, material of the category 2 and 3 are collected for practical reasons as category 1 material. Therefore, in Europe, approx. 50% of the substrates that could be used for meat and bone meal production are incinerated. For processed meat and bone meals, a common utilization is pet food. Because feed utilization is much more profitable than utilization as fertilizer, only small shares of the available MBM are used to produce fertilizers. E.g., in a French study, 12% of available MBM was used for fertilization ^{[4][5]}.

Production process

Pasteurisation and sterilisation

According to EU legislation, category 3 materials must be treated by pasteurisation (>70 °C, >1 hour), and category 2 material by pressure sterilisation (>133 °C, >3 bar, >20 min) before use as feed or fertilizer. Further, the particle size must be less than 50 mm size. After these processes, the material is commonly dried and can be used directly as fertilizer.

Combustion/ashing

Meat and bone meal has a heating value ranging between 13,000 and 30,000 MJ tonnes⁻¹ ^{[6][7]}. Therefore, a thermal treatment by combustion, gasification or pyrolysis¹⁾ could be an alternative utilization. Combustion of MBM in cement kilns

Table 1: Classification of substrates for the production of meat and bone meals according to regulation (EC) no. 1069/2009

Category 1	Category 2	Category 3
By-products of animals suspected of being infected by TSE (transmissible spongiform encephalopathy) and specified risk materials, including bovine brain and spinal cord.	By-products of animals presenting a risk of infection other than TSE, animals that have died in ways other than being slaughtered, animals killed to eradicate an epizootic disease, and contents of digestive tracts from slaughtering.	By-products arising from the production of goods intended for human consumption using slaughtered animals not affected by any sign of diseases transmissible to humans or other animals. These may also include leftovers from cantinas, food processing industry etc.
Material shall optionally be (a) disposed of as waste by incineration (b) recovered or disposed of by co-incineration (c) used as fuel. Very often, the material is incinerated in cement kilns, meaning an irreversible removal of the remaining nutrients P, K, Mg and Ca from the nutrient cycle.	Material can be (a) treated as category 1 material, (b) used for the manufacturing of organic fertilizers following processing by pressure sterilization (e.g. >133 °C and >3 bars of pressure for >20 minutes), and permanent marking of the resulting material, or (c) composted or transformed to biogas following processing by pressure sterilization.	Material shall be treated (a) as category 1 or 2 material (b) used for manufacturing animal feed after pasteurization (>70 °C, >1h), or (c) used for manufacturing organic fertilizers following processing by pasteurization.

(for instance) is a common practice [7] [8]. For each ton of MBM being incinerated, 100–300 kg of ash is produced [9]. Consequently, thermal treatment of the entire European production of MBM would produce an amount of 0.35–1.00 million tonnes per year of ashes [9]. During high temperature combustion (>800 °C), all of the organic matter in the material, including proteins, is degraded to CO₂, H₂O, nitrous and sulphur oxides etc. Minerals like Ca, Mg and P remain in the ashes [10].

Sintering and melting

Treatment alternatives for MBM and BM, separately or in combination with other organic wastes like dried sewage sludge, are sintering²⁾ and melting as well as pyrolysis. Due to the process management in rotary kilns³⁾ or cupola furnaces⁴⁾ (e.g. additions of carbonates, soda (Na₂CO₃) and quartz sand) it is possible to separate P from many other elements and to influence the crystal structure of the P containing slags (e.g. isomorphous substitution of the PO₄³⁻ ionic group by SiO₂²⁻ or CO₃²⁻) affecting the reactivity of the final product and therefore plant P availability [11, 12]. The final products show similar characteristics as Rhenania phosphate (a thermally produced phosphorus fertilizer which is made by calcining a mixture of phosphate rock, sodium carbonate, and silica in a rotary kiln at 1,250 °C) or Thomasphosphate [13]. Heavy metals are partially volatilized (Zn, Cd, Hg, F), partially remain in the metal fraction (e.g. Fe, Cu, Cr, Ni), or are present in the P-containing slag [13].

MBM and BM can also be treated by a controlled thermal procedure exceeding about 400 °C, resulting in a form of biochar that is rich in P, known as animal bone char [14].

Alkaline hydrolysis

Alkaline hydrolysis is an alternative treatment method to incineration or autoclaving during treatment and disposal. Alkaline hydrolysis uses sodium hydroxide (NaOH) or potassium hydroxide (KOH) to catalyse the decomposition of organic matter to a sterile aqueous solution consisting of small peptides, amino acids, sugars, and soaps. In addition, heat is applied (150 °C) to accelerate the process. Solid by-products of alkaline hydrolysis are mineral constituents of the bones and teeth of vertebrates. This residue is sterile and easily crushed into a powder that may be used as a fertilizer [15].

Nutrient concentrations and plant nutrient availability

The nutrient concentrations of various treated slaughterhouse waste products are relatively high (Table 2). However, the chemical composition is variable and largely depends on the raw materials, mainly the meat to bone ratio [16] [17]. Specific characteristics are the combination of high N, P and Ca concentrations and very low K concentrations.

Phosphorus concentration

All P concentrations in this document are given in units of P and not P₂O₅. The average P concentration in meat and bone meal is approximately 5.31 % in dry matter (DM) and ranges between 0.30 and 18.9 % DM, dependent on the bone-meat ratio (Table 2). The mean Ca/P ratio is 2.1:1, and ranges between 1.1 and 2.5:1. MBM-Phosphorus is present as apatitic phosphorus in the bone fraction while it is mainly in the organic form in the meat fraction [21] [22].

Table 2: Macronutrient, micronutrient and heavy metal concentration of meat and bone meals (in % of dry matter)*

	Dry matter	N	P	K	S	Mg	Ca	Si	References
Bone meal	95.3 (92.5–97.3)	5.30 (1.00–8.00)	10.5 (5.24–16.5)	0.34 (0.05–1.66)	0.42 (0.27–0.62)	0.48 (0.06–1.81)	21.6 (7.06–32.3)	–	[18]
Meat meal	93.9 (54.4–98.9)	8.00 (5.80–15.0)	3.42 (0.30–4.74)	2.09 (0.08–6.50)	0.44 (0.33–0.50)	0.16	6.79 (0.11–9.44)	–	
Meat and bone meal	96.2 (91.2–99.3)	8.28 (3.00–12.0)	5.31 (2.21–9.62)	0.67 (0.14– 3.95)	0.45 (0.04–1.90)	0.29 (0.14–1.02)	9.60 (5.30–19.6)	129	
MBM ashes	97.8	0.17	14.02 (6.07–18.9)	1.50	0.14	0.64	20.9	7000	[19] [20] [10]

* in parentheses: range of values

1) Pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen (or any halogen). (Wikipedia)

2) Sintering is the process of compacting and forming a solid mass of material by heat and/or pressure without melting it to the point of liquefaction.

3) A cupola furnace is a melting device used in foundries that can be used to melt cast iron, ni-resist iron and some bronzes. (Wikipedia)

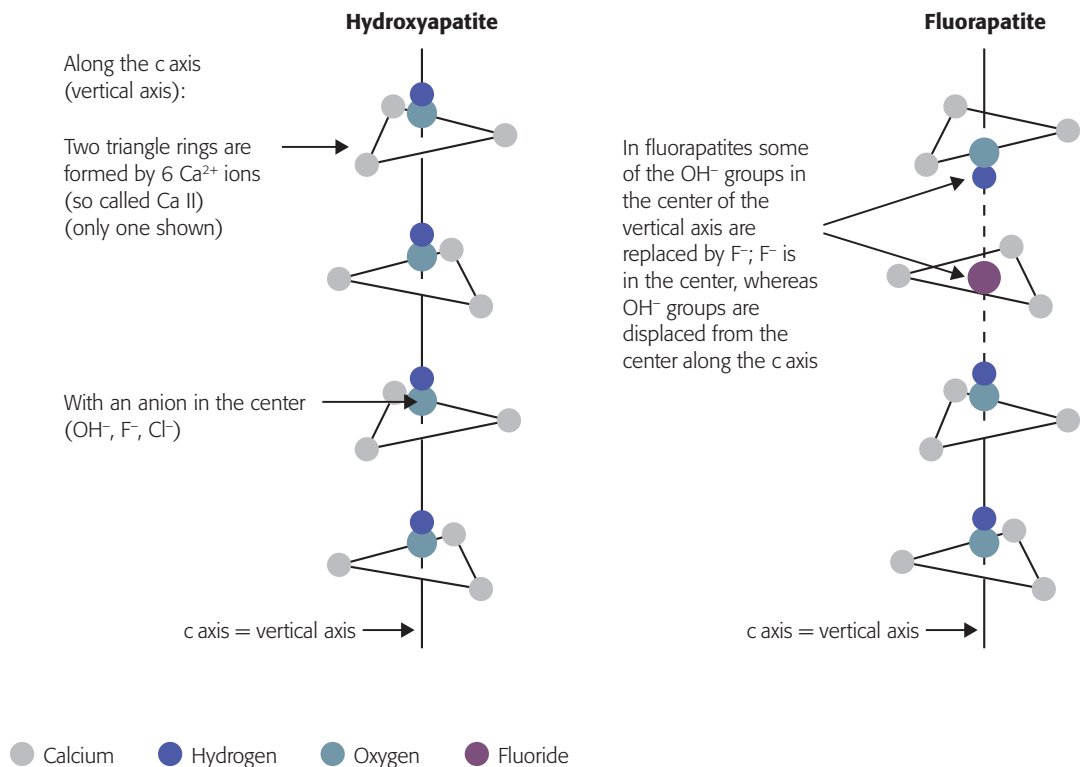
4) A rotary kiln is a pyroprocessing device used to raise materials to a high temperature (calcination) in a continuous process. (Wikipedia)

Phosphate speciation

The term "apatite" refers to a group of several minerals with the overall chemical formula $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$ (or $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH}, \text{F}, \text{Cl})_2$) as apatites crystallize with 2 units per cell). The term (OH, F, Cl) within the formula means that the OH-anion position within the axis (= hydroxyapatite) can be replaced also by F^- (= fluorapatite) or Cl^- (= chlorapatite).

The crystal structure is composed by a vertical axis composed by an anion (OH^- , F^- , or Cl^-) (Figure 2) and two 3 Ca-rings and a horizontal axis with another Ca-ring and phosphate (PO_4^{3-}) between the two rings. The phosphate constitutes the "skeleton" of the unit cell.

Figure 2: Perspective drawing of the apatite lattice in the vicinity of the OH-lattice sites along the vertical axis of apatites (c-axis)



Source: adapted from [22]

Two of the oxygens of the phosphate anion are aligned with the c-axis and the other two are in a horizontal plane, forming also a bridge to the next horizontal layer. The exact composition and crystal structure of apatite is more flexible than for most other minerals. Any chemical substitution in a crystal potentially changes its structure, which has effects on the minerals' properties such as solubility^[20] and plant P availability. For example, Fluor is the anion that best fits into the crystal structure and leads to a more compact mineral structure by a lower distance between the crystal layers^[22] (Figure 2). Also high contents of CO_3^{2-} are relevant, due to a replacement of some components by others in the crystal structure (called tetrahedral

ionic groups), a process called isomorphous substitution. For example, PO_4^{3-} can be replaced by carbonate (CO_3^{2-}). The oxygen-oxygen distance in a CO_3 group is 15% smaller than the oxygen-oxygen distance in a regular PO_4 group^[23]. This leads to structural instability of the crystal enhancing solubility, reactivity and plant P availability^[24, 20]. Biological apatite in bone meal for example contains with 7% (on dry matter base) substantial amounts of carbonate (CO_3^{2-})^[20] and low amounts of Fluor. Therefore, the low F contents combined with a relatively high isomorphous substitution of PO_4^{3-} groups by CO_3^{2-} mean a less compacted crystal structure and a higher plant P availability in bone meals than in apatites obtained by mining.

Phosphorus bioavailability and influencing factors

Due to the high ratio of apatitic P in meat and bone meal, plant P availability of bone meals depends largely on the soil characteristics. Ylivainio et al. (2008) [25] reported from experiments in soils with a pH ranging between 5.7 and 5.9, that the P availability of MBM was much lower than of solid manures, based on a three year pot experiment with ten ryegrass cuts. Approx. 19% of the phosphorus in meat and bone meal was immediately plant available in the year of application. Over the 3-year period, the P availability increased to 63% of the applied P.

As stated above, the more instable crystal structure of MBM as well as BM mean that these P sources should be preferred over phosphate rock [26][27]. As the dissolution of $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ in the bones requires H^+ ions, soil pH is an important factor influencing P release from bone meal [21][26]. Therefore, plant P availability is much higher in soils with a $\text{pH} \leq 6$ than in neutral and alkaline soils [26][25][28].

Concerning the use of MBM ashes, the ashes derive mostly from the bone component and contain high amounts of calcium and phosphorus (47–87%), mainly as a mixture of $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ and $\text{Ca}_3(\text{PO}_4)_2$ phases [10][11][8]. The conditions during combustion induce a wide range of structural modifications, such as crystallization of calcium phosphate, substitution reactions, etc., and concurrently a strong decrease of the particles' specific surface area because particles will stick to each other [10]. The ignition of carbonate apatites leads to a loss of CO_2 from the crystal structure, and they change in the direction of the carbonate free F- and OH- apatites with a more stable crystal structure [23][39]. These processes reduce the P-solubility and therefore the value of MBM ashes as P fertilizer in comparison to the original meat and bone meal. In ashes from mono-incinerated MBM, significant levels of sodium (2.7%), potassium (2.5%) and magnesium (0.8%) are measured, whereas the sum of trace element concentrations is below 0.6% [10][9]. Other important plant nutrients like nitrogen and sulphur are emitted as gas and not further available for agricultural use.

Phosphorus fertilizers produced by sintering or melting in rotary kilns or cupola furnaces are similar to Thomasphosphates [30][11][12], with an intermediate or short term P availability between rock phosphates and soluble mineral P fertilizers.

Other nutrients, their speciation and plant bioavailability

Nitrogen in meat and bone meals is mostly organically bound, with low concentrations of ammonium. C/N ratios range between 3.2 and 4.8:1. Studies on the effectiveness of meat and bone meal as

an organic N fertilizer have shown that the Nitrogen Use Efficiency (NUE) of MBM is 80% or even higher [21][32], meaning that 80% of the applied N or even more is released in the year of field application with nitrogen release starting shortly after soil application [21][33]. Cereal grain protein concentration can be significantly increased by MBM applications [34][35][36][32].

The potassium and sulphur concentrations of meat and bone meals are rather low. Sulphur is bound in organic forms. The calcium concentration of MBM is relatively high, and increases with the proportion of bone in the meal. The magnesium concentration is relatively low (Table 2). Despite high calcium concentrations, soil liming potential (CaCO_3 equivalency) is negligible, since calcium is mostly present as calcium phosphates. Their buffering effect is much lower than the buffering effects of carbonates, oxides or hydroxides [37].

By alkaline hydrolysis, all nutrients are conserved, and most of them completely mineralized to ammonium (NH_4^+). However, the very high pH value results in a high risk of ammonium losses as ammonia after field application. The type of alkali used during hydrolysis (NaOH or KOH) largely influences the fertilizer value of the end product.

Pollutant concentrations

Concentration of potentially toxic elements

The relationship of heavy metal loads to concentrations of plant nutrients is – in comparison to most other phosphorus fertilizers – very favorable, as indicated by the heavy metal-nutrient index (HMNI) (Table 3). Mean heavy metal concentrations, such as cadmium, for instance, are relatively low.

Meat and bone meal ashes have heavy metal concentrations of the same order of magnitude as those found in natural phosphate rocks or typical natural soils and rocks [9]. Industrial ashes with co-incineration of MBM contain much more hazardous elements than mono-incinerated MBM ashes [9].

Other pollutants

The concentration of organic pollutants in meat and bone meals like PCDDs (polychlorinated dibenzodioxins) and PCDFs (polychlorinated dibenzofurans) is very low [41][17]. Treatment of MBM in rotary kilns or a cupola furnace, destroys all persistent pollutants present in the feedstock [13].

The occurrence of tetracycline residues in poultry bones of slaughtered animals is more likely a normal than an exceptional finding (Table 4). This fact has consequences for the potential toxicological risk of products that contain bone portions like mechanically deboned poultry meat or poultry meat and bone meal [42].

Table 3: Available data on potentially toxic element contents (mg kg⁻¹ dry matter) contained in meat and bone meals

	Zn	Cu	Pb	Cd	Ni	Hg	Cr	References	HMN [1]
Bone meal	113 (89–133)	8.48 (0.50–50.0)	3.10 (0.40–10.0)	0.24 (0.21–0.30)	8.85 (1.00–24.0)	0.04 (0.02–0.05)	13.3 (0.30–37.5)	[17]	0.03
Meat meal	95.6 (47.0–140)	21.8 (0.05–29.4)	4.25	0.43	3.00 (0.77–3.10)	0.18	7.11 (5.90–8.31)		0.04
Meat and bone meal	107 (28.0–174)	11.2 (0.19–26.5)	2.97 (0.01–36.2)	0.21 (0.003–1.74)	3.31 (0.01–37.9)	0.02 (0.01–0.03)	4.15 (1.00–9.70)		0.03
Meat and bone meal ashes	171.6 (16.3–373.1)	21.7 (3.61–46.6)	13.1 (8.66–17.6)	0.82 (0.30–1.34)	27.9 (2.11–78.4)	<0.001	11.2 (5.28–20.8)	[18][19][9]	0.08
Rock phosphates [2]	20.3 (4–130)	155 (6–500)	10 (3–35)	25 (0.2–60)	29 (2–37)	0.05 (0.01–0.06)	188 (1–225)	[38][39]	0.99 (0.01–2.92)

Table 4: Tetrazycline-concentration [µg kg⁻¹ FM] in bone meals and meat meals [43]

	n	Positive samplings	Median	Min.	Max.
Bone meal	18	18	33,9	8,3	150,4
Greaves meal	16	16	38,9	19,9	317,1
Poultry meat and bone meal	15	15	309,1	72,7	606,9
Poultry meat meal	10	10	147,4	65,7	267,1
Meat and bone meal	49	49	615,1	157,8	1524,7

Hygienic aspects

Slaughterhouse wastes are materials potentially contaminated with pathogens including BSE. The current treatment methods forced by legislation destroy or inactivate almost all the potential pathogens in slaughterhouse waste products. Pressure sterilisation, for example, has been found to efficiently inactivate prions (>99.9 %) [44][45]. According to EU legislation, animals suspected of TSE infection are separated (category 1) and safely disposed of. Meat and bone meal includes much fewer potential harmful pathogens than for example animal manures and several other organic fertilizers that are commonly used. Nevertheless, during the BSE crisis in the 1990s and at the beginning of the 2000s, MBM was banned by several growers' organisations in Europe (e.g. Bioland, Demeter, Naturland) to reduce any residual risk of BSE contamination. However, the theoretical risk of BSE contamination decreased largely in the last decade, and in many countries no typical infectious BSE cases were found in the past few years [46]. Therefore, even the incineration and removal of category 1 material from the overall nutrient cycle in our societies should be re-evaluated.

Apart from incineration, alkali hydrolysis is the only effective method known for the complete destruction of prion material and any other pathogen [44][47].

Other aspects

No comparative data about the energy balance of different MBM and BM treatment options were found, and to the best of our knowledge, life cycle assessments have not yet been carried out for meat and bonemeal treatments.

Conclusions

The nutrient concentration in meat and bone meals varies according to the input materials and the bone to meat ratio in the original substrate. End-products contain (on a dry matter basis) N in a range of 1.00–15.0%, P in a range of 0.30–18.9% and minor concentrations of K (0.05–6.50 %). Note that these concentrations relate to elemental forms of the nutrients, and not to oxide forms. Nitrogen in MBM is highly available for plant uptake, whereas most of the P in the bone fraction is present as apatitic P with a very low plant P availability, especially under neutral and alkaline soil conditions. The organic P from the meat fraction has a high plant P availability after decomposition in the soil. Regarding the content of (potentially) toxic elements, the trade-off between (potentially) toxic element concentrations and potential benefits is very favorable for all fertilizers based on meat and bone meal. In organic farming, the use of MBM as a fertilizer for N demanding arable crops may enhance the recycling of P from the food chain back to agricultural land. However, MBM is less suited as fertilizer for inten-

sively managed horticultural and orchard fields, due to a not balanced nutrient spectra (high P content, low K content) increasing the risk of P oversupplies.

Assessment of the suitability for use in organic farming

A compliance with organic principles includes at least six aspects:

- › the sources of the feedstocks,
- › the effects on nutrient cycles and long term preservation of soil fertility,
- › the processes and additives applied to obtain the fertilizer – and their potential environmental impact,
- › the mode of action of the fertilizer in soil,
- › potential long term effects on soil contamination and environmental pollution and
- › potential effects on animal and human health.

As rendering by-products are a very relevant source of nutrients which includes a significant proportion of the overall N and P flows in our society, the use of rendering by-products like meat meal, bone meal as well as meat and bone meal as fertilizers would enhance nutrient cycling between rural and urban areas. However, there are also ethical aspects of animal welfare and industrial “animal factories” that should be considered, as most of the rendering waste products derive from highly intensive animal production systems (factory farming), with high inputs of concentrate grains produced on the expense of natural forests, and no enough arable land for reasonable field application of the animal

manures. By using of their waste products, organic farming may become the trash of intensive industrial animal production. Otherwise, organic farming is responsible for a certain ratio of the available rendering waste products, also meaning the responsibility to recycle at least this part of the overall waste stream.

Concerning the mode of action, meat and bone meals are best suited for fertilization of high N-demanding crops (e.g. cereals) on acidic soils with a pH <6 and low plant P availability. Also regarding the potential effects on soil contamination and pollution, MBM show very favorable characteristics. Concerning the potential effects on animal or human health, any evaluation of the BSE transmission risk from using meat and bone meals should consider that in most EU countries in the past few years no, or only a few cases of typical, transmissible BSE infected animals were found [46].

This means that the risk of BSE transmission by use of meat and bone meals as fertilizers is nowadays extremely low. Incineration is one treatment option to completely remove any risk of BSE transmission; however, incineration, sintering, melting or pyrolysis all result in losses of other nutrients like N and S, and reduced plant P availability. This opposes organic principles for efficient recycling and use of nutrients. Collection of slaughterhouse waste from animals raised on organic farms separately from conventional systems is not feasible for logistic reasons. Pasteurisation or sterilisation of rendering by-products remain the most effective ways to ensure that the final product meets the organic farming principles while minimizing risk to consumers.

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