Sulfuric Acid

Crops

Identification of Petitioned Substance

Chemical Names:
Sulfuric acid

Other Names:
battery acid
dihydrogen sulfate
dipping acid
dithionic acid
electrolyte acid
hydrogen sulfate
mattling acid
pyrosulphuric acid
vitriol
spirit of vitriol
sulphine acid
sulphuric acid
oil of vitriol
vitriol brown oil

Trade Names:
None

CAS Numbers:
7664-93-9

Other Codes:
X1002217-4 (ACX number)
2310 (OSHA IMIS Code Number)
WS5600000 (RTECS number)
4930040 (STCC number)
078001 (USEPA PC Code)
UN 1830 137 (DOT number; corrosive material)

Characterization of Petitioned Substance

Composition of the Substance:
Sulfuric acid (H_2SO_4) is a strong mineral acid that is highly soluble in water at all concentrations (HSDB 2005). The chemical structure of sulfuric acid is shown in Figure 1.

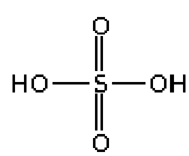

Figure 1. Chemical Structure of Sulfuric Acid

Properties of the Substance:

Sulfuric acid is a colorless to dark brown, oily, dense liquid (Chemfinder 2006). It is very corrosive and has a sharp, acrid odor. Although it is not combustible, concentrated sulfuric acid mixed with water generates a large amount of heat (HSDB 2005). Fire may result from the heat generated by contact of concentrated sulfuric acid solution with particulate combustible materials. Sulfuric acid reacts strongly with organic materials, chlorates, carbides, fulminates, water, and powdered metals. When heated, sulfuric acid emits highly toxic fumes that include sulfur trioxide. Sulfuric acid is most commonly marketed in four grades: commercial, electrolyte (high purity for batteries), textile (low organic content), and chemically pure or reagent grades (ATSDR 1998).

Sulfuric acid is one of the primary chemical agents of "acid rain" (ATSDR 2004). Because it is not very volatile, sulfuric acid from sources of air pollution can often be found in the air as microscopic liquid droplets or attached to other small particles in the air (NSC 2005). Atmospheric deposition of sulfuric acid from air pollution can lower the pH of surface waters and have a corrosive effect on living and non-living components of the aquatic and terrestrial environment.

<u>Specific Uses of the Substance</u>:

Sulfuric acid, along with phosphoric acid and citric acid, currently are approved for use as processing aids for pH adjustment in organically processed liquid fish products for use in crop production (NOP §205.601(j)(7)). The current approval allows for pH adjustment of liquid fish products to as low as 3.5. Sulfuric acid is petitioned to be used for the same purpose (i.e., processing aid for pH adjustment) in the production of dehydrated manure for subsequent use in organic crop production. For the petitioned use, the pH would not be lowered below 5.0.

Sulfuric acid is the world's largest volume industrial chemical in terms of production (ADEH 2003, EPA 1993); more sulfuric acid is produced in the United States than any other chemical (NSC 2005). The main use is in the production of phosphate fertilizers that convert phosphate rock to phosphoric acid, which consumes the sulfuric acid (ATSDR 1998). It is also used to manufacture explosives, other acids, dyes, glue, wood preservatives, and automobile batteries. It is used in the purification of petroleum, the pickling of metal, copper smelting, electroplating, metal work, the production of rayon and film, and as a laboratory reagent. In many of these applications, the sulfuric acid is recovered and reused. There also are numerous household products that contain sulfuric acid (HPD 2004).

<u>Approved Legal Uses of the Substance:</u>

Sulfuric acid is regulated as a pesticide under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (EPA 1993). It is exempt from the requirement of a tolerance for residues when used as a pH control agent in accordance with good agricultural practices as an ingredient in pesticide formulations applied to growing crops or to raw agricultural commodities after harvest (HSDB 2005). It is also exempt from the requirement of a tolerance for residues when used in accordance with good agricultural practice as an herbicide in the production of garlic and onions and as a potato vine desiccant in the production of potatoes (EPA 1993, HSDB 2005). The U.S. Food and Drug Administration (FDA) has determined under 21 CFR §184.1095 that sulfuric acid is a "Generally Recognized as Safe" (GRAS) substance in food.

Several other regulations apply to the transport, disposal, and accidental release of sulfuric acid. The U.S. Department of Transportation (DOT) forbids spent (i.e., used) sulfuric acid from being transported on passenger-carrying aircraft or railcars (NSC 2005). Under the Federal Water Pollution Control Act, sulfuric acid is considered a hazardous substance when discharged to surface waters; it is further regulated by the Clean Water Act (CWA) Amendments of 1977 and 1978 (HSDB 2005). Sulfuric acid is regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-to-Know Act of 1986 (EPCRA), under which releases of more than one pound of sulfuric acid into the air, water, or land must be reported annually and entered into the Toxic Release Inventory (TRI) (EPA 2005a). In 1993, EPA delisted non-aerosol forms of sulfuric acid (EPA 2005b); thus, aqueous solutions of sulfuric acid are no longer covered under TRI. Sulfuric acid (in all forms) is included on Canada's 2004 National Pollutant Release Inventory (EC 2005).

Several U.S. governmental and non-governmental organizations have published regulations and guidance regarding occupational exposure limits to airborne sulfuric acid; these are summarized in NSC (2005), OSHA (2003), and NIOSH (2000, 2005a, 2005b). NIOSH (2005b) also summarizes international standards and regulations concerning occupational exposure to sulfuric acid.

Action of the Substance:

According to the petition, liquid sulfuric acid would be added to adjust the pH of livestock manures prior to dehydrating the solids for final use as a soil amendment in organic crop production. More specifically, sulfuric acid would be used within livestock manures to keep biologically-derived nitrogen compounds in solution as opposed to being volatilized during the manure-drying process. The pH of some excreted manures tends to be alkaline (pH 7.8-8.3) due to the use of limestone as a calcium source for bone mass in the animal feed and due to the natural generation of uric acids and ammonium in the urine and feces of the animal. Adding a small amount of sulfuric acid to the manure lowers the pH and slows the biological breakdown of the uric acids and ammonium into more volatile forms of nitrogen and organic compounds (e.g., fatty acids) , thereby greatly decreasing the release of odorous compounds (McCrory and Hobbs 2001). For the petitioned use, the pH would not be lowered below 5.0.

Status

International

Sulfuric acid is not specifically listed for the petitioned use or other uses in the following international organic standards:

- CODEX Alimentarius Commission
- European Economic Community (EEC) Council Regulation 2092/91
- International Federation of Organic Agriculture Movements

The Canadian General Standards Board permits the use of fish emulsions to amend and improve soil fertility (CGSB 1999). Liquid fish products can be pH-adjusted using sulfuric acid, but the amount of acid used cannot exceed the minimum amount needed to lower the pH to 3.5 (CGSB 2004).

Sulfuric acid is listed in the Japan Agricultural Standard for Organic Production where it is allowed for use in adjusting pH of the extracted water in producing sugar (i.e., a pH adjustment agent) (JMAFF 2000).

Evaluation Questions for Substances to be used in Organic Crop or Livestock Production

***Evaluation Question #1:* Is the petitioned substance formulated or manufactured by a chemical process? (From 7 U.S.C. § 6502 (21))**

According to the petition, sulfuric acid is produced from sulfur dioxide (SO_2) collected by pollution control devices (scrubbers) during the smelting of various metal ores and ore concentrates. The sulfur dioxide is captured in the scrubbers to reduce emissions that would otherwise contribute to acid rain. The resulting "scrubber feedstock" is further purified, concentrated, and used for the subsequent production of sulfuric acid.

There are two major processes that have been used to produce commercial quantities of sulfuric acid: the "contact process" and the "chamber process" (ATSDR 1998). The contact process was developed in the early 1900s and has become the primary means of sulfuric acid production worldwide (IARC 1992). In brief, sulfur dioxide forms sulfuric acid in the presence of oxygen, water, and a catalyst (most commonly vanadium complexes), by a two-step chemical reaction shown in Figure 2 (EFMA 1997, HSDB 2005).

$$(1)\ 2SO_2 + O_2 \rightarrow 2SO_3$$
$$(2)\ SO_3 + H_2O \rightarrow H_2SO_4$$

Figure 2. Formulation of Sulfuric Acid via the Contact Process

This reaction can produce 98-99 percent pure sulfuric acid, which is stable for storage and is considered the usual form of "concentrated" sulfuric acid (ATSDR 1998, EFMA 1997). The petition includes a detailed summary of the production process, which is derived from information provided by the sulfuric acid manufacturer and sulfuric acid supplier.[1]

The other major sulfuric acid production process, the "chamber process," was once the predominant method for sulfuric acid production in the United States and western Europe, but it has dropped to virtually zero use since 1960 (ATSDR 1998).

<u>Evaluation Question #2:</u> Is the petitioned substance formulated or manufactured by a process that chemically changes the substance extracted from naturally occurring plant, animal, or mineral sources? (From 7 U.S.C. § 6502 (21).)

The starting point for commercial sulfuric acid manufacturing is sulfur dioxide, which is a byproduct of industrial pollution control systems (EFMA 1997). The manufacturing process involves a two-step chemical reaction using oxygen, water, and a vanadium oxide catalyst (HSDB 2005). See Evaluation Question #1 for further explanation of the manufacturing process.

<u>Evaluation Question #3:</u> Is the petitioned substance created by naturally occurring biological processes? (From 7 U.S.C. § 6502 (21).)

Commercial sulfuric acid is chemically synthesized. See Evaluation Question #1 for further explanation of the manufacturing process.

<u>Evaluation Question #4:</u> Is there environmental contamination during the petitioned substance's manufacture, use, misuse, or disposal? (From 7 U.S.C. § 6518 (m) (3).)

Globally, sulfuric acid is of environmental and regulatory concern as a result of acid rain deposition resulting from the burning of sulfur-containing fuels (ATSDR 2004). As described in Evaluation Questions #1 and #2, the feedstock for sulfuric acid manufacturing is a beneficial byproduct from the use of air pollution control devices during the smelting of various naturally occurring metal ores. Thus, according to the petition, if not turned into a commercial product, this byproduct would ultimately contribute to the formation of acid rain.

Manufacturing

Facilities that manufacture sulfuric acid are among the primary sources of sulfuric acid releases to the environment (ATSDR 1998). These releases are mainly emissions to the air. In the air, some sulfuric acid reacts with other chemicals (e.g., ammonia, magnesium, calcium), which act to neutralize the acid. Sulfuric acid droplets and particles that are not neutralized may dissolve in clouds, fog, rain, or snow, resulting in very dilute acid solutions which may impact the environment as acid precipitation.

When acid precipitation reaches surface water, the sulfuric acid dissociates to hydrogen and sulfate ions (H^+ and SO_4^{2-}); sulfate anions may combine with other metal cations, such as calcium and magnesium, to form particulate sulfate salts (ATSDR 1998). Aquatic sulfur may be oxidized to sulfuric acid by sulfur bacteria (Thiobacilli) that use sulfur to obtain energy for growth. Sulfate levels in water are highly dependent on nearby emissions of sulfur-containing compounds, which can be converted to sulfuric acid. Background sulfate concentrations in North American lakes are estimated at 20-40 µeq/L. In eastern North America where acid deposition occurs, sulfate concentrations are 80-100 µeq/L. Surface waters closer to sources of emission can have even higher concentrations.

[1] Additional information also is available from the web site of NorFalco LLC, one of the largest marketers of sulfuric acid in North America (http://www.norfalco.com/production+process.htm).

Use and Handling

The petition indicates that the method of sulfuric acid handling and addition to manure would vary between animal species, diet formulation, and respective farm manure handling facilities. Typically, small amounts of liquid sulfuric acid would be added on a continuous basis via a metering valve or pump connected to a supply tank. Addition of sulfuric acid would take place during manure transport, mixing, and storage to diminish odor generation. In cases of long storage times or noncontinuous mixing and transport of manure, sulfuric acid may be added in batch mode, but the volume of acid needed in such cases would be consistent with the continuous feed method.

According to the petition, following addition of sulfuric acid to manure, the acid is subsequently neutralized by the manure. The remaining sulfur is in the form of sulfate ions (SO_4^{2-}). Sulfate is an essential nutrient in the formation of chlorophyll and amino acids within plants (Baird 1997).

Misuse

No information sources reviewed for this report specifically address the issue of misuse of sulfuric acid during addition to manure. Accidental spills or improper disposal of liquid sulfuric acid or wastes containing sulfuric acid could result in environmental contamination. The presence of water in the soil or precipitation at the time of an accidental spill or release of liquid sulfuric acid will influence the rate of chemical movement in the soil and the likelihood that it will reach groundwater (HSDB 2005).

Disposal

As noted previously, when used as petitioned to adjust the pH of livestock manure, sulfuric acid is neutralized to sulfate, which is eventually taken up by crops as a nutrient. Disposal of unused sulfuric acid and wastes containing sulfuric acid in the United States is controlled by a number of federal regulations (e.g., EPCRA, CWA) intended to prevent environmental contamination.

<u>Evaluation Question #5:</u> Is the petitioned substance harmful to the environment? (From 7 U.S.C. § 6517 (c) (1) (A) (i) and 7 U.S.C. § 6517 (c) (2) (A) (i).)

Sulfuric acid is a component of acid rain, which is a well-known pollution problem of global concern (ATSDR 1998). Although sulfuric acid has been characterized as only slightly toxic to crustaceans and fish by the Pesticide Action Network (PAN 2005), the National Institute for Occupational Safety and Health (NIOSH) warns occupational users of sulfuric acid not to let it enter the environment and states that sulfuric acid is harmful to aquatic organisms (NIOSH 2000). EPA (1993) concluded that the use of registered pesticide products containing sulfuric acid in accordance with approved labeling "will not pose unreasonable risks or adverse effects to humans or the environment" except when it is used as a desiccant on potato vines. The use of sulfuric acid as a desiccant on potato vines poses significant hazards to birds and other terrestrial wildlife.

<u>Evaluation Question #6</u>*:* Is there potential for the petitioned substance to cause detrimental chemical interaction with other substances used in organic crop or livestock production? (From 7 U.S.C. § 6518 (m) (1).)

No information was identified to suggest that sulfuric acid applied to manure would cause detrimental chemical interaction with other substances used in organic crop production. If the acid is added to manure in the manner described in the petition, it is unlikely to be available to chemically interact with other substances used in organic crop or livestock production. This is because the acid is neutralized by the manure and converted to sulfate ions (see Evaluation Question #4).

Evaluation Question #7: Are there adverse biological or chemical interactions in the agro-ecosystem by using the petitioned substance? (From 7 U.S.C. § 6518 (m) (5).)

No information was identified to suggest that sulfuric acid applied to manure would result in adverse biological or chemical interactions in the agro-ecosystem. If the acid is added to manure in the manner described in the petition, it is unlikely to reach the greater agro-ecosystem in significant amounts and thus is unlikely to result in adverse chemical or biological interactions in the agro-ecosystem. This is because the acid is neutralized by the manure and converted to sulfate ions (see Evaluation Question #4).

In the event of a major spill of liquid sulfuric acid to soil, especially during a precipitation event, ions from liquid sulfuric acid (i.e., hydrogen and sulfate) can adsorb to soil particles, be converted to gases, or leach into surface water and groundwater, removing important nutrients such as ions of calcium, magnesium, potassium, and other metals attached to the clay and humus particles in the soil (Virtual Chembook 2003). Normally, the attractive forces of positive metal ions to negatively charged clay particles are sufficient to keep the metal ions in the soil despite the passage of water through the soil. However, the presence of sulfuric acid allows the hydrogen ions to trade places with the metal ions, which has two negative effects. First, the hydrogen ions are retained, which can lower the pH of the soil thereby slowing the growth of or even killing vegetation in the immediate area of the contaminated soil. Second, the metal ions are leached or washed out of the top soil into lower inaccessible subsoil, thereby making them unavailable as nutrients or fertilizers for tree and plant growth.

Evaluation Question #8: Are there detrimental physiological effects on soil organisms, crops, or livestock by using the petitioned substance? (From 7 U.S.C. § 6518 (m) (5).)

If the acid is added to manure according to the petitioned use, it is unlikely to reach the greater agro-ecosystem in significant amounts and thus is unlikely to be available to cause detrimental physiological effects on soil organisms, crops, or livestock. This is because the acid is neutralized by the manure and converted to sulfate ions (see Evaluation Question #4).

In the event of a major spill of large quantities of liquid sulfuric acid to soil, especially during a precipitation event, the pH of the soil would be lowered, which could slow the growth of or even kill vegetation in the immediate area of the contaminated soil (Virtual Chembook 2003). Lowered soil pH can also inhibit plant growth by its effect on activity of beneficial soil microorganisms. For example, bacteria that decompose soil organic matter are hindered in strongly acidic soils, which can prevent organic matter from breaking down, resulting in an accumulation of organic matter and tying up nutrients, particularly nitrogen, that are held in the organic matter (Bickelhaupt 2005).

Evaluation Question #9: Is there a toxic or other adverse action of the petitioned substance or its breakdown products? (From 7 U.S.C. § 6518 (m) (2).)

Sulfuric acid is very corrosive and irritating and can cause direct harmful effects on the skin, eyes, and respiratory and gastrointestinal tracts when there is direct exposure to sufficient amounts of concentrated acid (NSC 2005, EPA 1993). Exposure to sulfuric acid mist can irritate the eyes, nose, throat and lungs, and at higher levels can cause a buildup of fluid in the lungs (pulmonary edema) (ADEH 2003). Although liquid sulfuric acid is not absorbed through the skin, it is a corrosive chemical and can severely burn unprotected skin and eyes, causing third degree burns and blindness on contact (ATSDR 2004). Oral ingestion of concentrated sulfuric acid can burn the mouth, throat, and stomach, and can result in death (ATSDR 2004). EPA has placed sulfuric acid in Toxicity Category I (on a scale of I to IV) for eye and dermal irritations as well as inhalation effects in humans; it is in Toxicity Category II for acute oral toxicity (EPA 1993).

There are no human dietary concerns from the use of sulfuric acid as a pesticide on potato vines (EPA 1993). For this use, sulfuric acid was granted an exemption from tolerance requirements because it "is rapidly degraded in the environment to sulfate salts, which are of no toxicological concern and are Generally Recognized as Safe (GRAS) by the Food and Drug Administration."

The American Conference of Governmental Industrial Hygienists (ACGIH) has classified aerosol sulfuric acid as a suspected human carcinogen because it is carcinogenic in laboratory animals under conditions that are considered relevant to worker exposure (CCOHS 2003). However, available human studies are considered conflicting or insufficient to confirm an increased risk of cancer in exposed humans. The International Agency for Cancer Research (IARC) has determined that there is sufficient evidence that occupational exposure to strong-inorganic-acid mists containing sulfuric acid is carcinogenic to humans (IARC 1992, 1997).

From an occupational health perspective, inhalation and dermal exposure resulting from commercial production, industrial uses, and agricultural uses of sulfuric acid are of concern and subject to various exposure standards and guidance (NSC 2005, OSHA 2003, and NIOSH 2000, 2005a, 2005b). NIOSH recommends that workers wear appropriate personal protective clothing and eyewear to prevent skin and eye contact and use ventilation and breathing protection to prevent inhalation (NIOSH 2000, 2005a). Labels for pesticide products containing sulfuric acid must require use of personal protective equipment and clothing, as specified in the Worker Protection Standard, and workers must also wait 5 days before re-entering treated potato fields (EPA 1993).

Evaluation Question #10: Is there undesirable persistence or concentration of the petitioned substance or its breakdown products in the environment? (From 7 U.S.C. § 6518 (m) (2).)

According to the petition, sulfuric acid added to manure is subsequently neutralized by the manure leaving behind sulfate ions. Sulfate is an essential nutrient in the formation of chlorophyll and amino acids within plants (Baird 1997).

In the event of a spill of liquid sulfuric acid, the persistence of sulfuric acid in soil would be dependent on the extent to which soils can neutralize it, which in turn depends on several factors such as type of soil, thickness, weather, and water flow patterns (Virtual Chembook 2003). For example, if the ground is frozen, natural soil processes cannot function and the acid is not neutralized. If the soil is mainly quartz, such as those having a lot of sand, it is resistant to weathering and no bases are present to neutralize the acid. If the soil has very little base such as limestone, the acid is neutralized only slightly or with the passage of time, not at all. Sulfuric acid ions (i.e., hydrogen and sulfate) that do not adsorb to soil particles can be converted to gas and volatilize (ATSDR 1998).

Evaluation Question #11: Is there any harmful effect on human health by using the petitioned substance? (From 7 U.S.C. § 6517 (c) (1) (A) (i), 7 U.S.C. § 6517 (c) (2) (A) (i)) and 7 U.S.C. § 6518 (m) (4).)

The toxic effects of sulfuric acid were summarized above in Evaluation Question #9. From an occupational perspective, sulfuric acid is unlikely to have harmful effects on human health if it is properly handled by workers during its addition to manure (i.e., use of protective equipment and ventilation). Once added to manure, sulfuric acid is unlikely to reach the environment in significant amounts and thus is unlikely to be available to cause harmful effects on human health. This is because the acid is neutralized by the manure and converted to sulfate ions (see Evaluation Question #4).

Evaluation Question #12: Is there a wholly natural product which could be substituted for the petitioned substance? (From 7 U.S.C. § 6517 (c) (1) (A) (ii).)

There are a variety of substances that can be added to livestock manure to reduce ammonia production and odor emissions (McCrory and Hobbs 2001). Additives to decrease ammonia production include acidifying agents, bacterial–enzymatic preparations, plant extracts, oxidizing agents, disinfectants, urease inhibitors, masking agents, and adsorbents. Additives to reduce odor nuisance include digestive additives, disinfecting additives, oxidizing agents, adsorbents, and masking agents. The majority of these additives cannot be considered natural products, and their effectiveness is not well established. Some additives that can be considered natural product alternatives to the use of sulfuric acid are discussed below.

The application of unreacted carbon sources (e.g., potato starch, milled wheat) is often a less hazardous alternative to sulfuric acid and induces a reduction in livestock manure pH by stimulating the naturally-occurring microorganisms to produce organic acids (McCrory and Hobbs 2001). At present, the quantity of carbon material required to induce a significant pH decline is economically prohibitive. However, if the production of acid can be optimized, possibly by using suitable lactic acid bacteria, it would offer an effective and safe means to prevent ammonia production.

A variety of natural absorbents can be use to reduce ammonia production; some of the most commonly employed are peat and clinoptilolite (a naturally occurring alumino-silicate mineral with high cation exchange capacities). The advantages associated with the use of either clinoptilolite or peat are that they are nonhazardous and act as good soil conditioners when spread with manure.

Several additives to reduce ammonia production in livestock manure are based on saponins that are extracted from the sap of the yucca plant (McCrory and Hobbs 2001). Saponins are high-molecular-weight glycosides that are believed to be responsible for the yucca's capability to conserve ammonia. The exact mechanism of ammonia reduction is unclear mechanism, and commercial use of these products has yielded mixed results.

More broadly, the use of chemically-treated animal manure can be replaced by use of composted or raw manure (the latter with restrictions) and/or composted or non-composted plant materials, which are allowed under NOP §205.203(c). Hall and Sullivan (2001) provide a review of alternative soil amendments to agricultural fertilizers and manure, including several that can be considered wholly natural, such as various plant byproducts (e.g., composted leaves), rock and mineral powders (e.g., granite dust), and seaweed products.

<u>Evaluation Question #13:</u> Are there other already allowed substances that could be substituted for the petitioned substance? (From 7 U.S.C. § 6518 (m) (6).)

Various acids have been proven effective in reducing ammonia volatilization; these include sulfuric, hydrochloric, nitric, phosphoric, and lactic acid (McCrory and Hobbs 2001). Of these, sulfuric acid and phosphoric acid are currently approved for use as processing aids for pH adjustment in organically processed liquid fish products for use in crop production (NOP §205.601(j)(7)). Phosphoric acid is also allowed as an equipment cleaner in livestock production (NOP §205.203 (a)(14)) and in the cleaning of food-contact surfaces and equipment (NOP §205.605 (b)). Thus, phosphoric acid is an alternative to sulfuric acid as a processing aid in the production of dehydrated manure for subsequent use in organic crop production. However, phosphoric acid is not as cost-effective in reducing ammonia production in livestock manure (McCrory and Hobbs 2001).

As noted in the response to Evaluation Question #12, the use of chemically-treated animal manure can be replaced by use of (non-chemically-treated) composted or non-composted animal and/or plant materials, which are allowed under NOP §205.203(c).

<u>Evaluation Question #14:</u> Are there alternative practices that would make the use of the petitioned substance unnecessary? (From 7 U.S.C. § 6518 (m) (6).)

As specified under NOP §205.203(b): "The producer must manage crop nutrients and soil fertility through rotations, cover crops, and the application of plant and animal materials." Thus, the need to use manure (whether composted, non-composted, or chemically-treated) or plant materials could be replaced through crop rotation and use of cover crops. A cover crop is any crop grown to provide soil cover for a subsequent crop and which are grown primarily to prevent soil erosion by wind and water. Sullivan (2003) provides a review of these "green manuring" practices. Other alternative practices to improve soil health and sustainability, such as tillage reduction (i.e., intentional disruption and mixing of topsoil), are reviewed in Sullivan (2004).

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