Magnesium Oxide

Crops

Identification of Petitioned Substance

Chemical Names:
Magnesium oxide
Oxomagnesium

Other Name:
Magnesia
Periclase
Seawater magnesia
Maglite
Oxymag
Calcined magnesia
Magnesia monoxide

Trade Names:
F3 SurfActive
Basfoliar® Mg flo

CAS Numbers:
1309-48-4
1193320-89-6
13589-16-7
185461-91-0
187036-80-2
227961-49-1
52933-73-0
82375-77-7
146024-95-5
146024-97-7
148075-95-0
148075-92-7
1317-74-4
146024-94-4

Other Codes:
EC No. 215-171-9
ICSC No. 0504
RTECS No. OM3850000

Summary of Petitioned Use

Magnesium oxide is used in organic crop production as an additive to modify the physical properties of clay-humate mixtures for foliar applications. The United States Department of Agriculture (USDA) National Organic Program (NOP) has approved magnesium oxide as a "synthetic substance allowed for use in organic crop production," with the stipulation that it is "for use only to control the viscosity of a clay suspension agent for humates" in 7 CFR 205.601.

This technical report was requested by the National Organic Standards Board (NOSB) Crops Subcommittee in support of its sunset review of magnesium oxide.

Characterization of Petitioned Substance

Composition of the Substance:
Magnesium oxide is an ionic compound formed between magnesium cations (Mg^{2+}) and oxide anions (O^{2-}) and forms a solid with a rock salt crystal structure. Magnesium oxide is formed when pure magnesium reacts or is ignited in the presence of oxygen, as described below in Equation 1 (Atkins et al. 2008).

$$2\,Mg_{(s)} + O_{2\,(g)} \rightarrow 2\,MgO_{(s)}$$

Equation 1

Magnesium oxide may include a variety of metal ions that can be carried over from mineral and brine sources, including calcium, iron, aluminum, and manganese (de Sousa 2018). The composition and amount of these metals present in magnesium oxide are dependent on the source and production conditions. Iron is the most common contaminant in magnesium oxide produced from mineral sources due to its prevalence in the earth's crust (Atkins et al. 2008, de Sousa 2018). Iron accounts for 0.1–5% of the final mass of magnesium oxide from mineral sources, but it is rarely present in magnesium oxide produced from brine. Calcium makes up most of the impurity when brine is used to produce magnesium oxide, accounting for 0.5–3% of the final mass (de Sousa 2018). Mineral sources made of magnesium oxide may also include silicon, depending on the mineral and production conditions used. Magnesium oxide may contain boron if it is produced from some salt lake brine sources (de Sousa 2018).

Source or Origin of the Substance:

Magnesium is an earth abundant element. It is the 8th most abundant element in the earth's crust and the 3rd most abundant element in the oceans (Atkins et al. 2008, Baird and Cann 2008, USGS 2017, de Sousa 2018, Nobre et al. 2020). Magnesium oxide is a commercially available compound that can be produced from mineral and brine (seawater and salt lake) sources. Magnesium oxide exists in mineral form as periclase and can be produced from many magnesium-containing minerals, including brucite ($Mg(OH)_2$), magnesite ($MgCO_3$), hydro-magnesite ($Mg_5(CO_3)_4(OH)_2$), dolomite ($CaMg(CO_3)_2$), carnallite ($KMgCl_3$), and olivine (Mg_2SiO_4) (Panda and Mahapatra 1983, USDA 2007, Atkins et al. 2008, USGA 2017, de Sousa 2018, Nobre et al. 2020).

Properties of the Substance:

The high charge density of magnesium and oxide ions (Mg^{2+}, O^{2-}) creates strong electrostatic attraction between ions, resulting in a high melting point (2852 °C) (Atkins et al. 2008, SA 2020). The rock salt crystalline structure results in poor electrical conductivity, making magnesium oxide a good insulator (Atkins et al. 2008).

Magnesium oxide is insoluble in water but reacts with water to form magnesium hydroxide (brucite, [$Mg(OH)_2$]), as described below in Equation 2 (PC 14792, USDA 2007, Atkins et al. 2008, de Sousa 2018, SA 2020). The formation of magnesium hydroxide from magnesium oxide and water is a reversible process, and magnesium oxide can be reformed by heating magnesium hydroxide (Atkins et al. 2008, de Sousa 2018, Nobre et al. 2020).

$$MgO_{(s)} + H_2O_{(l)} \rightleftharpoons Mg(OH)_{2\,(s)}$$

Equation 2

Magnesium hydroxide is a basic substance that also has low water solubility, with a $K_{sp} = 6.3 \times 10^{-10}$ (Silberberg 2003). The basic nature of magnesium hydroxide results in increased solubility in acidic solutions (Silberberg 2003, Atkins et al. 2008).

General properties of magnesium oxide are listed below in Table 1.

Table 1. Properties of magnesium oxide

Property	Magnesium oxide
Appearance	White powder, white to translucent crystals
CAS number	1309-48-4
Molecular weight	40.3 g/mol
Solubility	Insoluble in water and ethanol, soluble in dilute HCl
Melting point	2852 °C; 5166 °F
Boiling point	3600 °C; 6512 °F
Density	3.580 g/cm^3
Reactivity	Reactive with water to form magnesium hydroxide (Equation 2)

Sources: PC 14792, Silberberg 2003, USDA 2007, Atkins et al. 2008, de Sousa 2018, SA 2020

Specific Uses of the Substance:

Magnesium oxide is used in organic crop production as an additive in mixtures of clay and humates to influence viscosity. The incorporation of magnesium oxide influences the interactions between clay particles and humates by affecting the viscosity of the solution and changing the surface charge of the clay particles to prevent aggregation between the two substances (Reid and Karr 2002, Tombacz 2003, USDA 2013).

Magnesium oxide has viscosity-related applications in aqueous fluids used for a variety of purposes, including environmental drilling and mining (Hoy 2005). Magnesium oxide has also been used to influence the interactions between suspensions of clays, polymers, and organic matter (including humates) in water purification applications (Bolto et al. 2001 Sabah and Ouki 2017). The addition of magnesium oxide to water purification processes facilitates the removal of organic matter from a solution and adsorption to clay and polymer surfaces; the opposite effect is seen when magnesium oxide is used in organic agriculture applications (Bolto et al. 2001, Tombacz 2003,Petzold et al. 2004, Nguyen et al. 2009). In the case of agricultural formulations, magnesium oxide is generally added in the absence of clay and polymer flocculants and is added to reach solutions with high ionic strength (high concentration of dissolved ionic components) (Tombacz 2003, Nguyen et al. 2009, Zhang et al. 2012). The high ionic strength of the solution increases ionic competition for attractive sites on organic material and increases electrostatic repulsions between organic material with associated multivalent cations (Wall and Mathews 2005). Magnesium oxide also increases the pH of the solution, promoting negative charges on organic carboxylic acids, and increasing electrostatic repulsions (Feng et al. 2005, Wall and Mathews 2005, Nguyen et al. 2009).

Magnesium oxide has many uses outside of influencing clay-humate interactions. Magnesium oxide is used as a foliar source of the micronutrient Mg^{2+} in conventional crop production and as a soil amendment to add magnesium and adjust soil pH (Reid and Karr 2002, CE 2006, Pereira et al. 2015). Magnesium oxide has several medicinal applications as an ingredient in antacids, laxatives, and magnesium supplements (Flommnebaum et al. 2002, USDA 2007). Magnesium oxide has several applications in industrial manufacturing as an alternative to lime (calcium oxide [CaO]) in Portland cement, a pH adjuster in tanning processes, and an alternative to titanium oxides in white pigments (Atkins et al. 2008, de Sousa 2018, Nobre et al. 2020). The high thermal stability and low electrical conductivity of magnesium oxide allow for applications in high temperature environments, including as a component of refractory lining in industrial furnaces and heating elements (Atkins et al. 2008).

Approved Legal Uses of the Substance:

The USDA NOP has approved magnesium oxide as a “synthetic substance allowed for use in organic crop production” with the stipulation that it is “for use only to control the viscosity of a clay suspension agent for humates” in 7 CFR 205.601.

The United States Food and Drug Administration (FDA) allows the use of magnesium as an ingredient in animal drugs and feeds in 21 CFR 558. Magnesium oxide is an approved ingredient in bambermycins in 21 CFR 558.95, chlortetracycline in § 558.128, fenbendazole in § 558.258, and lasalocid in § 558.311.

The FDA has designated magnesium oxide to be generally recognized as safe (GRAS) “when used in accordance with good manufacturing or feeding practice” in 21 CFR 582.1431 and § 582.5431. The FDA has also granted magnesium oxide GRAS status as a “direct food substance” in § 184.1431. The FDA recognizes magnesium oxide as a precursor for GRAS substances magnesium chloride in § 184.1426, magnesium hydroxide in § 184.1428, and magnesium sulfate in § 184.1443.

The FDA has approved the use of magnesium oxide as an active ingredient in “antacid products for over-the-counter (OTC) human use in 21 CFR 331.11 and as an ingredient in over-the-counter “weight control drug products” in § 310.545. The FDA has also approved magnesium oxide as an ingredient in canned peas in § 155.170.

The FDA has approved the use of magnesium oxide as an ingredient for several food additives, adjuvants, colorants, production aids, sanitizers, and polymers. These include perfluorocarbon cured elastomers in 21 CFR 177.2400, components of paper and paperboard in § 176.170, rubber articles in § 176.2600, petroleum wax in § 172.886, colorants in § 82.3 and § 178.3297, and sanitizing solutions in § 178.1010.

The United States Environmental Protection Agency (EPA) has listed magnesium oxide as an "inert ingredient used pre- and post-harvest" that are "exempt from the requirement of a tolerance" in 40 CFR 180.910, and is included on List 4. The EPA has granted magnesium oxide a "tolerance exemption for active and inert ingredients for use in antimicrobial formulations" in § 180.940. The EPA has also classified magnesium oxide as an "active ingredient permitted in exempted minimum risk pesticide products" in § 152.25.

Action of the Substance:

Magnesium oxide is used in organic crop production as a viscosity control additive to clay–humate mixtures (USDA 2013). Humates are mixtures of organic material that have been partially decomposed, primarily through oxidative processes. The oxidation of the organic components results in carboxylic acids and phenols making up most functional groups (Baird and Cann 2008, Sabah and Ouki 2017). These functional groups result in the formation of negatively charged carboxylate and phenolate anions that are stable across acidic, neutral, and basic pH (del Mar Ramos-Tejada et al. 2003, Feng et al. 2005, Nguyen et al. 2009).

Humates often adsorb to the surfaces of clay particles in aqueous environments due to ligand exchange interactions, metal bridging, and van der Waals interactions (Tombacz 2003, Petzold et al. 2004, Feng et al. 2005, Baird and Cann 2008, Zhang et al. 2012, Sabah and Ouki 2017). Clay–humate interactions are dependent on clay composition and surface structure and the pH and ionic strength of the aqueous environment. Humate adsorption onto clay surfaces increases with decreased pH and increased ionic strength (Bolto et al. 2001, del Mar Ramos-Tejada et al. 2003, Tombacz 2003, Feng et al. 2005, Zhang et al. 2012, Sabah and Ouki 2017).

Magnesium oxide has the potential to affect the surface of clay particles and the pH of the aqueous solution. Magnesium oxide is incorporated into the pores of clay particles, displacing other substances in a process referred to as exfoliation (Pereira et al. 2015). When the exfoliation process replaces trivalent ions (e.g., Al^{3+}, Fe^{3+}) with magnesium ions (Mg^{2+}), the clay particle exhibits a greater negative surface charge (Tombacz 2003, Zhang et al. 2012). Increased negative surface charges on clay particles exfoliated with magnesium oxide, and the negative surface charges of humates, increases electrostatic repulsions in solution and prevents aggregation of clay and humate particles (Reid and Karr 2002, Tombacz 2003, USDA 2013).

Magnesium oxide can also affect the pH of the aqueous solution, which decreases humate adsorption (Bolto et al. 2001, del Mar Ramos-Tejada et al. 2003, Tombacz 2003, Feng et al. 2005, Zhang et al. 2012, Sabah and Ouki 2017). As described in the "Properties of the Substance" section, magnesium oxide reacts with water to form the base magnesium hydroxide (Equation 2). Furthermore, the solubility of magnesium hydroxide improves in acidic solutions, increasing solution pH more dramatically in acidic solutions (Silberberg 2003). As described above, the surface charge of humates is dependent on pH, with a greater negative surface charge possible under basic conditions, whose high pH promotes the formation of carboxylate and phenolate ions (del Mar Ramos-Tejada et al. 2003). Therefore, adsorption of humates to clay surfaces is decreased at high pHs due to the increased electrostatic repulsions between the negatively charged clay and humate surfaces (Feng et al. 2005, Nguyen et al. 2009).

Magnesium oxide has also been reported to facilitate aggregation between individual humate particles and humates and clay particles (Bolto et al. 2001, Feng et al. 2005, Nguyen et al. 2009, Zhang et al. 2012, Zhang et al. 2020). Magnesium oxide is insoluble in water and remains solid in aqueous mixtures. Magnesium oxide surfaces promote the adsorption of humates through ligand exchange, which refers to interactions between carboxylate groups on the humate surface with the hydroxides present due to magnesium oxide-water interactions (Equation 2) (Zhang et al. 2020). Hydroxide–carboxylate interactions between magnesium oxide and humate surfaces are further enhanced by van der Waals interactions between the two substances (Zhang et al. 2020).

The incorporation of magnesium ions to the surface of clays may result in enhanced interactions between clay and humate particles. Improved adsorption following magnesium oxide exfoliation has been connected to improved ligand exchange interactions with the hydroxides that form at the interface of magnesium ion and the aqueous solution (Bolto et al. 2001, Feng et al. 2005, Zhang et al. 2012). Metal bridging between cations and carboxylate groups may also facilitate increased adsorption. Metal bridging occurs by chelate interactions (multiple points of interaction) between metals and carboxylate ions (Bolto et al. 2001, Feng et al. 2005).

Combinations of the Substance:

As described above in the "Specific Uses of the Substance" and "Action of the Substance" sections, magnesium oxide is used in combination with clays and humates in organic crop production. Clays and humates are classified as non-synthetic substances, which are allowed in organic production (NOP 5034-1).

Status

Historic Use:

Magnesium oxide does not have a historical use within organic crop production, and it was recently added to the National List in 2018 (AMS-NOP-14-0079). For conventional agriculture, magnesium oxide is used as a source of magnesium micronutrients in foliar fertilizers and as a soil amendment micronutrient and pH adjuster (Reid and Karr 2002, CE 2006, Pereira et al. 2015).

Organic Foods Production Act, USDA Final Rule:

Magnesium oxide is not listed in the Organic Foods Production Act of 1990 (OFPA).

The USDA NOP has approved magnesium oxide as a "synthetic substance allowed for use in organic crop production" with the stipulation that it is "for use only to control the viscosity of a clay suspension agent for humates" in 7 CFR 205.601.

International:

Describe the status of the substance among international organizations. Specifically, the report should address whether the petitioned substance is allowed or prohibited for use in other international organic standards such as:

The Canadian General Standards Board Permitted Substances List (updated November 2015)

The CAN/CGSB-32.311-2015 lists magnesium oxide as a "mineral" for use in "feed, feed additives and feed supplements" and in "health care products and production aids."

CODEX Alimentarius Commission, Guidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods (GL 32-1999)

Magnesium oxide is not listed in the CODEX GL 32-1999.

European Economic Community (EEC) Council Regulation, EC No. 834/2007 and 889/2008

Magnesium oxide is listed in ED No. 889/2008 as a "feed material of mineral origin." Magnesium oxide is not listed in EC. No 834/2007.

Japan Agricultural Standard (JAS) for Organic Production

Magnesium oxide is not listed in the JAS for organic production.

International Federation of Organic Agriculture Movements (IFOAM)

Magnesium oxide is not included in the IFOAM Norms for organic production and processing.

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

Evaluation Question #1: Indicate which category in OFPA that the substance falls under: (A) Does the substance contain an active ingredient in any of the following categories: copper and sulfur compounds, toxins derived from bacteria; pheromones, soaps, horticultural oils, fish emulsions, treated seed,

vitamins and minerals; livestock parasiticides and medicines and production aids including netting, tree wraps and seals, insect traps, sticky barriers, row covers, and equipment cleansers? (B) Is the substance a synthetic inert ingredient that is not classified by the EPA as inerts of toxicological concern (i.e., EPA List 4 inerts) (7 U.S.C. § 6517(c)(1)(B)(ii))? Is the synthetic substance an inert ingredient which is not on EPA List 4, but is exempt from a requirement of a tolerance, per 40 CFR part 180?

A) Magnesium oxide does not contain any of the listed categories as an active ingredient. However, magnesium oxide is an ionic compound that is found naturally in mineral form as periclase and may be produced from other mineral magnesium sources, as described in the "Source or Origin of the Substance" section (Baird and Cann 2008). Most commercially available magnesium oxide is derived by treatment of saltwater brines, but it may still be considered mineral in form.

B) Magnesium oxide is included in the EPA List 4 of inerts. Additionally, the EPA has listed magnesium oxide as an "inert ingredient used pre- and post-harvest" that are "exempt from the requirement of a tolerance" in 40 CFR 180.910. The EPA has granted magnesium oxide a "tolerance exemption for active and inert ingredients for use in antimicrobial formulations" in § 180.940, and classified magnesium oxide as an "active ingredient permitted in exempted minimum risk pesticide products" in § 152.25.

Evaluation Question #2: **Describe the most prevalent processes used to manufacture or formulate the petitioned substance. Further, describe any chemical change that may occur during manufacture or formulation of the petitioned substance when this substance is extracted from naturally occurring plant, animal, or mineral sources (7 U.S.C. § 6502 (21)).**

As described in the "Source or Origin of the Substance" section, magnesium oxide is commercially produced from both mineral and brine (seawater and salt lake) sources. There are multiple mineral sources for magnesium oxide production, although magnesite (magnesium carbonate [$MgCO_3$]) is the most used mineral (de Sousa 2018, Nobre et al. 2020). While magnesium oxide may also be produced from brines, mineral sources are used for most commercial production since they offer a less energy-intensive means of production (de Sousa 2018).

Calcination of magnesium salt is the most common method for producing magnesium oxide. Calcination is the process of "heat[ing] a solid to a high temperature to dive off volatile substances" or "heat[ing] a metal to a high temperature to form the oxide of the metal" (Goldman 1982). The common magnesium compounds and production methods of magnesium oxide from mineral and brine sources are discussed below.

Calcination of magnesium carbonates (magnesite)

The calcination of magnesite is the most common method of producing magnesium oxide (Atkins et al. 2008, Baird and Cann 2008, de Sousa 2018, Nobre et al. 2020). The calcination of magnesite produces solid magnesium oxide while liberating carbon dioxide gas, as described below in Equation 3. To remove carbon dioxide from the carbonate ion, magnesite is heated to between 600 °C and 700 °C (Panda and Mahapatra 1983, Nobre et al. 2020).

$$MgCO_{3\,(s)} \rightarrow MgO_{\,(s)} + CO_{2\,(g)}$$

Equation 3

While 600 °C represents the lower limit for the calcination process, different calcination conditions (temperature, residence times) may be used to alter the physical properties of the magnesium oxide product. The specific calcination processes allow the manufacturer to control the structural characteristics, specifically the surface area and porosity of the magnesium oxide product (de Sousa 2018, Nobre et al. 2020). These characteristics are influenced by the temperature and residence times of the calcination process, which determine the nature of the expulsion of carbon dioxide gas from the solid (de Sousa 2018).

High temperatures and long residence times promote particle growth and the formation of regular crystal lattices, which reduce porosity and surface area in the magnesium oxide product (de Sousa 2018, Nobre et al. 2020).

Magnesium oxide calcination products are classified by their reactivity, which is a kinetic measure of their neutralization of an acid source (de Sousa 2018, Nobre et al. 2020). The acid source used for these determinations is variable, although citric acid and acetic acid are commonly used (Nobre et al. 2020). The rate of acid neutralization is reportedly connected to hydration of magnesium oxide to form the base magnesium hydroxide ($Mg[OH]_2$, described in Equation 2), which neutralizes the acid. The rate of magnesium oxide hydration is based on the surface area and crystal structure of the solid, with solids with higher surface areas and greater porosity having faster rates of hydration, therefore, faster rates of acid neutralization (Atkins et al. 2008, de Sousa 2018, Nobre et al. 2020).

Specific calcination conditions and the reactivity of magnesium oxide solids are defined by their temperature ranges and are displayed below in Table 2. High temperature calcination conditions, also known as “dead-burned” in the literature, are the most common commercial conditions used in the production of magnesium oxide from mineral sources (de Sousa 2018).

Table 2. Calcination conditions for magnesium carbonate minerals

Method	Temperature range (°C)	Relative surface area	Reactivity
Caustic-calcined or light-burned	700 – 1000	Highest	Reactive
Hard-burned	1000 – 1500	High	Less reactive
Periclase or dead-burned	1400 – 2000	Low	Low reactivity
Fused	2800+	Lowest	Inert, unreactive

Sources: de Sousa 2018, Nobre et al. 2020.

Calcination of magnesium hydroxide

Magnesium hydroxide from mineral sources

Magnesium hydroxide is found in mineral form as brucite but may also be isolated from chemical treatment of other magnesium-containing minerals (i.e., magnesium silicates) (de Sousa 2018, Nobre et al. 2020). Magnesium silicates can be digested with hydrochloric acid (HCl) to produce water soluble magnesium chloride ($MgCl_2$), according to Equation 4 shown below. (Baird and Cann 2008, Nobre et al. 2020). Magnesium chloride can be isolated from the silicon dioxide solid via filtration.

$$Mg_3Si_2O_5(OH)_{4\,(s)} + 6\ HCl_{\,(aq)} \rightarrow 3\ MgCl_{2\,(aq)} + 2\ SiO_{2\,(s)} + 5\ H_2O_{\,(l)}$$

Equation 4

Magnesium chloride can be converted to magnesium hydroxide, which can be precipitated as a solid due to its low water solubility (Atkins et al. 2008, de Sousa 2018, Nobre et al. 2020). The conversion of magnesium chloride to magnesium hydroxide occurs through a metathesis reaction where the chloride ions (Cl^-) are exchanged for hydroxide ions (OH^-) (Atkins et al. 2008). The most common hydroxide sources for the magnesium metathesis are from sodium hydroxide (NaOH) or the *in situ* formation of hydroxide from lime (calcium oxide [CaO]) or dolomitic lime (calcium magnesium oxide [$CaMgO_2$]), as described in Equations 5, 6, and 7, respectively (Nobre et al. 2020). Dolomitic lime is the most common input due to its reduced cost compared to sodium hydroxide and increased efficiency compared to lime. However, sodium hydroxide is used to prepare magnesium oxide products with reduced levels of calcium impurities (Nobre et al. 2020).

$$MgCl_{2\,(aq)} + 2\ NaOH_{\,(aq)} \rightarrow Mg(OH)_{2\,(s)} + 2\ NaCl_{\,(aq)}$$

Equation 5

$$MgCl_{2\,(aq)} + CaO_{(s)} + H_2O_{(l)} \rightarrow Mg(OH)_{2\,(s)} + CaCl_{2\,(aq)}$$

Equation 6

$$MgCl_{2\,(aq)} + CaMgO_{2\,(s)} + 2\,H_2O_{(l)} \rightarrow 2\,Mg(OH)_{2\,(s)} + CaCl_{2\,(aq)}$$

Equation 7

Once magnesium hydroxide has been isolated as a solid, it is calcined to produce magnesium oxide by liberating water vapor, as shown below in Equation 8. The calcination of magnesium hydroxide occurs at lower temperatures than that of magnesium carbonate (350 °C), although temperatures of 1000 °C or higher may be required to liberate water molecules that have been incorporated into the ionic crystal structure (Nobre et al. 2020).

$$Mg(OH_2)_{(s)} \rightarrow MgO_{(s)} + H_2O_{(g)}$$

Equation 8

Magnesium hydroxide from brine

Magnesium is a major component of seawater, ranking as the third most abundant element (Nobre et al. 2020). Most magnesium present in brine exists as the soluble ionic compound magnesium chloride. When brines are used to produce magnesium oxide, the first step is to concentrate the brine, usually via solar evaporation (Panda and Mahapatra 1983). Once concentrated, the brine may be converted to magnesium oxide through two differing methods, described in more detail below.

Direct conversion to magnesium hydroxide

Once concentrated, the brine may undergo direct conversion to form magnesium hydroxide with the addition of sodium hydroxide, lime, or dolomitic lime, as described in Equations 5, 6, and 7, respectively. As with mineral sources, dolomitic lime is the most common additive to facilitate the magnesium metathesis (Panda and Mahapatra 1983). As with the mineral form, the isolated magnesium hydroxide is calcined to produce magnesium oxide, as described in Equation 8 (Panda and Mahapatra 1983, de Sousa 2018).

Purification to remove calcium and other metals

Rather than undergoing direct conversion of brine to magnesium hydroxide, additional purification steps may be added. These steps help to reduce the concentrations of calcium and other multivalent metal ions in the magnesium oxide product and to make the production process more efficient (Atkins et al. 2008, Nobre et al. 2020). The purification process occurs with the initial acidification of the brine solution to pH 4, which removes carbonates found primarily as calcium bicarbonate ($CaHCO_3$). The acidification process reduces the calcium concentration in the brine by the precipitation of water insoluble calcium sulfate, as shown below in Equation 9.

$$Ca(HCO_3)_{2\,(aq)} + H_2SO_{4\,(aq)} \rightarrow CaSO_{4\,(s)} + 2\,CO_{2\,(g)} + 2\,H_2O_{(l)}$$

Equation 9

Once the brine has been filtered to remove the calcium sulfate solids, the pH is raised and magnesium hydroxide is formed with the addition of sodium hydroxide, lime, or dolomitic lime, as described above in Equations 5, 6, and 7, respectively. As with the direct conversion of brine and the mineral production of magnesium hydroxide, dolomitic lime is more often used than lime due to its higher efficiency. Sodium hydroxide is used in the magnesium metathesis to produce magnesium hydroxide with higher purity and lower calcium content (Nobre et al. 2020). Once the purified magnesium salts have been converted to magnesium hydroxide, the substance is calcined to form purified magnesium oxide, as described above in Equation 8 (Nobre et al. 2020).

Evaluation Question #3: Discuss whether the petitioned substance is formulated or manufactured by a chemical process, or created by naturally occurring biological processes (7 U.S.C. § 6502 (21)).

Magnesium oxide is a naturally occurring compound that is found in the mineral periclase. However, as discussed above in the "Source of Origin of the Substance" section and Evaluation Question 2, the majority of commercially available magnesium oxide is formed through the calcination of magnesium carbonate–containing minerals (e.g., magnesite, hydro-magnesite), as shown in Equation 3. Magnesium can also be sourced from other mineral sources in the form of magnesium chlorides and silicates, which can be converted to magnesium hydroxide via acid-base and metathesis reactions described in Evaluation Question 2 and Equations 4–7. Magnesium hydroxide sourced as brucite or by the chemical processing of other magnesium-containing minerals is calcined to form magnesium oxide, as shown in Equation 8.

Magnesium oxide is also produced from seawater and salt lake brine sources, as described above in the "Source of Origin of the Substance" section and Evaluation Question 2. While magnesium is a common elemental component of brine, magnesium oxide is not present in brine sources due to its water insolubility. Magnesium chloride is the primary source of magnesium within brine and is converted to magnesium hydroxide using the same reactions used to process mineral sources of magnesium chloride described by Equations 5, 6, and 7. Additionally, brine may be treated with sulfuric acid to remove carbonates, reducing the amount of calcium in the final product, as described in Equation 9. Magnesium oxide from brine is also obtained by calcination of magnesium hydroxide, as described in Evaluation Question 2 and Equation 8.

NOP guidelines classify substances produced by the "heating or burning of non-biological matter (e.g., minerals) to cause a chemical reaction" as synthetic (NOP 5033). Based on this classification, all commercial sources of magnesium oxide are considered synthetic, formed by calcination (heating) to liberate carbon dioxide (Equation 3) or water (Equation 8).

Evaluation Question #4: Describe the persistence or concentration of the petitioned substance and/or its by-products in the environment (7 U.S.C. § 6518 (m) (2)).

At the time of publication, the author of this report found no studies on the environmental persistence of magnesium oxide. Magnesium oxide is likely to have a long persistence due to its water insolubility. The water insoluble nature of the substance makes it unlikely to enter water systems, and it is likely to have low bioavailability in terrestrial systems (USDA 2007).

The production of magnesium oxide from both brine and mineral sources results in the formation of magnesium and calcium salts, as described in Evaluation Question 2. These salt substances are prevalent in nature in seawater and in mineral forms, and therefore, the contributions from magnesium oxide production are difficult to quantify (Atkins et al. 2008, Baird et al. 2008, USGS 2017).

Evaluation Question #5: Describe the toxicity and mode of action of the substance and of its breakdown products and any contaminants. Describe the persistence and areas of concentration in the environment of the substance and its breakdown products (7 U.S.C. § 6518 (m) (2)).

At the time of publication, the author of this report found no studies on the environmental persistence or toxicity of magnesium oxide. Magnesium oxide, its production byproducts, and its breakdown products are ionic compounds that are commonly found in seawater and minerals (USDA 2007, Atkins et al. 2008, Baird and Cann 2008, USGS 2017). As described in the "Properties of the Substance" section and Evaluation Question 4, magnesium oxide is insoluble in water, making it unlikely to contaminate water systems and giving it low bioavailability in terrestrial systems (USDA 2007).

As described in the "Properties of the Substance" section, magnesium oxide reacts with water in a reversible manner to produce magnesium hydroxide. Magnesium hydroxide also has low water solubility, making it unlikely to contaminate water systems or be readily bioavailable in terrestrial systems (Silberberg 2003, USDA 2007).

Evaluation Question #6: Describe any environmental contamination that could result from the petitioned substance's manufacture, use, misuse, or disposal (7 U.S.C. § 6518 (m) (3)).

As described in Evaluation Questions 4 and 5, magnesium oxide and its breakdown and byproducts are prevalent in minerals, seawater and salt lakes and unlikely to contribute to environmental contamination. When used as approved within organic agriculture, magnesium oxide is applied in limited quantities as a viscosity control additive, making it unlikely to contribute to environmental contamination (NOSB 2013).

Given the ubiquitous nature of magnesium salts in terrestrial and aquatic systems, the most likely cause of environmental contamination is linked to mining minerals and the production of magnesium oxide. Mining operations may result in contamination through the release of naturally occurring contaminants released from mineral sources and accidental spills. Mining operations may also result in changes to ground water, which may be rerouted, affecting the water table (USGS 2001).

As described above in Evaluation Question 2, the most common method of magnesium oxide production is the calcination of magnesium carbonate. As shown in Equation 3, the calcination of magnesium carbonate directly contributes to carbon dioxide formation, which is a known greenhouse gas (Baird and Cann 2008, Nobre et al. 2020). The calcination process is energy intensive, and the energy consumption to facilitate this process may also contribute to additional carbon dioxide emissions if the power comes from the combustion of fossil fuels (Nobre et al. 2020). While magnesium oxide production from brine does not directly contribute to carbon dioxide emissions, it requires larger amounts of energy than mineral production methods and may contribute to carbon dioxide concentrations through energy consumption (de Sousa 2018, Nobre et al. 2020).

Evaluation Question #7: Describe any known chemical interactions between the petitioned substance and other substances used in organic crop or livestock production or handling. Describe any environmental or human health effects from these chemical interactions (7 U.S.C. § 6518 (m) (1)).

As described in the "Properties of the Substance" section, magnesium oxide is insoluble in water but will react with water to form magnesium hydroxide (Equation 2). Magnesium hydroxide also has low water solubility, although its basic nature gives it higher solubility in acidic environments (Silberberg 2003). The basic nature of magnesium hydroxide will result in the neutralization of acidic compounds present in terrestrial or water systems within the agro-ecosystem. Reactions between magnesium hydroxide and acidic soils may result in increased soil pH.

Evaluation Question #8: Describe any effects of the petitioned substance on biological or chemical interactions in the agro-ecosystem, including physiological effects on soil organisms (including the salt index and solubility of the soil), crops, and livestock (7 U.S.C. § 6518 (m) (5)).

At the time of publication, the author of this report found no studies on the environmental persistence or toxicity of magnesium oxide, or its effects on soil organisms.

As described in the "Properties of the Substance" section and Evaluation Question 7, magnesium oxide reacts with water to form the basic substance magnesium hydroxide. The basic nature of magnesium hydroxide results in increased solubility in acidic environments, driven by the neutralization of acidic compounds. The introduction of magnesium oxide may result in increased soil pH.

As described in the "Action of the Substance" section, magnesium oxide may interact with both clays and humates. Magnesium oxide may alter the surface of clays through exfoliation processes, which may result in changes to the surface chemistry and surface charge of clay particles in terrestrial and aquatic systems

(Nguyen et al. 2009, Pereira et al. 2015). Magnesium oxide can adsorb humates through ligand exchange and van der Waals interactions (Zhang et al. 2020).

Additionally, magnesium oxide can influence interactions between clay particles and humates in terrestrial and water systems, as discussed in the "Action of the Substance" section. The effect of magnesium oxide is dependent on the clay component, as well as the environmental conditions in terms of pH and ionic strength (Bolto et al. 2001, del Mar Ramos-Tejada et al. 2003, Tombacz 2003, Feng et al. 2005, Nguyen et al. 2009, Zhang et al. 2012, Sabah and Ouki 2017). The presence of magnesium oxide may increase clay–humate aggregation by facilitating ligand exchange and metal bridging interactions (Bolto et al. 2001, Feng et al. 2005, Zhang et al. 2012). Magnesium oxide may also decrease aggregation by increasing electrostatic repulsions between negatively charged clay and humate surfaces through clay exfoliation increasing the pH (Bolto et al. 2001, del Mar Ramos-Tejada et al. 2003, Tombacz 2003, Feng et al. 2005, Nguyen et al. 2009, Zhang et al. 2012, Sabah and Ouki 2017).

Evaluation Question #9: Discuss and summarize findings on whether the use of the petitioned substance may be harmful to the environment (7 U.S.C. § 6517 (c) (1) (A) (i) and 7 U.S.C. § 6517 (c) (2) (A) (i)).

At the time of publication, the author of this report found no studies on the environmental persistence or toxicity of magnesium oxide. As described in Evaluation Questions 4–8, the insoluble nature of magnesium oxide makes it unlikely to contaminate water systems, and its insolubility results in low bioavailability within terrestrial environments. Moreover, when used as approved within organic agriculture, magnesium oxide is applied in limited quantities as a viscosity control additive, making environmental contamination unlikely (NOSB 2013).

Evaluation Question #10: Describe and summarize any reported effects upon human health from use of the petitioned substance (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)).

Magnesium oxide has been classified as GRAS by the FDA and is a common ingredient for medicinal applications as a laxative, antacid, and magnesium supplement (Flommnebaum et al. 2002, USDA 2007). The Food and Agriculture Organization of the United Nations (FAO) has classified magnesium oxide as a substance with "no toxicological grounds to limit use in accordance with good manufacturing practices" (FAO 1967). The International Programme on Chemical Public Safety (IPCS) has not provided a hazard classification for magnesium oxide (IPCS 2010).

Magnesium oxide has been reported to be a respiratory irritant if airborne particles (i.e., magnesium oxide fume) are inhaled (NIOSH 1994, NJ DOH 2003, IPCS 2010). Inhalation of magnesium oxide fume may result in mechanical irritation and flu-like symptoms, including headache, fever and chills, aches, and cough (NJ DOH 2003, IPCS 2010). Health effects of magnesium oxide are not known to be chronic in nature, rather, they have been reported to be short term, lasting hours to days (NIOSH 1994, NJ DOH 2003, IPCS 2010). To prevent respiratory irritation, respirators should be worn when exposed to magnesium oxide fume (NIOSH 1994, NJ DOH 2003, IPCS 2010).

Evaluation Question #11: Describe all natural (non-synthetic) substances or products which may be used in place of a petitioned substance (7 U.S.C. § 6517 (c) (1) (A) (ii)). Provide a list of allowed substances that may be used in place of the petitioned substance (7 U.S.C. § 6518 (m) (6)).

As described in the "Source or Origin of the Substance" section, magnesium oxide is a naturally occurring substance that can be found in mineral form. Non-synthetic mineral forms of magnesium oxide offer a potential alternative to synthetic versions in the form of the mineral periclase. However, the mineral forms of magnesium oxide are likely to have greater concentration of other ions, which may make them less effective in the approved application of viscosity control of clay–humate mixtures.

Calcium oxide in the form of oystershell lime has been classified by the NOP as non-synthetic if it does not undergo calcination (NOP 5034-1). Calcium oxide, like magnesium oxide, forms rock salt crystals and reacts with water to form hydroxides (Atkins et al. 2008). Calcium oxide and hydroxide are basic, with calcium hydroxide classified as a strong base, which would result in increased pH (Silberberg 2003). However, calcium oxide and calcium hydroxide are more water soluble than the analogous magnesium compounds, which would result in increased ionic strength of the aqueous mixtures compared to magnesium oxide (Silberberg 2003, Atkins et al. 2008). Increased ionic strength of the solution promotes aggregation of clay and humate particles, as the increased charge in solution stabilizes the negative surface charges and reduces electrostatic repulsions (Tombacz 2003, Feng et al. 2005, Nguyen et al. 2009, Zhang et al. 2012, Sabah and Ouki 2017). Moreover, oystershell lime is likely to include other mineral salts, which may result in reduced efficacy compared to synthetic calcium oxide that has undergone purification processes.

As described in the "Action of the Substance" section, aggregation of clay and humate particles can be influenced by the pH and ionic strength of the mixture. Humate adsorption onto clay surfaces decreases with increased pH and decreased ionic strength (Bolto et al. 2001, del Mar Ramos-Tejada et al. 2003, Tombacz 2003, Feng et al. 2005, Zhang et al. 2012, Sabah and Ouki 2017). The addition of basic substances increases the pH of the clay–humate mixture, maximizing negative surface charges to prevent aggregation. Calcium carbonate (limestone) offers a potential alternative to magnesium hydroxide as a basic compound with limited solubility to avoid dramatic increases in ionic strength (Silberberg 2003, Hoy 2005, Atkins et al. 2008, USDA 2018). Calcium hydroxide (listed as hydrated lime) is a synthetic substance that is approved for use in organic crop production in 7 CFR 205.601. However, as discussed above in the context of oystershell lime, calcium hydroxide is a strong base that is soluble and would also result in increased ionic strength, which may reduce efficacy of viscosity control for clay–humate mixtures.

Evaluation Question #12: Describe any alternative practices that would make the use of the petitioned substance unnecessary (7 U.S.C. § 6518 (m) (6)).

Magnesium oxide is used as an additive to control mixture viscosity by preventing the aggregation of clay and humate particles. However, literature reports also state that the stabilization of colloidal clay suspensions can be facilitated by the adsorption of humates to the surface of clay particles (del Mar Ramos-Tejada et al. 2003, Tombacz 2003, Petzold et al. 2004, Baird and Cann 2008, Nguyen et al. 2009, Zhang et al. 2012, Pereria et al. 2015, Sabah and Ouki 2017). When humates adsorb onto the surface of clays, their negative surface charge prevents aggregation with other clay particles. In addition to electrostatic repulsions, humates provide steric repulsions due to their size, which further prevents aggregation (del Mar Ramos-Tejada et al. 2003, Tombacz 2003, Baird and Cann 2008, Sabah and Ouki 2017). Given the ability of clay–humate aggregates to stabilize colloidal mixtures, the correct ratio of clay to humate particles may alleviate the necessity for magnesium oxide or other additives to control the viscosity of the mixtures.

Report Authorship

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