United States Department of Agriculture
Agricultural Marketing Service | National Organic Program
Document Cover Sheet
https://www.ams.usda.gov/rules-regulations/organic/petitioned-substances

Document Type:

☐ **National List Petition or Petition Update**

A petition is a request to amend the USDA National Organic Program's National List of Allowed and Prohibited Substances (National List).

Any person may submit a petition to have a substance evaluated by the National Organic Standards Board (7 CFR 205.607(a)).

Guidelines for submitting a petition are available in the NOP Handbook as NOP 3011, National List Petition Guidelines.

Petitions are posted for the public on the NOP website for Petitioned Substances.

☒ **Technical Report**

A technical report is developed in response to a petition to amend the National List. Reports are also developed to assist in the review of substances that are already on the National List.

Technical reports are completed by third-party contractors and are available to the public on the NOP website for Petitioned Substances.

Contractor names and dates completed are available in the report.

# Ethylene

## Handling/Processing

### Identification of Petitioned Substance

**Chemical Names:**
acetene; $C_2H_4$; elayl; ethene

**Other Name:**
bicarburreted hydrogen; olefiant gas

**Trade Names:**
Biofresh Safestore;
Devices: Restrain, Catalytic Generators, Easy-Ripe

**CAS Numbers:**
74-85-1

**Other Codes:**
UN II: 91GW059KN7
EPA: PC code 41901
EC number: 200-815-3

### Summary of Petitioned Use

This limited scope technical report provides new information to the National Organic Standards Board (NOSB) to support the review of ethylene, petitioned for additional uses in 2023 (O'Shaughnessy, 2023). This report focuses on uses of ethylene in organic processing and handling, as a growth regulator for potatoes and onions during storage.

The National Organic Program (NOP) included ethylene on the National List of Allowed and Prohibited Substances (the National List) at 7 CFR 205.601(k) with the first publication of the NOP Final Rule (65 FR 80548, December 21, 2000), as a plant growth regulator for regulation of pineapple flowering. It was also listed for post-harvest handling to ripen tropical fruit at 7 CFR 205.605(b). Effective November 2003, the NOP changed the annotation for the post-harvest allowance to also allow for de-greening of citrus (68 FR 61987, October 31, 2003).

This limited scope technical report addresses the use of ethylene for regulating growth of stored potatoes and onions, during handling. The present petition specifically describes ethylene generated on-site by catalytic conversion of ethyl alcohol (O'Shaughnessy, 2023). However, most synthetic ethylene gas is made as a pyrolysis product of petroleum hydrocarbon feedstocks, such as natural gas liquids or crude oil (NOP, 2023b). Selected portions of the *Characterization of Petitioned Substance* section are included to address aspects unique to the petitioned use.

### Characterization of Petitioned Substance

**Source or Origin of the Substance:**
The 2023 technical report (Handling scope) describes global ethylene manufacturing (NOP, 2023b), including the process detailed in the present petition. The petitioner describes the use of an on-site catalytic generator to dehydrate ethanol, creating ethylene gas (O'Shaughnessy, 2023).

In the catalytic dehydration of ethanol to form ethylene, an acid catalyst first protonates the hydroxyl group, which leaves as a water molecule. The conjugate base of the catalyst then deprotonates the methyl group, and the hydrocarbon rearranges into ethylene. The reaction is endothermic, with an optimal reaction temperature ranging from 180 to 500°C. (Fan et al., 2012).

Producers also may use ethylene gas from cylinders (NFU Mutual, n.d.), generally produced from hydrocarbon stocks as described in *Summary of Petitioned Use*. Synthetic ethylene gas from these sources is chemically identical to the natural form produced by plants (NOP, 2023b).

**Specific Uses of the Substance:**

The petitioner is asking the NOP to expand the use of ethylene as a growth regulator for stored potatoes and onions (O'Shaughnessy, 2023). The petitioner notes that using ethylene to inhibit potato and onion sprouting during storage was not widespread before the last National List amendment regarding this material in 2003 (O'Shaughnessy, 2023). The British Potato Council reports that the first commercial use of ethylene for this purpose in the UK occurred in 2001. According to Briddon (2006), ethylene wasn't used for this purpose in Canada as of 2006.

*Application*

Similar to the process for fruit treatment described in the 2023 Ethylene technical report (Handling scope) (NOP, 2023b), potato producers and handlers introduce ethylene gas into a storage room that is closed, but not airtight (Dako et al., 2021). Higher concentrations would require tighter control and could drive up construction or security costs for operators (Dako et al., 2021). The gas may come from pressurized bottles (steel cylinders), or be generated with a device using a solid bed catalyst to dehydrate ethanol (NOP, 2023b). The gas is metered automatically and kept at a constant level throughout the storage period (see *Table 1*, below).

The required concentration varies with the storage temperature (Briddon, 2006) and humidity, but is generally 2-15 ppm (Dako et al., 2021). In comparison, for the use currently allowed at 7 CFR 205.605(b)(14), fruit ripening occurs at 4 to 1,200 ppm for 12 to 48 hours. De-greening of lemons occurs at 5 ppm for 5-8 days, or 0.5 ppm for 6-10 days (Kays & Beaudry, 1987).

*Sprouting inhibition in stored potatoes and onions (petitioned use)*

Potatoes and onions are seasonal crops (ARS, 2023; Ohanenye et al., 2019; Pinhero et al., 2009). To meet year-round demand, producers must either import or store harvested tubers and bulbs in carefully controlled conditions that prolong dormancy and discourage sprouting. Most regions produce only one crop per year, and maintaining a reliable supply may require months of storage (Alamar et al., 2017; Daniels-Lake & Prange, 2007).[1]

*Seed potatoes (petitioned use)*

In contrast to stored potatoes and onions bound for the fresh and processing markets, seed potato storage does not require permanent or complete inhibition of sprouting. Rather, seed potatoes will produce the next crop, and producers must be able to reliably predict or control their sprouting. Excessive sprouting prior to planting can reduce the yield, so seed tubers require carefully controlled conditions from harvest until replanting (Daniels-Lake & Prange, 2007). Therefore, any sprout inhibitor used on seed potatoes must be reversible, to eventually allow the seed to sprout and develop the new crop. Ethylene's sprout inhibition effect is reversible.

*Losses due to sprouting*

Sprouting leads to a loss of moisture, weight, and quality in both potatoes and onions. The onset of sprouting signals rapid increases in respiration and evaporation, which continue as the sprout grows. A sprout that increases tuber surface area by 1% leads to a doubling of moisture loss and corresponding weight (and value) loss from the tuber (Paul et al., 2016). Tlili et al. (2024) observed a 35.5% loss of fresh weight after 90 days in storage (at 8°C). Onions are subject to root growth as well as sprouting (Gouda et al., 2023). And bulbs in later stages of sprouting, with visible leaf growth, are unsellable by industry standards (Kleman et al., 2024).

The United States produces roughly 22.5 million tons of potatoes annually, harvesting about 90% of crops in the fall (ARS, 2023). Sprouting and damage during storage commonly cause losses of 10-15% of the harvested potatoes (ARS, 2023). The United Kingdom recorded overall losses of 17% (770,000 tons) of

[1] Ethylene use in conventional potato production is growing, partly due to the decline of chlorpropham isopropyl N-(3-chlorophenyl) carbamate (often just called chlorpropham or CIPC), a pesticide that has been subject to tighter EPA regulation, since 1996, for suspected carcinogenic residue (Alamar et al., 2017; Gumbo et al., 2021). It was prohibited for use in Europe in 2020 but remains widely used in the US. In 2016, ethylene use was still relatively rare in this country, accounting for 15% of conventional potato sprout-inhibition treatment in storage. Chlorpropham covered 82%, and spearmint essential oil the remaining 3% (Thoma & Zheljazkov, 2022).

harvested potatoes in 2012, where premature sprouting and rotting during storage were the main causes (Alamar et al., 2017). Sprouting and decay can be issues for onions too. Storage losses for onions exceed 13%, depending on cultivar and handling practices (Kleman et al., 2024).

Visual appearance is the main factor driving the purchase of fresh potatoes (Alamar et al., 2017), and consumers have expressed dislike for sprouted, soft potatoes and onions (Frazier et al., 2004; Gouda et al., 2023; Grudzińska et al., 2016; Jia et al., 2019). The sprouts and softer texture can make potatoes difficult to process with some types of equipment (Daniels-Lake & Prange, 2007).

Another negative effect of the sprouting process in potatoes is the breakdown of starch and accumulation of reducing sugars.[2] During cooking of chips or fries, these excess sugars react with free amino acids to produce a dark brown or black color (Pinhero et al., 2009). Producers of french fries, chips, and potato flakes prefer low reducing sugar concentrations to yield the preferred lighter color in finished products (Daniels-Lake & Prange, 2007). These sugars also react with free asparagine during cooking and contribute to the formation of the compound acrylamide (Alamar et al., 2017), which is under study for its carcinogenic and genotoxic effects. It forms especially in chips, fries, onion rings, and other starchy foods (Alamar et al., 2017; Başaran et al., 2023; Daniels-Lake & Prange, 2007; Khan et al., 2018; Pinhero et al., 2009; Tosetti et al., 2021).

Additionally, the skin, sprouts, and green parts of sprouted potato contain higher levels of glycoalkaloids, which are toxic to humans and animals (Beals, 2019; Sancer et al., 2022). This is another reason for consumer rejection and loss of potato value.

**<u>Action of the Substance:</u>**
As detailed in recent technical reports (NOP, 2023b, 2023a), ethylene performs numerous functions as a major hormone produced by plants. In both potatoes and onions, it can either induce or delay sprouting, depending on the concentration, cultivar, stage of growth, environmental conditions, and actions of other hormones and signal molecules (Bufler, 2009; Jahan et al., 2022). For example, a concentration of 5 ppm can de-green lemons in 5-8 days, while storing potatoes at 10-15 ppm can inhibit sprouting for months (see *Table 1*, below).

Ethylene affects many other aspects of plant growth, development, and survival, including (NOP, 2023b):

- seed germination
- shoot growth
- root development
- flowering, sex determination
- fruit ripening
- abscission of leaves and fruits
- senescence of flowers and leaves
- starch metabolism

Ethylene also has a role in plant adaptation to a variety of stresses, such as drought, flooding, pathogen attack and high salinity (Chang, 2016). However, there are many other hormones that also act as crucial messengers. For example, brassinosteroids act as key modulators of tuber sprouting. In addition, jasmonates, strigolactones, and salicylic acid also regulate potato dormancy and sprouting (Di et al., 2024).

As potato tubers and onion bulbs break dormancy in storage, respiration increases, desirable starches degrade, and reducing sugars accumulate (Alamar et al., 2017). This process results in undesirable darkening during high-temperature cooking (Tosetti et al., 2021), and an undesirable sweeter taste (Grudzińska et al., 2016).

In experiments with ethephon, Abeles et al. (1992) observed that ethylene treatment increased yields of marketable tubers (i.e., those with acceptable amounts of starch and reducing sugars).[3] Further, it reduced incidence of the brown center and stem-end hollow heart, physiological disorders related to

[2] Reducing sugars are small carbohydrates of one or two sugar units that can act as reducing agents towards metal salts such as $Ag^+$ or $Cu^{2+}$. In the case of potato, fructose and glucose (Ashenhurst, 2024).
[3] Ethephon is an ethylene releasing compound with the chemical name (2-chloroethyl)phosphonic acid; also known by the trade name "*Ethrel*" (NOP, 2023b).

stress conditions (Zotarelli et al., 2018). Overall, it encouraged better seed potato production due to increasing numbers of smaller tubers (Abeles et al., 1992).

Despite ethylene's role in sprout inhibition, scientific researchers generally agree that it does not fully prolong dormancy (Di et al., 2024; Pinhero et al., 2009). Ethylene treatment still allows for some of the undesirable starch mobilization (sweetening) that produces darker colors during cooking (Di et al., 2024). However, a 2019 industry-led consumer panel in the UK found no significant difference between ethylene-treated potatoes and untreated ones (Clarke, 2019).

There is continued research into ethylene's roles and mechanisms (Di et al., 2024). Daniels-Lake and Prange (2007), noting the potato's adaptability and range, expressed doubt, in their review's conclusion, that a single methodology would ever fill the needs of the entire industry for sprout inhibition. Other research has pointed to using substances in combination. In any case, producers must manage storage conditions carefully even when they employ ethylene.

Ethylene's ability to inhibit sprout growth in onions, in contrast, has attracted commercial interest only recently. One study revealed that ethylene both inhibits sprout elongation and interferes with dormancy (Bufler, 2009). A secondary effect was doubling the carbon dioxide ($CO_2$) produced by the bulbs (Bufler, 2009). Alamar et al. (2020) later showed that ethylene (10 µL/L, at 1°C ) can delay dormancy break by four weeks, and reduce sprout growth.

**Table 1: Effects of ethylene gas at different concentrations in air.**

| Ethylene concentration | Significance | Reference |
|---|---|---|
| <1-5 µg/m³ | Ambient air, rural or remote site | (IARC, 1994) |
| 0.01-1.0 ppm | Lower limit of biological activity | (Chang, 2016) |
| 0.3 ppm | Atmospheric level, banana-ripening facility | (IARC, 1994) |
| 0.7 ppm | Ambient air, Washington, D.C., Beltway (1973) | (Chang, 2016) |
| 5 ppm | De-greening of lemons (5-8 days) | (Kays & Beaudry, 1987) |
| Tens of ppm | Climacteric fruit emissions | (Chang, 2016) |
| 0.6-6 to 120 µg/kg | Plant emissions (fresh weight) during ripening, per hour | (Health Canada, 2016) |
| 7 µL /L | Onion storage in experiment (7 mos.) | (Forney et al., 2022) |
| 10-15 ppm | Potato or onion storage (months) | (O'Shaughnessy, 2023) |
| 1000 ppm | Humans experience dizziness | (Chang, 2016; NCBI, 2024; NOP, 2023b) |
| 5,750 mg/m³ | Long-term NOAEC (no observed adverse effect concentrations) for reproduction and developmental toxicity | (Health Canada, 2016) |
| 11,500 mg/m³ | Short-term LOAEC (lowest adverse effect concentrations) for sub-chronic effects on mammals | (Health Canada, 2016) |
| 27,000-31,000 ppm | Explosive | (Catalytic Generators, 2021; NOP, 2023b; Sherman, 1985) |
| 2.75 vol% or 34.6 g/m³ | Explosive, at 100 kPa and 20°C | (IARC, 1994) |
| 50% | Humans lose consciousness and risk death | (NCBI, 2024) |

## Evaluation Questions for Substances to be used in Organic Handling

The request for this limited scope technical report specified the following evaluation questions:

**<u>Evaluation Question #5</u>: Describe whether the primary technical function or purpose of the petitioned substance is a preservative. If so, provide a detailed description of its mechanism as a preservative [7 CFR 205.600(b)(4)].**
As petitioned, ethylene is used primarily to regulate plant growth. The quality, weight, and moisture preserved by this use are otherwise lost due to physiological processes of the potato tuber and onion bulb. Also, more seed potatoes are lost. Ethylene's function here is part of the life cycle of plants.

Reducing sugars accumulate, water is lost, and quality degrades due to plant respiration as it breaks dormancy and builds new tissue (not by decay alone) (Alamar et al., 2017; Muhie, 2022).

The U.S. FDA defines "chemical preservative" as "any chemical that, when added to food, tends to prevent or retard deterioration thereof, but does not include common salt, sugars, vinegars, spices, or oils extracted from spices, substances added to food by direct exposure thereof to wood smoke, or chemicals applied for their insecticidal or herbicidal properties" at 21 CFR 101.22(a)(5). Ethylene used as petitioned does not fit the FDA's definition of "chemical preservative" (see *Action of the Substance*).

To the extent that sprout inhibition is considered herbicidal, ethylene could also be excluded from the definition of preservative at 21 CFR 101.22(a)(5) as a chemical "applied for … herbicidal properties." EPA designated ethylene a biochemical pesticide in 1990 because it occurs naturally and has a nontoxic mode of action in target plants (EPA, 1993).

Further, although ethylene is a chemical that "tends to prevent or retard deterioration" per the definition in 21 CFR 101.22(a)(5), it is a volatile substance that does not remain in or on food. Ethylene is therefore not primarily a preservative when used this way. Neither does this use "recreate or improve flavors, colors, textures, or nutritive value lost during processing." Instead, it prevents the need for such preservatives. And it is used during storage, not processing.

Therefore, the primary technical function of the petitioned use of ethylene is not as a preservative.

**Evaluation Question #7*:* Describe any effect or potential effect on the nutritional quality of the food or feed when the petitioned substance is used [7 CFR 205.600(b)(3)].**
Potatoes are at peak nutritional quality during harvest (ARS, 2023). In delaying the sprouting event, ethylene maintains nutritional quality as well as safety (Chen et al., 2024; Paul et al., 2016). In addition to ethylene's primary function in the petitioned use as plant growth regulation (see *Evaluation Question #5*), it also has a role in preventing nutritional degradation.

As described in *Specific Uses of the Substance*, sprouting accompanies significant loss of water, weight, and quality. Potatoes and onions degrade nutritionally when they sprout, due to continued carbohydrate and protein metabolism. Weight and moisture loss generally accelerate after sprouting, further degrading quality (Daniels-Lake & Prange, 2007; Paul et al., 2016). Starches generally become less stable as simpler sugars accumulate (Daniels-Lake & Prange, 2007; Kleinkopf et al., 2003; Paul et al., 2016). As described in *Losses due to sprouting*, acrylamide and glycoalkaloid formation also increase with sprouting in potatoes. This is another way ethylene protects crop nutrition.

Available research has explored ethylene's role in the complex sprouting process, with little attention directed toward nutritional effects of the exposure itself. In general, researchers found no evidence that ethylene used for fruit ripening degraded nutritional quality (NOP, 2023b). This finding may or may not apply to potatoes and onions exposed to ethylene. We found no research regarding ethylene's direct effects on nutritional quality of onions or potatoes, other than the protection from starch and overall quality degradation, described earlier. Ethylene's volatility and ubiquity may suggest a minimal effect on nutrient content when used as petitioned (Di et al., 2024; EPA, 1993; NOP, 2023b).

**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)].**
North American potato and onion storage facilities are generally equipped to manage temperature, humidity, and ventilation. Ethylene is added in a controlled manner, and the concentration is maintained automatically (Catalytic Generators, 2021; NOP, 2023b; O'Shaughnessy, 2023). Workers could be exposed to ethylene in this atmosphere during initial storage, load-out, or inspection. The maximum concentration during this time would be 10-15 ppm (O'Shaughnessy, 2023; US EPA, 2020). Humans begin to feel dizziness at 1,000 ppm (see *Table 1*, above).

*Toxicity to humans*
The most likely adverse forms of human exposure from this use are accidental inhalation and possibly skin contact by workers (Airgas, 2021), whether using bottled ethylene or catalytic generators. Using

commonly available detectors, storage facilities can measure ethylene concentrations to maintain safety (Catalytic Generators, 2021; Sherman, 1985).

Based on the extensive use of ethylene as a clinical anesthetic since 1923, and a diverse body of published research, the EPA concluded that ethylene would be nontoxic to humans under the conditions of use as a plant regulator (EPA, 1993), which generally requires concentrations of 10-15 ppm.

In the *Food and Environment Protection Act 1985*, the UK first allowed the use of ethylene as a plant growth regulator beginning in 2003. The act requires operators to wear a self-contained breathing apparatus when concentrations are above 1000 ppm (Briddon, 2006). However, this concentration is significantly higher than that used to control sprouting in stored potatoes and onions (see *Table 1*, above). For example, the EPA-approved label for the Restrain Generator Fuel requires only long-sleeved shirt, long pants, shoes, and socks (US EPA, 2020).

As detailed by authors of the Ethylene full-scope technical report (NOP, 2023b), overexposure to ethylene can cause headache, drowsiness, and muscular weakness (see *Table 1*, above). At higher concentrations, dizziness or light-headedness (>1000 ppm), memory disturbances (37.5% ethylene for 15 min.), loss of consciousness (50%), and death by suffocation can occur. Chronic exposure can affect the nervous and endocrine systems (NCBI, 2024).

Ethylene neither persists nor bioaccumulates in the environment (Health Canada, 2016). Its high volatility prevents the possibility of residues remaining on treated food crops and minimizes exposure to people (EPA, 1993).

*Flammability and other physical effects*

Ethylene use requires careful preventive measures because it is a highly flammable, volatile substance. Explosive accidents have occurred (Catalytic Generators, n.d.), and operators should be well trained and prepared (NOP, 2023b; Sherman, 1985). Specifically, IARC (1994) reports the lower explosive limit in air is 2.75 vol% or 34.6 $g/m^3$ at 20°C in normal atmospheric pressure. The EPA, local fire marshal rules, and insurance companies all have very specific labelling and registration requirements for the ethylene itself and the process used to apply it, including the electrical wiring and piping used in ripening rooms (NOP, 2023a).

The production method described in the petition, catalytic generation, could potentially avoid some of these dangers because the ethylene need not be transported and transferred from a separate production site. In addition, the ethylene concentration required for sprout suppression (10-15 ppm) is much lower than explosive concentrations (27,000 ppm).

*Breakdown products*

Ethylene has a half-life in the atmosphere of about 1 day (Health Canada, 2016). A study described by Health Canada estimated that 9 grams of ozone are produced for each gram of ethylene added to the atmosphere (2016). Carbon dioxide and carbon monoxide are also decomposition products of ethylene. (Health Canada, 2016). Both are ubiquitous in the atmosphere.

**Evaluation Question #11: Describe any alternative practices that would make the use of the petitioned substance unnecessary [7 U.S.C. 6518(m)(6)].**

Numerous factors affect sprouting an dormancy break, including the following (Di et al., 2024):

- temperature
- humidity
- light
- day length
- cultivar
- curing
- oxygen and carbon dioxide levels
- soil quality
- interactions among 12 or more different hormones
- timing of sprout inhibitor treatment
- maturity at harvest
- irrigation practices

*Nutrient management*

Producers can do much to control sprouting without using chemical inhibitors (Muhie, 2022). For example, they can ensure crops have adequate nutrients like sulfur and potassium (Muhie, 2022), and manage (limit excess) nitrogen. Excess nitrogen fertilizer can accelerate growth and reduce the dormancy period of potatoes (Di et al., 2024) or harm tuber quality generally (Pinhero et al., 2009). Excess nitrogen may also encourage moisture retention in onion bulbs and subsequent rotting in storage (Muhie, 2022).

Plant breeders continue to develop varieties with longer dormancy (Pinhero et al., 2009). In situations where demand and supply can be synchronized, shortening storage times could make exogenous treatments unnecessary, especially when the conditions listed above are optimized.

*Temperature*

Most handlers in North America and Europe can control the temperature of potatoes and onions in storage, although refrigeration is energy intensive. Holding potatoes at 8–12°C delays sprouting for several months, depending on cultivar (Paul et al., 2016). In general, higher temperatures lead to pathogen growth and tissue breakdown; lower temperatures contribute to undesirable sweetening and darker fry color. The processing market is more sensitive to the latter problem, due to high cooking temperatures of chips and fries. (Daniels-Lake & Prange, 2007; Pinhero et al., 2009; Tosetti et al., 2021; Zhang et al., 2024). However, researchers' specific temperature recommendations vary or even conflict depending on the varieties under study, inhibitors tested, and the interactions of other conditions. According to Alamar et al. (2017), tubers for the fresh market can be stored below 7°C, while tubers destined for processing should be stored at 8–13°C to avoid darkening, or as high as 15.5°C in the case of French fries (Pinhero et al., 2009). For seed potatoes, refrigeration at 2–4°C is appropriate, as starch mobilization and sweetening are not a concern.

Pinhero et al. described a technique of pre-conditioning and reconditioning, or gradually acclimating the tubers to different temperatures upon entering and leaving cold storage, to avoid formation of reducing sugars during storage and sprout control. They also emphasized the importance of selecting and breeding varieties that resist sweetening (2009).

Onions similarly require a balance of factors for successful storage. Commonly recommended conditions are 0°C with 70-75% relative humidity. Storing at higher temperatures can still provide sprout inhibition, but is associated with weight loss, desiccation, and rot. (Opara & Mejía, 2003). Excessive humidity in-store will lead to the development of roots and promote rotting while higher temperatures will result in sprouting and promote development of pathological disorders such as Botrytis rots (Opara & Mejía, 2003).

As noted in *Action of the Substance*, using ethylene for sprout inhibition on potatoes does not prevent reducing sugars or potentially harmful compounds from accumulating, and the risk of browning during cooking remains (Tosetti et al., 2021; Zhang et al., 2024). Ethylene therefore presents limited advantage over temperature control in this regard.

*The following practices are in development or are undergoing gradual adoption by industry (Daniels-Lake & Prange, 2007):*

Cold plasma (non-thermodynamic equilibrium plasma)

Cold plasma is a novel non-thermal technology that applies energy to a gas, causing it to emit various active species such as free radicals, electrons, ions, and ultraviolet light (Di et al., 2024). An argon plasma jet can damage the surface tissue to arrest germination and sprouting. Yang et al. (2023) also observed that the treatment led to an overall reduction in reactive oxygen species, which inhibited germination. And their experimental plasma-treated groups lost less weight and produced less reducing sugar than control group tubers. Plasma jet devices are not yet appropriate for large-scale agricultural use.

Natural ethylene emissions

Storing certain crops together with potatoes and onions could allow natural ethylene emissions from fruits, flowers, leaves, roots, and tubers to inhibit sprouting. Some climacteric fruits, such as tomatoes and apples, can generate tens of ppm of ethylene (Chang, 2016).[4] The rate of release varies over the life cycle

[4] Climacteric fruits can continue to ripen after they are harvested from the plant. They continue respiration, starch conversion, and ethylene production.

of the plant. Endogenous production generally increases rapidly during ripening of fruits and during senescence and loss of leaves (IARC, 1994). Plant emissions may increase from a low of 0.6-6 µg/kg fresh weight per hour to 120 µg/kg per hour during ripening (Health Canada, 2016).

Light

When moved from darkness to fluorescent light, sprouted tubers appear to halt sprout growth. Then, tubers moved from light to dark conditions increase their sprout growth to a rate similar to those that have stayed in the dark continuously. Light exposure therefore significantly influences sprout development of tubers during post-harvest storage (Di et al., 2024). Di et al. (2024) also suggested that applying white light can reduce starch and sucrose levels and extend dormancy; red LED light also showed an ability to suppress sprout growth.

**Evaluation Question #12: Describe all natural (nonsynthetic) 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)].**

The following substances already on the National List may be used for inhibiting sprouting in potatoes and onions during storage.

*Hydrogen peroxide (allowed synthetic)*

Synthetic hydrogen peroxide is allowed for use in or on processed products labeled as "organic" or "made with organic" at 7 CFR 205.605(b)(17). It provides similar mechanisms and efficacy as essential oils (see *Evaluation Question #13*, below), including possible pathogen reduction (Frazier et al., 2004). Sprout suppression is temporary, and multiple applications are necessary. It also breaks down into oxygen and water (Thoma & Zheljazkov, 2022).

*Carbon dioxide (allowed synthetic)*

Synthetic carbon dioxide ($CO_2$) is allowed for use in or on processed products labeled as "organic" or "made with organic" at 7 CFR 205.605(b)(10). Gouda et al. (2023) treated onions with carbon dioxide in air for eight weeks. They found that onions treated with 20% carbon dioxide had reduced weight loss (roughly 13% compared to 15%), reduced respiration rate, delay of senescence, and an increase in phenolic compounds and antioxidant activity, compared with untreated bulbs.

In potatoes, however, $CO_2$ can damage tissues if not controlled carefully, and its level should be kept at 1500-2500 ppm (Sercu, 2023). Kardos and Blood (1947) found in early experiments that a 7-13% carbon dioxide treatment reduced the weight of sprouts by at least 50% after 12 weeks, compared to untreated potatoes. Like ethylene, carbon dioxide can produce opposing results depending on concentration, duration, and state of the tuber (Kardos & Blood, 1947). It presents less risk of explosion than ethylene.

Guidance NOP 5023 clarifies that "…nonsynthetic substances allowed for use in crop production may be used post-harvest on raw agricultural commodities either on a farm or in a handling facility, provided that there is no limitation in 7 CFR 205.602 of the National List that prevents or restricts their use." The following nonsynthetic materials are not present on 7 CFR 205.602 and are therefore allowed for use in post-harvest handling, per NOP 5023.

*Carvone*

Carvone, a constituent of the oils from caraway, spearmint, and dill seeds, became commercially available in 2004 (UC SAREP, 2004), and is used in the UK (Clarke, 2019), the Netherlands, and Switzerland (Alamar et al., 2017; Gómez-Castillo et al., 2013; Paul et al., 2016; Thoma & Zheljazkov, 2022). The compound burns soft tissue in the tuber's eyes or on sprouts and disrupts growth (Clarke, 2019). According to Mehta (2002), a concentration of 300 µL/L completely inhibited potato sprouting for 110 days of storage, while control tubers began sprouting after 20 days and eventually developed a mean of 4.36 sprouts. Furthermore, potatoes treated with carvone were free from rot after 80 days, stored at 24°C. Thoma and Zheljazkov (2022) reported 274 days of effective sprout suppression. Although it is much more costly than conventional chlorpropham treatment (often called CIPC), carvone does not cause darkening during frying. Also, it can be used with seed tubers because its sprout inhibition action is reversible (Pinhero et al., 2009). Available products are Biox-M by Xeda (Clarke, 2019) and Talent.

*Limonene*
This component of orange peel essential oil gained approval in the UK, the Netherlands, Ireland by 2020. It shows efficacy in longer dormant potato cultivars (Clarke, 2019; Thoma & Zheljazkov, 2022). Argos is an available product.

*Eugenol*
This component of clove oil requires repeated applications for sprout suppression, in intervals of two to three weeks (Frazier et al., 2004; Thoma & Zheljazkov, 2022). Chen et al. (2024) described experimental findings of better sprout control than carvone, depending on administration conditions. Experimental applications also mitigated decay (Chen et al., 2024), including the fungal pathogen silver scurf (Frazier et al., 2004). Its effects are permanent, and it cannot be used on seed potatoes.

OMRI listed products contain clove oil and other ingredients:
- Decco Decco 070 EC Potato Sprout Inhibitor (elf-4325) 70% clove oil
- Decco 050 EC Potato Sprout Inhibitor (elf-5669) 50% clove oil

Table 2 briefly compares some of the commonly used substances listed above.

**Table 2: Classification of sprout control products. Source: (Immaraju, 2020).**

| Trade name | Common or chemical name | Sprouting effect | Comments |
|---|---|---|---|
| Restrain | Ethylene | Dormancy maintainer | Needs constant air concentration of 10 ppm throughout the storage period. Requires specialized equipment to generate/maintain gas levels. |
| Biox-C | Clove oil | Sprout pruners | Burns/Prunes small sprouts. No residual activity. Needs to be applied regularly to maintain sprout control. |
| Biox-M | Mint oil | | |
| Argos | d-limonene | | |

**<u>Evaluation Question #13:</u> Provide a list of organic agricultural products that could be alternatives for the petitioned substance [7 CFR 205.600(b)(1)].**

*Essential oils*
Chen et al. (2024) found that citronella and wintergreen essential oils controlled potato sprouting better than chlorpropham (often called CIPC). They also slowed the accumulation of reducing sugars. Jia et al. (2019) reported citronella suppressed sprouting in storage for 60 days and also mitigated weight loss. They further noted that the harmful glycoalkaloid solanine also decreased with the use of essential oils. In other research, mint essential oil damaged apical meristem and vascular tissues to induce tuber bud necrosis (Gumbo et al., 2021). Eugenol and menthol reportedly had the same effect (Chen et al., 2024).

Essential oils can be applied by fogging or vaporization, which some handlers might consider more practical than ethylene. Further, because the sprout suppressing action of essential oils is reversible, they allow for storing seed potatoes in the same facility with treated potatoes. And their volatility simplifies cleaning of storage facilities (Gumbo et al., 2021).

At the same time, volatile compounds dissipate and must be applied more often, especially when storage areas are not well sealed (Clarke, 2019). In addition, the variations within and among essential oils and their active constituents will complicate efforts to create reliable sprout suppression protocols until the compounds themselves can be produced more predictably (Thoma & Zheljazkov, 2022).

Grudzińska et al. (2016) reported that the use of peppermint, caraway (carvone), and clove (eugenol) oils all affected the organoleptic properties of the cooked tuber less than the cultivar itself. That is, essential oils were not detectable upon eating. Laboratory studies have shown that many of these compounds can also reduce pathogens (Frazier et al., 2004).

Certified organic essential oils are widely available, according to the NOP organic integrity database (OID) (USDA, 2023). However, researchers generally acknowledge these inputs, regardless of certification status are cost-prohibitive compared to synthetic treatments. For example, even nonorganic carvone could cost 10 times as much as conventional chlorpropham treatment (Pinhero et al., 2009).

The following have also been shown to inhibit sprouting. (Gumbo et al., 2021; Paul et al., 2016; Pinhero et al., 2009) However, the wide variance of study conditions and cultivars used prevents general conclusions about how they compare to the petitioned substance (Gumbo et al., 2021):

- eucalyptus
- citronella
- citrus
- coriander
- dill seed
- fenchone (from fennel)
- lavender
- lemongrass
- menthol
- rosemary
- sage
- various mints

A USDA grant project underway at two universities is examining 200 different plant oils for anti-sprouting properties, specifically in organic crops. (Bull, 2023). Researchers have not published results as of this writing.

## Report Authorship

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All individuals are in compliance with Federal Acquisition Regulations (FAR) Subpart 3.11—Preventing Personal Conflicts of Interest for Contractor Employees Performing Acquisition Functions.

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