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Alternative Deicers for Winter Road Maintenance—A Review

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Abstract The use of roadway deicers, typically made of sand or salt, is essential for achieving safe roadway conditions by reducing ice and snow. Unfortunately, deicers can have detrimental effects on the surrounding infrastructure and environment. Traditional inorganic deicers, such as abrasives and chloride salts, have the most widespread usage, but recent concerns of the negative effects of chlorides on the environment have led to emerging alternative organic deicers. This paper provides a comprehensive review of the effectiveness and impacts of organic deicers including agro-based products, acetates, formates, glycols, and succinates. The benefits and negative impacts on the road, environment, and infrastructure are reviewed, as well as the performance of each deicer for snow and ice control on roadways. The environmental concerns of the organic deicers are discussed, including the largest environmental concern: the increase in biological oxygen demand (BOD) to receiving water bodies. The impact of deicers on metals and infrastructure is presented as it varies considerably for each alternative deicer. Finally, opportunities and challenges to implementing alternative deicers in the field is discussed.

Keywords Organic deicers · Snow and ice control · Chlorides · Environmental impacts · Infrastructure impacts

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1 Introduction

Winter weather conditions can make traveling by vehicle during winter months perilous. In the USA, an estimated 21% of car crashes are weather related, resulting in nearly 5400 deaths and 418,000 people injured per year based on 10-year averages from 2007 to 2016 (US DOT 2020). Both snow and rain increase the crash and injury rate (Andrey 2010; Qiu and Nixon 2008). In the same period of time, an estimated 18%, 13%, and 16% of weather-related car crashes occurred during snow/sleet, icy pavement, and snow/slushy pavement, respectively (US DOT 2020). Snow can increase the crash rate by more than 80%, the injury rate by more than 70%, the serious injury or fatality rate by 50%, and the fatality rate by 9% (Andrey 2010; Qiu and Nixon 2008). In addition to the loss of human life, car crashes are costly; in 2010 alone, crashes cost the US $242 billion (Blincoe et al. 2015). To reduce the hazards drivers face, transportation agencies conduct winter road maintenance. One aspect of winter road maintenance is the inhibition and removal of snow and ice from roads in order to return roads to bare pavement as quickly as possible. This aspect of winter road maintenance includes plowing snow built up on roads and the application of physical and chemical substances before winter weather events (anti-icing) and either during or after winter weather events (deicing). Anti-icing and deicing are an essential part of winter road maintenance, resulting in a decreased rate of traffic accidents, decreased severity in traffic accidents, decreased traffic accident costs, and decreased travel time costs (Kuemmel and Hanbali 1992).

Currently, most state transportation agencies use abrasives or traditional chloride-based salts as the primary winter maintenance materials (henceforth referred to as deicers), and maintenance practices for both have been thoroughly researched, refined, and used for decades (Fay et al. 2008; Nixon 2001a). However, the high corrosion costs and environmental impacts on water quality, soil, and vegetation associated with abrasives and chloride deicers have resulted in the need for potential alternatives. Vignisdottir et al. (2019) review on environmental effects of winter road maintenance found that globally, winter road maintenance contributed to climate change and atmospheric ozone depletion, and that locally, chloride deicers degraded water, soil, and air quality in addition to damaging vegetation and biodiversity. Consequently, there has been a proliferation of alternatives to traditional deicers, although none have unseated the predominance of abrasives and chlorides.

This manuscript builds upon previous literature reviews on the evaluation (Fischel 2001), the effects and costs (Kelting 2010), and the environmental impacts (Fay and Shi 2012) of deicers to provide an overview of conventional deicers, a detailed performance of various organic alternative deicers based on the effectiveness, environmental impacts, and corrosion/infrastructure impacts, and the perceived challenges to alternative deicer field implementation. This state-of-the-practice review focuses on agro-based products, acetates, formates, glycols, and succinates as alternative deicers used in roadway applications. Urea is not discussed in this review because of its decline in use in the field due to high environmental impacts to aquatic life and water quality (elevated nitrogen concentrations lead to eutrophication, dissolved oxygen consumption, and harmful impacts to the ecology) (Corsi 2009; Turnbull and Bevan 1995), and due to the lack of new publications since a review by Fay and Shi (2012). A summarizing figure for the focus of the review can be seen in Fig. 1.

1.1 Search Methodology

General search terms for winter maintenance materials as well as specific search series were performed for each alternative in Google Scholar, as seen in Fig. 2, while each search term used in this study can be seen in Fig. 3. The number of results for each search term was recorded, and the first fifty results of each search were examined for inclusion into the manuscript as relevancy declined in later results. Search results were analyzed based on their titles, keywords, and abstracts for relevance to the study. Fourteen studies that were identified as potentially relevant were unattainable. As the review focuses on the utility of road salt alternatives and the environmental and infrastructural effects related to their use in the field, technical papers on the formulation of deicers or development of specific test methods were excluded. Studies on glycols which focused on specific proprietary products produced for aircraft deicing as opposed to pure products were also excluded. Reports and peer-reviewed articles published after 1990 were selected for inclusion as this study builds upon literature reviews that cover material prior to that timeframe.

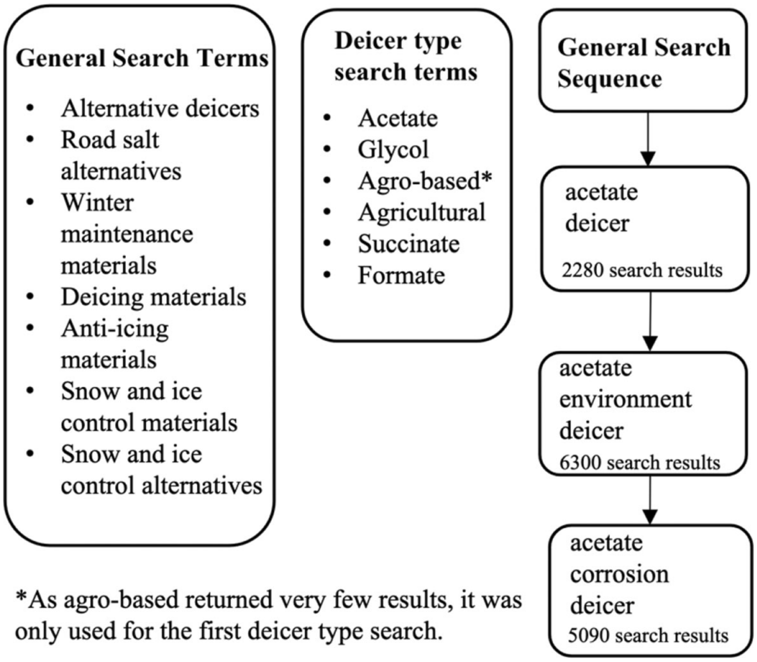
A total of 129 sources are included in the literature review, of which 89 of the sources convey information about alternatives deicers. Of the 89 alternative deicer sources, 62 were peer-reviewed articles, 25 were reports, and two were patents. Twelve of 89 sources about alternative deicers were identified through other means than the methodology stated above (Alizadeh and Berglund 2015; Essarras et al. 2018; Freeman et al. 2015; Frolova et al. 2015; Fay et al. 2015; Harris et al. 2013; Western Transportation Institute 2017; CDOT 2017; Clear Roads 2020; PNSA 2010; MDOT 2017; EPA 2018). Research on alternative deicers has increased over the past two decades, averaging 2.5 manuscripts per year and 1 report per year since 2000, as seen in Fig. 4.

Fig. 1 State-of-the-practice review topics

1.2 Overview of Conventional Deicers: Abrasives and Chloride-Based Salts

Abrasives have been used since the beginning of the twentieth century to increase friction on icy pavements (Nadezhdin et al. 1988; Yonge and Marcoe 2001). Agencies have commonly used abrasives on unpaved roads since deicing chemicals tend to cause destabilizations of the granular material roadways (Nadezhdin et al. 1988; Nixon 2001a; Salimi et al. 2014). Sand has been the most commonly used abrasive as it is inexpensive ($6–$16 per ton); however, sand can damage windshields and paint on vehicles—leading to increased costs (Chang et al. 1995; Fay et al. 2015; Fortin Consulting Incorporated 2014). Excess abrasive runoff increases stress on roadside soil and vegetation while also clogging storm water drains (Staples et al. 2004; Chang et al. 1995). Abrasives can displace pollutants in soil and cause pollutants to leach into nearby water sources. Upon entering surface waters, abrasives increase water turbidity, reduce dissolved oxygen, clog small streams, and affect water quality (Staples et al. 2004; Nixon 2001b) Overall, sand has greater impacts on the environment than chloride-based salts, so transportation agencies have largely transitioned away from abrasive use and towards chemical deicers, such as chloride-based salts, which have a higher effectiveness (Nixon 2001a; Nixon 2001b; Shi et al. 2013). The use of abrasives, along with other solid chemical deicers including chloride salts, may increase the concentration of particulate matter (PM) in the air, reducing visibility (Staples et al. 2004; Nixon 2001b; Chang et al. 1995). Particulate matter is a criteria air pollutant regulated by the Environmental Protection Agency (EPA) under the Clean Air Act as PM_{10} (PM 10 μm or less in diameter) and $PM_{2.5}$ (PM 2.5 μm or less in diameter), and is carcinogenic, contributes to eye and throat irritation, and can damage to the respiratory system (EPA 2019a).

Fig. 2 Search criteria and procedure detailing how relevant articles were found. Each alternative search followed the general search sequence



Traditional chloride-based salts, such as sodium chloride, calcium chloride, and magnesium chloride, have become the most commonly used chemical deicers (Fay and Shi 2012; Yonge and Marcoe 2001). Of these,

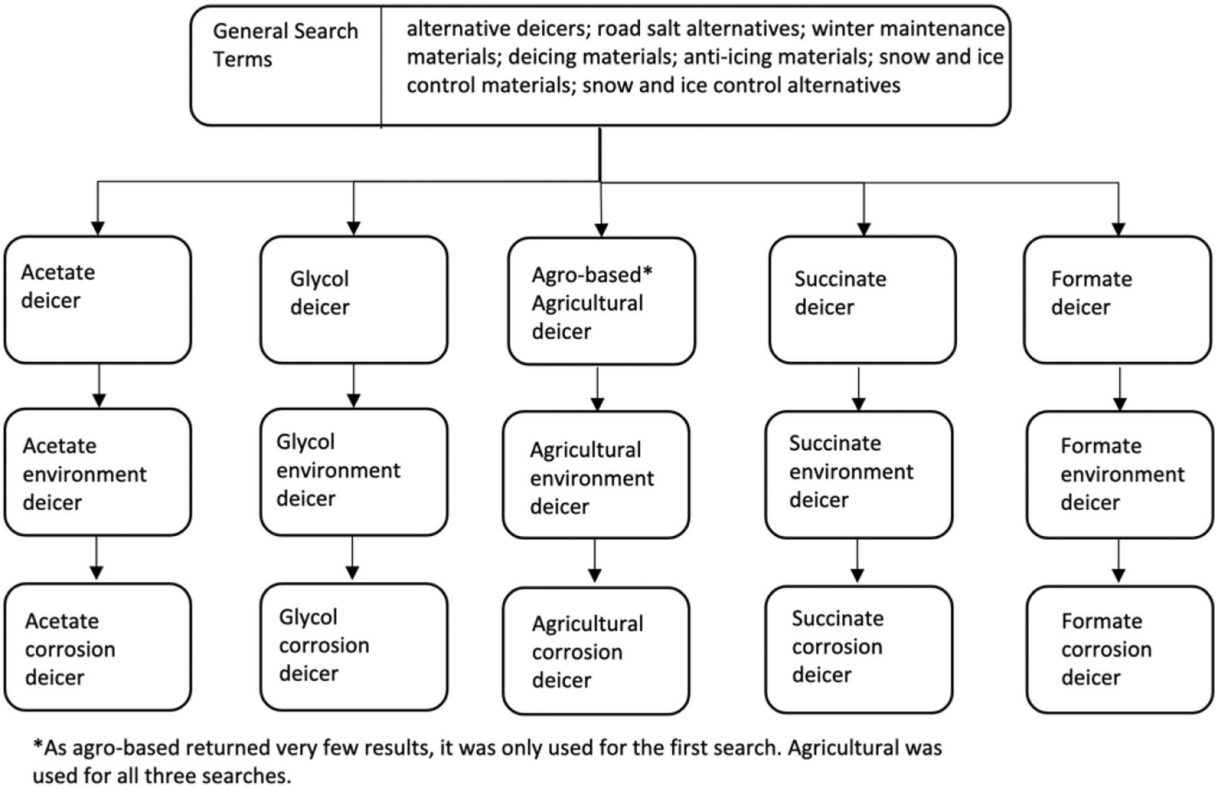


Fig. 3 Comprehensive list of search criteria and search terms

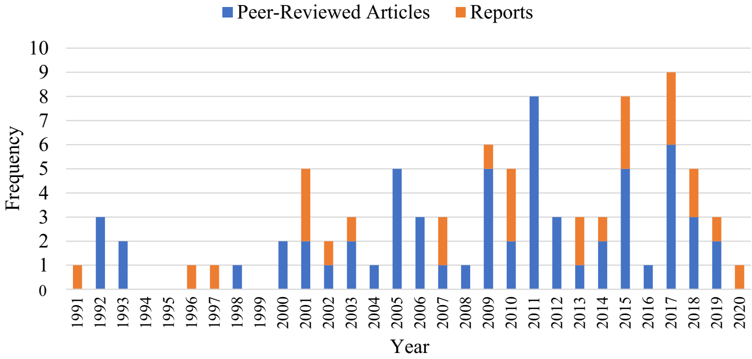


Fig. 4 Number of reports and publications on alternatives to road salts and abrasives over the past three decades

sodium chloride (rock salt) has become the most frequently employed because it is inexpensive ($30–$100/ton) and it is effective at common winter temperatures (Akin et al. 2013; Chang et al. 1995; Fortin Consulting Incorporated 2014; Western Transportation Institute 2017). Calcium chloride and magnesium chloride have been reported to be more effective at colder temperatures than sodium chloride, but can be difficult to handle, more expensive, and more damaging to infrastructure (Du et al. 2019; Jungwirth and Shi 2017; Ketcham et al. 1996; Kuemmel 1994; Laurinavičius et al. 2016; Shi et al. 2009a). Traditional chlorides have been normally used to treat roads in one of three ways: anti-icing, deicing, or pre-wetting (i.e., treating rock salt with a liquid deicer such as brine before application to decrease deicer scatter) (Shi 2010; Shi et al. 2013).

Traditional chlorides also have many negative environmental impacts and have been categorized as a water pollutant by the EPA under the Clean Water Act (Strifling 2018). The EPA has established the secondary drinking water standard for chloride of 250 mg/L; above this level, drinking water can have a salty taste (EPA 2019b). Deicing material pollution can occur through material loss during transportation and storage or during application on roads as shown in Fig. 5. Lost material follows one of four pathways: material drains into streams or other surface water bodies via roadways, ditches, culverts, or percolation into soil; material splashes onto vegetation, damaging the vegetation; material percolates into well-drained soils and reaches groundwater; or material percolates into slow-drained soils where it accumulates. Material that accumulates in surface water can decrease water quality and negatively affect aquatic flora and fauna. Material that reaches groundwater can decrease the water quality of local wells, affect vegetation, and flow into surface water. Material that accumulates in the soil can affect the soil structure, erosion, and vegetation. Material lost during application can also be resuspended through traffic or wind and create PM_{10} and $PM_{2.5}$ (Kolesar et al. 2018; National Academies, Engineering, and Medicine 1991; Rogge et al. 1993).

The use of traditional chlorides can increase the overall salinity of the soil and water systems as well as increase the sodium and chloride concentrations in drinking water and groundwater wells (Fay and Shi 2012; Jamshidi et al. 2020; Jones et al. 1992; Kelly et al. 2018; National Academies of Sciences, Engineering, and Medicine 1991; Pieper et al. 2018). Sodium chloride has been found to have negative ecological and toxicological impacts to receiving water bodies and subsequent aquatic organisms and species (Cui et al. 2015; Hintz and Relyea 2019; Nazari et al. 2015). Traditional chlorides in the soil damage terrestrial vegetation and a high sodium cation concentration can reduce soil permeability and aeration, increasing erosion and surface runoff and reducing plant growth (Bryson and Barker 2002;; Findlay and Kelly 2011; Jones et al. 1992; Public Sector Consultants Inc. 1993; Ramakrishna and Viraraghavan 2005). However, calcium and magnesium cations have been shown to increase soil stability, permeability, and aeration (Levelton Consultants 2007). Chlorides can mobilize mercury and heavy metals from the soil through ion exchange, lowered pH, or chloride complexation and then transport the metals into groundwater systems (National Academies of Sciences, Engineering, and Medicine 1991; Nazari et al. 2015; Sucoff 1975). A growing body of literature has also found that road salt use affects the microbial communities in local soils; in particular, the concentration of halotolerant and halophilic microorganisms was greater in soils exposed to road salts (Pecher et al. 2019). It has been estimated that about 10–60% of sodium chloride applied to roads as a deicer

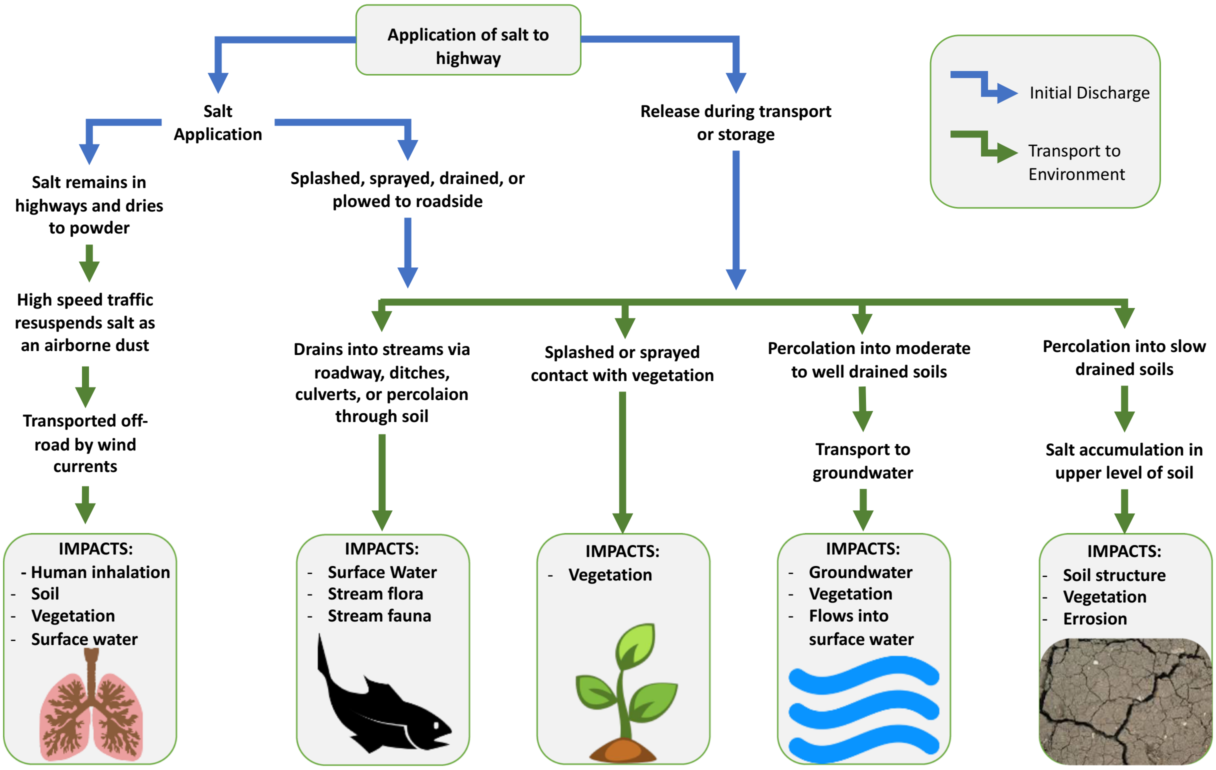


Fig. 5 Pathways for chlorides used in winter maintenance to enter the surrounding environment (Graphic adapted from similar graphics in Fay et al. 2015, Levelton Consultants 2007, and National Academies, Engineering, and Medicine 1991)

accumulates into subsurface water (Environment Canada 2001; Fay and Shi 2012).

Traditional chlorides were considered the most corrosive to metal winter maintenance material in a survey of winter maintenance professionals, which was generally consistent with the literature (Shi et al. 2009a). Traditional chlorides can corrode steel bridges, large span supported structures, reinforced concrete structures, parking garages, pavements, and vehicles (Shi et al. 2010a; Shi et al. 2013; Shi et al. 2014). Chloride ions also diffuse into concrete and initiate corrosion in reinforced steel, which causes cracking, increased permeability, decreased compressive strength, loss of material, concrete scaling, and paste disintegration (Shi et al. 2013; Xie et al. 2015). Xie et al. (2015) found magnesium chloride imparted the most severe concrete damage of the chloride deicers. These infrastructure and environmental effects of traditional chloride-based salts and abrasives have led to a search for alternative winter maintenance materials that can achieve black-top pavement conditions at a similar upfront cost as chlorides yet have fewer adverse impacts to infrastructure and the environment.

1.3 Alternative Winter Maintenance Materials Reviewed in This Study

Agro-Based Products Agriculturally derived (agro-based) deicing products have emerged as alternative deicers in snow and ice control operations and have been applied as additives to inorganic deicers or as standalone deicers (Nixon and Williams 2001). Agro-based materials are by-products of chemical processes and manufactured through fermentation or other sustainable processes such as processing of beet juice, molasses, corn, and/or cane barley (Fay and Shi 2012; Muthumani et al. 2015). Common agro-based deicers contain chloride salts and low-molecular weight carbohydrates (Fay and Shi 2012). In general, agro-based deicers increase upfront cost since they are typically added to chloride deicers, yet these materials potentially lower the eutectic temperature (lowest temperature at which the deicer will freeze), reduce corrosion impacts, and may persist longer on the roads (Nixon and Williams 2001), which may lower overall cost. Specific performance results and costs for agro-based materials vary depending on the manufacturer, specific product, and composition, which is often proprietary (Du et al. 2019).

Acetates Acetates have been the most commonly used alternative deicer for snow and ice control. Acetate-based products have been used by transportation agencies as the primary deicer for airport pavements and bridges since acetates have been considered to have minimal corrosive impacts on infrastructure compared with chloride salts (Western Transportation Institute 2017; Fischel 2001; Kelting and Laxson 2010). However, widespread use of acetate deicers has been hampered due to high cost compared with chloride deicers and higher application rates to achieve the same level of service as chloride deicers (Fay and Shi 2012; Du et al. 2019). The three main acetate deicer products include potassium acetate (KAc), sodium acetate (NaAc), and calcium magnesium acetate (CMA). Acetate production consists of combining acetic acid with cation functional groups. Potassium acetate products are usually sold as liquids with a concentration of 49%, while sodium acetate and calcium magnesium acetate products are typically sold as solids (Fortin Consulting Incorporated 2014; Kelting and Laxson 2010). Studies have shown that calcium magnesium acetate deicing products must contain at least 32.5% of calcium magnesium acetate and 25.0% acetic acid to be a viable and efficient deicer (Fortin Consulting Incorporated 2014; Kelting and Laxson 2010).

Formates Formates have primarily been used by airports for deicing runways (Fortin Consulting Incorporated 2014). Formates exist in a solid or liquid form and are sold primarily as sodium formate (NaFm) or potassium formate (KFm). Sodium formate, a solid, comes from a by-product of pentaerythritol manufacturing (Fortin Consulting Incorporated 2014; Frolova et al. 2015), while potassium formate is available as a liquid product (Fortin Consulting Incorporated 2014). Formates can also be combined with other alternative deicers, such as acetate products, for winter maintenance operations.

Glycols Glycol deicing products have been mainly used by airports and military bases for aircraft deicing and airfield anti-icing due to glycol product certification by the United States Aviation Administration (Castro et al. 2005; Western Transportation Institute 2017). Propylene and ethylene glycols have been the most commonly used products for aircraft deicing and can contain corrosion inhibitor or surfactant additives (Fay and Shi 2012). Few glycol products have been manufactured for roadway winter operations due to the high cost compared with chloride deicers (Western Transportation Institute 2017; Freeman et al. 2015). A typical glycol deicer product contains 10–11% water, 1–2% additives (such as benzotriazole), and 88% freezing point depressant, which can include glycols, glycerol, or glycerin (Western Transportation Institute 2017; Freeman et al. 2015). Strict regulations control the collection and treatment of glycol deicer waste in order to minimize environmental impacts (Castro et al. 2005). Ethylene glycol is tracked and regulated by multiple EPA statues and regulations such as the Clean Air Act, Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), Toxic Substances Control Act (TSCA), and the Emergency Planning and Community Right to Know Act (EPCRA) (EPA 2018).

Succinates Succinates can serve as corrosion-inhibiting additives in traditional chloride deicing products but are not currently mass produced as deicing products (Fay and Akin 2018). Succinates occur naturally in the environment, can be genetically synthesized, or can be manufactured by derivation from succinic acid, $(CH_2)_2(CO_2H)_2$ (Berglund et al. 2001; Berglund et al. 2003; Muthumani et al. 2015; Potera 2005). The future manufacturing process for succinates is predicted to be sustainable with the consumption of large amounts of carbon dioxide and organic by-products of other manufacturing processing, such as corn processing, to create succinic acid, which will then become succinate deicing products (Fay and Akin 2018; Muthumani et al. 2015; Potera 2005). Potassium succinate has been the most commonly researched potential deicing product, but ammonium succinate and sodium succinate may become future options (Berglund et al. 2001). Potential deicing formulations include a blend of 50% by weight potassium succinate with 20% by weight of salt brine at 2:98 or 18:82 ratios (Muthumani et al. 2015).

2 Results and Discussion

This section offers a detailed overview of the performance of each road salt alternative found in the literature, as well as the environmental impacts on water, soil, flora and fauna, and the concurrent corrosion and infrastructure impacts on metals and concrete (roads).

2.1 Comparison of the Performance of Various Organic Deicing Products

Deicer performance, or effectiveness, can be described by a variety of factors including ice melting, ice undercutting, ice penetration, provided friction, and effective temperature. Most studies in the literature tend to compare the performance of one deicer with either the performance of chlorides or of a similar type of product (e.g., sodium acetate versus potassium acetate). It is not uncommon for a deicer to have superior performance by one metric and inferior performance by another.

2.1.1 Agro-Based Products

Agro-based products have the most varied performances due to the many different application methods. Agro-based products can be used to pre-wet rock salt, to mix with salt brine, and to directly apply to pavement. In general, agro-based products increase the effectiveness of manual snow/ice removal, i.e., plowing, by interfering with the ice and pavement bonds (Fu et al. 2012). Agro-based products were found to increase friction of asphalt pavements by 10–40% compared with the control sections (no treatment) and were at least as effective as the sodium chloride controls (Hosseini et al. 2017). Agro-based products tend to have lower eutectic temperatures than sodium chloride, thus lower effective temperatures (Nazari et al. 2019). One lab study found the freezing point of liquid agro-based products to be − 42.8 °C (− 45 °F) and to have comparable effectiveness with sodium chlorides at temperatures as low as − 15 °C (5 °F) (Muthumani et al. 2015). Fay et al. (2008) found that at − 5 °C (23 °F), an agro-based product performed similarly to an acetate product and two chloride-based products, although it underperformed compared with a third chloride-based product and reagent-grade chlorides. Studies have shown that prewetting rock salt with agro-based products reduces salt use by 28–38% and abrasive use by 78% since agro-based materials increase traction (Kahl 2002). In a 2012 study by Fu et al., using agro-based products in place of salt brine for prewetting showed comparable results for 85% of nine snow events measured within one winter maintenance season (Fu et al. 2012). Agro-based materials should only be applied with direct liquid application for anti-icing purposes before the storm and not for deicing purposes during the storm (Kahl 2002). Despite added friction, organic materials are more viscous than salt brine and have the potential to clump and cause vehicle skidding (Taylor et al. 2010). Agro-based materials have shown to be more effective than salt brine even at lower application rates, although agro-based products have some variances in effectiveness with direct liquid application; darker agro-based products have been shown to have a higher ice-melting capacity than lighter products (Fu et al. 2012; Muthumani et al. 2015). Overall, agro-based materials have shown to create more traction, faster reactions, and increased time for maintenance operations than salt brine (Fu et al. 2012; Kahl 2002).

Muthumani et al. (2015) compared agro-based material performance during direct liquid application with that of 23.3% by-weight salt brine and mixtures of salt brine and agro-based at 80:20 or 70:30 solutions. The use of agro-based products worked well by themselves and improved the performance of salt brine when in solution. The four pure agro-based products produced more ice melt and weakened snow/pavement bonds more than pure salt brine. While the mixture of products and salt brine did not produce more ice melt, the mixture increased viscosity and friction values compared with salt brine. Additionally, agro-based products dissolved less into snow and ice so the mixture of agro-based products and brine increased the time the brine solution remained on the road (Muthumani et al. 2015). Another lab study found that adding agro-based products to brine at 23% by-weight significantly decreased the freezing point of the deicer but did not significantly improve the ice-melting capacity of the brine at the tested temperatures (Muthumani and Shi 2017). In agreement, Jungwirth and Shi (2017) found that an agro-based sugar beet product and a blend of the sugar beet product plus salt brine had lower ice-melting capacity than a sodium chloride control at − 9.4 and − 15 °C, which suggest the agro-based product does not perform as well as the salt control as a liquid deicer at lower temperatures. Taylor et al. compared solutions of agro-based products and salt with rock salt and salt brine solutions (2014). Both agro-based products tested had a significantly lower freezing point than the rock salt, and one of the tested products also created more ice melt. However, all tested agro-based formulations created less traction than the salt (Taylor et al. 2014). Nazari and Shi (2019) found an agro-based mixture (0.89% Concord grape extract, 4.57% glycerin, 4.54% sodium formate, 0.19% sodium metasilicate, 18.4% NaCl, and water) outperformed both a 23% NaCl brine and a beet juice/ salt brine blend in terms of ice-melting capacity and friction coefficient of anti-iced asphalt pavement in a simulated black ice scenario. Nazari et al. (2019) investigated 16 agro-based mixtures (dandelion leaf extract and/or sugar beet leaf extract blended with 23% salt brine and other compounds) and found the best performing anti-icer (a water-based solution made of 3 wt% sugar beet leaf extract, 0.67 wt% sodium metasilicate, and 23 wt% NaCl) had a high ice-melting capacity at − 3.9 °C, improved the friction coefficient on pavement, and had a low impact on Portland concrete properties.

During storage and application, some agro-based products may have quality control issues or expiration dates (Muthumani et al. 2015). Sprayers have the potential of being clogged during application due to higher viscosities (Muthumani et al. 2015), and although solutions can be diluted for easier applications, dilutions can cause the solution to be less effective (Fay and Shi 2012). Additionally, during anti-icing operations, darker colored products may look like black ice and crews may mistakenly apply other deicers (Kahl 2002).

2.1.2 Acetates

Unlike agro-based products, acetate products have not been used to bolster the performance of chlorides. Acetates can be used for deicing and anti-icing in sleet, snow, and ice weather events with temperatures ranging between − 17.8 and 4.4 °C (0 to 40 °F), although each deicer product has a lowest effective temperature range (Western Transportation Institute 2017). Potassium acetate lower effective temperature has been reported between − 32.2 and − 26.1 °C (− 26 to − 15 °F) (Akin et al. 2013; Western Transportation Institute 2017; Fischel 2001), the lowest effective temperature for acetate winter maintenance materials. The lowest effect temperature of calcium magnesium acetate has been reported from − 17.8 to − 5 °C (0 to 23 °F), while the lowest effective temperature of sodium acetate has been reported from − 17.8 to − 15 °C (0 to 5 °F) (Akin et al. 2013; Fischel 2001; Western Transportation Institute 2017). However, a mixture of sodium acetate/sodium formate was found to be ineffective at − 15 °C (5 °F) and − 20 °C (4 °F) (Ružinskas et al. 2016).

When compared with traditional chlorides, potassium acetate products have shown better performance at all temperatures on concrete pavements and produce more ice melt than sodium chlorides at colder temperatures (Akin et al. 2013; Fay and Shi 2011; Western Transportation Institute 2017). Potassium acetate produced greater friction than alcohol-based deicers such as glycols initially; however, this friction quickly declined, as glycols produced greater friction over time (Laforte et al. 2015). Calcium magnesium acetate was found to perform similarly to an agro-based product and chloride-based products at − 5 °C (23 °F), although it underperformed compared with another chloride-based product and reagent grade chlorides (Fay et al. 2008). Calcium magnesium acetates have not performed well in thick snow/ice conditions due to poor ice penetration abilities and reacted with water slower than sodium chlorides, so more applications of the product will be needed to achieve similar effects (Fischel 2001; Kelting and Laxson 2010; Western Transportation Institute 2017). Parker (1997) found over a t2-year study that calcium magnesium acetate as an anti-icing chemical worked well in temperature conditions of − 4 °C (25 °F) to − 2 °C (28 °F) and higher to significantly reduce the amount of sand employed during the snow event. Most studies reported that the slower reaction time of calcium magnesium acetate leads to a higher application rate of the product in order to achieve the same performance (Fischel 2001; Kelting and Laxson 2010; Western Transportation Institute 2017). Kelting and Laxson (2010) suggest that calcium magnesium acetate products should be applied before the start of precipitation for optimal performance since calcium magnesium acetate can take 20 to 30 min to penetrate ice and snow before initiating melting reactions. Field tests have indicated that calcium magnesium acetate products are less effective than sodium chlorides during freezing rain, drier storms, and in areas with light traffic volumes (Harris et al. 1993; National Academies of Sciences, Engineering, and Medicine 1991; Manning and Perchanok 1993; Western Transportation Institute 2017).

2.1.3 Formates

In general, formates have been reported to have an effective temperature range of − 6.7 to 0 °C (− 20 to 32 °F) (Fortin Consulting Incorporated 2014). Sodium formate cannot be used at temperatures lower than − 7 to − 10 °C (19.4 to 14 °F), while potassium formate may be effective at lower temperatures (Frolova et al. 2015). While the two deicing products exhibited similar ice-melting capacities between 0 and − 16 °C (32 and 3.2 °F), sodium formate exhibited a slightly higher ice-melting capacity between − 5 and − 10 °C (23 and 14 °F) (Frolova et al. 2015). One study found that potassium formate and potassium acetate performed similarly in terms of ice melting, ice undercutting, and ice penetration (Laforte and Tremblay 2017). Hossain et al. (2015) found that sodium formate treated with Gen3 runway deicing fluid outperformed rock salt in all application and pavement conditions in terms of bare pavement regain time (a surrogate for level of service). This study was completed over 21 snow events in a parking lot without traffic, thus further field studies with traffic variables are suggested for winter maintenance application.

2.1.4 Glycols

Glycols have been shown to work well at extremely low temperatures but the temperature range varies based on the specific deicer product (Western Transportation Institute 2017). The effective temperature for propylene glycol has been reported to range between − 28.9 and − 9.4 °C (− 20 to 15 °F) but it has been shown to have a melting temperature as low as − 58.9 °C (− 74 °F) (Fay et al. 2015; Ramakrishna and Viraraghavan 2005; Western Transportation Institute 2017). Very little data exists on the effectiveness of glycol deicers on roadways or in comparison with other deicers since glycols are not commonly used on roadways (Western Transportation Institute 2017). However, one study reported that glycols are effective at deicing but slower acting and more viscous than potassium acetates (Fay et al. 2015).

2.1.5 Succinates

Succinates are not currently employed as a deicing product, but succinates have displayed the properties of a potential alternative deicer and been used as corrosion-inhibiting agents in some traditional deicing formulations (Berglund et al. 2001; Berglund et al. 2003; Taylor et al. 2010). Succinates act as a freezing point depressant by lowering the freezing point of snow/ice and producing heat when in contact with water (Berglund et al. 2003). Lab tests have shown that potassium succinate exhibited a higher performance as a deicer and corrosion inhibitor than other succinate salts tested and had an effective temperature range of − 28.9 to 0 °C (− 20 to 32 °F); however, succinates have not functioned well as a deicer below − 5 °C (23 °F) (Fay and Akin 2018; Fortin Consulting Incorporated 2014). Compared with salt brine, potassium succinate performed similarly at improving friction values but did not work as well at colder temperatures (Fay and Akin 2018). Potassium succinate also had a slightly lower ice-melting rate (2.6 mL/g) after 60 min than salt brine (3.5 mL/g) (Fay and Akin 2018). Succinate salts also can be mixed with sodium chloride or other deicing products to improve deicing performance or decrease corrosion to infrastructure (Berglund et al. 2001). Field tests have not been conducted using succinate deicing products, so information about roadway use, optimal application rates, and equipment compatibility are an area for future research.

2.1.6 Performance Summary

Table 1 summarizes the different conventional and alternative deicers available for winter maintenance. There is great variability in deicer performance and temperature range. However, at the coldest reported temperatures, glycols, potassium acetate, and potassium formate were the most effective. Overall, the literature suffers from a dearth of field tests. The most studied alternatives are agro-based products and calcium magnesium acetate. Calcium magnesium acetate was found not to be as effective as chlorides, yet agro-based products were most effective in mixtures with chlorides, reducing the amount of chloride applied to the roadway while maintaining the same level of service.

2.2 Environmental Impacts

Alternative deicers affect the natural receiving environment in different ways depending on the type and quantity of materials used, transport and exposure pathways, exposure duration, chemical-specific effects, and site-specific environmental characteristics (Levelton Consultants 2007). This section discusses the effect of organic deicers, agro-based products, acetates, formates, glycols, and succinates, on the following environmental categories: water, soil, and flora and fauna.

Some of the constituents of natural sources of salts are considered contaminants due to their toxicity towards aquatic life above a certain threshold level. Such is the case with heavy metals present in natural salt sources used in deicers. Additionally, heavy metals can also be added to deicers to reduce corrosion or to avoid caking of the ingredients (Levelton Consultants 2007). To avoid damage to the aquatic life, these

Table 1 Summary of conventional and alternative deicers (Table adapted from tables in Levelton Consultants 2007)

Deicer		Primary components[a]	Common application phase	Optimum eutectic temperature °C (°F) @ % concentration[a]	Minimum effective temperature °C (°F)	Common sources[a]
Abrasives		Sand or other[l]	Solid [l]			
Chlorides	Sodium chloride (NaCl)	Cl combined with a metal	Solid or liquid (brine)	− 21 (− 5.8) @ 23.3%[g]	− 9.4 (15)[c]	Mined from natural deposits, solarization of natural brines[a]
	Calcium chloride ($CaCl_2$)			− 51 (− 60) @ 29.8%[g]	− 26.1 (− 15)[c]	Natural well brines, by-product of the Solvay process [a]
	Magnesium chloride ($MgCl_2$)			− 33 (− 28) @ 21.6%[g]	− 20.6 (− 5)[c]	Solarization of natural brines, natural well brines, by-product of metallurgical process[a]
Agro-based products		Complex sugars	Liquid only[a]	Usually blended with chloride-based products[a]	Usually blended with chloride-based products	Refined from agricultural base materials[a]
Acetates	Sodium acetate (NaAc)	Acetic acid combined with a metal	Solid or liquid[j]		− 17.8 (0)[c] − 15 (5)[d]	
	Potassium acetate (KAc)		Liquid only[a]	− 60 (− 76) @ 49%[g]	− 32.2 (− 26)[b,c] − 26.1 (− 15)[d]	Reaction of highly concentrated acetic acid with caustic potash (KOH). This reaction produces potassium acetate and water[a]
	Calcium magnesium acetate (CMA)		Solid or liquid[j]	− 27.5 (− 17.5) @ 32.5%[g]	− 17.8 (0)[c] − 5 (23)[b]	Reaction of highly concentrated acetic acid with dolomite limestone [a]
Formates	Sodium formate	Formic acid combined with a metal	Solid or liquid [j]	− 16 (3.2)[f]	− 28.9 (− 20)[e] − 10 (14)[f]	Product of pentaerythritol manufacturing[f]
	Potassium formate			− 61 (− 77.8)[f]	− 28.9 (− 20)[e]	Origin not in currently cited literature
Glycols	Propylene glycol Ethylene glycol	Polyhydric alcohols[j]	Liquid[j]	Varies with product	− 58.9 (− 74)[c] − 28.9 (− 20)[e]	Varies
Succinates	Potassium succinate	Succinic acid combined with a metal	Liquid [h]	− 12 (10.4) @ 50%[h]	− 5 (23)[h]	Occur naturally, genetically synthesized, or manufactured by derivation from succinic acid[h,i]

[a] Language verbatim from Levelton Consultants 2007

[b] Akin et al. 2013

[c] Western Transportation Institute 2017

[d] Fischel 2001

[e] Fortin Consulting Incorporated 2014

[f] Frolova et al. 2015

[g] Ketcham et al. 1996

[h] Fay and Akin 2018

[i] Berglund et al. 2001

[j] Fay et al. 2015

[l] Nixon 2001b

additives must respect toxicity thresholds as presented in Table 2 (most department of transportations (DOTs) defer to the Clear Roads Qualified Product List (Clear Roads 2020) to meet toxicity thresholds set by the Pacific Northwest Snowfighters Association (PNSA 2010)).

2.2.1 Environmental Fate of Deicers in Water Bodies

In surface waters, agro-based products, acetates, formates, and glycols are broken down by microbes, causing an increase in biochemical or biological oxygen demand (BOD) in the receiving water body (Boyles 1997; Fischel 2001; Fortin Consulting Incorporated 2014; Kelting and Laxson 2010; Levelton Consultants 2007; Western Transportation Institute 2017). High BOD levels deplete dissolved oxygen (DO) in surface waters because aquatic microorganisms utilize the organic compounds in organic deicers for metabolism and growth while concurrently consuming oxygen as the electron acceptor. This depletion of dissolved oxygen can cause suffocation and death of aquatic organisms in the receiving water body (Fay and Shi 2012; Levelton Consultants 2007). Chemical oxygen demand (COD), a

Table 2 Heavy metals of interest and the allowable limits defined by Pacific Northwest Snowfighters Association (PNSA) (2010) and Clear Roads Qualified Product List (QPL), Colorado Department of Transportation (CDOT), and Michigan Department of Transportation (MDOT) (Table adapted from Fay and Shi 2012; additional data from CDOT 2017, Clear Roads 2020, PNSA 2010, and MDOT 2017)

Element	Total concentration limits (mg/L)		
	PNSA and clear roads QPL	Colorado DOT	Michigan DOT
Ammonia	–	5.0	–
Arsenic	5.0	5.0	5.0
Barium	100	10	100
Cadmiun	0.2	0.2	0.2
Chromiun	1.0	1.0	1.0
Copper	1.0	1.0	1.0
Lead	1.0	1.0	1.0
Mercury	0.05	0.05	0.05
Molybdenum	–	15	–
Zinc	10	10	10
Selenium	5.0	0.3	5.0
Cyanide	0.2	0.125	0.2

measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant, is another parameter that measures oxygen-depletion capacity of a water sample (Boyles 1997). Thus, the primary concern for organic-based deicers in water bodies has been the high organic matter concentration, which leads to an increase in BOD or COD levels followed by a decrease in DO.

Agro-Based Products The microbial breakdown of agro-based products increases the BOD in water bodies due to high levels of nitrate, phosphate, and total organic carbon content (Fay and Shi 2012; Levelton Consultants 2007). High phosphate and nitrate concentrations may also increase algal growth and cause eutrophication in lakes, which can also lead to DO depletion (Fay and Shi 2012; Levelton Consultants 2007). The level of DO depletion depends on the specific agro-based BOD and COD. Nazari and Shi (2019) found a best-performing agro-based mixture of 0.89% Concord grape extract, 4.57% glycerin, 4.54% sodium formate, 0.19% sodium metasilicate, 18.4% NaCl, and water had less BOD_5 demand (0.77 mg/L BOD_5) and COD demand (135.17 mg/L COD) than a traditional beet juice/salt brine blend (25.82 mg/L BOD_5 and 277.94 mg/L COD), yet the 23% NaCl control had the least BOD_5 demand (0.15 mg/L BOD_5). This suggest agro-based products can be produced to lower the oxygen demand on receiving water bodies compared with traditional agro-based blends.

Acetates The impact of acetate on surface water DO has been investigated in depth. Calcium magnesium acetate was reported not to increase algal growth in surface waters or significantly deplete DO in most applications (Fischel 2001). However, acute toxicity tests have shown that calcium magnesium acetate concentrations of 100 mg/L will completely deplete DO within 2 days, while chronic toxicity tests have shown that calcium magnesium acetate concentrations of 10 mg/L will temporarily reduce saturated DO in ponds by 50% (Fischel 2001). Acetate-based deicers also contain phosphorus, which can lead to lake eutrophication due to an increase in algal growth, which will deplete the DO in receiving water bodies (Fischel 2001). In cases where water temperatures are naturally higher, the potential for DO depletion is further increased (Fischel 2001). A 5-year field test found that while the use of a calcium magnesium acetate deicer resulted in some short-term increases in total organic carbon after rain, there was no detectable effect on DO concentrations in streams (Burkett and Gurr 2004). Additionally, acetates were reported less likely than salts to reach groundwater due to biodegradability in soils and low soil mobility (National Academies of Sciences, Engineering, and Medicine 1991). However, when using sodium and potassium acetate products, sodium and potassium ions are not strongly absorbed by soils and may leach into surface or groundwater (Fischel 2001; Kelting and Laxson 2010).

Formates Formates have the lowest BOD in comparison with other non-chloride deicers (Fortin Consulting Incorporated 2014). Sodium formate, in particular, has lower COD than acetates, but can increase turbidity, hardness, and alkalinity in water (Fay and Shi 2012). Formates do not appear to have a significant adverse impact on groundwater characteristics (Fay and Shi 2012; Fortin Consulting Incorporated 2014; Hellstén et al. 2005b).

Glycols Glycols, on the other hand, have an extremely high BOD in surface waters—the highest of most deicing materials—since it is readily biodegraded (Castro et al. 2005; Fay et al. 2015). Propylene glycol has a higher BOD than ethylene glycol (Fay et al. 2015; Western Transportation Institute 2017). Due to microbial degradation, glycol runoff is easily transported to surface and groundwater, but does not tend to accumulate (Western Transportation Institute 2017). The microbial oxygen demand is typically reduced at lower temperatures, but the difference varies by deicer (Corsi et al. 2012). The water-soluble, corrosion-inhibiting additive, benzotriazole, can decrease microbe degradation of glycols, and significant amounts of benzotriazole can enter surface and ground waters (Castro et al. 2005). The maximum permissible concentration of ethylene glycol and benzotriazole in surface waters has been suggested to be 1 mg/L and 0.1 mg/L, respectively (Castro et al. 2005). The frequent use of glycol-based deicing products by airports create more harmful surface waters in nearby environments if not treated properly (Western Transportation Institute 2017).

Succinates There is limited information in the literature on how succinates affect water bodies. The BOD of potassium succinate was found to be similar to the BOD of potassium acetate and potassium formate (Fay and Akin 2018).

2.2.2 Environmental Fate of Deicers in Soil

Deicer alternatives can influence soil in several aspects. Some of the deicers can reduce oxygen content in the soil leading to temporary anaerobic conditions and stimulate plant growth, as well as increase or decrease permeability. Additionally, heavy metal mobilization can occur as the result of deicer laden runoff. The mobilization of heavy metals (e.g., Cu, Ni, Cr, Pb, and Fe) from roadside soils has been shown to be mostly controlled by organic matter mobilization, which occurred in soils with high exchangeable sodium ions and low electrolyte concentration (Amrhein et al. 1992). Any changes in soil conditions can also influence water conditions, as the runoff of the deicer products can percolate from the soil into water bodies.

Agro-Based Products Agro-based products are composed of organic material that is readily broken down in the environment by microorganisms. The breakdown of high concentrations of organic material can cause temporary anaerobic soil conditions, as microorganisms biodegrade the agro-based product and consume oxygen as the electron acceptor (Fay and Shi 2012).

Acetates Similarly, acetate-based deicer runoff can cause temporary anaerobic soil conditions in the same mechanistic way as agro-based deicers due to the organic acetate ion (Levelton Consultants 2007; Western Transportation Institute 2017). Horner and Brenner (1992) found calcium magnesium acetate in soils showed complete decomposition (biodegradation) within 4 weeks at 2 °C and 2 weeks at 10 °C. In modeling studies, researchers found that during routine operation, calcium magnesium acetate runoff concentrations range between 10 and 100 mg/L (avg.) with a maximum value of 500 mg/L (Fischel 2001). When using calcium magnesium acetate and potassium acetate deicing products, calcium and magnesium ions accumulate in the soil and increase soil permeability by up to 20% (Amrhein et al. 1992; Fischel 2001). High calcium concentrations can cause clumping of fine clay particles to form aggregates and reduce organic matter and clay dispersion, which increase soil aeration and water drainage (Fischel 2001). This increase improves soil structure and has other beneficial impacts such as stimulating plant growth (Amrhein et al. 1992; Fischel 2001; Kelting and Laxson 2010). On the other hand, sodium acetate can decrease soil structure and permeability due to high sodium ion concentrations (Fischel 2001; Levelton Consultants 2007). The degradation of acetate ions can also release trace metals entrapped in the soil ("exchangeable ions") although studies have shown this is unlikely, as acetates degrade rapidly (Horner and Brenner 1992; Fischel 2001; Kelting and Laxson 2010; National Academies of Sciences, Engineering, and Medicine 1991; Western Transportation Institute 2017). Researchers found that high concentrations of calcium magnesium acetate solutions leached slightly more Ni, Cr, Cd, Pb, and Fe from soils than equivalent NaCl solutions due to effects of ligand complexation (Cl vs acetate) and competitive metal mobilization exchange. The concentrations of the heavy metals did not exceed the drinking water criteria, but the concentrations of Cu, Ni, and Fe did exceed the criteria for protection of freshwater aquatic life (Amrhein et al. 1992). However, a 5-year-long field test found no evidence that the use of a calcium magnesium deicer affected soil chemistry (Burkett and Gurr 2004).

Formates Potassium formate has been shown to biodegrade in soils even at low temperatures, − 2 to 6 °C (28.4 to 42.8 °F) (Hellstén et al. 2005b) and at rates faster than potassium acetate in low temperatures 3 to 6 °C (26.6 to 42.8 °F) (Hellstén and Nystén 2003). Potassium formate is expected to have less of a negative impact on soils than acetate deicers, as potassium formate has a lower carbon content than acetate, less of an effect on oxygen levels during decomposition, and leached less metals from the soil (Hellstén and Nystén 2003; Rasa et al. 2006; Salminen et al. 2011). One incubation lab study found that incubation with sodium chloride created more water-soluble cadmium compounds than with potassium formate suggesting that using potassium formate instead of traditional chlorides would reduce the risk of cadmium transfer from the soil into water bodies (Rasa et al. 2006).

Glycols Glycols have high mobility in soils, since aerobic psychrophilic microbes in soils are capable of degrading glycols at temperatures below 0 °C, assuming pockets of liquid water are available, making the bioaccumulation and absorption potentials very low (Castro et al. 2005; Fay et al. 2015; Western Transportation Institute 2017). Plants have also been shown to aid in the biodegradation of glycol waste by providing better habitats and nutrients to soil microbes, while uptaking and transforming the corrosion inhibitor, benzotriazole, to compounds used for metabolism and growth (Castro et al. 2005).

Succinates There were no significant succinate effects on soil reported in the literature at the time of this article.

2.2.3 Potential Impacts on Flora and Fauna

Deicing materials have a variety of effects on flora and fauna, especially due to influences on soil and water as discussed above. Consumption of deicing materials by animals or absorption via plant root systems can contribute to biological changes, even provide necessary nutrients for growth, or can be toxic. All solid deicing materials, i.e., abrasives, chlorides, calcium magnesium acetate, sodium acetate, and sodium formate have the potential, at high concentrations, to create small particles that can become airborne and increase air pollution, which causes irritation of the eyes, throat, skin, respiratory systems, and digestive systems (Fischel 2001).

Agro-Based Products Few studies exist for the environmental impacts of agro-based winter maintenance materials concerning vegetation, fauna, and human health. However, there is a suggestion that agro-based products may attract wildlife to roadways and increase vehicle-animal collisions, but few field tests have been conducted to support this hypothesis (Fay and Shi 2012). Schuler et al. (2017) assessed three road salts (NaCl, $MgCl_2$, and ClearLane™) and two road salts mixed with organic additives (GeoMelt™ and Magic Salt™) and found NaCl had few impacts on aquatic organisms, but the organic additives led to increased microbial activity in the water body, which decreased dissolved oxygen, converted unusable phosphorous to a usable form that led to algal growth and subsequent zooplankton growth.

Acetates With respect to plant life, acetate winter maintenance materials have been considered less harmful than chloride salts, because potassium acetates have minimal impacts on vegetation growth at concentrations below 500 mg/L, the concentration of normal deicing operations (Fischel 2001). Calcium magnesium acetates are generally harmless to vegetation and may even stimulate plant growth, as long as high calcium magnesium acetate concentrations do not accumulate near roots (Fischel 2001). A 5-year-long field test of calcium magnesium acetate found no evidence that the deicer's use affected the vegetation or aquatic invertebrates (Burkett and Gurr 2004). High concentrations of acetates, above 2500 mg/L, can cause osmotic stress in vegetation, but these concentrations are not seen during routine winter operations (Kelting and Laxson 2010). However, one study that investigated the ecotoxicity of deicers found that potassium acetate and calcium magnesium acetate had greater toxicity than chloride salts to plant growth in vitro based on *Lemna* growth inhibition and *Allium cepa* root elongation tests (Joutti et al. 2003). Of the deicers tested, only potassium formate had greater toxicity than potassium acetate (Joutti et al. 2003).

In relation to aquatic organisms, the most relevant risk from acetates is suffocation due to DO depletion in the water body, and with the exception of calcium magnesium acetate, acetates can be more toxic than traditional chlorides to fish, water fleas, and algae (Fischel 2001). However, acetate deicer products are generally harmless to most land animals when ingested (Fischel 2001; Kelting and Laxson 2010). Sodium acetate has the potential to attract animals to roadways due to the sodium content (Fischel 2001; Levelton Consultants 2007), which increases the risk of vehicle-animal collisions. Researchers compared the toxicity of calcium magnesium acetate, potassium acetate, and a blend of calcium magnesium acetate and potassium acetate with the toxicity of chlorides on fathead minnows, *Selenastrum capricornutum*, and *Ceriodaphnia dubia* (Levelton Consultants 2007). Overall, the acetates were less toxic than the chlorides, although the potassium acetate and the blend of calcium magnesium acetate and potassium acetate were equally toxic to the fathead minnows as the chlorides (Levelton Consultants 2007). However, a dilution of 500:1 would not be great enough for the *Selenastrum capricornutum* and *Ceriodaphnia dubia* to avoid nonlethal effects (Levelton Consultants 2007). Pilgrim (2013) also examined the impact of a potassium acetate–based deicer (CF-7 by Cryotec) on fathead minnows, *Selenastrum capricornutum*, and *Ceriodaphnia dubia* and found a reduced growth with increased product dose for each species. Other researchers found that larval wood frogs (*Rana[Lithobates]sylvatica*) exposed to a range of environmentally realistic concentrations of six deicers were least sensitive (i.e., had the lowest mortality rate) to urea, sodium chloride, and magnesium chloride and most sensitive to acetates (calcium magnesium acetate, potassium acetate) and calcium chloride (Harless et al. 2011). Another study examining the ecotoxicity of deicers found that calcium magnesium acetate was significantly less toxic than sodium formate and sodium chloride, although there was some variability between species and endpoints (Roubidoux and Delisle 2001).

Calcium magnesium acetate has similar toxicity levels to chlorides for oral toxicity and skin and eye irritation and has low toxicity for inhalation and dermal toxicity (Levelton Consultants 2007). Due to the potassium ion content in potassium acetate, the deicer may cause “irritation or inflammation of the stomach lining, muscular weaknesses, burning, tingling and numbness sensations of hands and feet, slower heartbeat, reduced blood pressure, and irregular heartbeats” in young children or adults suffering from kidney or heart disease if ingested (Fischel 2001).

Formates The calcium, magnesium, and potassium ions in formates have beneficial applications for plants, thus low concentrations of formate deicers can stimulate growth (Hanslin 2011). High concentrations of formate can have detrimental effects on vegetation. One experiment, which sought to study the degradation of potassium formate in soil, found that the application of 3.4 kg/m^2 of potassium acetate resulted in the death of perennial plants (Hellstén et al. 2005a). A concentration of 3.4 kg/m^2 is unlikely to reach vegetation in field conditions but demonstrates the necessity of further study (Hellstén et al. 2005a). In addition, while sodium formate has similar toxicity levels as sodium chloride to some plants and the invertebrate *Eisenia fetida*, it is more toxic than calcium magnesium acetate (Roubidoux and Delisle 2001). As mentioned previously, one study found that potassium formate had the highest toxicity to plant growth by inhibiting root elongation in vitro more than potassium acetate, calcium magnesium acetate, calcium chloride, sodium chloride, and magnesium chloride (Joutti et al. 2003). The environmental impacts of a product comprised of equimolar sodium formate and sodium acetate were investigated in the study by Bang and Johnston (1998) and the authors concluded that the product was “relatively harmless to aquatic animals.” The same study also stated that formates promoted bacterial growth, and that rainbow trout living in tanks with water mixed with equimolar sodium formate and sodium acetate at higher concentrations suffered disorientation, concave abdomen, gill distention, and spinal curvature (Bang and Johnston 1998). However, the product had low toxicity to rainbow trout and roadside vegetation (Bang and Johnston 1998). Another study regarding the toxicity for aquatic fauna including a species of minnow and water flea found that both acute and chronic toxicity end points were generally smaller for potassium acetate than for sodium formate (Corsi et al. 2009). No impacts of formates on humans were found in the literature.

Glycols Glycols can inhibit plant growth, but not more than traditional chlorides (Fay et al. 2015), yet glycol deicing products are toxic at high concentrations and possibly carcinogenic to fauna (Western Transportation Institute 2017). Ethylene glycol is acutely toxic to fauna and is subject to the EPA regulations under the Clean Air Act, CERCLA, TSCA, and EPCRA (EPA 2018; Fay et al. 2015; Western Transportation Institute 2017). Glycols can harm kidney and central nervous systems in aquatic and land organisms, and some additives may be known endocrine disruptors (Castro et al. 2005; Western Transportation Institute 2017). Additives may also inhibit the growth of glycol degrading microbes and slow the biodegradation process (Corsi et al. 2012). The additive benzotriazole is known to be the most toxic component of glycol-based products (Castro et al. 2005). Pillard et al. (2001) tested the toxicity of benzotriazole and its derivatives to fathead minnows and water fleas. The LC_{50} of benzotriazole was 102 mg/L and 65 mg/L, respectively, and the LC_{50} of butylbenzotriazole, the most toxic derivative tested, was 1.1 mg/L and 3.3 mg/L, respectively (Pillard et al. 2001). In addition, Pillard and DuFresne (1999) found pure ethylene glycol and propylene glycol were less toxic to lettuce (*Lactuca sativa*), perennial ryegrass (Lo-lium perenne), a green alga (*Selenastrum capricornutum*), and duckweed (*Lemna minor*) than two formulated glycol aircraft deicing/anti-icing fluids, which suggest other compounds in the formulated mixture contribute to the toxicity of the deicers. Additionally, Pilgrim (2013) examined the impact of a glycol-based deicer (Apogee by Envirotech Services) on fathead minnows, *Selenastrum capricornutum*, and *Ceriodaphnia dubia* and found an extremely low survival rate (10%) at a chronic exposure time of 7 days.

Ethylene glycol is toxic to humans at a lethal dose of 1.0–1.5 mL/kg body weight (Essarras et al. 2018). Ingestion can lead to acute kidney failure, central nervous system depression, and tachycardia (Castro et al. 2005; Essarras et al. 2018; Western Transportation Institute 2017). In 2003, ethylene glycol was the chemical responsible for the most human deaths in the USA (Essarras et al. 2018). However, propylene glycol alone is non-toxic (Fay et al. 2015; Western Transportation Institute 2017).

Succinates Studies examining the environmental effects of succinate deicers on flora and fauna were not available in the literature reviewed.

2.2.4 Environmental Impacts Summary

The use of alternative deicers is not without environmental drawbacks. While chloride salts accumulate in the environment, organic alternatives are broken down and increase BOD/COD levels in receiving environments. Microbial biodegradation of the deicers decreases the available oxygen in the environment and can lead to anoxic environments. In addition, heavy metal mobilization can be a concern; however, recent studies have found little cause for alarm. Several deicers are toxic to organisms at certain concentrations, thus appropriate concentrations of deicers to achieve sufficient winter road maintenance must be considered when determining toxicity and impacts (Harless 2011; Roubidoux and Delisle 2001). A summary of environmental impacts of alternative deicers is presented in Table 3.

2.3 Corrosion and Infrastructure Impacts

Deicing materials affect corrosion and infrastructure on the fabricated environment in a variety of ways depending on the specific weather conditions, product concentrations, metal types, and other complex processes. Deterioration rates via corrosion of metals and concrete, which make up vehicle bodies, roads, bridges, and buildings, can have detrimental long-term effects on infrastructure and individual property. Thus, corrosion and infrastructure impacts are reviewed in this section in two parts: the effect on metals and the effect on road infrastructure.

2.3.1 Corrosion of Metals

Deicing alternatives examined in this review generally led to lower levels of corrosion initiation than similar quantities of chloride-based inorganic deicers or acted as corrosion inhibitors.

Agro-Based Products As a corrosion inhibitor, agro-based additives can “reabsorb and cover metal surfaces,” which decreases chemical penetration of corrosion initiating ions and protects against corrosion attacks (Taylor et al. 2010; Nazari et al. 2017). Agro-based products have been shown to reduce corrosion-induced rusting on equipment, which can reduce maintenance costs overtime (Fay and Shi 2012; Kahl 2002). Nazari et al. (2017) found the use of a sugar beet by-product enhanced the resistance of carbon steel due to the formation of a temporary protective coating. Nazari and Shi (2019) found the corrosion rates of most C1010 carbon steel samples exposed to 21 anti-icing agro-based mixtures were lower than the corrosion rates of the samples exposed to 23% NaCl brine and beet juice/salt brine blend. In addition, Jungwirth and Shi (2019) found an agro-based sugar beet product and a blend of the sugar beet product and salt brine both exhibited lower corrosion rates than a salt brine control. While significantly less corrosion inducing than chlorides, agro-based products can still reduce the electrochemical threshold of corrosion initiation which can lead to deterioration (Levelton Consultants 2007).

Acetates The effects of acetate-based deicing materials on metals have been studied extensively. While some generalizations can be made, the relative ability of acetates to induce corrosion compared with road salts varies by formulation and alloy. Acetates tend to initiate corrosion on galvanized steel and some metals by reducing the electrochemical threshold of corrosion initiation, similar to agro-based products but not to such low levels that are achieved with chloride-based salts on bridge steel, automobiles, and aircraft metals (Kelting and Laxson 2010; Western Transportation Institute 2017; Xie et al. 2015). Lab studies show that calcium magnesium acetate initiates corrosion on steel, cast iron, aluminum, and galvanized steel but not to such low levels as those alloys exposed to sodium chloride (Xie et al. 2015). One lab study reported that potassium acetate products do not significantly initiate corrosion to stainless steel or plain steel (Xie et al. 2015). Another lab study found that potassium and sodium acetate products were much less corrosive to mild steel than chloride-based deicers (Shi et al. 2009a). Kelting and Laxson (2010) found that acetate products initiate corrosion in bridge metal anywhere from 30 to 90% less and concrete steel rebar 2–4 times less than sodium chloride products. Several lab studies tested the effects of different acetate formulations on specific alloys; the results are shown below in Table 4 (Huttunen-Saarivirta et al. 2009; Levelton Consultants 2007; Shi et al. 2009a; Xie et al. 2015).

Table 3 Environmental impacts of deicers (Table adapted from Fay and Shi 2012)

	Chlorides	Abrasives	Agro-based	Acetates	Formates	Glycols	Succinates
Surface and ground water	Can cause lake stratification by increasing algal growth Harden water can cause anoxic conditions	Increase turbidity Clog small streams Limit DO supply	Increases BOD Decreases DO Increase algal growth Potential for eutrophication	Increase BOD Decrease DO Increase K concentration Can induce lake stratification by increasing algal growth	Less BOD than acetates and glycols Promote bacterial growth Increase turbidity, alkalinity, and hardness	Highest BOD Decrease DO Potential to leach heavy metals into water	Significantly increase BOD Decrease DO
Soil	Potential to mobilize heavy metals Increase salinity Change permeability and decrease fertility	Accumulate	High concentrations can create anaerobic soil conditions	Potential to cause anaerobic conditions Potential to leach trace metals from soil Increase soil permeability	Smaller impact than acetates Reduce risk of cadmium transfer from soil to water	Potentially toxic components Potential to cause anaerobic conditions	No significant impact found
Fauna	Potential to increase	animal-vehicle collisions	Reduce oxygen in stream bed Reduces fish reproduction	Hypothesis: Potential to increase animal-vehicle collisions	May cause the suffocation of aquatic organisms due to oxygen depletion Potential toxicity to aquatic life Potential to increase		
		animal-vehicle collisions	Potential to harm aquatic life	Bacterial and algal growth Ethylene glycol is toxic when ingested	Hypothesis: May cause the suffocation of aquatic organisms		
Flora	Reduce vegetation growth Potential to stress and kill roadside vegetation	Potential for accumulation and stress	Hypothesis: No effect	Little to no impact at relevant deicer's concentration	Little impact at lower concentrations More toxic than acetates	In low concentrations have fertilizer effects In high concentrations inhibit plant growth	More research needed
Human	Can lead to hypertension, skin, and eye irritation.	Potential to increase $PM_{2.5}$ & PM_{10} that can be carcinogenic, cause throat and eye irritation	Hypothesis: No effect	Solids can increase particulate matter in air Skin and eye, nose, and digestive system irritant	Solids can increase particulate matter in air Skin and eye, nose, and digestive system irritant	Ethylene glycol is toxic when ingested Skin and eye irritation	More research needed

Table 4 Corrosion impacts of acetates and formates on metal alloys

Metal	Deicer					
	Acetates				Formates	
	Sodium acetate (NaAc)	Potassium acetate (KAc)	Calcium magnesium acetate (CMA)	Blend of CMA and KAc	Potassium formate	Sodium formate
	Cadmium-coated and chromate-treated steel AISI 4340	Initiates corrosion[a]	Initiates corrosion[a]			Initiates corrosion[a]
Initiates corrosion[a]						
Anodized aluminum alloy 7075-T6	Initiates corrosion[a]	Initiates corrosion[a]			Initiates corrosion[a]	Initiates corrosion[a]
	Chromate-treated aluminum alloy 7075-T6	Initiates corrosion[a]	Initiates corrosion[a]			Initiates corrosion[a]
Initiates corrosion[a]						
	Aluminum-coated steel AISI 4340	Initiates corrosion[a]	Initiates corrosion[a]			Initiates corrosion[a]
Initiates corrosion[a]						
Magnesium alloy AZ91C-T6		Initiates less corrosion than chlorides[b]	Initiates less corrosion than chlorides[b]	Initiates less corrosion than chlorides[b]		
Structural steel alloy A36		Greatly less corrosion initiation than chlorides[b]	Greatly less corrosion initiation than chlorides[b]	Greatly less corrosion initiation than chlorides[b]		
Wrought aluminum alloy AA6061-T6		Similar corrosion initiation as chlorides[b]	Similar corrosion initiation as chlorides[b]	Similar corrosion initiation as chlorides[b]		
Cast aluminum alloy AA356.2		Similar corrosion initiation as chlorides[b]	Similar corrosion initiation as chlorides[b]	Similar corrosion initiation as chlorides[b]		

Table 4 (continued)

Metal	Deicer					
	Acetates				Formates	
	Sodium acetate (NaAc)	Potassium acetate (KAc)	Calcium magnesium acetate (CMA)	Blend of CMA and KAc	Potassium formate	Sodium formate
Free machining brass CDA 360		Similar or more corrosion initiation as chlorides[b]	Similar or more corrosion initiation as chlorides[b]	Similar or more corrosion initiation as chlorides[b]		
Galvanized steel	Similar corrosion initiation as chlorides[c]	Similar corrosion initiation as chlorides[c]	Initiates less corrosion than chlorides[d]			

[a] Huttunen-Saarivirta et al. 2009

[b] Levelton Consultants 2007

[c] Shi et al. 2009a

[d] Xie et al. 2015

Formates Similar studies have investigated the corrosion initiation behavior of formates. There is some disagreement in the literature about the effects of formates on steel. Certain studies reported that sodium and potassium formate do not initiate corrosion in steel (Fortin Consulting Incorporated 2014) and sodium formate served as a corrosion inhibitor (Nazari and Shi 2019). However, potassium formate was found to initiate corrosion in plain steel and galvanized steel, but not stainless steel (Xie et al. 2015). Another study found that potassium formate induced more corrosion to cadmium plating than potassium acetates (Huttunen-Saarivirta et al. 2013). Potassium formate has also been reported to initiate corrosion in landing gear and wiring in aircraft (Shi et al. 2009b).

Glycols Glycols are non-corrosive to steel (Western Transportation Institute 2017). No other impacts to roadway metals were found in the literature.

Succinates Succinates can be used as corrosion-inhibiting additives (Berglund et al. 2001; Fay and Akin 2018). One study found the use of succinate reduced the corrosion rate of brine to steel significantly, but slightly increased the corrosion rate to aluminum (Alizadeh and Berglund 2005).

2.3.2 Impacts on Road Infrastructure

In general, chloride ion penetration into concrete initiates the corrosion of concrete reinforcing steel and reactions of deicers (especially magnesium and calcium) with cement paste, which deteriorates the cement matrix (Farnam et al. 2015; Levelton Consultants 2007). In addition, deicers can have negative impacts on asphalt, including negative effects on skid resistance, pavement structure (e.g., loss of structure or elasticity) and increased freeze/thaw cycles which could lead to stripping, cracking, or damage to internal surface microstructure (Shi et al. 2009c; Nazari and Shi 2019). However, research has been conducted to counteract non-chloride deicer asphalt deterioration through the addition of nanoclay and carbon microfibers (Yang et al. 2018). The researchers discovered that the incorporation of a small amount of nanoclay in four different non-chloride deicers (dipotassium succinate, potassium formate, potassium propionate, and potassium acetate) applied on asphalt concrete produced an improved stripping resistance and reduced moisture susceptibility, yet the addition of carbon microfiber increased moisture susceptibility (Yang et al. 2018).

Agro-Based Products Agro-based impacts on infrastructure vary based on the makeup of the deicer. One study found that when comparing concrete deterioration caused by agro-based materials with traditional chloride salts and potassium acetate, agro-based materials had the least chemical penetration and scaling damage (Taylor et al. 2010). Other researchers found that mortar samples exposed to agro (bio)-based anti-icers had a higher splitting tensile strength after ten freeze/thaw cycles than when exposed to 23% NaCl control, which suggest less internal damage (Nazari and Shi 2019). In conjunction, Jungwirth and Shi (2017) found an agro-based sugar beet product and a blend of the sugar beet product plus salt brine led to less freeze-thaw-related surface scaling or visible distress in the Portland cement concrete compared with the salt brine control; however, the agro-based product and blend exhibited more chemical attacks on the concrete than the salt brine control as indicated by a reduction of concrete strength. Wang et al. (2006) found that Portland cement paste and concrete experienced minor scaling when exposed to an agro-based product in both freeze/thaw cycling and wet/dry cycling. The agro-based product also resulted in significant mass loss, although overall it caused significantly less damage than calcium chloride (Wang et al. 2006).

Acetates A variety of studies have been performed to determine the effects of acetates on road infrastructure such as asphalt and concrete, and acetates have largely been found to negatively affect the infrastructure. Potassium and sodium acetate have the potential to induce alkali-silica reactivity (ASR) in susceptible aggregates and high-alkali cement systems, and potassium acetate can amplify several distress mechanisms (Rangaraju et al. 2006; Rangaraju et al. 2007; Truschke et al. 2011; Western Transportation Institute 2017). ASR occurs when reactive aggregates are in the presence of alkali hydroxides; potassium acetate appears to increase the activity of hydroxides, increasing the pH and potentially exacerbating ASR (Math et al. 2011). However, researchers found that for tested aggregates, low-lime and intermediate-lime fly ash at 25% replacement level or higher and ground granulated blast furnace slag at 50% replacement level can mitigate expansion due to ASR from potassium acetate (Rangaraju and Desai 2009). In regard to asphalt, Pan (2007) found the acetate anion in sodium acetate contributed to the emulsification of the asphalt.

There are conflicting studies on the effect of acetates on Portland cement: one study found that potassium acetate was damaging to Portland cement durability while calcium magnesium acetate was not (Fay and Shi 2011), while another found that potassium acetate resulted in only limited deterioration (Wang et al. 2006). Three other studies found that calcium magnesium acetate had deleterious effects on Portland cement systems (Xie et al. 2015). Shi et al. (2010b) tested the effect of diluted chloride, acetate, and formate-based deicers on Portland cement durability to better simulate the deicer concentrations in the field and found that all tested deicers underwent chemical reactions with the cement. However, the calcium magnesium acetate and magnesium chloride–based deicer did not affect the cement durability, the sodium acetate sodium/formate blend had a moderate effect on the cement durability, and the potassium acetate and sodium chloride–based deicers had the greatest effect on the cement durability (Shi et al. 2010b). However, Santagata and Collepardi (2000) found that continuous exposure of limestone-Portland cement to calcium magnesium acetate results in mass loss and decreased load capacity through the deterioration of the concrete matrix and exposure of the aggregates, although using slag cement instead of limestone resulted in less damage.

Both calcium magnesium acetate and potassium acetate have been shown to cause concrete surface scaling (Wang et al. 2006; Xie et al. 2015). However, the life of concrete may be extended by using sodium acetate by reducing scaling and water penetration (Kelting and Laxson 2010; Xie et al. 2015). One lab test found that concrete samples exhibited more surface distress after freeze thaw cycles submerged in alkali-based deicer solutions (including sodium chloride and potassium acetate) than alkali earth–based deicers (including calcium acetate) (Xie et al. 2015). Another lab study found that potassium acetate can chemically attack isolated aggregate particles of limestone and quartzite; however, the study used parameters that were not representative of field conditions (Hassan et al. 2002). Xie et al. (2017) examined field concrete cores exposed to potassium acetate deicers (Nebraska bridge decks) and sodium chloride deicers (Utah bridge decks). The researchers found concrete cores exposed to potassium acetate experienced a higher reduction in mechanical properties (compressive strength, splitting tensile strength, and microhardness) than the cores exposed to sodium chloride. However, potassium acetate exhibited a higher ice-melting capacity than sodium chloride, thus a lower application rate could be used for similar level of service. Similarly, Lee et al. (2000) compared Iowa highway concrete cores exposed to sodium, calcium, and magnesium chloride and lab mixtures of calcium and magnesium acetate in wet/dry cycles and freeze/thaw cycles and found that the acetate mixture was the most destructive to the cores.

Formates Like acetates, formates have been found to negatively affect concrete. Formates may cause concrete deterioration by increasing the solubility of portlandite in cement due to the formation of Ca-formate complexes (Giebson et al. 2010). Potassium formate and a blend of sodium acetate and formate did cause noticeable deterioration of concrete (Xie et al. 2015). Shi et al. (2010b) found a diluted potassium formate and sodium formate/sodium acetate blend resulted in moderate damage to Portland cement concrete. Researchers found that sodium formate solutions can chemically attack isolated aggregate particles of limestone and quartzite; however, the study used parameters that were not representative of field conditions (Hassan et al. 2002).

Glycols Unlike acetates and formates, glycols have few impacts on infrastructure as they are non-corrosive to steel but may degrade concrete (Ma et al. 2011; Western Transportation Institute 2017). One freeze-thaw study found that glycol decreased Portland cement concrete durability to a degree comparable with sodium chloride and found there was significant surface deterioration (Ma et al. 2011). Another study found that as ethylene glycol concentration increased, the ice formation pressure (indicative of freeze/thaw cycles) decreased, yet ethylene glycol deicer imparted surface deterioration and inner crack penetration under freeze/thaw cycles in concrete (Ma et al. 2018).

Succinates Potassium succinate causes little to no concrete scaling (Fay and Akin 2018). No other corrosion or infrastructure impacts from potassium succinate were found in the literature.

2.3.3 Corrosion and Infrastructure Summary

Most of the literature focuses on corrosion and infrastructure impacts of acetates and formates. While generally accepted as less corrosion inducing than chlorides, these materials still have the potential to initiate corrosion on several alloys. Neither material is gentle on road infrastructure, but the extent to which acetates and formates damage and whether acetates and formates are more or less damaging than chlorides is contested in the literature. The literature indicates agro-based and succinate deicers have only negligible corrosion and infrastructure effects. Glycol is non-corrosive to steel but may be damaging to cement and concrete.

3 Challenges for Implementing Alternative Deicers in the Field

With the importance of finding alternative deicing materials that will not harm the environment or infrastructure, there are also challenges with implementing alternative deicers in the field. Operations staff must be adequately prepared to handle the alternative deicing product. The perception among administrators and operations staff is that any change to current practices would involve a high monetary cost (Personal correspondence with Maryland Transportation Authority Operations Administrators and Chief Facility Maintenance Officers). Expenses, in addition to those for any new product purchased, would include personnel training, equipment purchases or modifications, storage considerations, and new policies. The operation modifications must be considered prior to implementation of an alternative deicer.

Liquid non-chloride products often require special handling and application, such as mixing before use if stored over the summer or using automated spray systems to apply the product (Western Transportation Institute 2017). Special protective gear might also be needed while using some of these products (Western Transportation Institute 2017). Once an alternative deicing material is deemed appropriate for use on roadways, manufacturers should be researched to assure that large quantities of the product will be accessible when needed and the proper inventory is maintained. The supplier also must be able to provide accurate, consistent blends of the product (Shi et al. 2009a). In addition, storage concerns must be considered including any new storage facilities that must be provided and storage conditions for “when these materials dry out or are mixed with salt” (Personal correspondence with Maryland Transportation Authority Operations Administrators and Chief Facility Maintenance Officers). Storage conditions may be different for each product (Western Transportation Institute 2017).

If alternative materials require higher application frequency than salt, trucks with a larger capacity may need to be purchased. An additional concern with products that are added to salt, such as agro-based, is that anything that helps salt stick to the roads will also increase the likelihood of the product sticking to the trucks. Reid (2017) states that “Substitutes for salt can cause problems of their own, including clogging the equipment, generating an unpleasant odor, or leaving a residue that sticks to tires or other parts of a vehicle.” In other cases, such as the use of abrasives, additional clean up may be required after a storm or storm season has passed. In Madison, WI, for example, street cleaners are employed in early spring to remove the sand remaining on roadways after winter road maintenance months (Talend 2016).

Training for equipment operators and mechanics is imperative, whether salt or an alternative product is used. Equipment calibration is necessary to reduce the amount of misapplied or over-applied product (Talend 2016), and equipment operators need to know when the calibrations need adjustment. Mechanics often do not know how to repair malfunctioning calibration equipment (Personal correspondence with Maryland Transportation Authority Operations Administrators and Chief Facility Maintenance Officers) and this can cause operators to revert to “manual settings,” which can defeat the purpose of using alternative products. Thus, further field and pilot studies are needed to elucidate the additional challenges of implementing specific alternative deicers in the field so proper preparations and training can be developed to ensure safe winter road conditions.

4 Conclusion

Deicers used for roadway snow and ice control have significant impacts on the surrounding environment and infrastructure depending on a wide array of factors including where and how the deicer is applied, and the chemical makeup of each deicer. The focus of this review is to compare the effectiveness, environmental effects, and infrastructure effects of alternative organic deicers. For most organic deicers, the biggest environmental concern is the increase in BOD in surface waters resulting from organic deicer breakdown, which leads to dissolved oxygen depletion. Little corrosion and infrastructure effects have been found for agro-based and glycol products; however, acetates and formates have been found to have greater corrosion impacts than road salts, depending on the material. Given glycol's toxicity, high BOD, and lack of current application to roadways, it is unlikely this alternative will replace road salts for general deicer application. Succinates are still extremely new to the market; thus, few data are available for understanding the environmental and infrastructure impacts. Acetates and formates have a similar corrosivity to infrastructure as chlorides yet are not as effective as chlorides during routine winter weather temperatures. Agro-based products have the most potential to be used as an alternative deicer, primarily as an additive to road salts. As new deicers continue to emerge on the market for snow and ice control, robust research must continue to assess the infrastructure and environmental impacts to protect the surrounding environments.

Further investigation into a variety of research topics is needed to continue to mitigate the environmental and infrastructure impacts deicers have on the surrounding environment. First, focused laboratory and field studies are needed to fully understand alternative deicers' long-term impacts on environmental and roadway systems at the effective field temperature ranges to develop specific winter maintenance practices for each deicer. Second, field tests on succinates should be investigated to determine if succinates are viable alternatives. Third, sodium chloride is the most effective and affordable deicer currently, thus continued research to mitigate the environmental and corrosive damages of sodium chloride through use of best management practices is vital for the protection of surrounding infrastructure. Fourth, there is a significant need to develop a comprehensive life cycle assessment and total life cycle cost of each deicer in order to accurately explore the feasibility of each alternative deicer over short- and long-time frames. Future research should include a cost benefit analysis of each alternative in order to compare capital and long-term costs. Finally, winter road maintenance must take a holistic view incorporating all the concerns related to environmental, safety, cost, and infrastructure management.

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Compliance with Ethical Standards

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