HIGH SCHOOL EDITION
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An Evaluation of the Ice-Melting Capacity, Ecotoxicity, and Corrosivity of Agro-Based Deicers

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ABSTRACT

Despite being affordable and accessible, traditional road salts have introduced pressing environmental and physical implications. Agro-based deicers decrease the concentration of NaCl required by supplementing a carbohydrate-rich food product. Previous literature has shown that agro-based deicers may be a promising alternative, but potential confounding environmental and physical impacts are still under researched. This study observed prevalent carbohydrates found in fermented food waste–sucrose, fructose, and sorbitol–in brines (23.3 wt% NaCl in water). Each agro-based deicer's performance and impact attributes were evaluated. The Mechanical Rocker Test for Ice-Melting Capacity (MRT-IMC) was used to determine deicing effectiveness. Ecotoxicity was measured by examining the 24-hour lethality of *Daphnia magna*. Finally, physical impact was investigated by testing steel corrosion. This three-fold analysis was adopted to holistically evaluate the effectiveness and confounding effects of novel, food-based road salts. The study concluded sorbitol was the best agro-based deicer additive, having outperformed 25.0 wt% NaCl by over 20% at 45 minutes. It also mediated ecotoxicity–with a negative correlation between *D. magna* lethality and carbohydrate concentration–and presented powerful corrosion-inhibiting properties, especially at higher weight fractions. These results shed light on the innovative formulation of deicers that could help support the sustainability of northern cities globally.

Introduction

Road salts play imperative roles in northern temperate communities, minimizing vehicular accidents and maintaining social order. Road salts were introduced to cities in North America in the 1930s and usage has skyrocketed since (Figure 1). 2019 statistics show that the U.S. mined 42 metric tonnes of NaCl and highway deicing accounts for 43% of all salt consumed (U.S. Geological Survey, 2020). Other common deicers include calcium chloride, magnesium chloride, potassium chloride, urea, and more recently, agro-based deicers such as beet brines.

Road salts are a deicer. It works to inhibit ice formation through the process of freezing point depression. However, there are significant concerns about the implications of traditional road salts, particularly their unintended consequences on the natural environment and physical infrastructures. According to a study conducted by Nazari & Shi (2019), the U.S. spends approximately \$2.3 billion USD on winter maintenance annually, and confounding damages to infrastructure and the environment add \$5.0 billion USD.

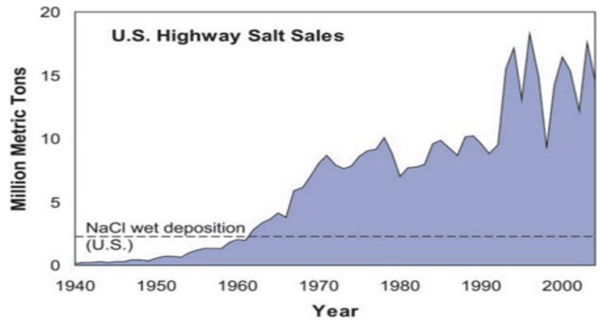

Figure 1. Amount of NaCl used on U.S. roads over time (Jackson & Jobbagy, 2005)

Scientists and city managers have sought to find road salt alternatives that are just as effective but mitigate the environmental and physical implications of traditional road salts. Particular interest has been on agro-based deicers, which are formed using the plant-based residues of distilled or fermented agricultural products (Gillis et al., 2021). Agro-based deicers decrease the amount of NaCl needed and thus the amount released into surrounding environments and exposed to infrastructure materials. Its efficacy isn't compromised due to the added food product. However, few studies explore the environmental and physical impact of agro-based deicers. Some studies raise concerns or even disprove claims about sustainability (Gillis et al., 2021; Li et al., 2019). There's also a lack of side-by-side comparative analyses of different agro-based deicers.

The question this study sought to answer was: What is the best agro-based deicer additive to mitigate the environmental and physical implications of traditional road salts while maintaining effectiveness?

Literature Review

The predominant road salt used is sodium chloride (NaCl). When winter conditions in northern climates cause icy and slippery conditions, deicers provoke friction between vehicle tires and road surfaces, decreasing traffic and rates of accidents/injuries (Durickovic, 2019). A chemical is an effective deicer if its physical and chemical properties permit it to move water's freezing point of 0°C (Durickovic, 2019). Freezing point is a colligative property (Figure 2): an increased presence of a solute is proportional to a decrease in freezing point until the solubility limit is reached (Figure 3). However, this means that larger quantities of deicing chemicals are required to fully melt ice. Thus, cities are often reliant on using mechanical snow removal mechanisms after deicers are applied (Klein-Paste & Potapova, 2014).

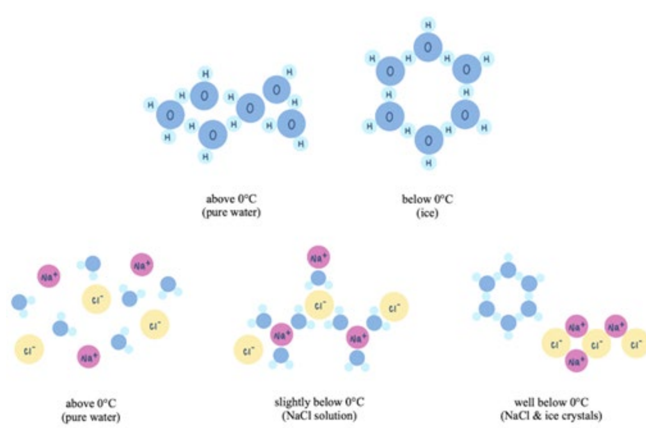

Figure 2. The freezing of pure water vs. aqueous NaCl

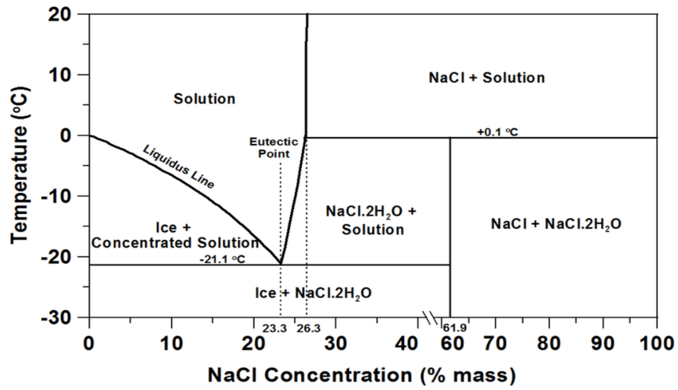

Figure 3. Phase diagram for NaCl and water (Farnam et al., 2014)

Environment Impact

After being dispersed, road salts spread into surrounding environments due to meteorological conditions and traffic or remain on road surfaces until precipitation carries it within road runoff. It is predicted that 20 - 40% of the road salts used are directly projected out of roads into roadside environments and 20 - 63% are transported by air upon being stirred by vehicles and wind (Durickovic, 2019).

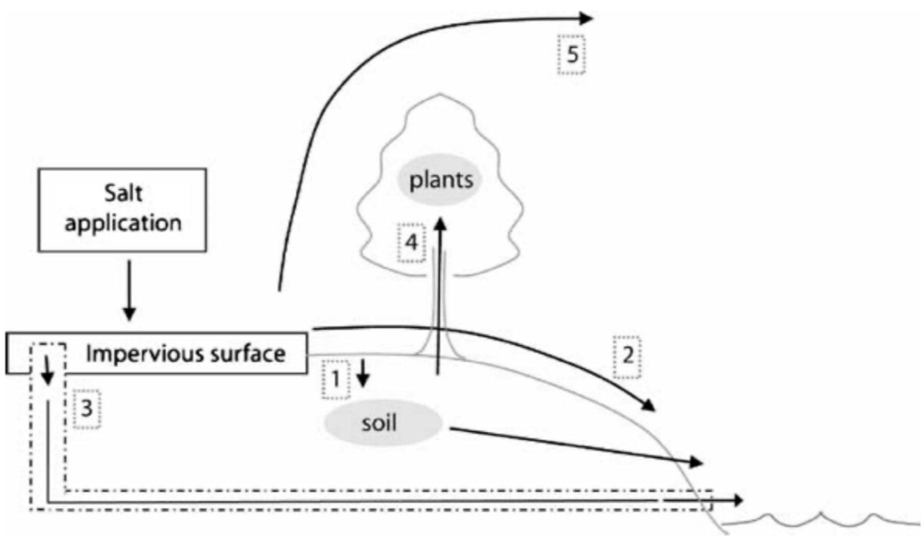

Figure 4. Pathways salt ions move from salt-applied roads to the natural environment (Cunningham et al., 2008)

Increased salinity in water sources and soil near roadsides–marked by the infiltration of cations (i.e. Na^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-)–are associated with increased health risks, vegetation biodiversity loss, the release of heavy metals, and more (Fay & Shi, 2012).

Soil & Vegetation Implications

Many studies have recorded significantly higher ion concentrations in roadside soils. A study conducted by Howard & Haynes (1993) found that 65% of Cl^- applied to roads are removed while the rest remain in the soil. In fact, NaCl has been shown to affect soil 15 ft from roadways (Fay & Shi, 2012). After collecting samples from well-trafficked Nebraska highways at various distances from the road, Mills et al. (2020) studied the physical and chemical properties of roadside soils such as bulk density, water infiltration, pH, conductivity, and concentration of organic matter. Results found that Na^+ concentration, conductivity, and pH were the highest for roadside samples, and a strong, negative correlation with distance from the road; Na^+ concentrations were 2.3 times higher near the road than the black slopes 7 m away from the road (Mills et al., 2020). A correlation is also seen between a community's population and chloride concentration. A study conducted by Pouyat et al. (2007) found that total salt concentrations were significantly higher in urban than suburban and rural forest patches, and that chloride concentrations positively correlated with road density and traffic volume. This raises particular concerns on already degrading urban ecosystems.

Soil particles are negatively charged, causing them to be attracted to salt cations (ex: Na^+, Ca^{2+}, Mg^{2+}). When soils absorb and retain cations, it facilitates the transport of anions like Cl^- (Durickovic, 2019; Fay & Shi, 2012; Löfgren et al., 2001). Elevated ion activity in soils causes permeability, surface runoff, and erosion (Fay & Shi, 2012).

Severe alterations to the geochemistry of soil have led to the toxicity of urban soils, decreased vegetation biodiversity, inhibited plant growth and reproduction, and nutrient deficiencies (Durickovic, 2019; Li et al., 2022). A study by Durickovic (2019) estimated that road salts are responsible for the death of 700,000 trees per year in Western Europe. Another study found that a highway-adjacent lagoon saw a reduction in the area of vegetation by 30% since 1970 and 60% since 1939 (Eyles et al., 2012). A more recent study from Li et al. (2022) collected data comparing plant diversity between the roadside and interior landscapes. It found that roadside plots only contained 14.62% of the total number of species recorded in interior communities (Li et al., 2022). The ingestion of road salts transferred into natural environments is also problematic for mammalian and avian behaviour (Fay & Shi, 2012).

Freshwater Implications

The percolation of road salts has directly led to the salinization of freshwater lakes, rivers, and groundwater (Dungan & Arnott, 2022). A study conducted by the Credit Valley Conservation Authority on Sheridan Creek–which streams near a highly urbanized region in Ontario–found that chloride concentrations have been increasing non-stop since the mid-1970s (Environment and Climate Change Canada, 2023). A study performed by Lawson & Jackson (2021) collected data from four Toronto watersheds to test the spatial variability of summer chloride conditions–as it's when many freshwater taxa reproduce and are the most sensitive to chloride–and found that 89% of 214 samples exceeded the federal chronic exposure guideline of 120 mg/L and 13% exceeded the federal acute guidelines of 640 mg/L. As chloride concentrations tend to peak during the winter, these results raise urgency on the long-term impacts of winter maintenance practices. A study conducted in New York found that mean chloride levels increased in Otsego Lake by 1.0 mg/L each year, and during runoff events, chloride concentrations spiked above 1,000 mg/L (Fay & Shi, 2012). Groundwater samples also reveal increased chloride concentrations due to winter maintenance chemicals: chloride concentrations have recently shown results of 40 - 60 mg/L while historic concentrations are 1 - 2 mg/L (Fay & Shi, 2012).

Road salt runoff into freshwater systems is toxic to freshwater organisms. According to a study performed by Woddley et al. (2023), freshwater ecotoxicity can occur at 4 - 40 mg Cl^-/L, which is well below the acute guideline of 120 mg Cl^-/L set by the Canadian government. Their study looked into the effect NaCl has on *Daphnia pulex* survival, and found that survival rates in soft water were 90% in the control and 120 mg Cl^-

/L, 40% in 640 mg Cl^-/L, and no *D. pulex* survived in 1200 mg Cl^-/L (Woddley et al., 2023). These results are affirmed by Parlato & Kopp (2020), who conducted a similar experiment using *Daphnia magna* while also exploring adaptive tolerance.

Physical Implications

70% of roadways in the U.S. are located in snowy regions (Sajid et al., 2020). Road salts have caused serious damage to infrastructure like bridges, asphalt, and cars. Of the physical concerns, metal corrosion is the most prevalent and costly. According to a review by Fay et al. (2008), corrosion caused by deicers costs an estimated $32 USD per year per vehicle. It's also estimated that corrosion on motor vehicles costs $2.8 - $5.6 billion USD annually and damage to protecting and repairing bridges costs $250 - $650 million USD annually (Fay & Shi, 2011).

Metal corrosion is a result of exacerbated ion-related activity. When metal and salt ions interact, it causes metal ions to bond with oxygen atoms, consequently increasing the perceived weight of metals. High ion activity compromises the protective layer of roadside infrastructures and their functionality. Deicing salts not only cause metal corrosion in direct contact, but corrosion can occur 1.9 km away from the salt deposits accumulated on major highways (Sajid et al., 2020).

Agro-Based Deicers

Since first introduced in the late 1930s, road salt use has dramatically increased and so have concerns surrounding its unintended consequences. Deicer additives are added to traditional road salt brines, which are used to pre-wet roads–a technique where a concentrated liquid freeze point depressant is sprayed onto roads to reduce salt waste and increase salt's ability to stick to the ground (Environment and Climate Change Canada, 2023). As shown in Figure 5, the use of liquid deicers is becoming increasingly popular. Their benefits are also becoming recognized. A study by Haake & Knouft (2019) in St. Louis County, Missouri found a 45% average reduction of chloride runoff for areas that used brines before a snowstorm than those that only used rock salts, indicating potential benefits to using brine deicers.

Agro-based additives are deemed to be effective brine salt additives as they contain low molecular weight carbohydrates (Fay & Shi, 2012). Examples of researched agro-based deicers include beet molasses, corn, cheese, beer byproducts, grape skin, particulate plant material, and more (Fay & Shi, 2012).

A public perception survey revealed that residents are concerned about the variety of environmental effects caused by road salts and are strongly supportive of finding an alternative (Fay & Shi, 2012). Respondents also demonstrated a willingness to pay more in exchange for less vehicular corrosion, better water quality, and other reductions in perceived detrimental effects (Fay & Shi, 2012). Another study surveyed highway maintenance agencies and found that average ranking results show agricultural product-based dealers being the most advantageous (Fay et al., 2008).

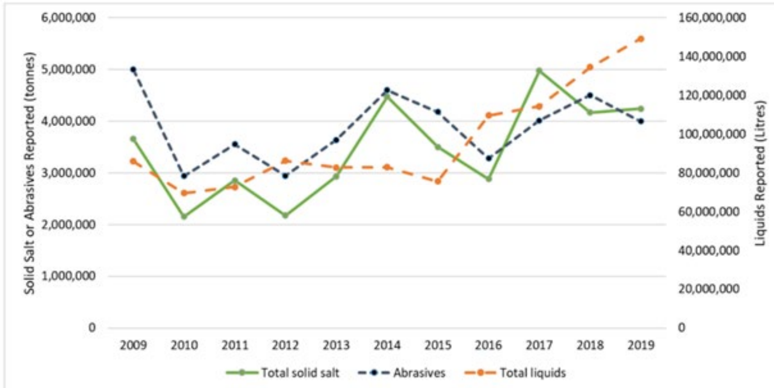

Figure 5. Quantity of solid road salts, liquid deicers, and abrasives of organizations (municipal, provincial, federal, and private) in Canada (Environment and Climate Change Canada, 2023)

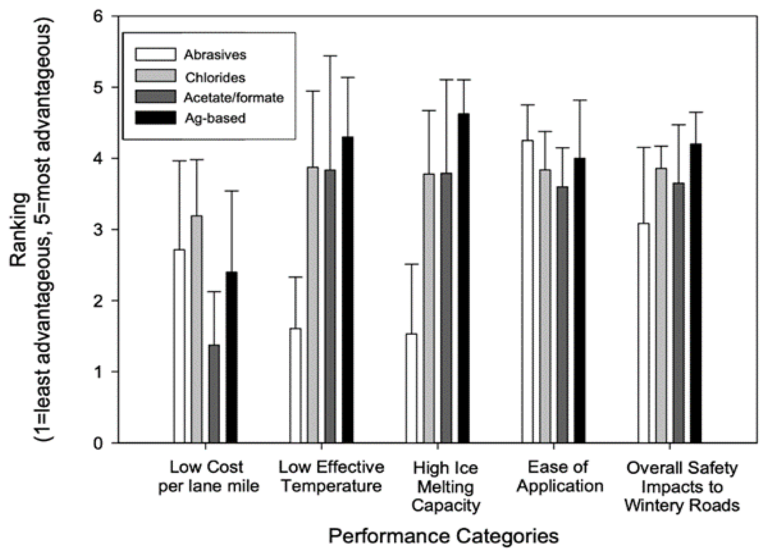

Figure 6. User-perceived ranking of deicers based on various performance categories (Fay et al., 2008)

Deicing Efficacy of Agro-Based Deicers

A range of agro-based deicers have been tested. Many studies have found that their freezing points continue to decrease until the agro-additive's solubility limit while in a chloride salt brine is reached (Abbas et al., 2021; Klein-Paste & Potapova, 2014). The foremost researched agro-based deicers is beet juice, specifically sugar beet molasses. It's also the only agro-based deicers currently being adopted, including in seven Canadian provinces and numerous American states (Gillis et al., 2021). A study conducted by Muthumani & Shi (2014) studied the freezing point and ice-melting capacity of NaCl, complex chlorides/minerals (CCM), and beet deicers. Agro-based additives significantly lowered freezing points when compared with 23 wt% NaCl but didn't show better ice-melting capacities (Muthumani & Shi, 2014).

A diverse array of other food products have also been studied. A report by Abbas et al. (2021) compared sorbitol, maltitol, and mannitol, corn-derived polyols (chemical compounds with three or more hydroxyl groups). It was found that the addition of 27 wt% sorbitol, 27 wt% maltitol, and 13.33 wt% mannitol in 23.3

wt% salt-brine exhibited freezing point depressions as low as -38.1°C, -35.6°C, and -27.00°C respectively (Abbas et al., 2021). A different study by Nazari & Shi (2019) compared a novel composition that utilized Concord grape extract and glycerin to NaCl brines. Their study only found a particular few concentrations performed better than the 23 wt% NaCl brine.

Environmental Implications of Agro-Based Deicers

Despite decreasing the concentration of chloride in a deicer and adding food-derived additives, possible unintended consequences may still persist. According to Nazari & Shi (2019), agro-based deicers may induce acute impacts on the receiving environment due to the high oxygen demand of organic compounds. A study conducted by Gillis et al. (2021) explored the freshwater impact of beet juice deicers and found that dissolved oxygen levels significantly decreased upon the addition of beet juice. The 1% beet juice treatment decreased oxygen levels from 5.8mg/L to 0.54mg/L, while the control beakers remained at roughly 8.6mg/L, indicating high oxygen demand from the beet juice deicers (Gillis et al., 2021). Furthermore, there is evidence that suggests that agro-based additives, which are often fermented or distillation byproducts, contain phosphorus and can unintentionally fertilize aquatic ecosystems (Schuler & Relyea, 2017).

Understanding of the ecotoxicity of agro-based deicers on organisms also raises confusion. A study conducted by Nutile & Solan (2019) found that beet juice had roughly the same lethal concentration of 50% (LC_{50}) as NaCl on *Chironomus dilutus*, a fly species. When tested on *Glochidia*–a freshwater mussel–it was found that beet juice was the most toxic of the three (Gillis et al., 2021). However, more holistic studies on various agro-based deicers are limited, a gap this paper sought to address.

Physical Implications of Agro-Based Deicers

Literature shows that agro-based deicers exhibit corrosion-inhibiting properties. According to a study by Muthumani & Shi (2014), agro-based additives exhibit significant benefits in reducing the corrosivity of 23 wt% NaCl brines. An extensive study on corn-derived polyols studied the corrosivity of polyol deicers on a variety of metals. It was found that the corrosivity of sorbitol, maltitol, and mannitol was 3.5 - 8 times lower than 23 wt% NaCl (Yellavajjala et al., 2020). Additionally, there was a strong, negative correlation between polyol concentration and corrosivity, demonstrating the corrosivity-inhibiting properties of corn (Sajid et al., 2020; Yellavajjala et al., 2020). In a study conducted by Nazari & Shi (2012) on grape skin deicers, it was found that most corrosion rates on exposed carbon steel were lower than samples exposed to 23 wt% NaCl brines and beet juice or salt brines.

Methodology

To effectively answer the research question at hand, this study sought to determine the deicing effectiveness, ecotoxicity, and metal corrosivity of agro-based deicers in comparison to traditional road salts. To imitate agro-based deicers, this study selected three food-derived carbohydrates as NaCl additives. NaCl was the chosen traditional road salt as it's widely used and highly accessible. These chemicals were sucrose, fructose, and sorbitol, and were chosen due to their high prevalence in fermented food by-products like beet molasses, corn juice, grape skin, beer, etc., which have been previously studied. Fermented food products weren't accessible. Furthermore, using carbohydrates ensured chemical purity and allowed conclusions to be broader, providing greater scope for future research to test various food products containing the tested carbohydrates.

All procedures discussed below were approved by the researcher's institution's Internal Review Board.

Ice-Melting Capacity (IMC) Experiment

To measure deicing effectiveness, the Mechanical Rocker Test for Ice-Melting Capacity (MRT-IMC) procedure was adopted. Methods documented by the Strategic Highway Research Program (SHRP) have been the most widespread procedures used to measure freezing point depression. However, concerns have shed light on its lack of replicability between laboratories. More recently, researchers have brought forth MRT-IMC, which was thus chosen for this study. It's deemed to be a more consistent and robust approach to evaluating the amount of ice that can be melted at sub-zero temperatures given a set amount of deicer treatment (Hansen & Halsey, 2019). In this experiment, ice cubes of volume 2.7 ±0.3 mL were frozen at -17.8°C for at least 6 hours. The IMC of treatments summarized in Table 1 were tested at 5, 10, 15, 30, and 45 minutes. These rocking time stamps were selected to allow for a greater understanding of both short and long-term performance, and provide enough data variation to determine a correlation, if present.

For this experiment, there were 21 deicer treatments and 1 control (Table 1). All deicers containing carbohydrates had the same amount of NaCl added: 3.00 g. All treatments were 10 mL, which translated to a base 23 wt% NaCl brine (widely considered the most optimal NaCl concentration) before carbohydrates were added. Each treatment was mixed using a magnetic stirrer at 300 - 400 rpm until fully homogeneous. Styrofoam cups labelled A and B were used, and the weight of each was recorded. 15 ice cubes were added to cup A and the total weight was recorded. The ice and treatment were poured into a thermos, and the thermos was placed onto a mechanical rocker. When the rocking time concluded, the contents within the thermos were put through a sieve and poured into cup B. The weight of cup B and the leftover ice were recorded. The formula for ice-melting capacity is:

$$\frac{(\text{mass of cup } A \text{ \& ice} - \text{mass of cup } A) - (\text{mass of cup } B \text{ \& ice} - \text{mass of cup } B)}{10}$$

Table 1. Treatments used for the ice-melting capacity (IMC) tests

	Weight percent of solute (wt%)			
Mixture No.	**Sodium Chloride (NaCl)**	**Sucrose ($C_{12}H_{22}O_{11}$)**	**Fructose ($C_6H_{12}O_6$)**	**Sorbitol ($C_6H_{14}O_6$)**
1	0	0	0	0
2	5.0	0	0	0
3	10.0	0	0	0
4	15.0	0	0	0
5	20.0	0	0	0
6	23.3	0	0	0

7	25.0	0	0	0
8	22.2	3.7	0	0
9	21.4	7.1	0	0
10	20.7	10.3	0	0
11	20.0	13.3	0	0
12	19.4	16.1	0	0
13	22.2	0	3.7	0
14	21.4	0	7.1	0
15	20.7	0	10.3	0
16	20.0	0	13.3	0
17	19.4	0	16.1	0
18	22.2	0	0	3.7
19	21.4	0	0	7.1
20	20.7	0	0	10.3
21	20.0	0	0	13.3
22	19.4	0	0	16.1

Freshwater Ecotoxicity Experiment

With freshwater sources being the heart of many urban ecosystems, it's imperative to understand how freshwater systems would react to the presence of agro-based deicers. *Daphnia magna* is an abundant urban water flea species, making it a good environmental indicator. It is also widely used in the scientific community as an ecotoxicity subject due to its abundance and sensitivity to toxins like NaCl. *D. magna* was chosen due to its larger size in comparison to other species, which made it easier to analyze results without specialized equipment. As an invertebrate, there were limited ethical concerns as there are no real threats to the species 'existence/genetic variation. All organisms were tested with care.

The purpose of this experiment was to determine the lethal concentration of 50% (LC_{50}) of NaCl and carbohydrates in agro-based deicers by creating a correlation between deicer concentration and *D. manga* mortality. In this experiment, *D. magna* was purchased from Boreal Science, cultured under a plant lamp with a 12:12 light:dark cycle, and fed yeast every ~3 days. To test lethality, 60 mL of treatment was used per *D. magna*. A singular, healthy *D. magna* neonate (<24 hours old) was transferred from its culture into each test tube. 5 *D. magna* was used for each treatment, each in a separate test tube to remove competition as a confounding variable. After 24 hours, each *D. magna* was placed in a well under a microscope at 100x magnification to determine the presence of a heartbeat.

Table 2. Treatments used for the D. magna lethality tests

	Weight percent of solute (wt%)			
Mixture No.	**Sodium Chloride (NaCl)**	**Sucrose ($C_{12}H_{22}O_{11}$)**	**Fructose ($C_6H_{12}O_6$)**	**Sorbitol ($C_6H_{14}O_6$)**
1	0	0	0	0
2	0.3	0	0	0
3	0.5	0	0	0
4	0.8	0	0	0
5	1.0	0	0	0
6	0.64	0.20	0	0
7	0.64	0.43	0	0
8	0.64	0.64	0	0
9	0.64	0	0.20	0
10	0.64	0	0.43	0
11	0.64	0	0.64	0
12	0.64	0	0	0.20
13	0.64	0	0	0.43
14	0.64	0	0	0.64

Metal Corrosion Experiment

To determine the corrosivity of agro-based deicers, zinc-plated steel washers were purchased from Rona Canada. These were chosen over alternatives like stainless steel and carbon steel which are more corrosion-resistant. A more corrosive option provided increased differentiability in observed corrosion. The average weight of each washer was 5.95 ±0.05 g. A setup (see Image D1 in Appendix D) was created using Petri dishes and string to prop each washer upright. Each treatment had three washers 50% submerged. Saran wrap sealed the setup to minimize evaporation and exposure to other chemicals/disturbances. Each week, photographs were taken and qualitative observations (crystallization, rust, disintegration, patina, mould, etc.) were recorded. After three weeks, deicer treatments were re-added. After six weeks, the setup was taken down, each washer was rinsed using deionized water, and washers were placed flat to air dry. Photographs were taken and each washer was weighed.

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Table 3. Treatments used for corrosivity tests

	Weight percent of solute (wt%)			
Mixture No.	**Sodium Chloride ($NaCl$)**	**Sucrose ($C_{12}H_{22}O_{11}$)**	**Fructose ($C_6H_{12}O_6$)**	**Sorbitol ($C_6H_{14}O_6$)**
1	0	0	0	0
2	5.0	0	0	0
3	10.0	0	0	0
4	15.0	0	0	0
5	20.0	0	0	0
6	25.0	0	0	0
7	22.2	3.7	0	0
8	21.4	7.1	0	0
9	20.7	10.3	0	0
10	20.0	13.3	0	0
11	19.4	16.1	0	0
12	22.2	0	3.7	0
13	21.4	0	7.1	0
14	20.7	0	10.3	0
15	20.0	0	13.3	0
16	19.4	0	16.1	0
17	22.2	0	0	3.7
18	21.4	0	0	7.1
19	20.7	0	0	10.3
20	20.0	0	0	13.3
21	19.4	0	0	16.1

Hypothesis

It was hypothesized that deicers with added carbohydrates would have higher IMC due to more solutes and that there would be a positive correlation between salt/carbohydrate concentration and IMC. Second, it was hypothesized that agro-based deicers would be less toxic than NaCl on *D. magna* as carbohydrates provide an energy source, likely exemplified by a less steep concentration vs. lethality slope. Finally, it was hypothesized that agro-based deicers would exhibit corrosion-inhibiting properties by impeding the ion-related activity between NaCl and steel, and corrosion would decrease as carbohydrate concentration increased.

Results

Ice-Melting Capacity (IMC) Experiment

The Mechanical Rocker Test for Ice-Melting Capacity (MRT-IMC) was employed to determine deicing effectiveness of each deicer by measuring the amount of ice that could be melted with a set amount of deicing treatment. The results are summarized in Tables 4 - 7, divided per deicer group, and plotted using R shown in Figures 7 - 14. All deicers demonstrated a positive correlation between time and IMC.

Analyzing Figure 7, it was observed that the control (water) had a negative IMC at time intervals under 30 minutes. This insinuates that the lack of a solute caused the water to freeze while being rocked with ice. Though treatment performance differs at each rocking time stamp, the data results at 45 minutes show a positive correlation between NaCl concentration and IMC. The IMC of 23.3 wt% NaCl and 25.0 wt% NaCl were very similar.

Figures 9, 11, and 13 observe the correlation between rocking time and IMC for sucrose, fructose, and sorbitol agro-based deicers respectively. Similar to NaCl, there were strong, positive correlations. However, the differences between each treatment's IMC were less apparent than for NaCl treatments. Figures 10, 12, and 14 plot the relationship between sucrose/fructose/sorbitol concentration and IMC. Unlike NaCl, no clear correlation was derived and there were greater fluctuations, likely indicating a weaker causal effect when carbohydrates were added to NaCl.

Table 4. Summarized data of NaCl IMC

wt% of NaCl	Rocking Time (mins)									
	5		10		15		30		45	
	Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD
0	-0.068	0.124	-0.103	0.103	-0.187	0.086	0.017	0.114	0.171	0.208
5.0	0.194	0.143	0.216	0.153	0.178	0.031	0.429	0.137	0.618	0.145
10.0	0.281	0.128	0.498	0.160	0.398	0.098	0.704	0.072	0.821	0.200
15.0	0.435	0.056	0.513	0.155	0.552	0.037	0.701	0.085	1.018	0.264

20.0	0.286	0.088	0.485	0.121	0.688	0.134	0.852	0.047	1.179	0.056
23.3	0.480	0.047	0.680	0.104	0.765	0.054	1.034	0.037	1.266	0.034
25.0	0.443	0.131	0.611	0.035	0.765	0.156	1.174	0.238	1.286	0.206

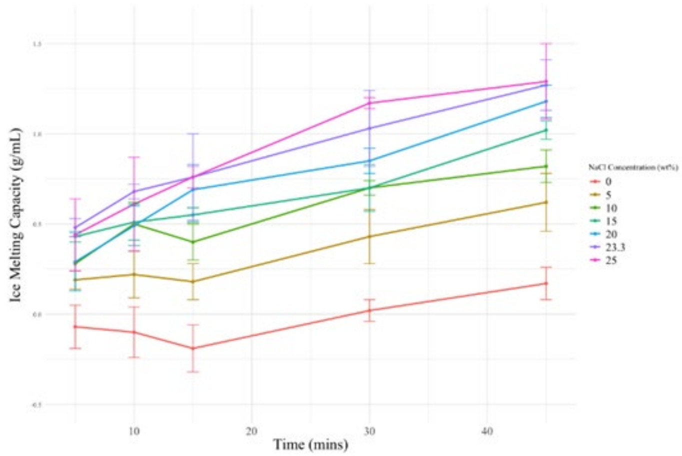


Figure 7. Ice-melting capacity of NaCl brines in relation to time

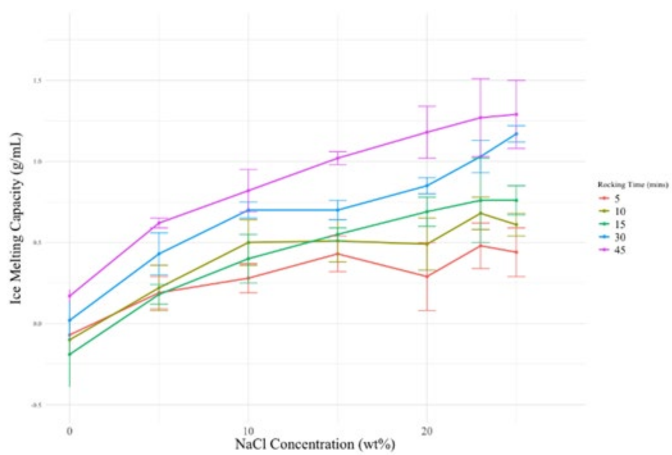


Figure 8. Ice-melting capacity of NaCl brines in relation to NaCl concentration

Table 5. Summarized data of sucrose IMC

wt% of NaCl	wt% of Sucrose	Rocking Time (mins)				
		5	10	15	30	45

		Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD
22.2	3.7	0.521	0.010	0.541	0.093	0.734	0.039	0.980	0.059	1.224	0.079
21.4	7.1	0.531	0.053	0.736	0.075	0.680	0.223	0.914	0.079	1.220	0.174
20.7	10.3	0.486	0.103	0.755	0.173	0.687	0.058	0.944	0.101	1.391	0.143
20.0	13.3	0.496	0.091	0.660	0.028	0.783	0.119	0.973	0.093	1.361	0.157
19.4	16.1	0.640	0.074	0.713	0.068	0.854	0.212	1.126	0.167	1.397	0.087

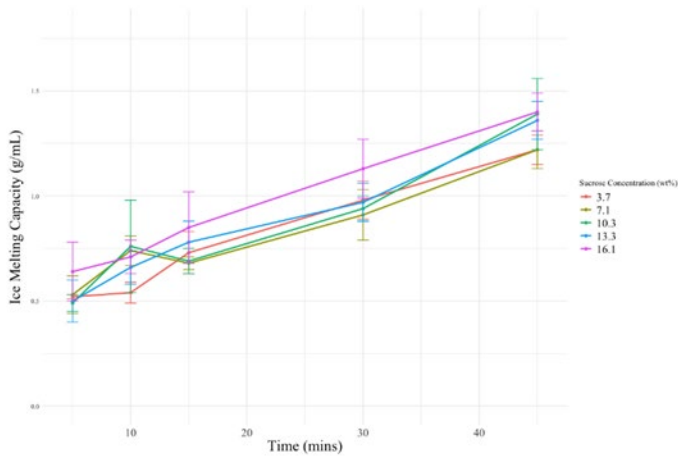


Figure 9. Ice-melting capacity of sucrose and NaCl brines in relation to time

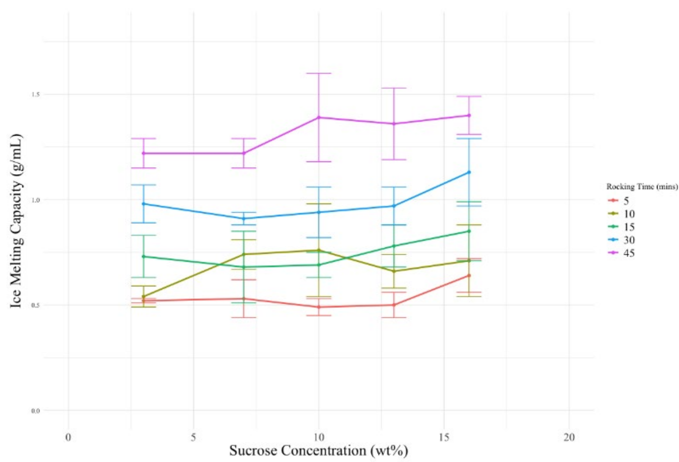


Figure 10. Ice-melting capacity of sucrose and NaCl brines in relation to sucrose concentration

Table 6. Summarized data of fructose IMC

wt% of NaCl	wt% of Fructose	Rocking Time (mins)									
		5		10		15		30		45	
		Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD
22.2	3.7	0.596	0.076	0.621	0.030	0.662	0.123	0.881	0.111	1.355	0.108
21.4	7.1	0.607	0.060	0.783	0.028	0.724	0.107	1.008	0.145	1.286	0.106
20.7	10.3	0.695	0.086	0.837	0.102	0.978	0.148	0.908	0.090	1.311	0.086
20.0	13.3	0.661	0.071	0.720	0.062	0.774	0.022	0.976	0.151	1.220	0.084
19.4	16.1	0.579	0.092	0.778	0.070	0.720	0.034	1.029	0.075	1.460	0.100

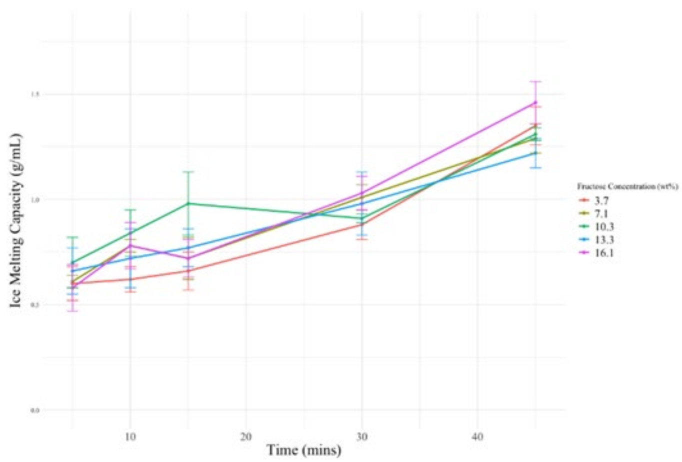


Figure 11. Ice-melting capacity of fructose and NaCl brines in relation to time

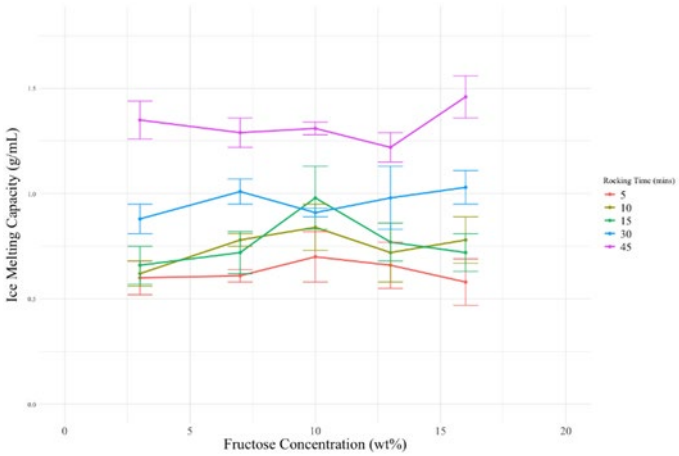


Figure 12. Ice-melting capacity of fructose and NaCl brines in relation to fructose concentration

Table 7. Summarized data of sorbitol IMC

wt% of NaCl	wt% of Sorbitol	Rocking Time (mins)									
		5		10		15		30		45	
		Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD	Average IMC	STD
22.2	3.7	0.463	0.089	0.481	0.040	0.563	0.119	0.855	0.079	1.349	0.150
21.4	7.1	0.519	0.173	0.667	0.138	0.804	0.128	1.058	0.159	1.576	0.080
20.7	10.3	0.472	0.005	0.787	0.113	0.803	0.056	1.001	0.222	1.250	0.126
20.0	13.3	0.672	0.054	0.638	0.100	0.680	0.056	0.967	0.094	1.431	0.109
19.4	16.1	0.489	0.082	0.603	0.187	0.712	0.165	1.045	0.011	1.319	0.115

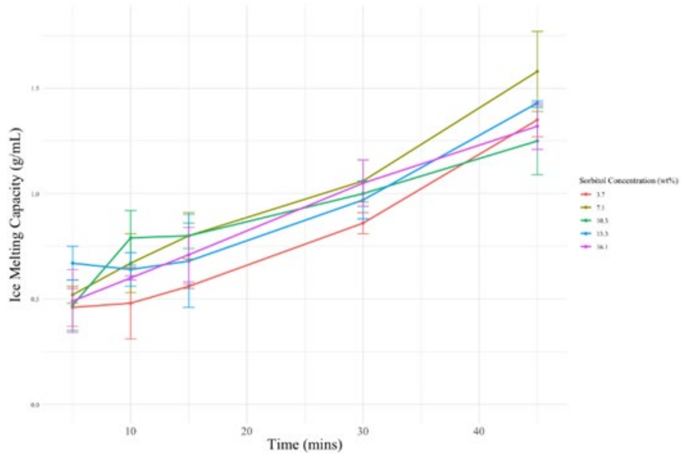


Figure 13. Ice-melting capacity of sorbitol and NaCl brines in relation to time

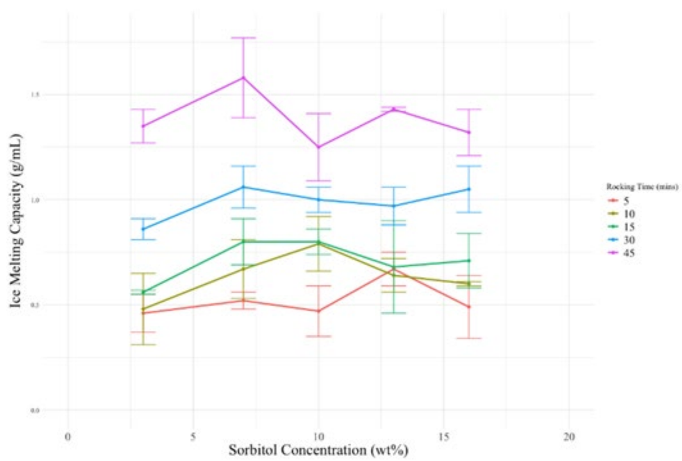


Figure 14. Ice-melting capacity of sorbitol and NaCl brines in relation to sorbitol concentration

Single-factor ANOVA tests were performed using XLMiner Analysis ToolPak on Google Sheets. The p-values derived (Table 5) were used to understand the differentiability between each deicer's IMC results. Though they weren't used to prove or disprove conclusions, a low p-value provided greater confidence. Tests were performed for each deicing group as well as all deicers as a whole. The p-values for the IMC of NaCl treatments were incredibly low, insinuating high differentiability. Due to the variable nature of working with ice and the inclusion of outlier trials, a p-value of 0.15 was considered passable in this study. Results with p-values greater than 0.15 equated to a confidence lower than 85% and weren't used to factor while creating conclusions. The p-values for sucrose and NaCl brines were lower at 5 and 10 minutes, and weak at all other time intervals. The p-values for fructose and NaCl brines were low at 10, 15, and 45 minutes. The p-values for sorbitol and NaCl brines were all low except for 30 minutes. The p-values for all treatments together were incredibly low, demonstrating high differentiability when reviewing IMC results collectively.

Table 8. Single-factor ANOVA p-values for IMC results at each rocking time point

p-value ANOVA test at [Rocking Time]

5 minutes	10 minutes	15 minutes	30 minutes	45 minutes
for NaCl				
3.1 E-4	3.4 E-5	4.7 E-8	3.1 E-7	1.7 E-5
for sucrose and NaCl brines				
0.16	0.14	0.61	0.21	0.32
for fructose and NaCl brines				
0.38	0.019	0.025	0.51	0.11
for sorbitol and NaCl brines				
0.13	0.13	0.10	0.41	0.055
for all treatments				
2.6 E-11	1.4 E-11	7.1 E-13	1.1 E-12	1.0 E-13

23.3 wt% NaCl is widely considered the best concentration for road salt brines. Though higher concentrations of NaCl do further decrease the freezing point, it's deemed that 23.3 wt% won't cause freezing in most northern climates and depression above 23.3 wt% begins to plateau. Thus, given most urban systems use 23.3 wt% NaCl brines, it's important to compare its deicing effectiveness with the deicing effectiveness of agro-based deicers. Table 9 shows the percent difference in IMC of agro-based deicers to 23.3 wt% NaCl. At 5 minutes, there was the greatest, positive percent difference in IMC, which indicates carbohydrate's fast-acting properties. At 45 minutes, the majority of agro-based deicers performed better than 23.3 wt% NaCl. No clear correlation between concentration and percent difference was found, however.

Table 9. The percent difference between agro-based deicers and 23.3 wt% NaCl

Mixture Composition (wt%)				Percent Difference at [Rocking Time]				
NaCl	**Sucrose**	**Fructose**	**Sorbitol**	**5 min**	**10 min**	**15 min**	**30 min**	**45 min**
22.2	3.7	0	0	8.0	-23.0	-4.0	-5.0	-4.0
21.4	7.1	0	0	9.9	8.5	-11.1	-12.4	-4.0
20.7	10.3	0	0	2.1	11.1	-9.7	-9.1	9.0
20.0	13.3	0	0	4.1	-3.0	2.6	-6.0	6.8
19.4	16.1	0	0	28.6	4.3	11.2	9.3	9.7

22.2	0	3.7	0	22.2	-9.2	-14.1	-15.7	6.1
21.4	0	7.1	0	23.9	13.7	-5.4	-2.0	1.6
20.7	0	10.3	0	37.3	21.1	25.3	-12.4	3.1
20.0	0	13.3	0	31.6	5.7	1.3	-5.0	-4.0
19.4	0	16.1	0	18.9	13.7	5.4	0.0	13.9
22.2	0	0	3.7	-4.3	-34.5	-30.3	-18	6.1
21.4	0	0	7.1	8.0	-1.5	5.1	2.9	21.8
20.7	0	0	10.3	-2.1	15.0	5.1	-3.0	-1.6
20.0	0	0	13.3	33.0	-6.1	-11.1	-6.0	11.9
19.4	0	0	16.1	2.1	-13.0	-6.8	1.9	3.9

Freshwater Ecotoxicity Experiment

The second experiment conducted observed the ecotoxicity of agro-based deicers on *D. magna.* The raw data is shown in Table 10. 10 *D. magna* were used when testing the control and had a 90% survival rate. 5 *D. magna* were used to test each NaCl and agro-based deicer treatment.

Table 10. Recorded results from D. magna lethality experiments

	Number of *D. magna*			Number of *D. magna*	
Mixture No.	**Alive**	**Dead**	**Mixture No.**	**Alive**	**Dead**
1	9	1	8	4	1
2	5	0	9	1	4
3	4	1	10	1	4
4	1	4	11	3	2
5	0	5	12	0	5
6	3	2	13	2	3
7	2	3	14	2	3

Figure 15 plots the correlation between NaCl concentration and *D. magna* lethality. With a high significant R-squared value of 0.982, the line of best fit was 152x - 48.6, with x representing NaCl concentration.

Using this equation, the LC_{50} of *D. magna* in NaCl was determined to be 0.65 wt%. As the *D. magna* were put in 60 mL of treatment, this translated to 0.39 g of NaCl. 0.39 g of NaCl was used to create all agro-based deicers, however, the concentration of sucrose, fructose, or sorbitol varied. The results of this experiment are shown in Figures 16 - 18. All lethality plots for agro-based deicers had a negative correlation between carbohydrate concentration and *D. magna* lethality.

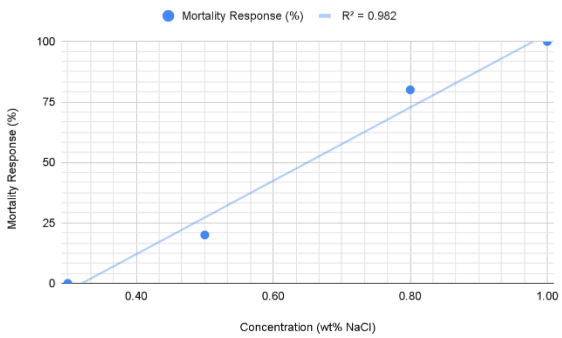


Figure 15. D. magna lethality in NaCl brines

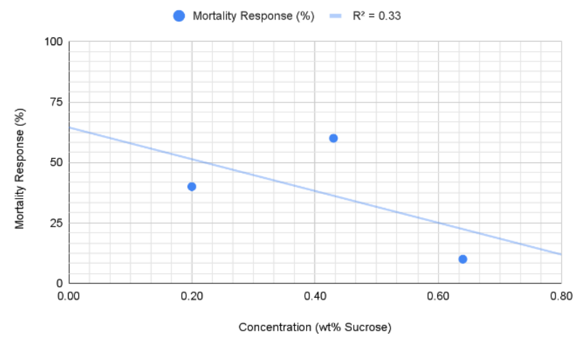


Figure 16. D. magna lethality in NaCl (0.64 wt%) and Sucrose brines

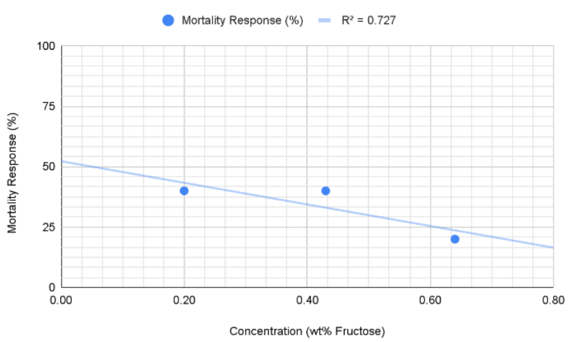


Figure 17. D. magna lethality in NaCl (0.64 wt%) and Fructose brines

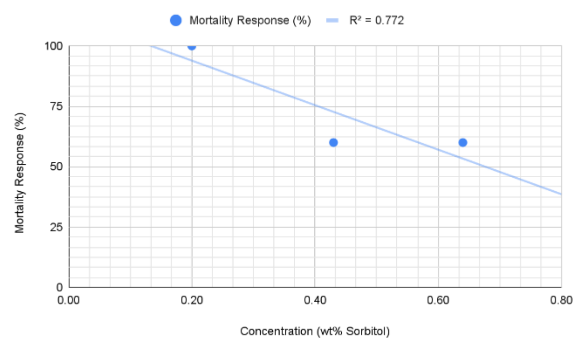


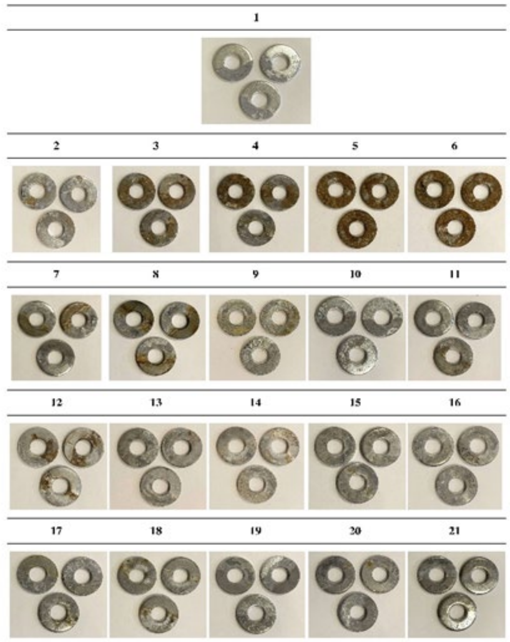
Figure 18. D. magna lethality in NaCl (0.64 wt%) and Sorbitol brines

Metal Corrosion Experiment

The results from testing steel corrosion after being exposed to various deicers for six weeks are shown in Table 11. There was a st rong, positive correlation between NaCl concentration and corrosion (row 2). There were strong, negative correlations between carbohydrate concentration and corrosion (rows 3 - 5), and some treatments–such as 20 and 21–had results comparable to the control (1).

The final weights of each steel washer were recorded and visualized in Figure 19. All final weights increased from the original 5.95 ±0.05 g. The average final weight was also calculated for the washers in each deicer group type (NaCl, sucrose and NaCl, fructose and NaCl, and sorbitol and NaCl) to determine differentiability as there was no apparent correlation between weight and salt/carbohydrate concentration. There was no significant correlation between treatment composition and steel weight difference.

Table 11. Images of steel washers submerged in various deicing treatments after six weeks



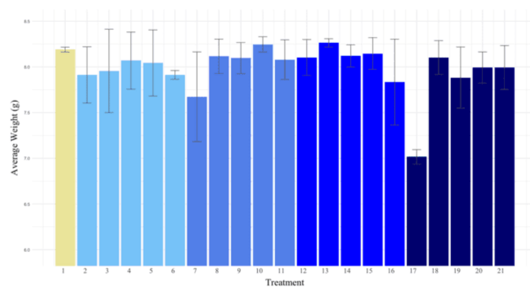


Figure 19. Average weight of steel washers after being submerged in deicing treatments for six weeks

Table 12. Average weight of steel washers per deicing group

NaCl	Sucrose & NaCl	Fructose & NaCl	Sorbitol & NaCl
7.98 g	8.04 g	8.09 g	7.80 g

Note. The p-value calculated using a single-factor ANOVA test was 0.091.

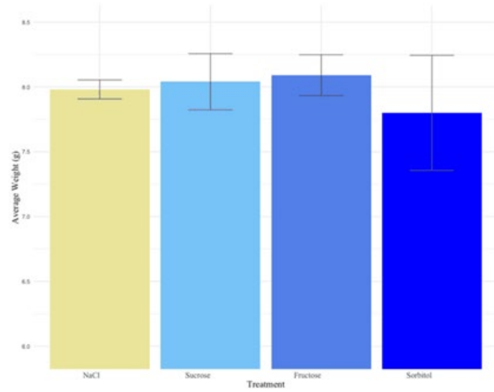


Figure 20. Average final weights per deicing group

Discussion

Ice-Melting Capacity (IMC) Experiment

From Figures 9, 11, and 13, it was evident that agro-based deicers had short-term boosts in IMC, seen by a greater slope at 5 to 15 minutes than at 15 to 45 minutes. This pattern was further supported by the results in Table 9. All but two agro-based deicers outperformed 23.3 wt% NaCl at 5 minutes, while 7, 8, 11, and 4 deicers failed to outperform 23.3 wt% NaCl at 10, 15, 30, and 45 minutes respectively.

The best overall performing deicers were isolated from each deicer group: 25.0 wt% NaCl, 16.1 wt% sucrose and 19.4 wt% NaCl, 16.1 wt% fructose and 19.4 wt% NaCl, and 7.1 wt% sorbitol and 21.4 wt% NaCl. Their IMC results were separately plotted in Figure 21. Furthermore, each line-of-best fit (Table 13) was derived due to the significant overlaps in the plot. A greater slope insinuates better IMC. All were highly significant with large R-squared values. Ranking from best to worst IMC based on line-of-best fit slope was: sorbitol and NaCl, NaCl, fructose and NaCl, sucrose and NaCl.

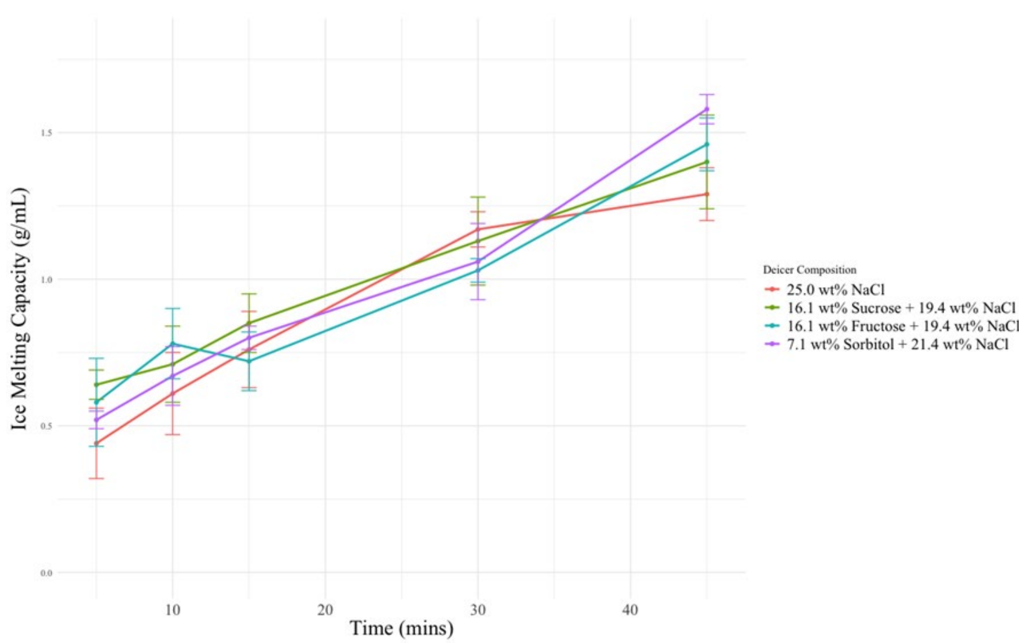


Figure 21. Ice-melting capacity plot for best overall performing treatment in each deicer group

Table 13. Line of best fit for the overall best-performing deicers

Treatment	Line of Best Fit for IMC	R^2 value
25.0 wt% NaCl	0.0215x + 0.404	0.944
16.1 wt% Sucrose, 19.4 wt% NaCl	0.0191x + 0.544	0.997
16.1 wt% Fructose, 19.4 wt% NaCl	0.0207x + 0.478	0.957
7.1 wt% Sorbitol, 21.4 wt% NaCl	0.0251x + 0.398	0.982

Note. x represents time

Single-factor ANOVA tests were used to determine the differentiability between IMC results of the best-performing deicers (Table 15). With relatively high p-values, the differentiability was low, especially for 15 and 30 minutes. This diminishes the confidence of rankings. The p-value for the results at 45 minutes was the lowest.

Table 14 summarizes the percent difference between the best-performing agro-based deicers and the best-performing NaCl deicer (25.0 wt% NaCl). There were high percent differences at 5 and 10 minutes, which aligned with the initial observations of the fast-acting nature of carbohydrates. All agro-based deicers underperformed 25.0 wt% NaCl at 30 minutes. However, all agro-based deicers outperformed 25.0 wt% NaCl at 45 minutes. Given that IMC results at 45 minutes had the lowest p-value of 0.12 and provided the best context for long-term performance, its data was the most important. At 45 minutes, sorbitol outperformed NaCl the greatest–by over 20%. It was concluded that sorbitol was the most effective agro-based deicer additive.

Table 14. The percent difference between the best overall performing agro-based deicer and 25.0 wt% NaCl

Mixture Composition (wt%)				Percent Difference at [Rocking Time]				
NaCl	Sucrose	Fructose	Sorbitol	5 min	10 min	15 min	30 min	45 min
19.4	16.1	0	0	37.0	15.15	11.12	-3.5	8.2
19.4	0	16.1	0	27.5	24.5	-5.4	-12.7	12.4
21.4	0	0	7.1	16.7	9.4	5.1	-9.9	20.2

Table 15. Single-factor ANOVA p-values for IMC results of best-performing deicers at each rocked time point

5 minutes	10 minutes	15 minutes	30 minutes	45 minutes
0.31	0.19	0.73	0.73	0.12

The ice-melting capacity results could be attributed to the molecular structure of sucrose, fructose, and sorbitol (Figures 22 - 24). Sorbitol was the only studied compound not in a cyclic arrangement. Its linear arrangement provides flexibility to effectively line up with H_2O molecules. Furthermore, the simpler arrangement of fructose compared to sucrose indicates that there are more moles of fructose given a set mass of carbohydrates. A greater number of moles provides fructose more opportunities to bond with H_2O than sucrose at the same concentration, thus providing greater capacity to impede water's ability to freeze.

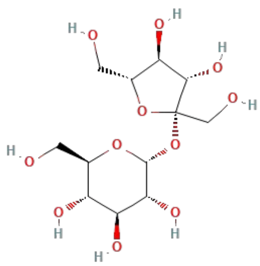


Figure 22. 2D molecular structure of sucrose (National Center for Biotechnology Information, 2024)

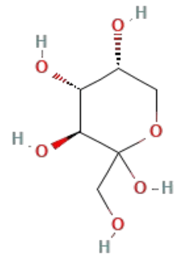


Figure 23. 2D molecular structure of fructose (National Center for Biotechnology Information, 2024)

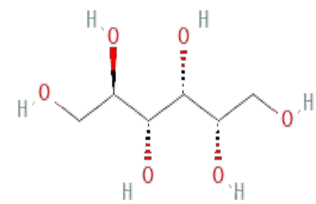


Figure 24. 2D molecular structure of sorbitol (National Center for Biotechnology Information, 2024)

Freshwater Ecotoxicity Experiment

Daphnia magna is an urban water flea sensitive to toxins like road salts. The LC_{50} of the *D. magna* culture used in this study was 0.65 wt% NaCl. While maintaining the amount of NaCl added to each agro-based deicer, the negative correlation observed between carbohydrate concentration and *D. magna* lethality could be attributed to the added carbohydrates (Figures 16 - 18). This makes sense because carbohydrates are an energy source for *D. magna*. Energy likely provided them resilience to defy the toxicity of NaCl present. Due to moderate R-squared values for fructose and sorbitol, and a weak correlation for sucrose, this experiment wasn't unable to rank the carbohydrates 'ecotoxicity. However, the results could still be used dynamically, proving the mediated ecotoxicity of agro-based deicers.

Table 16. LC_{50} of D. magna in various deicing brines

LC_{50} Salt Concentration for [treatment]	LC_{50} Carbohydrate Concentration for [treatment]		
NaCl brines	**Sucrose + NaCl brines**	**Fructose + NaCl brines**	**Sorbitol + NaCl brines**
0.65 wt%	0.22 wt%	0.05 wt%	0.67 wt%

Metal Corrosion Experiment

Images in Table 11 show the results of steel corrosion after being half submerged in various deicers for six weeks. Row one, two, three, four, and five show the control, NaCl, sucrose and NaCl, fructose and NaCl, and sorbitol and NaCl treatments respectively. For the agro-based deicers, carbohydrate concentration increased from left to right. The amount of NaCl in all agro-based deicers was uniform and equivalent to an amount greater than treatment 5 but less than treatment 6. It was noted that sucrose treatments had the stickiest residue and sorbitol the least. Fructose treatments turned a yellowish-brown colour (see Appendix D). Furthermore, greater corrosion was observed on the steel washers directly exposed to sunlight. Crystals were observed for all treatments except the control after a week, with the greatest formations for treatments with lower carbohydrate concentrations or no carbohydrates.

All agro-based deicers demonstrated lower corrosivity than NaCl brines and the presence of high carbohydrates showed even greater corrosion-inhibiting properties. This makes sense because carbohydrates aren't ionically bonded; it's the ion-related activity between NaCl and steel that accelerates corrosion. Sucrose deicers appeared to have the greatest corrosion, then fructose, and sorbitol the least. Treatments with 13.3 wt% and 16.1 wt% sorbitol appeared to be comparable to the control. The final average weights of steel washers submerged in NaCl, sucrose and NaCl, fructose and NaCl, and sorbitol and NaCl were 7.98 g, 8.04 g, 8.09 g, and 7.80 g respectively (Figure 20). Based on having the least corrosion, lowest weight gain, and minimal presence of physical changes, like colouration and patina, sorbitol was concluded to be the least metal-corrosive agro-based deicer additive.

Limitations and Future Research

The treatments in this study only went up to a 1:1 salt:carbohydrate ratio. This could limit the result's full scope of understanding the effectiveness and effects of each agro-based deicer. Furthermore, the laboratory IMC tests should be taken with a grain of salt. Highly regulated and standardized deicing experiments, though provide grounds to compare deicers, don't replicate the realities of deicers when air pressure, vehicle friction, and wind are factors. Furthermore, the ecotoxicity test results only examined *D. magna* lethality, but water chemical composition could also react differently and even negatively–a property future research should examine. The results were also statistically moderate and were only used dynamically. Future research should conduct more trials to bolster statistical significance. Finally, the corrosion experiment only looked at steel corrosion, but observations cannot extend to other metals or infrastructure materials. Other physical properties future research should examine include friction, abrasion resistance, ice permeability, and free-thaw cycles. Future research should also test agro-based deicers created using food products with high sorbitol content, such as cranberries, corn, apples, plums, and grapes.

Conclusions

Determining an optimal agro-based deicer requires a holistic evaluation of its functionality and confounding effects. This study observed ice-melting capacity, *Daphnia magna* lethality, and metal corrosivity to evaluate deicing effectiveness, freshwater ecotoxicity, and physical impact on infrastructure respectively. It was concluded that sorbitol was the best agro-based deicer additive. The 7.1 wt% sorbitol and 21.4 wt% NaCl deicer outperformed 25.0 wt% NaCl by over 20% at 45 minutes. For ecotoxicity, all agro-based deicers had lower ecotoxicity than NaCl, marked by remediated *Daphnia magna* lethality. Finally, agro-based deicers demonstrated powerful corrosion inhibition, especially sorbitol. This threefold study holistically and effectively analyzed the performance and impact attributes of agro-based deicers by testing various carbohydrates. Future research should study fermented food products, and various other environmental and physical impact criteria to understand if agro-based deicers are viable options for snowy communities.

Acknowledgments

I would like to thank my advisor for the valuable insight provided to me on this topic.

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