Agro-Based Road Salt Additives: An Evaluation of the Ice-Melting Capacity, Ecotoxicity, and Corrosivity of Food-Derived Carbohydrates

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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 trading in a carbohydrate-rich food product. Previous literature has shown that agro-based deicers may be a promising alternative that could alleviate the environmental and physical pressures of traditional road salts. This study observed prevalent carbohydrates found in fermented food waste–sucrose, fructose, and sorbitol–as NaCl additives. 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 metal corrosion. This three-fold analysis was adopted to holistically analyze the effectiveness and confounding effects of novel, food-based road salt additives. The study concluded sorbitol as the best agro-based deicer additive, having outperformed 25.0 wt% NaCl by over 20%. It also mediated ecotoxicity–with a negative correlation between *D. magna* lethality and carbohydrate concentration–and presented powerful corrosion-inhibiting properties. These results shed light on the innovative formulation of deicers that could help support the sustainability of northern cities.

Keywords: road salts, winter management, agro-based, deicers, anti-icers, ice-melting, freezing point depression, ecotoxicity, corrosion

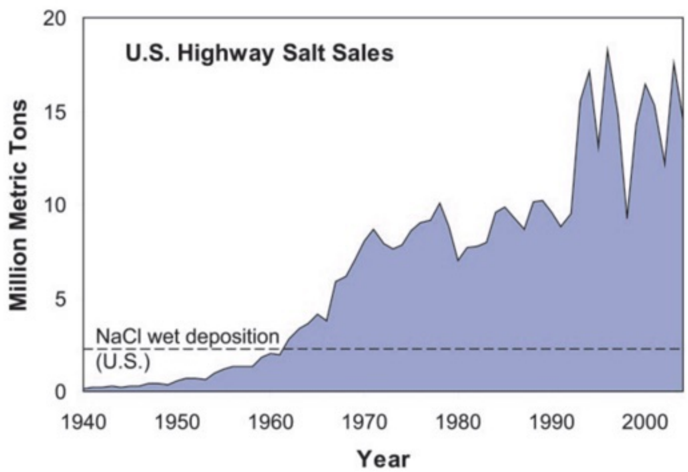
INTRODUCTION

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

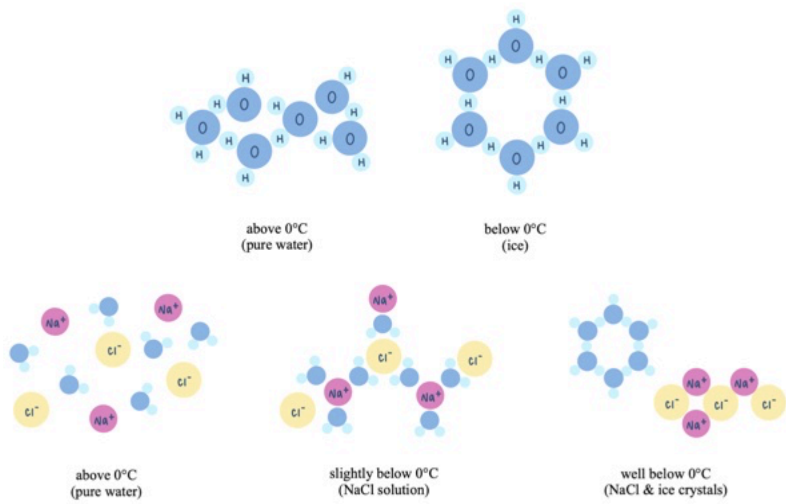
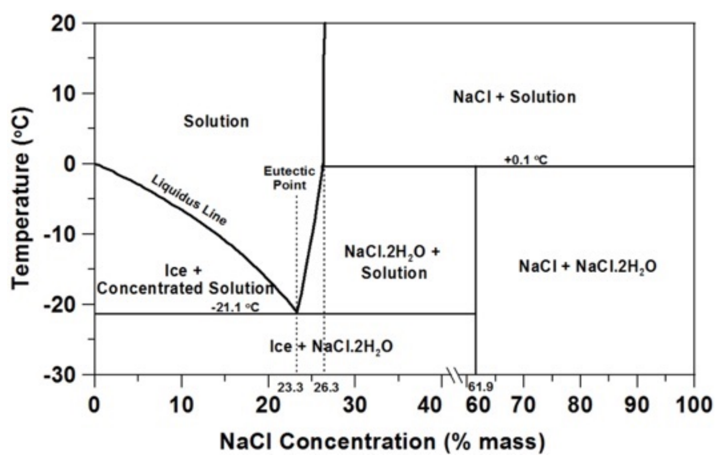


Figure 3

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

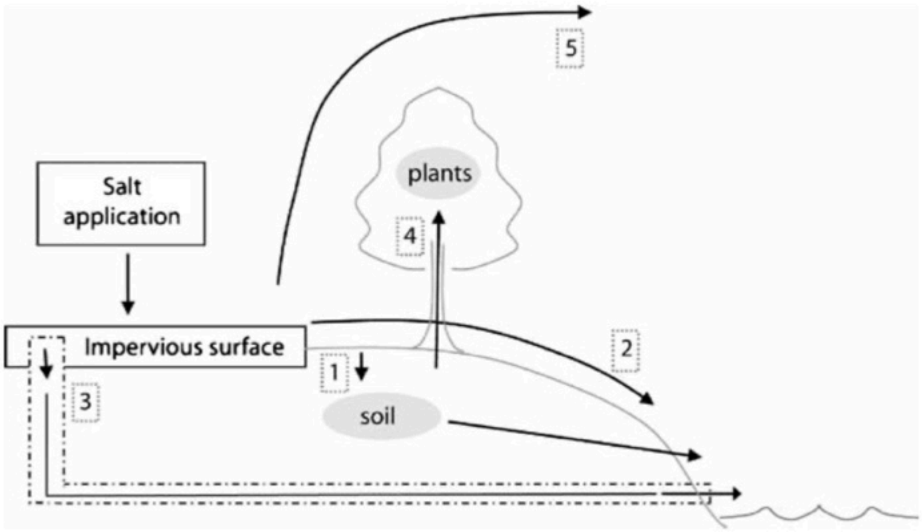


Environment Impact

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)

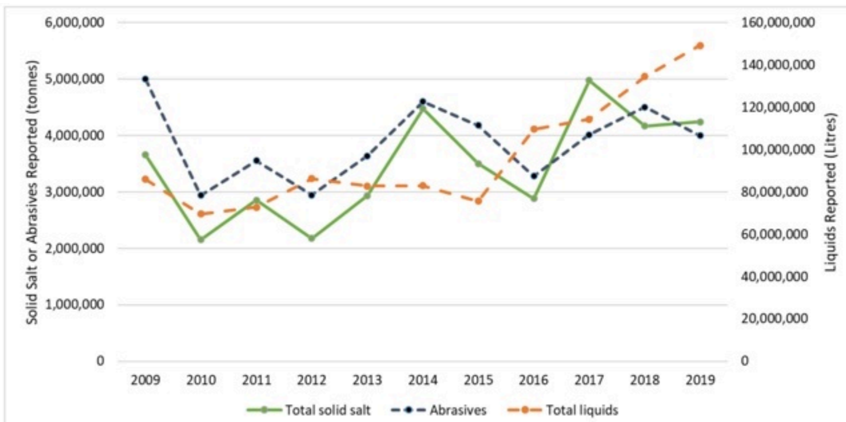
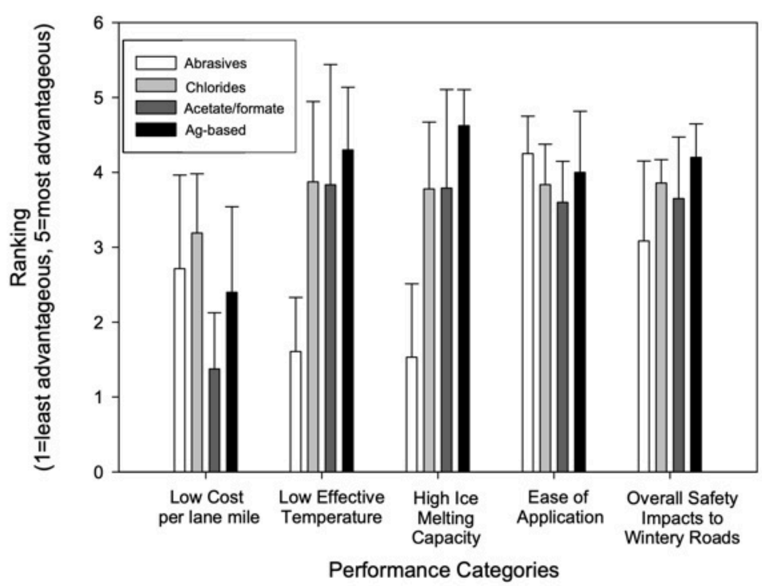


Figure 6

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 was 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.

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

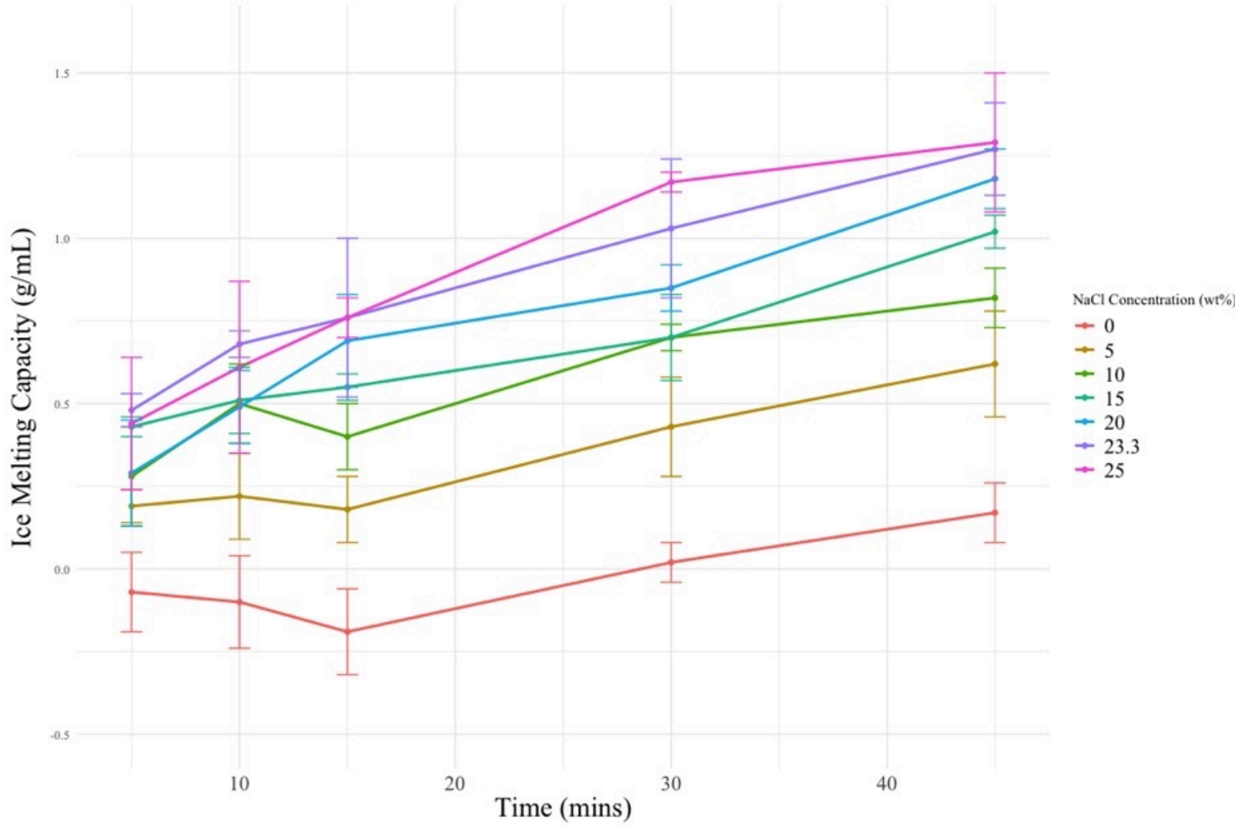


Figure 8

Ice-melting capacity of NaCl brines in relation to NaCl concentration

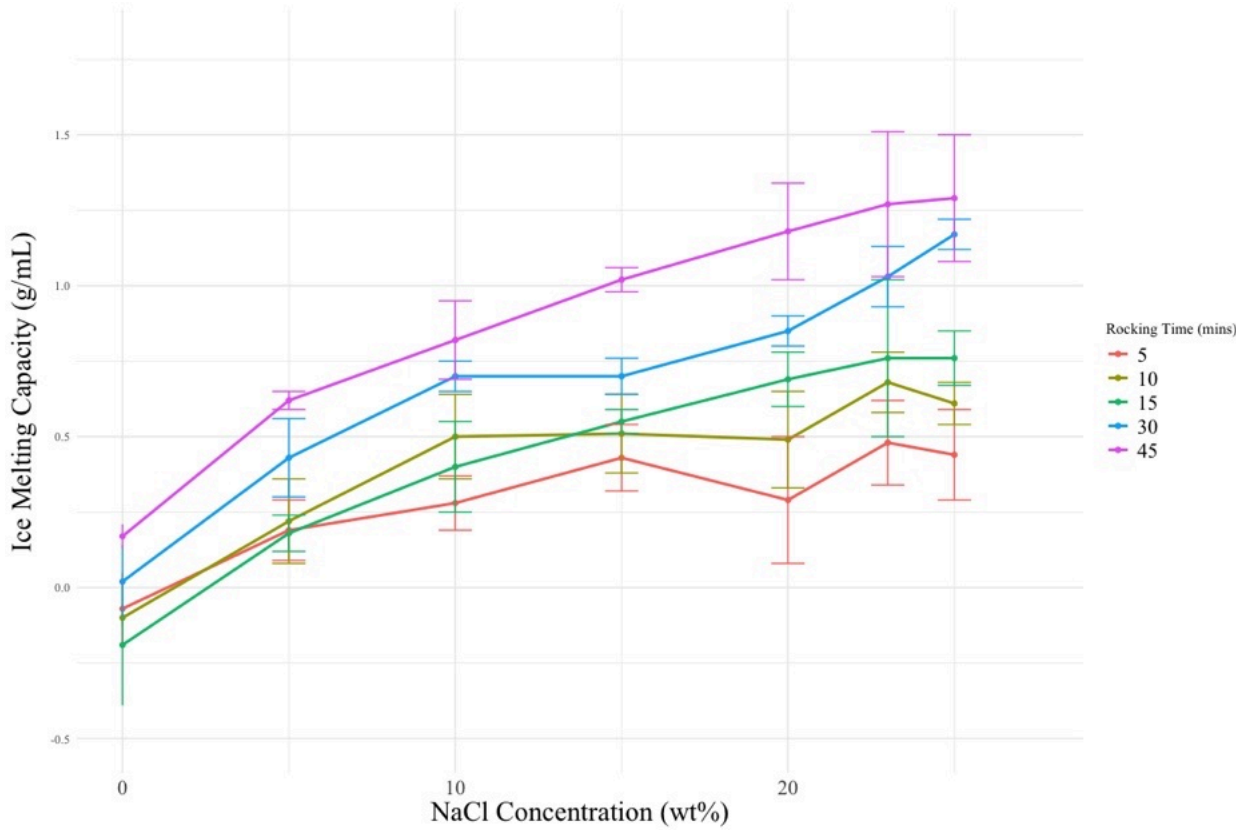


Table 5

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

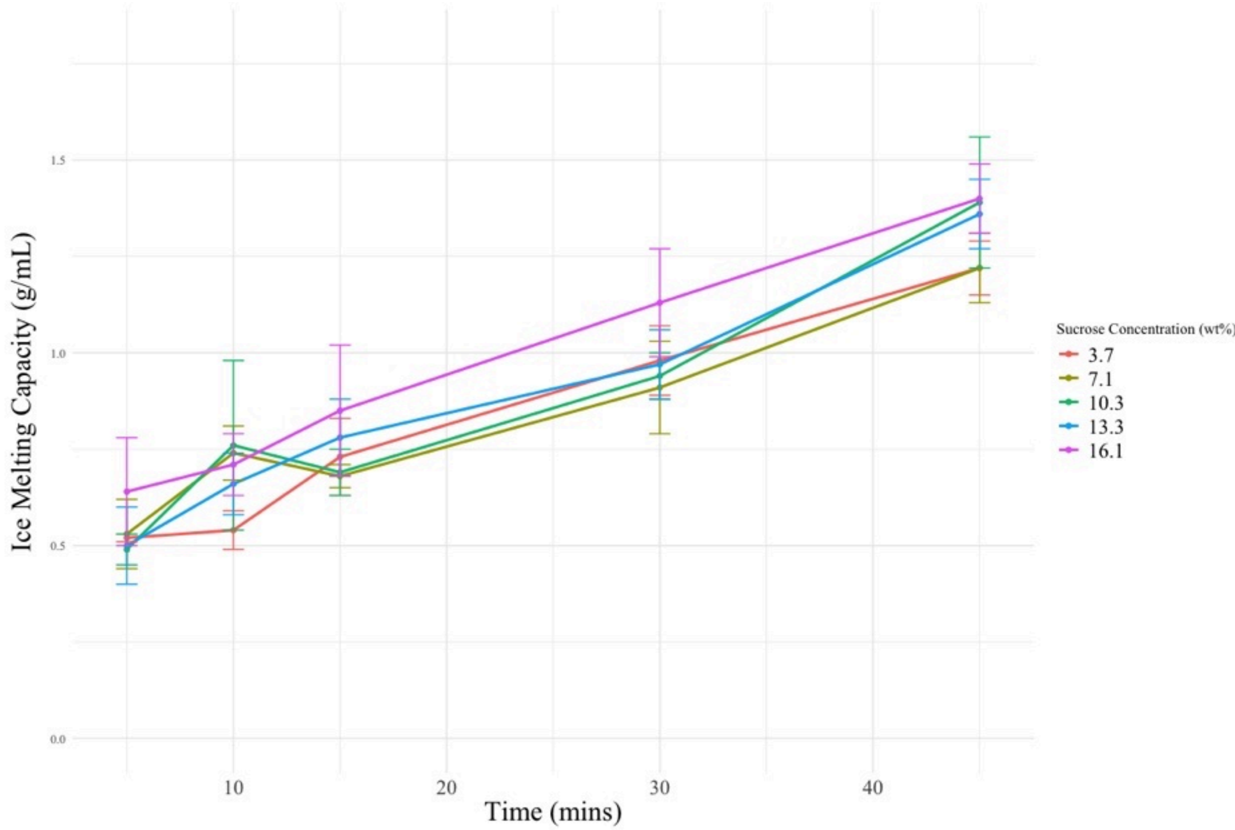


Figure 10

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

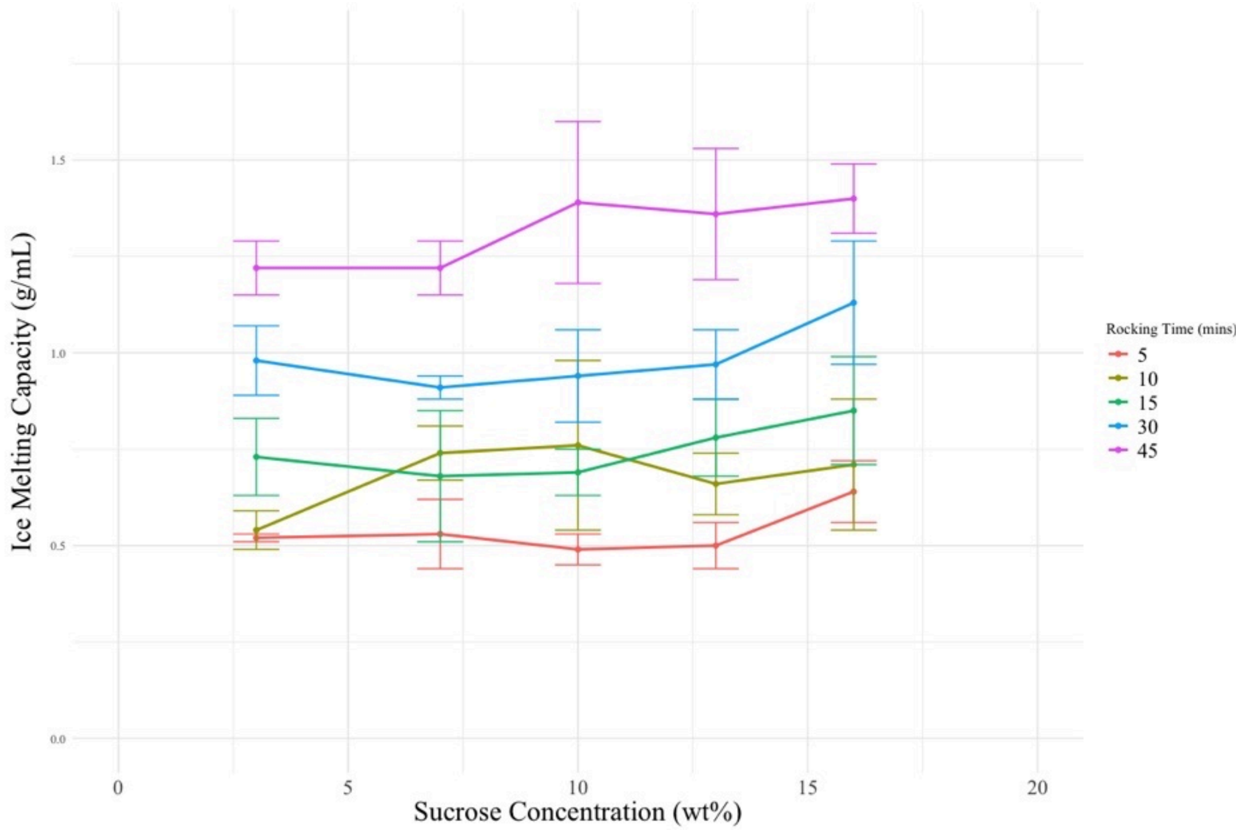


Table 6

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

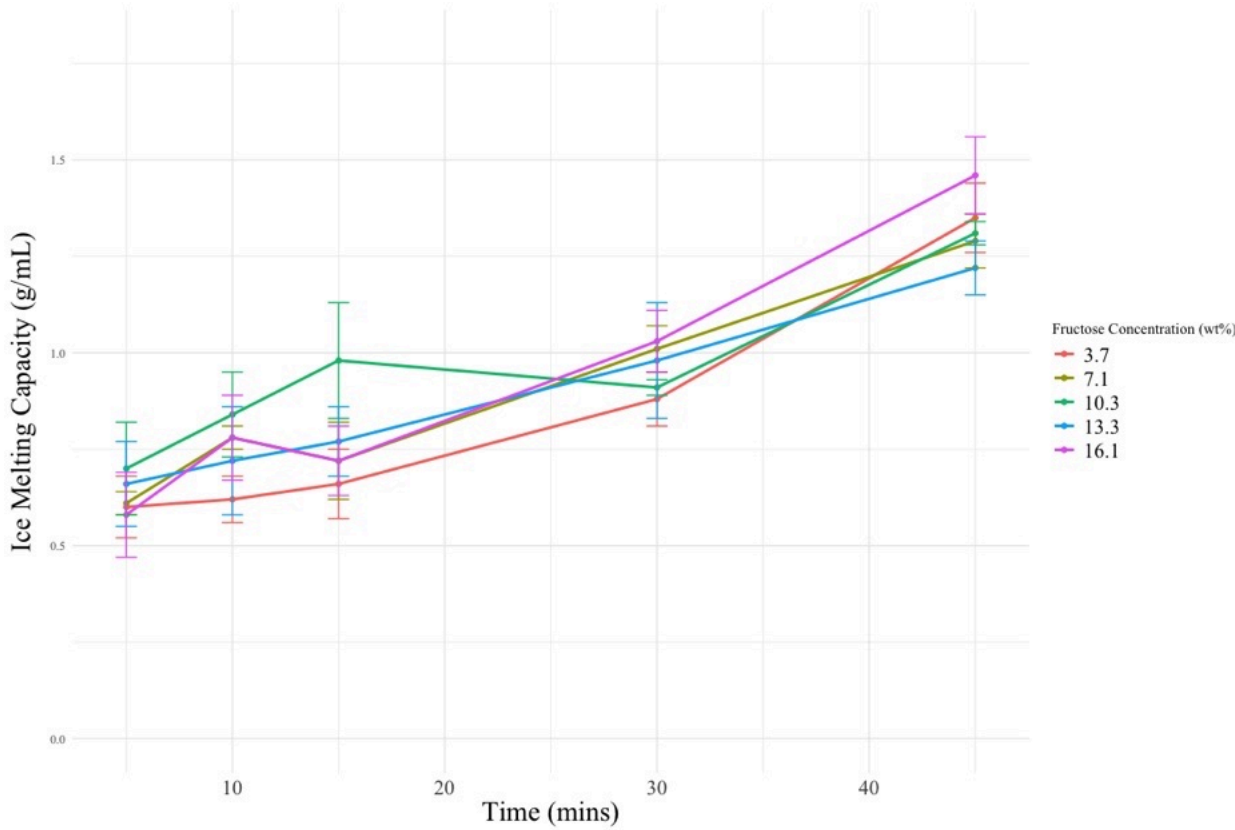


Figure 12

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

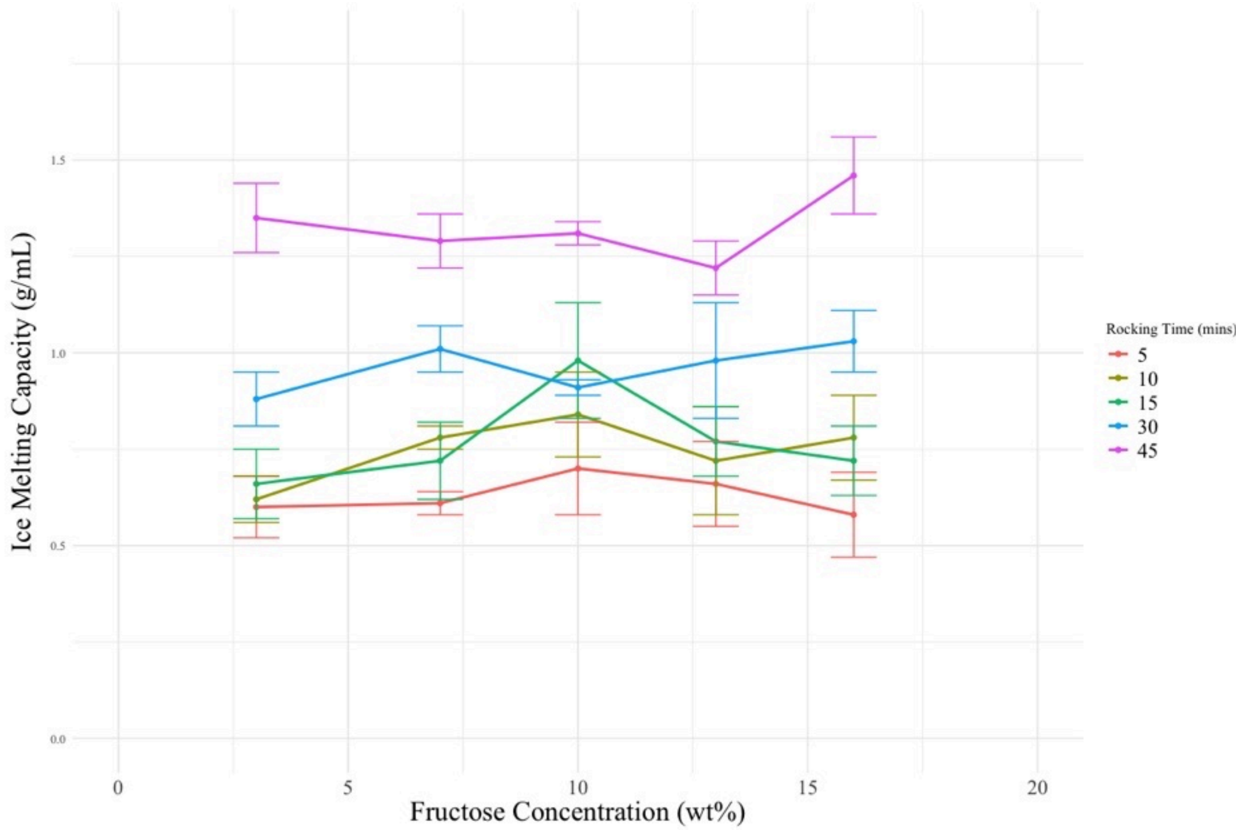


Table 7

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

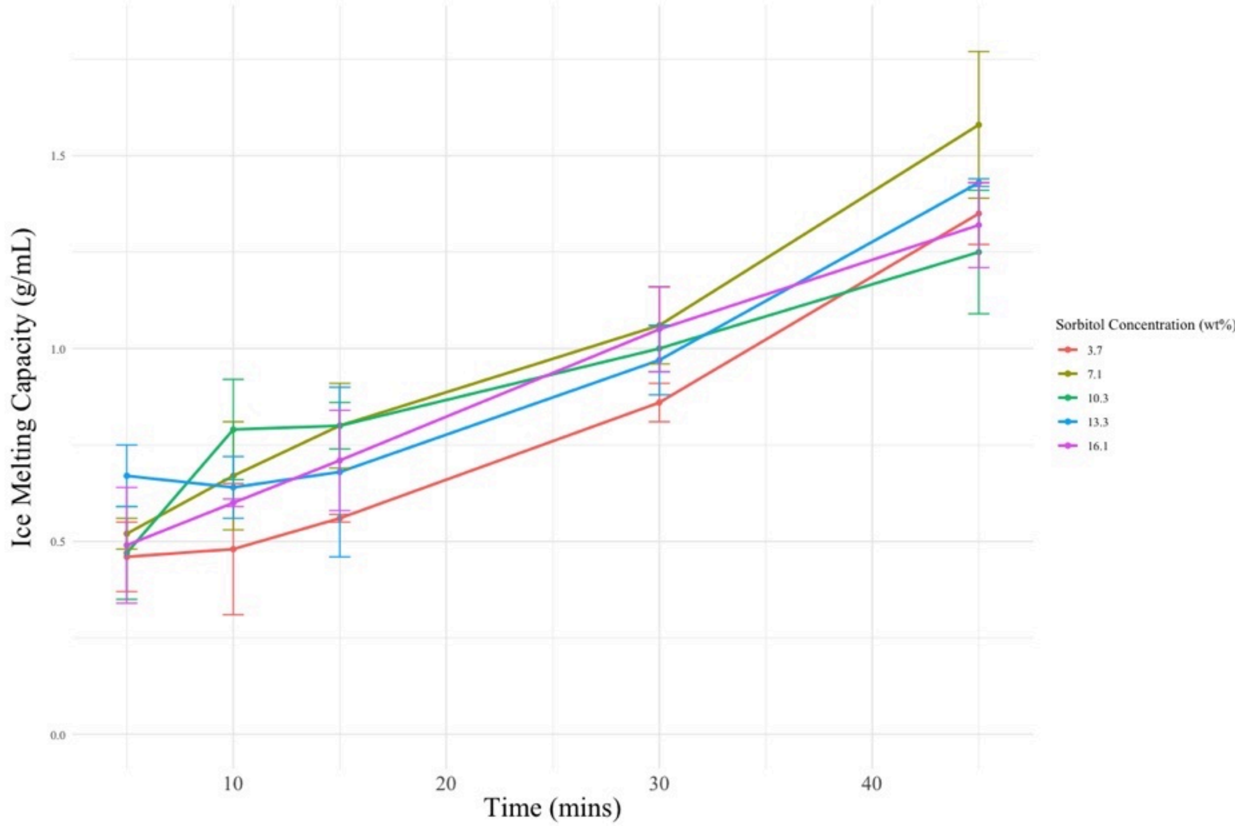
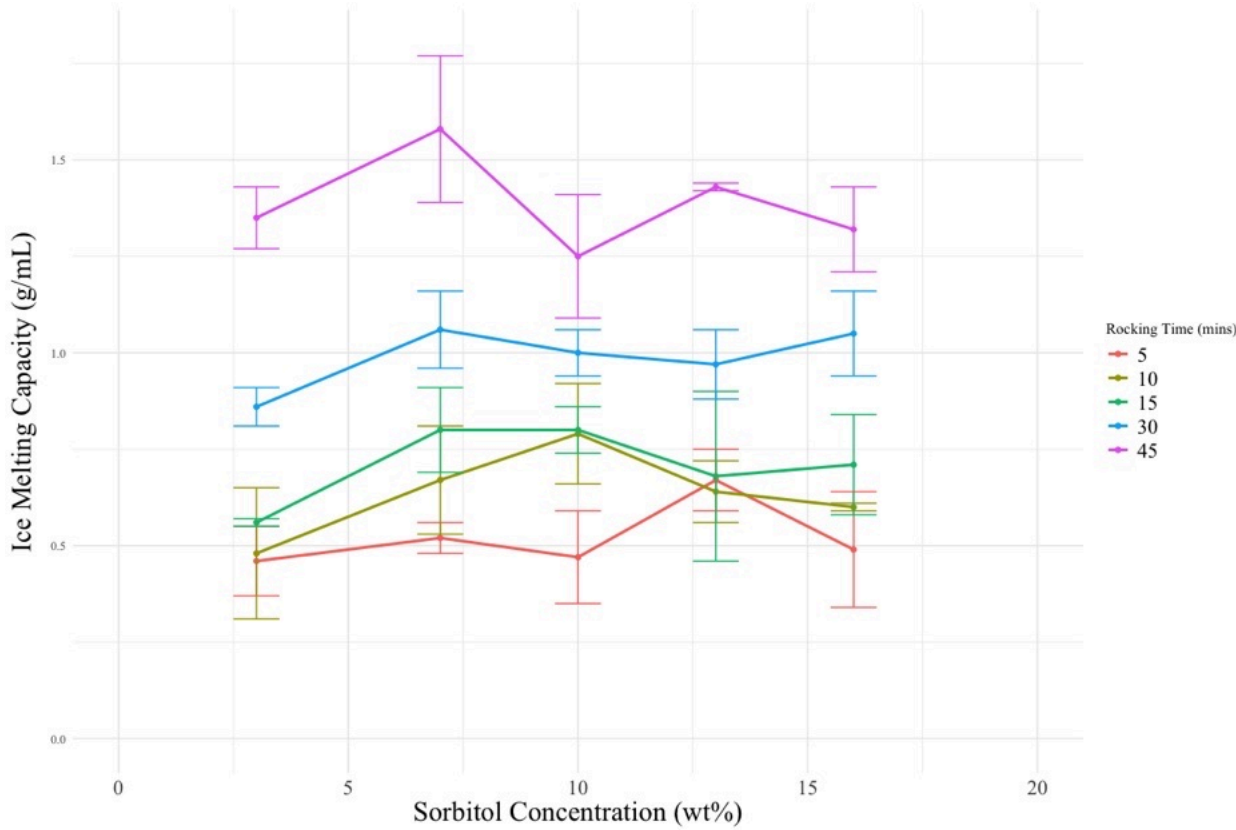


Figure 14

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

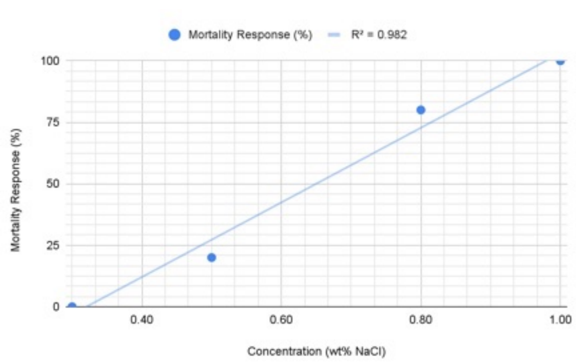


Figure 16

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

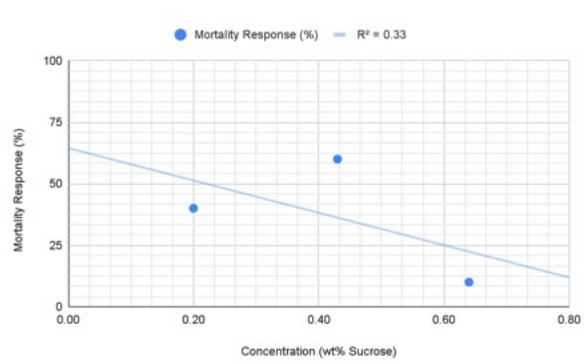


Figure 17

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

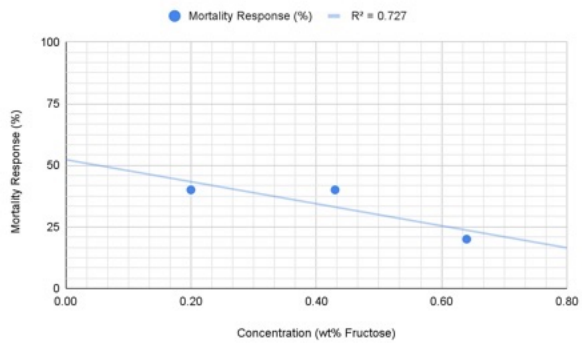
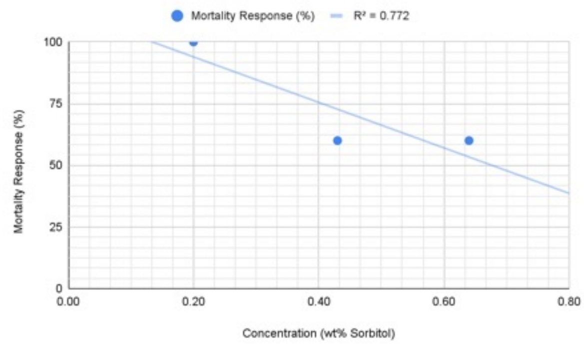


Figure 18

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 strong, 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

1


2	3	4	5	6
				
7	**8**	**9**	**10**	**11**
				
12	**13**	**14**	**15**	**16**
				
17	**18**	**19**	**20**	**21**
				

Figure 19

Average weight of steel wasters after being submerged in deicing treatments for six weeks

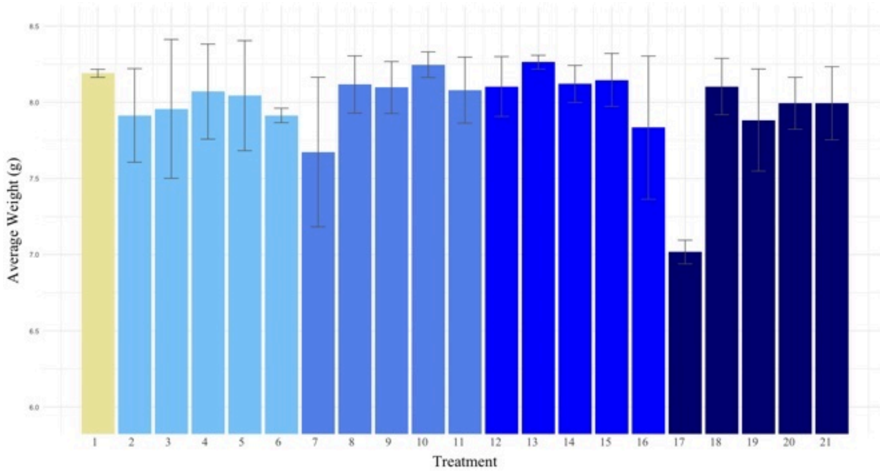


Table 12

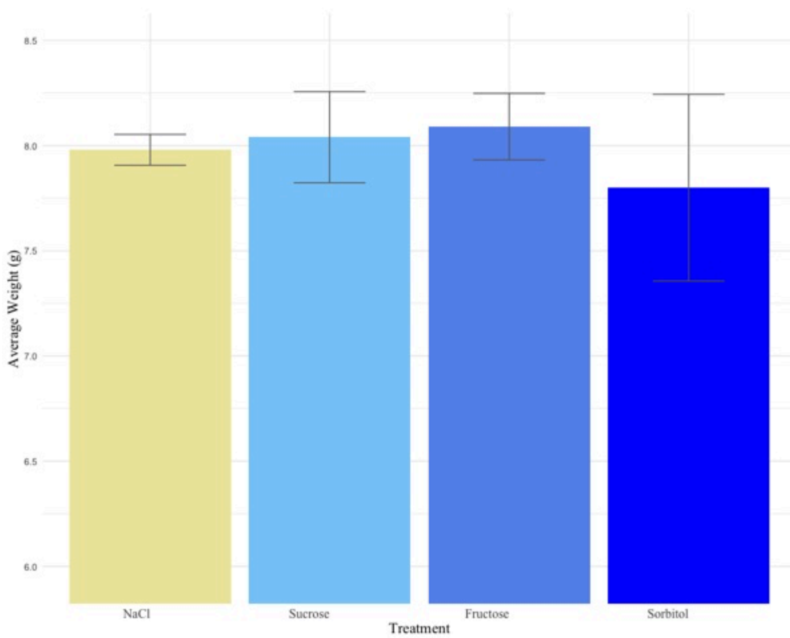
Average weight of steel washers per deicing group

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

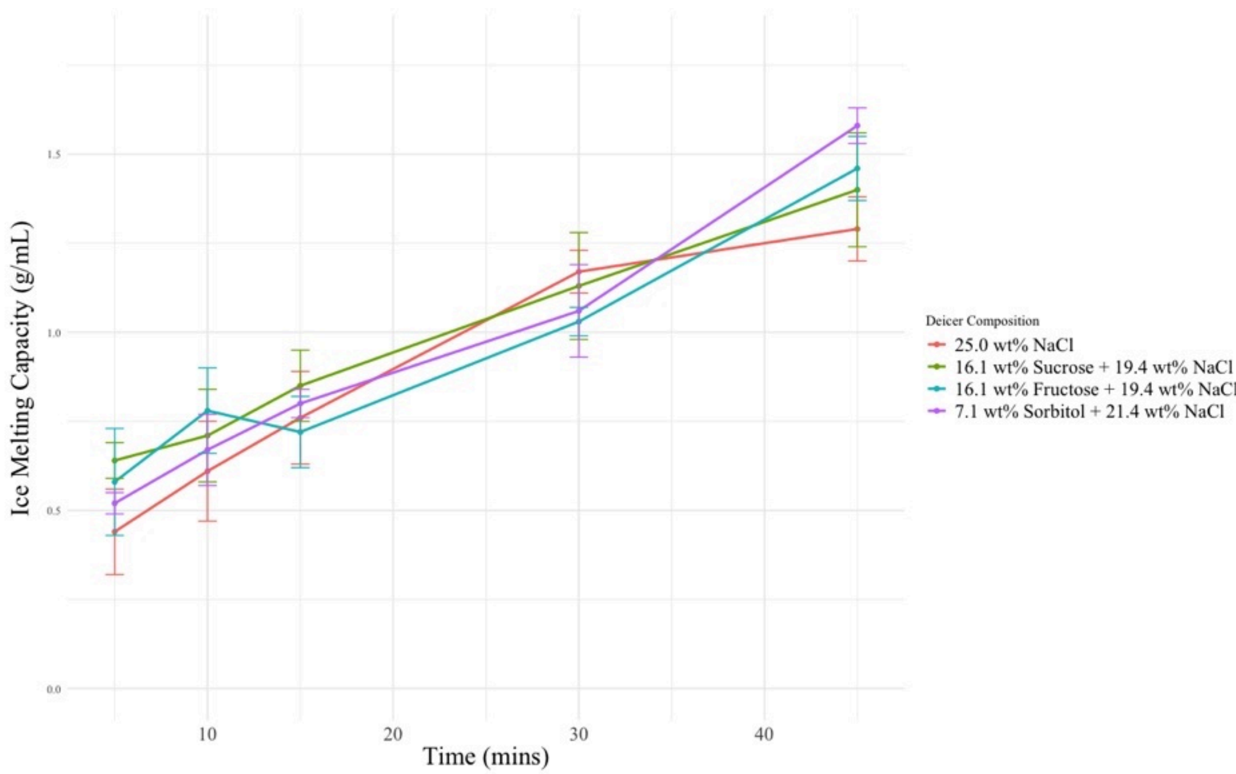


Table 13

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)

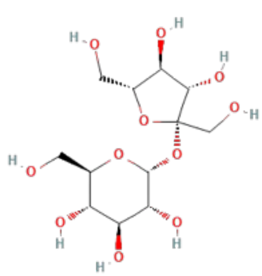


Figure 23

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

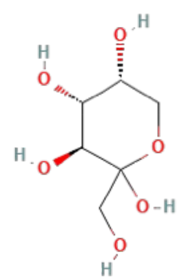
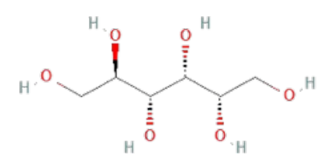


Figure 24

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 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.

CONCLUSION

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 criterias to understand if agro-based deicers are viable options for snowy communities.

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APPENDIX A

General Background Information

Table A1

IUPAC names for carbohydrates tested in this study

Sucrose	beta-D-arabino-hex-2-ulofuranosyl_alpha-D-gluco-hexopyranoside
Fructose	D-arabino-hex-2-ulopyranose
Sorbitol	(2R,3R,4R,5S)-hexane-1,2,3,4,5,6-hexol

Table A2

Physicochemical properties of chemicals tested in this study

	Sodium Chloride (NaCl)	**Sucrose**	**Fructose**	**Sorbitol**
Molecular Formula	$NaCl$	$C_{12}H_{22}O_{11}$	$C_6H_{12}O_6$	$C_6H_{14}O_6$
Molecular weight (g/mol)	58.44	342.30	180.16	182.17
Water solubility at 25°C (g/100 mL)	36.0	210	375	275

APPENDIX B

Ice-Melting Capacity (IMC) Experiment

Image B1

Image of IMC experiment setup

Table B1

Raw results of NaCl IMC

wt% of NaCl	Trial no.	Rocking Time (mins)				
		5	10	15	30	45
		Ice-Melting Capacity (g/mL)				
0	1	0.021	-0.165	-0.207	0.060	0.388
	2	-0.210	-0.160	-0.261	-0.113	0.152
	3	-0.016	0.016	-0.092	0.103	-0.026
5.0	1	0.055	0.242	0.189	0.586	0.718
	2	0.186	0.355	0.143	0.366	0.683
	3	0.340	0.052	0.202	0.336	0.452
10.0	1	0.372	0.330	0.465	0.738	1.050
	2	0.135	0.516	0.443	0.752	0.730
	3	0.335	0.648	0.285	0.621	0.683
15.0	1	0.447	0.686	0.520	0.724	1.284
	2	0.374	0.465	0.542	0.606	0.757
	3	0.483	0.388	0.593	0.772	1.013
20.0	1	0.200	0.426	0.543	0.822	1.118
	2	0.282	0.624	0.807	0.906	1.191
	3	0.375	0.406	0.714	0.827	1.229
23.3	1	0.428	0.565	0.803	1.002	1.234
	2	0.509	0.766	0.788	1.075	1.261
	3	0.510	0.709	0.703	1.025	1.302
25.0	1	0.294	0.648	0.944	1.444	1.500
	2	0.536	0.578	0.661	0.994	1.267
	3	0.500	0.608	0.689	1.085	1.090

Table B2

Raw results of sucrose IMC

wt% of NaCl	wt% of Sucrose	Trial no.	Rocking Time (mins)				
			5	10	15	30	45
			Ice-Melting Capacity (g/mL)				
22.2	3.7	1	0.532	0.560	0.727	0.913	1.315
		2	0.513	0.440	0.698	1.023	1.184
		3	0.519	0.624	0.776	1.004	1.174
21.4	7.1	1	0.518	0.705	0.535	0.860	1.272
		2	0.590	0.821	0.568	1.005	1.362
		3	0.486	0.681	0.937	0.877	1.026
20.7	10.3	1	0.378	0.718	0.742	0.827	1.555
		2	0.495	0.604	0.626	1.004	1.290
		3	0.584	0.943	0.693	1.000	1.328
20.0	13.3	1	0.419	0.628	0.669	0.986	1.366
		2	0.597	0.680	0.906	1.059	1.202
		3	0.472	0.672	0.775	0.874	1.516
19.4	16.1	1	0.562	0.637	1.093	1.203	1.445
		2	0.650	0.733	0.781	0.934	1.449
		3	0.708	0.768	0.688	1.240	1.296

Table B3

Raw results of fructose IMC

wt% of NaCl	wt% of Fructose	Trial no.	Rocking Time (mins)				
			5	10	15	30	45
			Ice-Melting Capacity (g/mL)				
22.2	3.7	1	0.682	0.653	0.664	0.857	1.232

		2	0.539	0.594	0.538	1.002	1.438
		3	0.568	0.617	0.783	0.784	1.394
21.4	7.1	1	0.665	0.757	0.844	0.855	1.255
		2	0.546	0.779	0.690	1.028	1.404
		3	0.61	0.812	0.639	1.142	1.199
20.7	10.3	1	0.777	0.801	0.949	0.894	1.216
		2	0.702	0.952	0.847	0.825	1.335
		3	0.606	0.759	1.140	1.004	1.383
20.0	13.3	1	0.743	0.686	0.769	0.871	1.150
		2	0.617	0.683	0.756	0.908	1.314
		3	0.622	0.791	0.798	1.149	1.197
19.4	16.1	1	0.685	0.852	0.697	1.053	1.385
		2	0.522	0.714	0.759	1.089	1.422
		3	0.531	0.767	0.705	0.945	1.574

Table B4

Raw results of sorbitol IMC

wt% of NaCl	**wt% of Sorbitol**	**Trial no.**	**Rocking Time (mins)**				
			5	**10**	**15**	**30**	**45**
			Ice-Melting Capacity (g/mL)				
22.2	3.7	1	0.404	0.457	0.700	0.851	1.295
		2	0.419	0.459	0.503	0.936	1.233
		3	0.565	0.528	0.485	0.779	1.519
21.4	7.1	1	0.322	0.823	0.94	0.878	1.609
		2	0.648	0.621	0.685	1.177	1.634
		3	0.587	0.558	0.788	1.120	1.484

20.7	10.3	1	0.477	0.895	0.867	0.803	1.391
		2	0.467	0.67	0.777	1.241	1.210
		3	0.473	0.795	0.764	0.958	1.148
20.0	13.3	1	0.614	0.721	0.734	0.887	1.537
		2	0.721	0.527	0.683	1.070	1.319
		3	0.680	0.666	0.623	0.940	1.437
19.4	16.1	1	0.550	0.814	0.902	1.049	1.436
		2	0.396	0.536	0.607	1.053	1.207
		3	0.521	0.459	0.628	1.033	1.314

Table B5

Single-factor ANOVA test for NaCl treatments' IMC results at 5 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	-0.205	-0.06833333333		0.01539433333	
Column 2	3	0.581	0.1936666667		0.02035033333	
Column 3	3	0.842	0.2806666667		0.01625633333	
Column 4	3	1.304	0.4346666667		0.003084333333	
Column 5	3	0.857	0.2856666667		0.007666333333	
Column 6	3	1.447	0.4823333333		0.002214333333	
Column 7	3	1.33	0.4433333333		0.01704933333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.6574539048	6	0.1095756508	9.352270172	0.0003105254829	2.847725996
Within Groups	0.1640306667	14	0.01171647619			

Total	0.8214845714	20				

Table B6

Single-factor ANOVA test for Sucrose + NaCl treatments' IMC results at 5 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	1.564	0.5213333333		0.00009433333333	
Column 2	3	1.594	0.5313333333		0.002837333333	
Column 3	3	1.457	0.4856666667		0.01067433333	
Column 4	3	1.488	0.496		0.008353	
Column 5	3	1.92	0.64		0.005404	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.04553973333	4	0.01138493333	2.080351813	0.1584455431	3.478049691
Within Groups	0.054726	10	0.0054726			
Total	0.1002657333	14				

Table B7

Single-factor ANOVA test for Fructose + NaCl treatments' IMC results at 5 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	1.789	0.5963333333	0.005714333333
Column 2	3	1.821	0.607	0.003547
Column 3	3	2.085	0.695	0.007347
Column 4	3	1.982	0.6606666667	0.005090333333

Column 5	3	1.738	0.5793333333		0.008394333333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.02810333333	4	0.007025833333	1.167353427	0.3815007427	3.478049691
Within Groups	0.060186	10	0.0060186			
Total	0.08828933333	14				

Table B8

Single-factor ANOVA test for Sorbitol + NaCl treatments' IMC results at 5 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	1.388	0.4626666667		0.007910333333	
Column 2	3	1.557	0.519		0.030037	
Column 3	3	1.417	0.4723333333		0.00002533333333	
Column 4	3	2.015	0.6716666667		0.002914333333	
Column 5	3	1.467	0.489		0.006697	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.08844293333	4	0.02211073333	2.323336976	0.1275019443	3.478049691
Within Groups	0.095168	10	0.0095168			
Total	0.1836109333	14				

Table B9

Single-factor ANOVA test for all treatments' IMC results at 5 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	-0.205	-0.06833333333	0.01539433333
Column 2	3	0.581	0.1936666667	0.02035033333
Column 3	3	0.842	0.2806666667	0.01625633333
Column 4	3	1.304	0.4346666667	0.003084333333
Column 5	3	0.857	0.2856666667	0.007666333333
Column 6	3	1.447	0.4823333333	0.002214333333
Column 7	3	1.33	0.4433333333	0.01704933333
Column 8	3	1.564	0.5213333333	0.00009433333333
Column 9	3	1.594	0.5313333333	0.002837333333
Column 10	3	1.457	0.4856666667	0.01067433333
Column 11	3	1.488	0.496	0.008353
Column 12	3	1.92	0.64	0.005404
Column 13	3	1.789	0.5963333333	0.005714333333
Column 14	3	1.821	0.607	0.003547
Column 15	3	2.085	0.695	0.007347
Column 16	3	1.982	0.6606666667	0.005090333333
Column 17	3	1.738	0.5793333333	0.008394333333
Column 18	3	1.388	0.4626666667	0.007910333333
Column 19	3	1.557	0.519	0.030037
Column 20	3	1.417	0.4723333333	0.00002533333333
Column 21	3	2.015	0.6716666667	0.002914333333
Column 22	3	1.467	0.489	0.006697
ANOVA				

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.951766	21	0.0929412381	10.93102881	2.59274823832811E-11	1.800885055
Within Groups	0.3741106667	44	0.008502515152	10.95817521	8.97282248502052E-12	1.77796144
Within Groups	0.4014713333	46	0.008727637681			
Total	2.325876667	65				
Total	2.505528957	68				

Table B10

Single-factor ANOVA test for NaCl treatments' IMC results at 10 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	-0.309	-0.103		0.010627	
Column 2	3	0.649	0.2163333333		0.02344633333	
Column 3	3	1.494	0.498		0.025524	
Column 4	3	1.539	0.513		0.023929	
Column 5	3	1.456	0.4853333333		0.01452133333	
Column 6	3	2.04	0.68		0.010731	
Column 7	3	1.834	0.6113333333		0.001233333333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	1.314005143	6	0.2190008571	13.93489801	0.00003438895493	2.847725996
Within Groups	0.220024	14	0.015716			

Total	1.534029143	20

Table B11

Single-factor ANOVA test for Sucrose + NaCl treatments' IMC results at 10 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	1.624	0.5413333333		0.008725333333	
Column 2	3	2.207	0.7356666667		0.005605333333	
Column 3	3	2.265	0.755		0.029757	
Column 4	3	1.98	0.66		0.000784	
Column 5	3	2.138	0.7126666667		0.004600333333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.08824493333	4	0.02206123333	2.229668634	0.1385198064	3.478049691
Within Groups	0.098944	10	0.0098944			
Total	0.1871889333	14				

Table B12

Single-factor ANOVA test for Fructose + NaCl treatments' IMC results at 10 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	1.864	0.6213333333	0.0008843333333
Column 2	3	2.348	0.7826666667	0.0007663333333
Column 3	3	2.512	0.8373333333	0.01030233333

Column 4	3	2.16	0.72		0.003783	
Column 5	3	2.333	0.7776666667		0.004846333333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.08067173333	4	0.02016793333	4.899331142	0.01897934869	3.478049691
Within Groups	0.04116466667	10	0.004116466667			
Total	0.1218364	14				

Table B13

Single-factor ANOVA test for Sorbitol + NaCl treatments' IMC results at 10 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	1.444	0.4813333333		0.001634333333	
Column 2	3	2.002	0.6673333333		0.01916633333	
Column 3	3	2.36	0.7866666667		0.01270833333	
Column 4	3	1.914	0.638		0.009997	
Column 5	3	1.809	0.603		0.034873	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.1460829333	4	0.03652073333	2.329752442	0.1267852938	3.478049691
Within Groups	0.156758	10	0.0156758			
Total	0.3028409333	14				

Table B14

Single-factor ANOVA test for all treatments' IMC results at 10 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	-0.309	-0.103	0.010627
Column 2	3	0.649	0.2163333333	0.02344633333
Column 3	3	1.494	0.498	0.025524
Column 4	3	1.539	0.513	0.023929
Column 5	3	1.456	0.4853333333	0.01452133333
Column 6	3	2.04	0.68	0.010731
Column 7	3	1.834	0.6113333333	0.001233333333
Column 8	3	1.624	0.5413333333	0.008725333333
Column 9	3	2.207	0.7356666667	0.005605333333
Column 10	3	2.265	0.755	0.029757
Column 11	3	1.98	0.66	0.000784
Column 12	3	2.138	0.7126666667	0.004600333333
Column 13	3	1.864	0.6213333333	0.0008843333333
Column 14	3	2.348	0.7826666667	0.0007663333333
Column 15	3	2.512	0.8373333333	0.01030233333
Column 16	3	2.16	0.72	0.003783
Column 17	3	2.333	0.7776666667	0.004846333333
Column 18	3	1.444	0.4813333333	0.001634333333
Column 19	3	2.002	0.6673333333	0.01916633333
Column 20	3	2.36	0.7866666667	0.01270833333
Column 21	3	1.914	0.638	0.009997
Column 22	3	1.809	0.603	0.034873

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	2.796698197	21	0.1331761046	11.33653397	1.39114275654606E-11	1.800885055
Within Groups	0.5168906667	44	0.01174751515	10.95817521	8.97282248502052E-12	1.77796144
Within Groups	0.4014713333	46	0.008727637681			
Total	3.313588864	65				
Total	2.505528957	68				

Table B15

Single-factor ANOVA test for NaCl treatments' IMC results at 15 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	-0.56	-0.1866666667		0.007450333333	
Column 2	3	0.534	0.178		0.000961	
Column 3	3	1.193	0.3976666667		0.009641333333	
Column 4	3	1.655	0.5516666667		0.001402333333	
Column 5	3	2.064	0.688		0.017931	
Column 6	3	2.294	0.7646666667		0.002908333333	
Column 7	3	2.294	0.7646666667		0.02431633333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	2.241205238	6	0.3735342063	40.46916058	0.00000004671126241	2.847725996

Within Groups	0.1292213333	14	0.009230095238			
Total	2.370426571	20				

Table B16

Single-factor ANOVA test for Sucrose + NaCl treatments' IMC results at 15 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	2.201	0.7336666667		0.001554333333	
Column 2	3	2.04	0.68		0.049809	
Column 3	3	2.061	0.687		0.003391	
Column 4	3	2.35	0.7833333333		0.01409433333	
Column 5	3	2.562	0.854		0.045003	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.06310226667	4	0.01577556667	0.692812285	0.6136631519	3.478049691
Within Groups	0.2277033333	10	0.02277033333			
Total	0.2908056	14				

Table B17

Single-factor ANOVA test for Fructose + NaCl treatments' IMC results at 15 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	1.985	0.6616666667	0.01501033333
Column 2	3	2.173	0.7243333333	0.01139033333
Column 3	3	2.936	0.9786666667	0.02212233333

Column 4	3	2.323	0.7743333333		0.0004623333333	
Column 5	3	2.161	0.7203333333		0.001137333333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.1794944	4	0.0448736	4.476377953	0.02486855003	3.478049691
Within Groups	0.1002453333	10	0.01002453333			
Total	0.2797397333	14				

Table B18

Single-factor ANOVA test for Sorbitol + NaCl treatments' IMC results at 15 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	1.688	0.5626666667		0.01422633333	
Column 2	3	2.413	0.8043333333		0.01645633333	
Column 3	3	2.408	0.8026666667		0.003146333333	
Column 4	3	2.04	0.68		0.003087	
Column 5	3	1.809	0.603		0.034873	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.1489417333	4	0.03723543333	2.593394067	0.1010143058	3.478049691
Within Groups	0.143578	10	0.0143578			
Total	0.2925197333	14				

Table B19

Single-factor ANOVA test for all treatments' IMC results at 15 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	-0.56	-0.1866666667	0.007450333333
Column 2	3	0.534	0.178	0.000961
Column 3	3	1.193	0.3976666667	0.009641333333
Column 4	3	1.655	0.5516666667	0.001402333333
Column 5	3	2.064	0.688	0.017931
Column 6	3	2.294	0.7646666667	0.002908333333
Column 7	3	2.294	0.7646666667	0.02431633333
Column 8	3	2.201	0.7336666667	0.001554333333
Column 9	3	2.04	0.68	0.049809
Column 10	3	2.061	0.687	0.003391
Column 11	3	2.35	0.7833333333	0.01409433333
Column 12	3	2.562	0.854	0.045003
Column 13	3	1.985	0.6616666667	0.01501033333
Column 14	3	2.173	0.7243333333	0.01139033333
Column 15	3	2.936	0.9786666667	0.02212233333
Column 16	3	2.323	0.7743333333	0.0004623333333
Column 17	3	2.161	0.7203333333	0.001137333333
Column 18	3	1.688	0.5626666667	0.01422633333
Column 19	3	2.413	0.8043333333	0.01645633333
Column 20	3	2.408	0.8026666667	0.003146333333
Column 21	3	2.04	0.68	0.003087
Column 22	3	1.809	0.603	0.034873
ANOVA				

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.852319818	21	0.1834438009	13.43579544	7.11652958784725E-13	1.800885055
Within Groups	0.600748	44	0.01365336364	10.95817521	8.97282248502052E-12	1.77796144
Within Groups	0.4014713333	46	0.008727637681			
Total	4.453067818	65				
Total	2.505528957	68				

Table B20

Single-factor ANOVA test for NaCl treatments' IMC results at 30 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	0.05	0.01666666667		0.01307233333	
Column 2	3	1.288	0.4293333333		0.01863333333	
Column 3	3	2.111	0.7036666667		0.005174333333	
Column 4	3	2.102	0.7006666667		0.007297333333	
Column 5	3	2.555	0.8516666667		0.002220333333	
Column 6	3	3.102	1.034		0.001393	
Column 7	3	3.523	1.174333333		0.05661033333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	2.699263238	6	0.4498772063	30.16389158	0.0000003110911242	2.847725996
Within Groups	0.208802	14	0.01491442857			

Total	2.90806523 8	20

Table B21

Single-factor ANOVA test for Sucrose + NaCl treatments' IMC results at 30 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	2.94	0.98		0.003457	
Column 2	3	2.742	0.914		0.006283	
Column 3	3	2.831	0.9436666667		0.01021233333	
Column 4	3	2.919	0.973		0.008683	
Column 5	3	3.377	1.125666667		0.02789433333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.0800396	4	0.0200099	1.76985830 4	0.21140972 25	3.47804969 1
Within Groups	0.11305933 33	10	0.01130593 333			
Total	0.19309893 33	14				

Table B22

Single-factor ANOVA test for Fructose + NaCl treatments' IMC results at 30 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	2.643	0.881	0.012313
Column 2	3	3.025	1.008333333	0.02088233333
Column 3	3	2.723	0.9076666667	0.008150333333
Column 4	3	2.928	0.976	0.022789

Column 5	3	3.087	1.029		0.005616	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.04899626667	4	0.01224906667	0.8780609026	0.5105341981	3.478049691
Within Groups	0.1395013333	10	0.01395013333			
Total	0.1884976	14				

Table B23

Single-factor ANOVA test for Sorbitol + NaCl treatments' IMC results at 30 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	2.566	0.8553333333		0.006176333333	
Column 2	3	3.175	1.058333333		0.02520233333	
Column 3	3	3.002	1.000666667		0.04932633333	
Column 4	3	2.897	0.9656666667		0.008866333333	
Column 5	3	3.135	1.045		0.000112	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.07923133333	4	0.01980783333	1.104320758	0.4064773203	3.478049691
Within Groups	0.1793666667	10	0.01793666667			
Total	0.258598	14				

Table B24

Single-factor ANOVA test for all treatments' IMC results at 30 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	0.05	0.01666666667		0.01307233333	
Column 2	3	1.288	0.4293333333		0.01863333333	
Column 3	3	2.111	0.7036666667		0.005174333333	
Column 4	3	2.102	0.7006666667		0.007297333333	
Column 5	3	2.555	0.8516666667		0.002220333333	
Column 6	3	3.102	1.034		0.001393	
Column 7	3	3.523	1.174333333		0.05661033333	
Column 8	3	2.94	0.98		0.003457	
Column 9	3	2.742	0.914		0.006283	
Column 10	3	2.831	0.9436666667		0.01021233333	
Column 11	3	2.919	0.973		0.008683	
Column 12	3	3.377	1.125666667		0.02789433333	
Column 13	3	2.643	0.881		0.012313	
Column 14	3	3.025	1.008333333		0.02088233333	
Column 15	3	2.723	0.9076666667		0.008150333333	
Column 16	3	2.928	0.976		0.022789	
Column 17	3	3.087	1.029		0.005616	
Column 18	3	2.566	0.8553333333		0.006176333333	
Column 19	3	3.175	1.058333333		0.02520233333	
Column 20	3	3.002	1.000666667		0.04932633333	
Column 21	3	2.897	0.9656666667		0.008866333333	
Column 22	3	3.135	1.045		0.000112	
ANOVA						
Source of	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**

Variation						
Between Groups	4.005520197	21	0.190739057	13.09838347	1.11832765270492E-12	1.800885055
Within Groups	0.6407293333	44	0.0145620303	10.95817521	8.97282248502052E-12	1.77796144
Within Groups	0.4014713333	46	0.008727637681			
Total	4.64624953	65				
Total	2.505528957	68				

Table B25

Single-factor ANOVA test for NaCl treatments' IMC results at 45 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	0.514	0.1713333333		0.04312933333	
Column 2	3	1.853	0.6176666667		0.02089033333	
Column 3	3	2.463	0.821		0.039883	
Column 4	3	3.054	1.018		0.069451	
Column 5	3	3.538	1.179333333		0.003182333333	
Column 6	3	3.797	1.265666667		0.001172333333	
Column 7	3	3.857	1.285666667		0.04228633333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	2.972455619	6	0.4954092698	15.76340437	0.00001679087389	2.847725996
Within Groups	0.4399893333	14	0.03142780952			
Total	3.41244495	20				

	2

Table B26

Single-factor ANOVA test for Sucrose + NaCl treatments' IMC results at 45 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	3.673	1.224333333		0.006190333333	
Column 2	3	3.66	1.22		0.030252	
Column 3	3	4.173	1.391		0.020533	
Column 4	3	4.084	1.361333333		0.02466533333	
Column 5	3	4.19	1.396666667		0.007604333333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.09531133333	4	0.02382783333	1.334967412	0.3226447574	3.478049691
Within Groups	0.17849	10	0.017849			
Total	0.2738013333	14				

Table B27

Single-factor ANOVA test for Fructose + NaCl treatments' IMC results at 45 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	4.064	1.354666667	0.01176933333
Column 2	3	3.858	1.286	0.011227
Column 3	3	3.934	1.311333333	0.007392333333
Column 4	3	3.661	1.220333333	0.007132333333

Column 5	3	4.381	1.460333333		0.01003233333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.09553906667	4	0.02388476667	2.511366185	0.1083154503	3.478049691
Within Groups	0.09510666667	10	0.009510666667			
Total	0.1906457333	14				

Table B28

Single-factor ANOVA test for Sorbitol + NaCl treatments' IMC results at 45 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	4.047	1.349		0.022636	
Column 2	3	4.727	1.575666667		0.006458333333	
Column 3	3	3.749	1.249666667		0.01594233333	
Column 4	3	4.293	1.431		0.011908	
Column 5	3	3.957	1.319		0.013129	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.1873104	4	0.0468276	3.341312238	0.05542977342	3.478049691
Within Groups	0.1401473333	10	0.01401473333			
Total	0.3274577333	14				

Table B29

Single-factor ANOVA test for all treatments' IMC results at 45 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	0.514	0.1713333333	0.04312933333
Column 2	3	1.853	0.6176666667	0.02089033333
Column 3	3	2.463	0.821	0.039883
Column 4	3	3.054	1.018	0.069451
Column 5	3	3.538	1.179333333	0.003182333333
Column 6	3	3.797	1.265666667	0.001172333333
Column 7	3	3.857	1.285666667	0.04228633333
Column 8	3	3.673	1.224333333	0.006190333333
Column 9	3	3.66	1.22	0.030252
Column 10	3	4.173	1.391	0.020533
Column 11	3	4.084	1.361333333	0.02466533333
Column 12	3	4.19	1.396666667	0.007604333333
Column 13	3	4.064	1.354666667	0.01176933333
Column 14	3	3.858	1.286	0.011227
Column 15	3	3.934	1.311333333	0.007392333333
Column 16	3	3.661	1.220333333	0.007132333333
Column 17	3	4.381	1.460333333	0.01003233333
Column 18	3	4.047	1.349	0.022636
Column 19	3	4.727	1.575666667	0.006458333333
Column 20	3	3.749	1.249666667	0.01594233333
Column 21	3	4.293	1.431	0.011908
Column 22	3	3.957	1.319	0.013129
ANOVA				

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.09889353	21	0.2904235014	14.96794557	1.01807451358127E-13	1.800885055
Within Groups	0.8537333333	44	0.0194030303	10.95817521	8.97282248502052E-12	1.77796144
Within Groups	0.4014713333	46	0.008727637681			
Total	6.952626864	65				
Total	2.505528957	68				

Figure B1

IMC of 25.0 wt% NaCl deicer

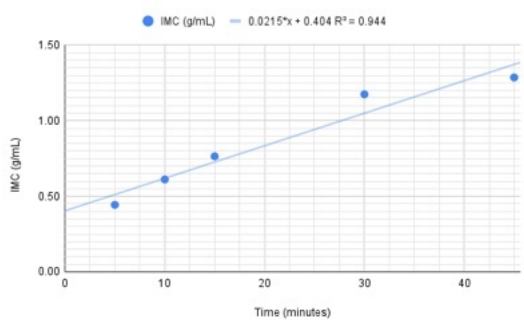


Figure B2

IMC of 19.4 wt% NaCl and 16.1 wt% sucrose deicer

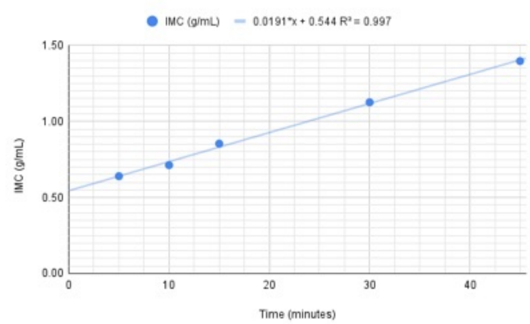


Figure B3

IMC of 19.4 wt% NaCl and 16.1 wt% fructose deicer

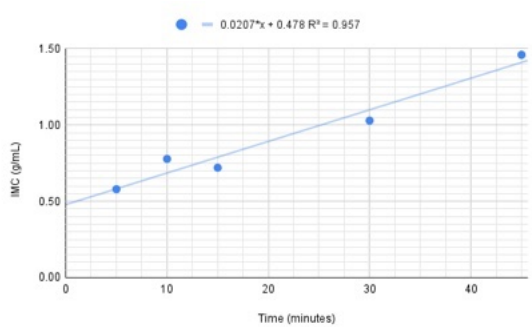


Figure B4

IMC of 21.4 wt% NaCl and 7.1 wt% sorbitol deicer

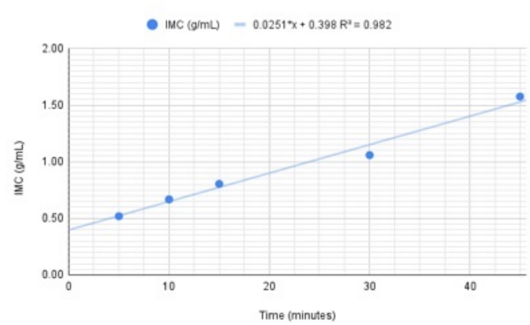


Table B30

Single-factor ANOVA test for best-performing deicers at 5 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	1.33	0.4433333333		0.01704933333	
Column 2	3	1.92	0.64		0.005404	
Column 3	3	1.738	0.5793333333		0.008394333333	
Column 4	3	1.557	0.519		0.030037	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.06364558333	3	0.02121519444	1.393795555	0.3135216277	4.066180557
Within Groups	0.1217693333	8	0.01522116667			
Total	0.1854149167	11				

Table B31

Single-factor ANOVA test for best-performing deicers at 10 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	1.834	0.6113333333		0.001233333333	
Column 2	3	2.138	0.7126666667		0.004600333333	
Column 3	3	2.333	0.7776666667		0.004846333333	
Column 4	3	2.002	0.6673333333		0.01916633333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between	0.04464358	3	0.01488119	1.99437489	0.19348781	4.06618055

Groups	333		444	1	29	7
Within Groups	0.05969266 667	8	0.00746158 3333			
Total	0.10433625	11				

Table B32

Single-factor ANOVA test for best-performing deicers at 15 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	2.294	0.7646666667		0.02431633333	
Column 2	3	2.562	0.854		0.045003	
Column 3	3	2.161	0.7203333333		0.001137333333	
Column 4	3	2.413	0.8043333333		0.01645633333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.02918166 667	3	0.00972722 2222	0.44767628 42	0.72573746 15	4.06618055 7
Within Groups	0.173826	8	0.02172825			
Total	0.20300766 67	11				

Table B33

Single-factor ANOVA test for best-performing deicers at 30 minutes

Summary				
Groups	**Count**	**Sum**	**Average**	**Variance**
Column 1	3	3.523	1.174333333	0.05661033333
Column 2	3	3.377	1.125666667	0.02789433333
Column 3	3	3.087	1.029	0.005616

Column 4	3	3.175	1.058333333		0.02520233333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.03876366667	3	0.01292122222	0.4481750292	0.7254162357	4.066180557
Within Groups	0.230646	8	0.02883075			
Total	0.2694096667	11				

Table B34

Single-factor ANOVA test for best-performing deicers at 45 minutes

Summary						
Groups	**Count**	**Sum**	**Average**		**Variance**	
Column 1	3	3.857	1.285666667		0.04228633333	
Column 2	3	4.19	1.396666667		0.007604333333	
Column 3	3	4.381	1.460333333		0.01003233333	
Column 4	3	4.727	1.575666667		0.006458333333	
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	0.13224425	3	0.04408141667	2.656253766	0.1197317769	4.066180557
Within Groups	0.1327626667	8	0.01659533333			
Total	0.2650069167	11				

APPENDIX C

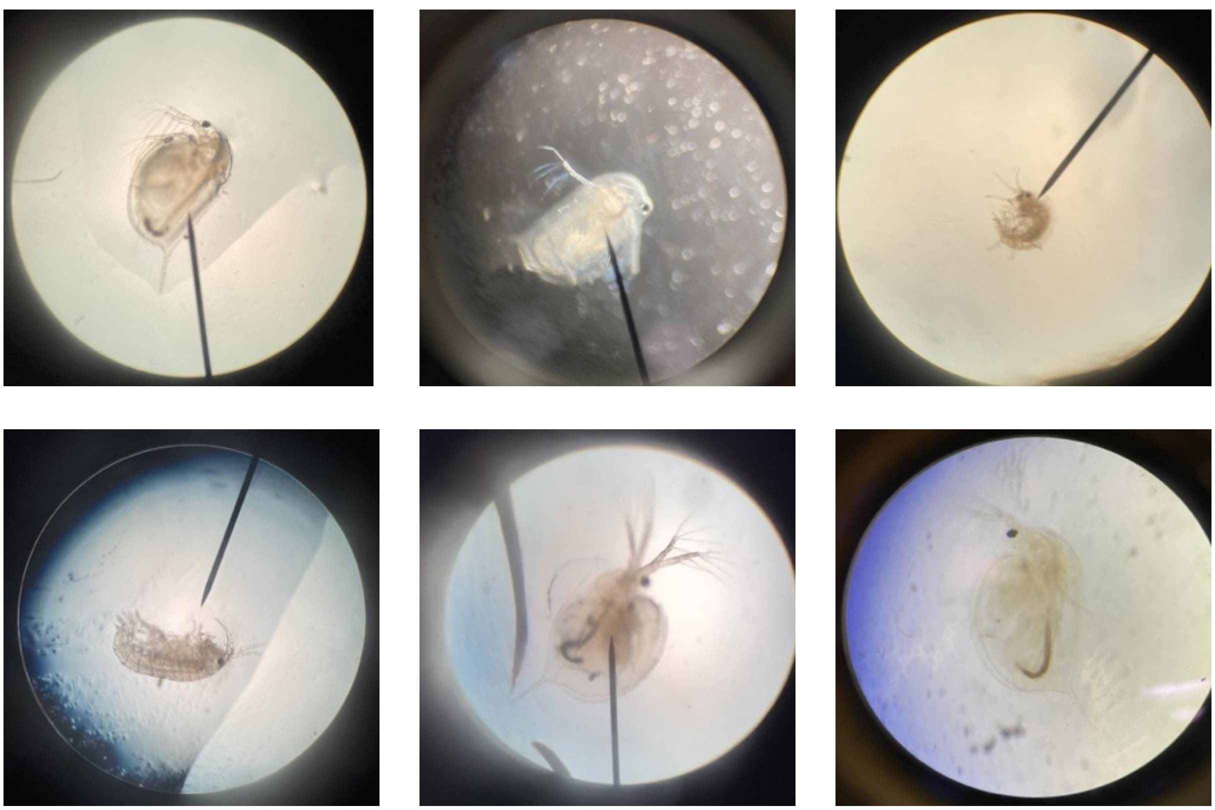
Freshwater Ecotoxicity Experiment

Image C1

Experiment setup

Figure C1

D. magna under the microscope



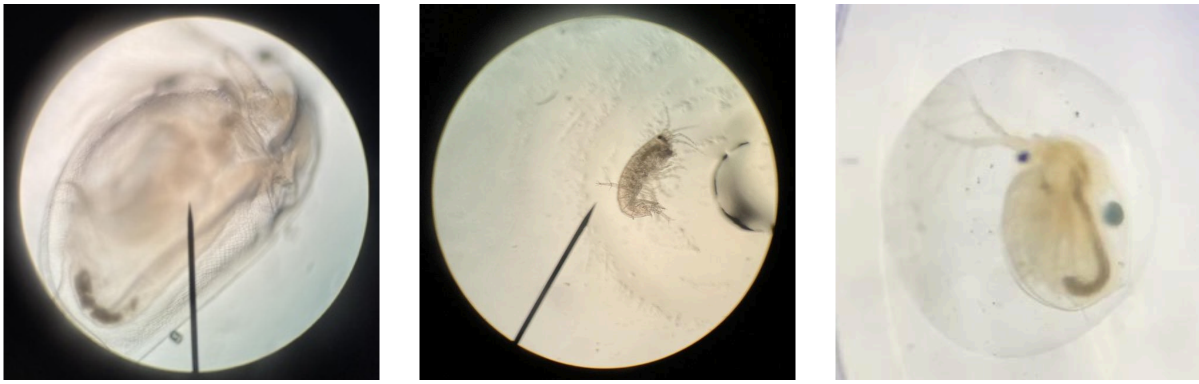
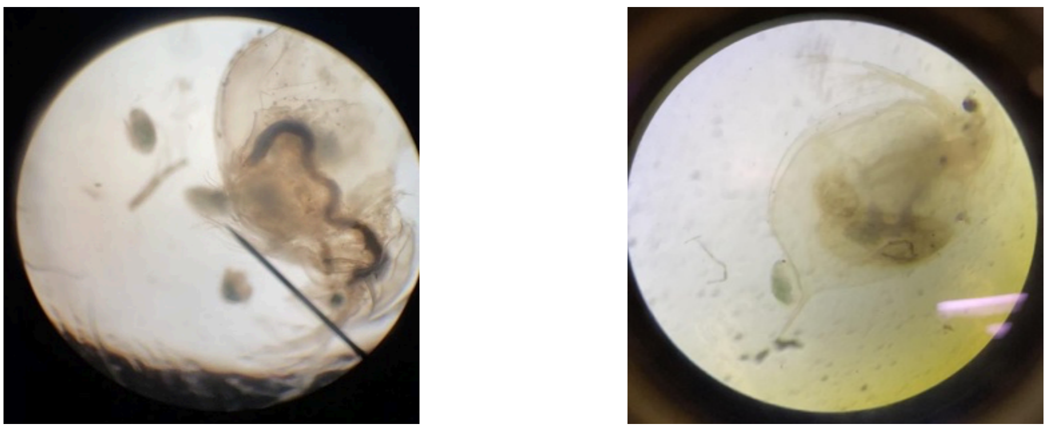


Image C2

D. magna with newly born neonates post-experimentation



APPENDIX D

Corrosion Experiment

Image D1

Corrosion experimentation setup

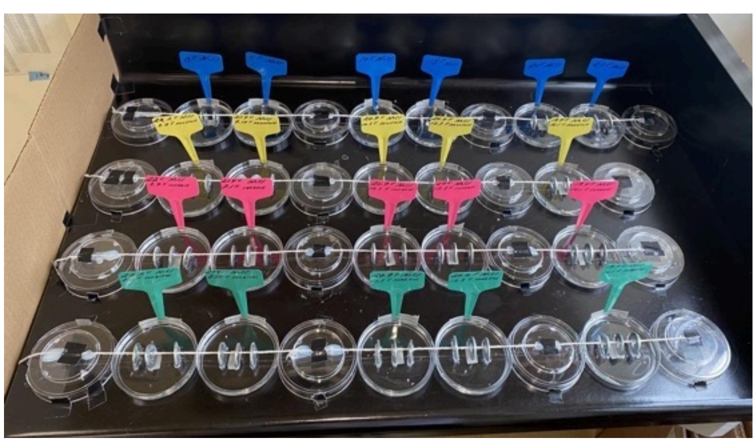


Table D1

Steel washer corrosion experiment with control treatment (water)

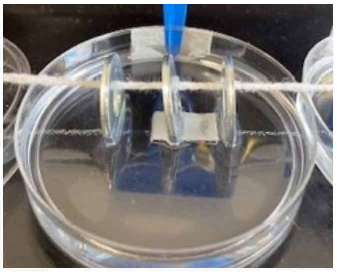
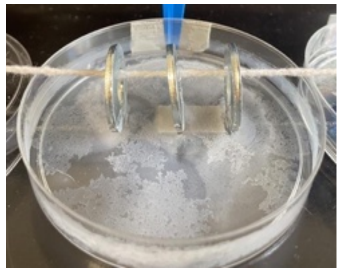
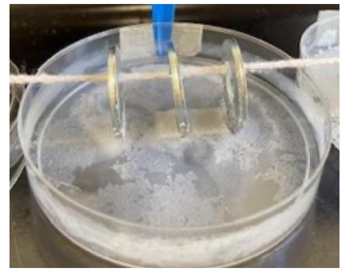
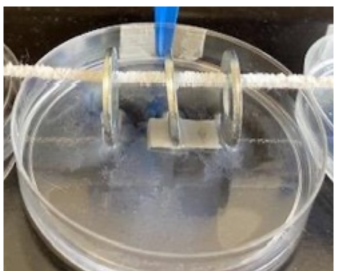
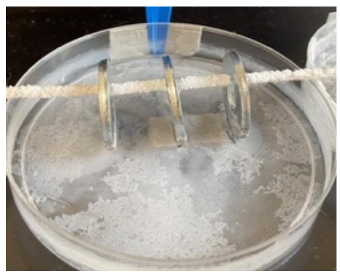
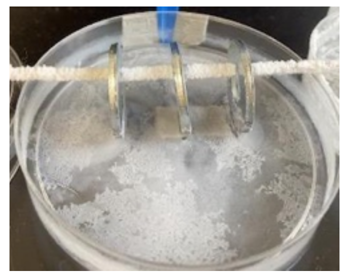
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D2

Steel washer corrosion experiment with 5.0 wt% NaCl

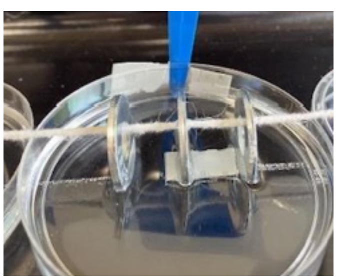
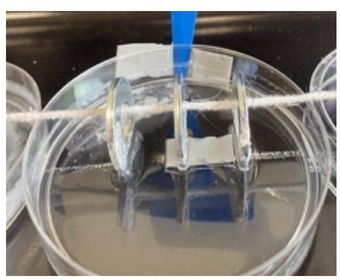
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D3

Steel washer corrosion experiment with 10.0 wt% NaCl

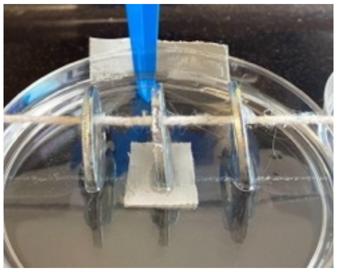
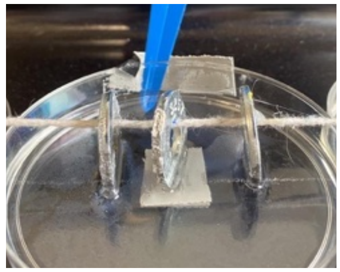
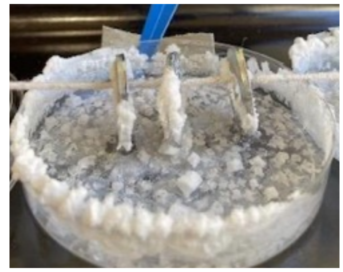
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D4

Steel washer corrosion experiment with 15.0 wt% NaCl

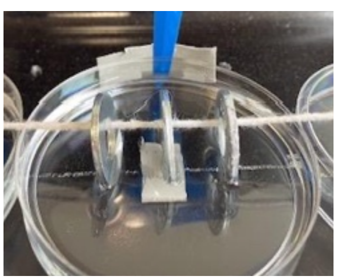
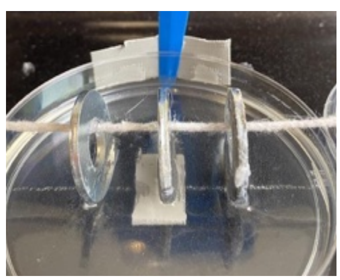
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D5

Steel washer corrosion experiment with 20.0 wt% NaCl

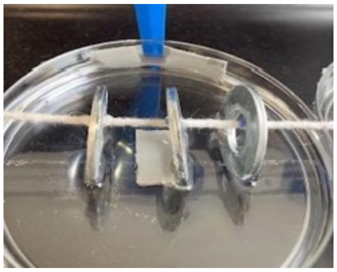
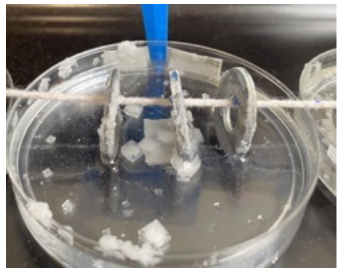
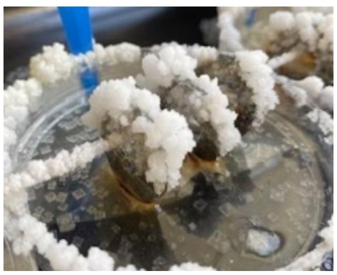
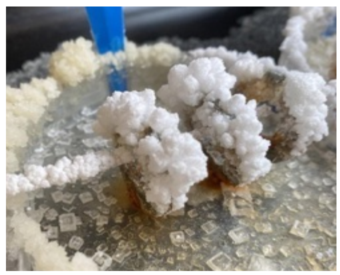
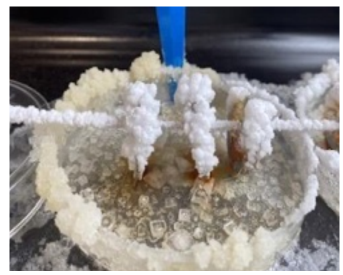
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D6

Steel washer corrosion experiment with 25.0 wt% NaCl

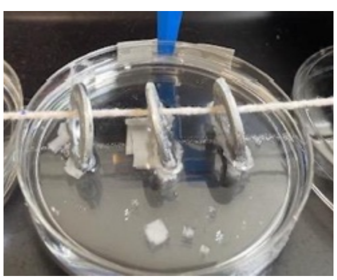
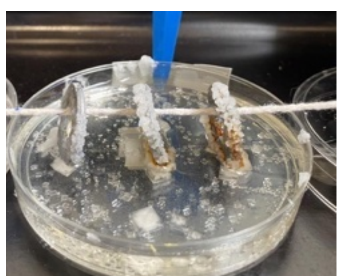
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D7

Steel washer corrosion experiment with 22.2 wt% NaCl and 3.7 wt% Sucrose

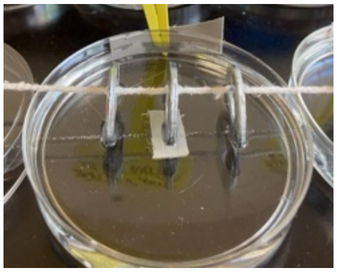
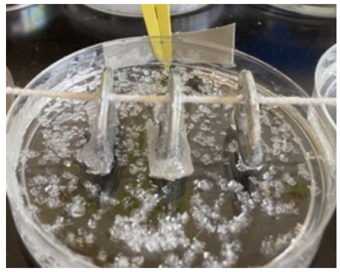
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D8

Steel washer corrosion experiment with 21.4 wt% NaCl and 7.1 wt% Sucrose

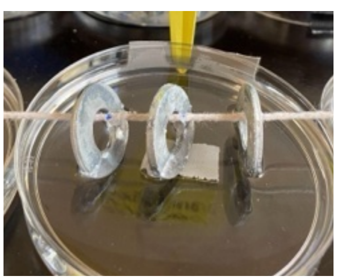
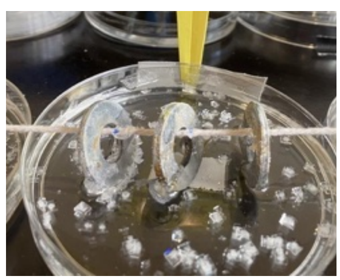
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D9

Steel washer corrosion experiment with 20.7 wt% NaCl and 10.3 wt% Sucrose

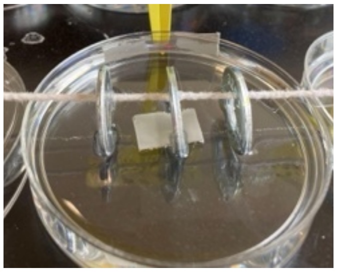
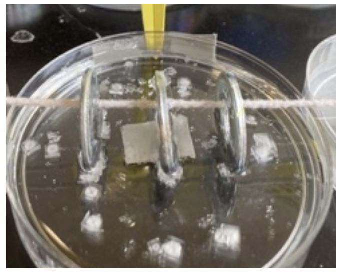
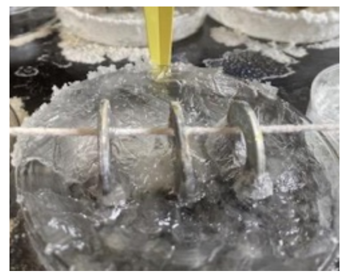
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D10

Steel washer corrosion experiment with 20.7 wt% NaCl and 13.3 wt% Sucrose

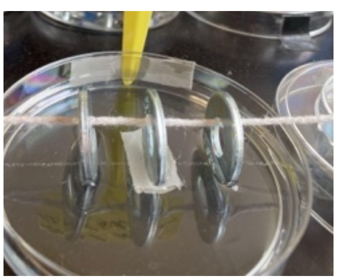
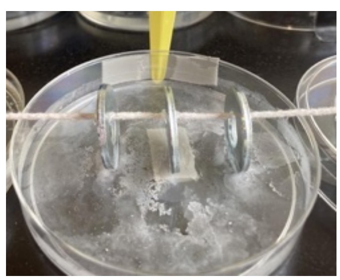
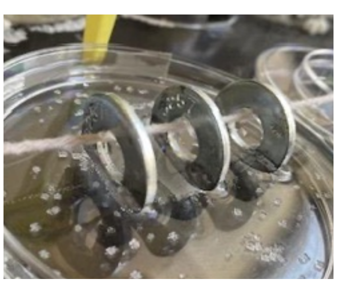
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D11

Steel washer corrosion experiment with 19.4 wt% NaCl and 16.1 wt% Sucrose

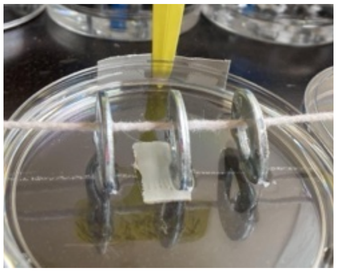
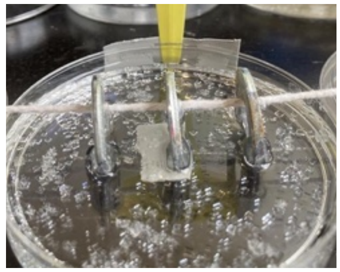
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D12

Steel washer corrosion experiment with 22.2 wt% NaCl and 3.7 wt% Fructose

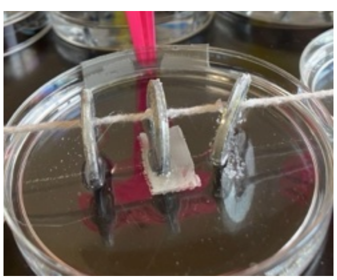
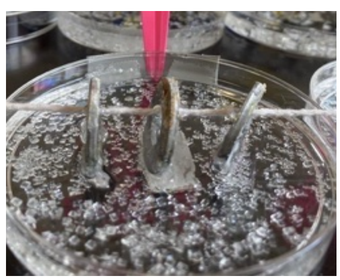
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D13

Steel washer corrosion experiment with 21.4 wt% NaCl and 7.14 wt% Fructose

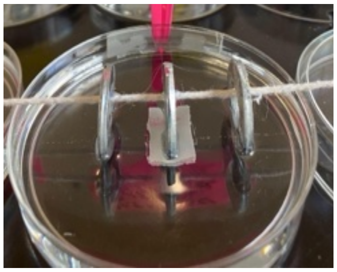
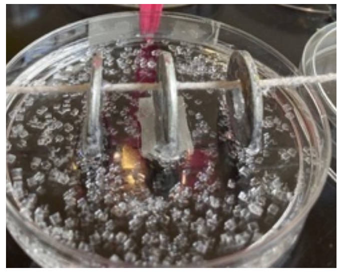
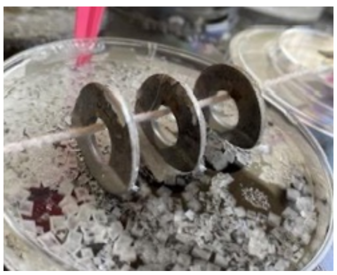
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D14

Steel washer corrosion experiment with 20.7 wt% NaCl and 10.3 wt% Fructose

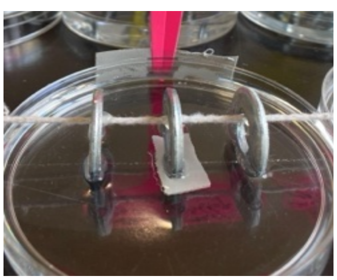
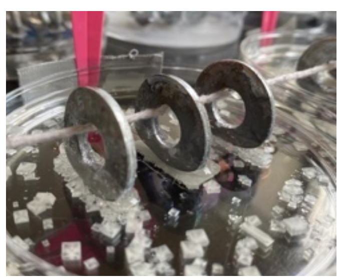
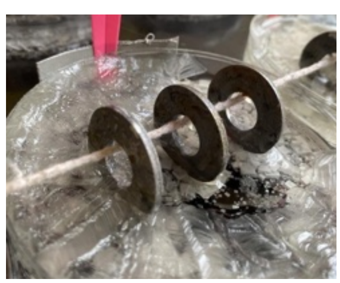
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D15

Steel washer corrosion experiment with 20.7 wt% NaCl and 13.3 wt% Fructose

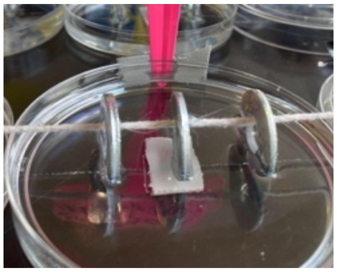
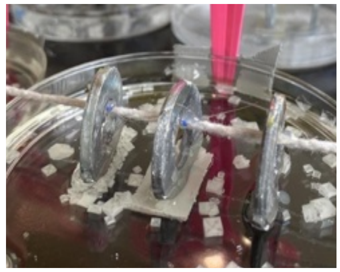
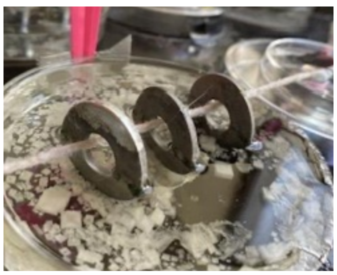
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D16

Steel washer corrosion experiment with 19.4 wt% NaCl and 16.1 wt% Fructose

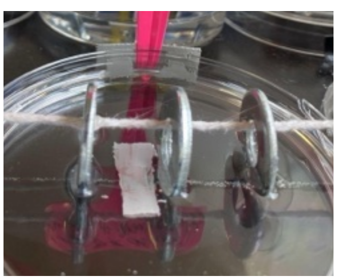
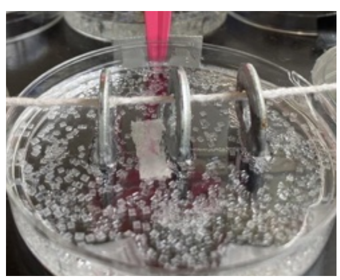
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D17

Steel washer corrosion experiment with 22.2 wt% NaCl and 3.7 wt% Sorbitol

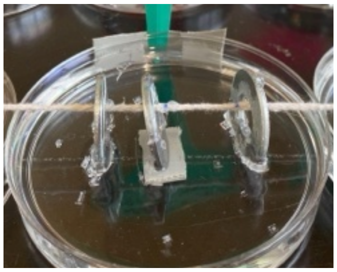
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D18

Steel washer corrosion experiment with 21.4 wt% NaCl and 7.14 wt% Sorbitol

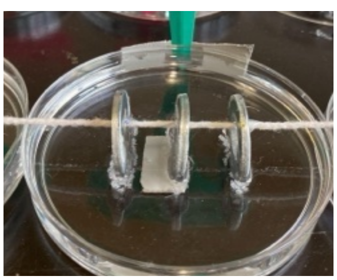
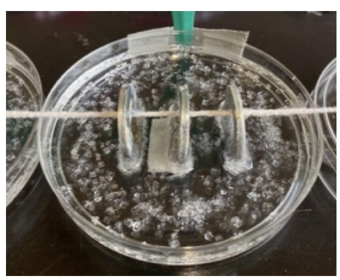
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D19

Steel washer corrosion experiment with 20.7 wt% NaCl and 10.3 wt% Sorbitol

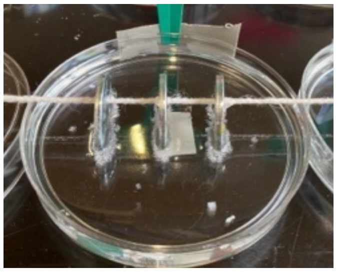
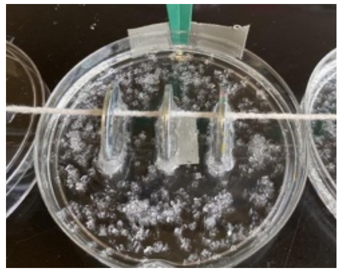
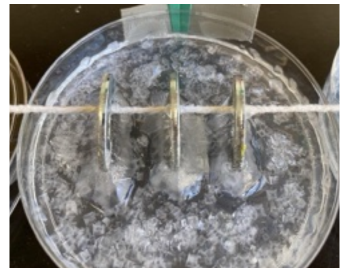
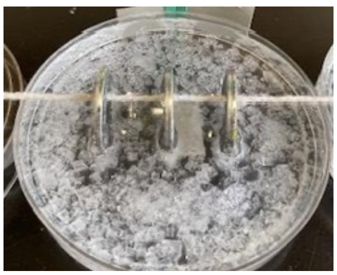
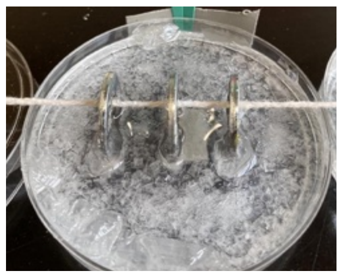
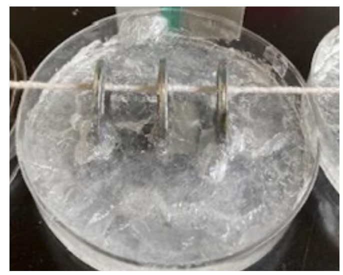
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D20

Steel washer corrosion experiment with 20.7 wt% NaCl and 13.3 wt% Sorbitol

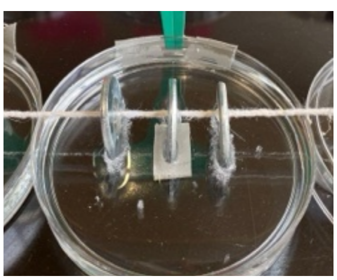
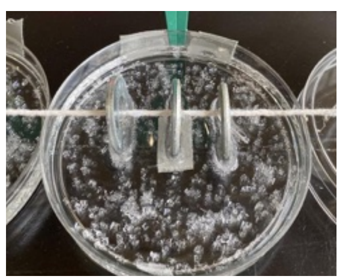
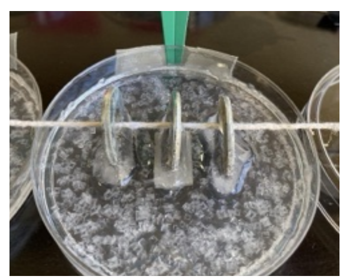
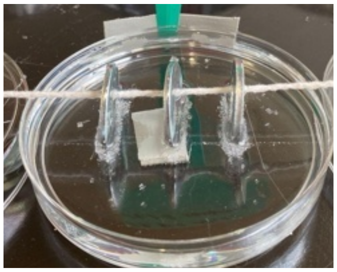
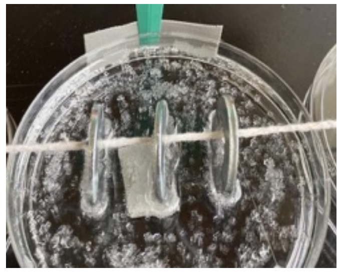
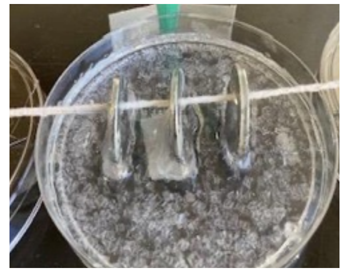
Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**
		

Table D21

Steel washer corrosion experiment with 19.4 wt% NaCl and 16.1 wt% Sorbitol

Week 1	Week 2	Week 3
		
Week 4	**Week 5**	**Week 6**