

Effect of imidazolium salts on the mortality of the maize weevil *Sitophilus zeamais* (Coleoptera: Curculionidae)

Efeito de sais imidazólicos na mortalidade do gorgulho do milho *Sitophilus zeamais* (Coleoptera: Curculionidae)

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ABSTRACT - The maize weevil *Sitophilus zeamais* Motschulsky, 1855 (Coleoptera: Curculionidae), is mainly controlled by insecticides with detrimental impacts on both the environment and public health, making it necessary to search for sustainable alternatives. Thus, this study aimed to explore the effect of different salts on the mortality of this insect under laboratory conditions. Imidazolium salts (1-hexadecyl-3-methylimidazolium chloride (C₁₆MImCl), 1-hexadecyl-3-methylimidazolium methanesulfonate (C₁₆MImMeS) and 1-methyl-3-octadecylimidazolium chloride (C₁₈MImCl)), and sodium chloride (NaCl) were tested at concentrations of 0.01, 0.02, 0.04, 0.1, and 0.2 g per 20 g of maize grains, with 10 insects in four replicates. The results were tested by analysis of variance and represented as control efficiency (CE%), and median lethal time (LT₅₀), and survival curves were constructed. All imidazolium salts caused significant mortality of *S. zeamais* at concentrations as low as 0.01 g per 20 g of maize grains. After 10 days, C₁₆MImCl showed 100 CE% for all concentrations tested. This study provides the first experimental evidence of the effectiveness of imidazolium salts against adults of *S. zeamais* under laboratory conditions.

RESUMO - O gorgulho-do-milho, *Sitophilus zeamais* Motschulsky, 1855 (Coleoptera: Curculionidae), é controlado principalmente por inseticidas com impactos prejudiciais ao meio ambiente e à saúde pública, tornando necessária a busca por alternativas sustentáveis. Assim, este estudo teve como objetivo explorar o efeito de diferentes sais na mortalidade deste inseto em condições de laboratório. Sais imidazólicos (cloreto de 1-hexadecil-3-metilimidazólio (C₁₆MImCl), metanossulfonato de 1-hexadecil-3-metilimidazólio (C₁₆MImMeS) e cloreto de 1-metil-3-octadecilimidazólio (C₁₈MImCl)), e cloreto de sódio (NaCl) foram testados em concentrações de 0,01, 0,02, 0,04, 0,1 e 0,2 g por 20 g de grãos de milho, com 10 insetos em quatro repetições. Os resultados foram testados por análise de variância e representados como eficiência de controle (CE%) e tempo letal mediano (LT₅₀), sendo construídas curvas de sobrevivência. Todos os sais imidazólicos causaram mortalidade significativa de *S. zeamais* em concentrações tão baixas quanto 0,01 g por 20 g de grãos de milho. Após 10 dias, C₁₆MImCl apresentou 100 CE% para todas as concentrações testadas. Este estudo fornece a primeira evidência experimental da eficácia dos sais imidazólicos contra adultos de *S. zeamais* em condições de laboratório.

Keywords: Alternative control. 1-Hexadecyl-3-methylimidazolium chloride (C₁₆MImCl). Maize storage. Pest control.

Palavras-chave: Armazenamento de milho. Cloreto de 1-hexadecil-3-metilimidazólio (C₁₆MImCl). Controle alternativo. Controle de pragas.

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INTRODUCTION

To ensure the viability of grain production in terms of quality and quantity, it is essential to adopt appropriate storage practices and effective protection strategies to minimize post-harvest losses (LORINI et al., 2015; VAZ et al., 2020). In this context, sustainable pest management approaches that reduce losses throughout the production chain, from harvest to storage, have become increasingly relevant.

The maize weevil, *Sitophilus zeamais* Motschulsky, 1855 (Coleoptera: Curculionidae), is one of the most destructive pests of stored maize worldwide (TREMATERRA et al., 2013). Its damage results from feeding and reproductive activities within the grain mass, leading to rapid population growth and severe qualitative and quantitative losses. Under maize-based substrates, egg hatching occurs within three to six days, and the developmental period from egg to adult emergence is approximately 34 days (LORINI; SCHNEIDER, 1994). After emergence, adults may survive for long periods, contributing to sustained infestation pressure. Post-harvest losses associated with insect infestation can reach up to 25% during storage (MANANDHAR; MILINDI; SHAH, 2018).

Chemical control remains the most widely used strategy for managing stored-grain pests (KIM et al., 2019), particularly through fumigant insecticides in

Brazil (JAGADEESAN et al., 2018). However, the intensive use of these products has been associated with toxicity to humans and non-target organisms, environmental contamination, socioeconomic impacts, and the selection of resistant insect populations (NASR; EL-DEMERDASH; EL-NAGAR, 2016; KIM et al., 2019; HAWKINS et al., 2019). In recent years, resistance to conventional insecticides, including pyrethroids, has become increasingly frequent in *Sitophilus* populations, reinforcing the need for alternative control strategies (NAYAK et al., 2020; SAKKA; ATHANASSIOU, 2021; SINGH et al., 2021).

In this scenario, organic salts particularly imidazolium salts (IS) have emerged as promising alternatives for insect control. Over the last decade, and especially in recent years, research groups based in southern Brazil, notably in the state of Rio Grande do Sul, have played a leading role in investigating the bioactivity of IS against insects (GOELLNER et al., 2018; PILZ-JUNIOR et al., 2023). These studies are relatively recent and still expanding, having focused mainly on insects of sanitary importance, such as mosquitoes (*Aedes aegypti* (Linnaeus, 1762) (Diptera: Culicidae) (GOELLNER et al., 2018; SILVA et al., 2024) and *Culex quinquefasciatus* Say, 1823 (Diptera: Culicidae) (PILZ-JUNIOR et al., 2023), and, to a lesser extent, on agricultural pests.

The growing interest in IS is also related to their potential as more sustainable alternatives when compared to conventional insecticides. Their insecticidal activity can be achieved at relatively low concentrations, which may reduce the chemical load applied to the environment (BICZAK et al., 2014; XU; CHENG, 2021). In addition, their structural tunability allows the modulation of biological activity through adjustments in alkyl chain length and counterion type, offering the possibility of optimizing efficacy while minimizing adverse effects on non-target organisms (BICZAK et al., 2014; EGOROVA; GORDEEV; ANANIKOV, 2017; KUMARI; PILLAI; BENEDETTO, 2020). These characteristics contrast with many commercial fumigants, which are volatile, broadly toxic, and prone to resistance development (XU; CHENG, 2021).

Despite these advantages, aspects related to environmental persistence, effects on non-target organisms, and the potential presence of residues in stored grains remain insufficiently explored, particularly for agricultural pests.

Thus, while imidazolium salts have shown promising results in recent studies, their applicability to stored-grain pest management still requires systematic evaluation.

Within this context, the present study aimed to evaluate the insecticidal activity of different IS against adults of *S. zeamais* under laboratory conditions, contributing to the development of alternative and potentially more sustainable strategies for the control of pests in stored maize.

MATERIAL AND METHODS

Insects, maize grains, and salts

The study was conducted at the Insect Ecology Laboratory (LABEL), Institute of Biology, Federal University of Pelotas (UFPel), Campus Capão do Leão, RS, Brazil, in 2021. Maize (*Zea mays* L.) grains were purchased from local commercial suppliers. Prior to the experiments, the grains were sieved and disinfested by freezing at -4 °C for seven days. Afterward, they were stored in glass containers covered with voile fabric for ten days to achieve hygroscopic equilibrium and to prevent infestation by pre-existing pests.

Adults of *S. zeamais* Motschulsky, 1855 (Coleoptera: Curculionidae) were obtained from laboratory colonies maintained at LABEL. To obtain insects of similar age, twenty unsexed adults were placed in glass containers containing maize grains and kept for 15 days. After this oviposition period, the adults were used in the experiments at approximately 14 days of age, ensuring physiological uniformity among test insects.

The IS 1-hexadecyl-3-methylimidazolium chloride ($C_{16}MimCl$, purity > 99%) and 1-methyl-3-octadecylimidazolium chloride ($C_{18}MimCl$, purity > 99%) were purchased from CJC China Jie Chemical and recrystallized prior to use (Figure 1). The salt 1-hexadecyl-3-methylimidazolium methanesulfonate ($C_{16}MimMeS$, purity > 99%) was synthesized according to Pilz-Junior et al. (2023) (Figure 1), and its yield and nuclear magnetic resonance (NMR) characterization were consistent with previously reported data. Sodium chloride (NaCl, analytical grade) was obtained from Sigma-Aldrich and used as an inorganic salt for comparison, being applied under the same experimental conditions and concentrations as the IS.

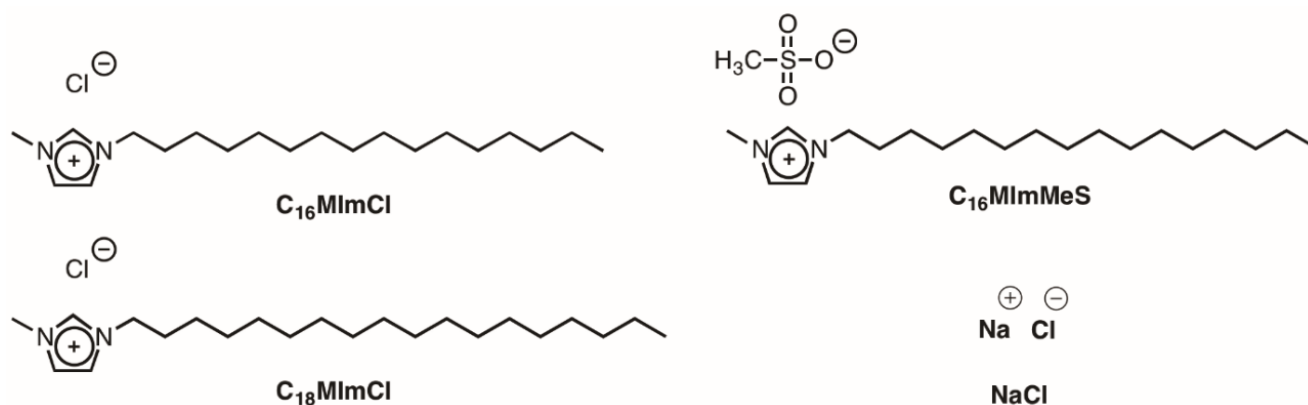


Figure 1. Chemical structures of the Chemical Structures of the imidazolium salts - $C_{16}MimCl$, $C_{16}MimMeS$ and $C_{18}MimCl$ and the inorganic salt sodium chloride (NaCl) used in the experimental evaluation of insecticidal activity against *S. zeamais*.

Experimental design and treatments

The experiment was conducted in a completely randomized design, consisting of 21 treatments with four replications each (Table 1), using 10 adult insects per experimental unit (JAIROCE et al., 2016). Each unit consisted of 20 g of maize grains (approximately 12% moisture content) placed in glass containers.

The grains were treated with the IS or NaCl at concentrations of 0.01, 0.02, 0.04, 0.1, and 0.2 g per 20 g of maize grains, corresponding to 100, 200, 400, 1,000, and 2,000 g t⁻¹, respectively. Untreated maize grains were used as the control. After addition of the compounds, the containers

were manually shaken for approximately two minutes to ensure uniform distribution of the treatments. Subsequently, ten adult insects were introduced into each container.

The container lids were fitted with voile fabric to prevent insect escape while allowing air exchange. All experimental units were maintained in a biochemical oxygen demand (BOD) incubator at 28 ± 3 °C, 30 ± 10% relative humidity, and a 12 h photophase.

Insect mortality was evaluated daily for 15 days after application. Insects were considered dead when no movement was observed after gentle stimulation with a soft, fine-tipped brush for two minutes (ANTUNES et al., 2013).

Table 1. Experimental treatments applied to *Zea mays* grains, including IS (C₁₆MImMeS, C₁₆MImCl and C₁₈MImCl) and sodium chloride (NaCl), tested at five concentrations (0.01, 0.02, 0.04, 0.1, and 0.2 g per 20 g of maize grains), corresponding to 100, 200, 400, 1,000, and 2,000 g t⁻¹, respectively, as well as an untreated control. Each experimental unit consisted of 20 g of maize grains and 10 adult insects, with four replicates per treatment.

Treatment	IS / NaCl	Content (g)	(g/t)
T1	C ₁₆ MImMeS	0.2	2,000
T2	C ₁₆ MImMeS	0.1	1,000
T3	C ₁₆ MImMeS	0.04	400
T4	C ₁₆ MImMeS	0.02	200
T5	C ₁₆ MImMeS	0.01	100
T6	C ₁₆ MImCl	0.2	2,000
T7	C ₁₆ MImCl	0.1	1,000
T8	C ₁₆ MImCl	0.04	400
T9	C ₁₆ MImCl	0.02	200
T10	C ₁₆ MImCl	0.01	100
T11	C ₁₈ MImCl	0.2	2,000
T12	C ₁₈ MImCl	0.1	1,000
T13	C ₁₈ MImCl	0.04	400
T14	C ₁₈ MImCl	0.02	200
T15	C ₁₈ MImCl	0.01	100
T16	NaCl	0.2	2,000
T17	NaCl	0.1	1,000
T18	NaCl	0.04	400
T19	NaCl	0.02	200
T20	NaCl	0.01	100
T21 - Control	-	-	-

Statistical analysis

Mortality data were initially assessed for normality using the Shapiro–Wilk test and for homogeneity of variances using Bartlett's test. As the assumptions of normality and homoscedasticity were not met, even after data transformation, the results were analyzed using the non-parametric Kruskal–Wallis analysis of variance, followed by Dunn's post-hoc test with Bonferroni correction (p < 0.05). All analyses were performed using R software version 4.0.0 (R DEVELOPMENT CORE TEAM, 2020).

Corrected mortality, expressed as control efficiency (CE%), was calculated using the Schneider–Orelli formula:

$$CE\% = [(Mt - Mc)/(100 - Mc)] \times 100,$$

where Mt is the mortality observed in the treatment and Mc is the mortality observed in the control (PÜNTENER, 1981).

Survival over time was analyzed using Kaplan–Meier estimators to calculate the median lethal time (LT₅₀). Survival curves were compared using the log-rank test with Holm–Sidak multiple comparison procedure (p < 0.05), performed with SigmaPlot version 12.3 (Systat Software, San Jose, CA, USA).

For graphical representation of survival curves, only a subset of treatments was selected. These treatments corresponded to the highest and lowest insecticidal efficiencies within each compound, based on mortality results, in order to facilitate visual comparison and avoid redundancy among curves with similar responses.

RESULTS AND DISCUSSION

The survival curves referring to the exposure of the most and the least efficient treatments indicated that all IS

caused high mortality in *S. zeamais* when mixed with maize grains, and the treatments with NaCl did not differ statistically from the control treatment (Figure 2).

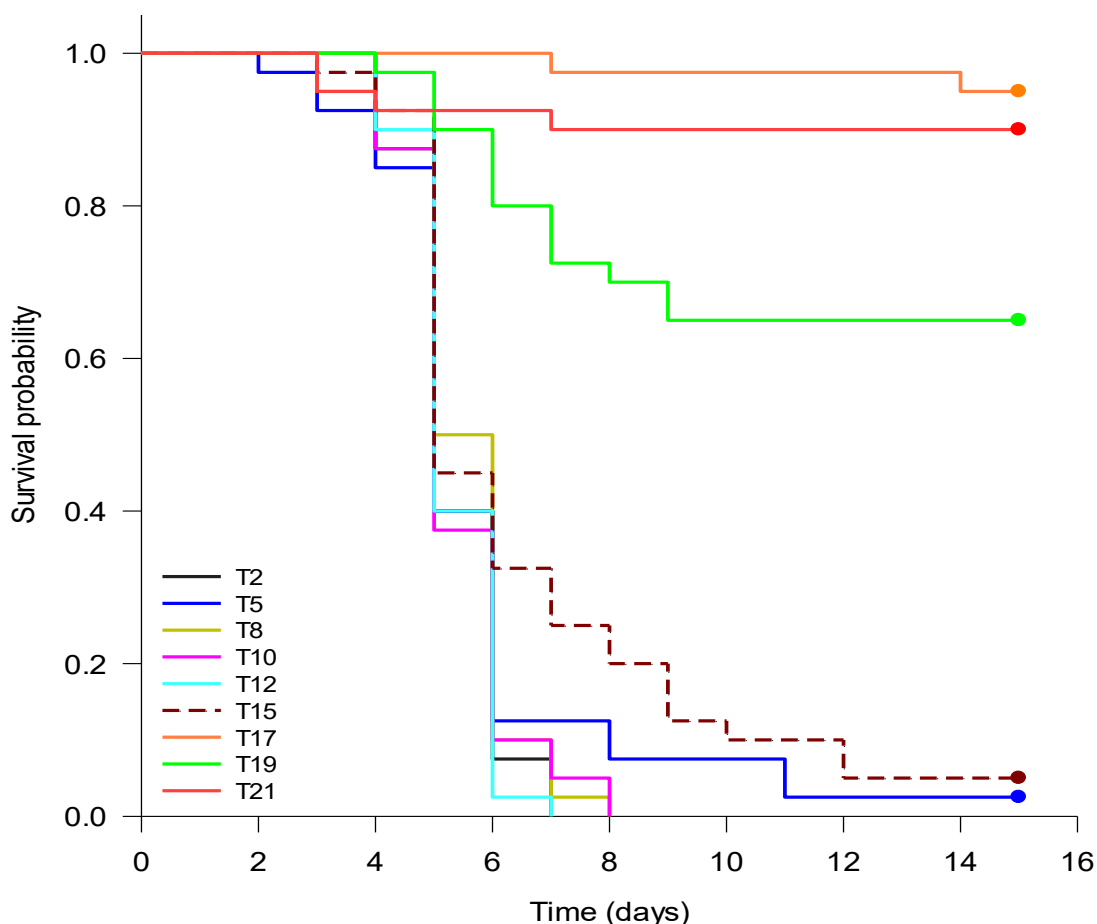


Figure 2. Survival curves of *S. zeamais* adults exposed to maize grains treated with selected doses of IS (C_{16} MImMeS, C_{16} MImCl, and C_{18} MImCl) and NaCl under laboratory conditions. The most and least efficient treatments are indicated: T2 (0.1 g C_{16} MImMeS), T5 (0.01 g C_{16} MImMeS), T8 (0.04 g C_{16} MImCl), T10 (0.01 g C_{16} MImCl), T12 (0.1 g C_{18} MImCl), T15 (0.01 g C_{18} MImCl), T17 (0.1 g NaCl), T19 (0.02 g NaCl), and T21 (untreated control), all expressed per 20 g of maize grains.

Five days after application, most treatments with IS differed significantly from the control group, with control efficiencies ranging from 18.92% to 62.16%, but similar to each other. At 10 days after application, all treatments with IS differed from the control group, with efficiencies between 88.89% and 100.00%. The same pattern occurred at 15 days with efficiencies between 94.44% and 100.0%. For NaCl, constancy and proximity to the control group were observed throughout the entire evaluation period (Table 2).

In five days of exposure, a control efficiency above 60% was achieved for the treatment with a dose of 0.2 g of C_{16} MImMeS in 20 g of maize grains (T1), and efficiencies superior to 50% for all other related treatments with lower contents of this IS. Such efficiency was also achieved in the treatments (20 g of maize grains) with C_{16} MImCl at contents of 0.2 g (T6), 0.02 g (T9) and 0.01 g (T10), and with

C_{18} MImCl at contents of 0.1 g (T12) and 0.01 g (T15). After 10 days, control efficiencies greater than 90% were obtained for almost all treatments with IS, except for C_{18} MImCl at the lowest content of 0.01 g (T15), but already showing mortality greater than 80%. At the end of the evaluations (15 days), 100% mortality was observed for nearly all treatments with IS, except for C_{16} MImMeS and C_{18} MImCl at the lowest dose of 0.01 g, which reached mortality rates of 97.22% (T5) and 94.44% (T15), respectively.

The average survival time (LT_{50}) of exposed maize weevil adults varied significantly between treatments (DF 8; X^2 263.43; $p < 0.001$), accounting for a lethal average of around five to seven days for all treatments with IS. The treatments with NaCl took an average of 12 to 14 days to reach the lethal average, statistically similar to the control treatment (Table 3).

Table 2. Mean mortality (%) and control efficiency (%) of *S. zeamais* adults exposed to maize (*Zea mays* L.) grains treated with different doses of IS and NaCl under laboratory conditions.

Treatment ^b	5 DAA ^a		10 DAA ^a		15 DAA ^a	
	m ± SE ^c	CE% ^d	m ± SE ^c	CE% ^d	m ± SE ^c	CE% ^d
T1	6.50 ± 1.55 a	62.16	9.25 ± 0.75 a	91.67	10.00 ± 0.00 a	100.00
T2	6.00 ± 1.00 a	56.76	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T3	5.50 ± 0.96 a	51.35	9.75 ± 0.25 a	97.22	10.00 ± 0.00 a	100.00
T4	5.50 ± 1.50 a	51.35	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T5	6.00 ± 1.73 a	56.76	9.25 ± 0.75 a	91.67	9.75 ± 0.25 a	97.22
T6	5.50 ± 0.87 a	51.35	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T7	5.00 ± 1.78 ab	45.95	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T8	5.00 ± 0.82 ab	45.95	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T9	6.00 ± 1.22 a	56.76	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T10	6.25 ± 0.75 a	59.46	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T11	4.00 ± 0.41 bc	35.14	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T12	6.00 ± 0.71 a	56.76	10.00 ± 0.00 a	100.00	10.00 ± 0.00 a	100.00
T13	2.50 ± 0.87 cd	18.92	9.50 ± 0.50 a	94.44	10.00 ± 0.00 a	100.00
T14	5.00 ± 0.58 ab	45.95	9.75 ± 0.25 a	97.22	10.00 ± 0.00 a	100.00
T15	5.50 ± 1.26 a	51.35	9.00 ± 0.71 ab	88.89	9.50 ± 0.50 a	94.44
T16	0.25 ± 0.25 d	0.00	3.00 ± 1.08 bc	22.22	3.00 ± 1.08 b	22.22
T17	0.00 ± 0.00 d	0.00	0.50 ± 0.29 c	0.00	0.75 ± 0.48 b	0.00
T18	1.50 ± 1.19 d	8.11	3.00 ± 2.04 bc	22.22	3.25 ± 1.97 b	25.00
T19	1.00 ± 0.41 d	2.70	3.50 ± 1.66 bc	27.78	3.50 ± 1.66 b	27.78
T20	0.00 ± 0.00 d	0.00	2.50 ± 2.18 c	16.67	2.75 ± 2.10 b	19.44
T21 - Control	0.75 ± 0.48 d	--	1.00 ± 0.58 c	--	1.00 ± 0.58 b	--
DF _{Treat; Error} ^e	20; 63	--	20; 63	--	20; 63	--
X ²	53.87	--	69.16	--	76.79	--
p ^f	< 0.001	--	< 0.001	--	< 0.001	--
CV% ^g	50.67	--	22.37	--	20.28	--

^a DAA = days after application; ^b See Table 1; ^c Mean of dead individuals (m) ± standard error (SE). Means followed by the same lowercase letters in the column do not differ significantly from each other, whereas means followed by different letters indicate significant differences according to the Kruskal–Wallis test followed by Dunn’s post-hoc test with Bonferroni correction ($p < 0.05$); ^d Control mortality/efficiency (CE%) according to the Schneider-Orelli formula; ^e DF = degrees of freedom; ^f p = probability value; ^g CV = coefficient of variation (%).

Table 3. Median lethal time (LT₅₀, days) of *S. zeamais* adults exposed to 20 g of maize (*Zea mays* L.) grains treated with the most and least efficient doses of IS (C₁₆MImMeS, C₁₆MImCl, and C₁₈MImCl), sodium chloride (NaCl), and an untreated control under laboratory conditions.

Treatment ^a	IS ^b / NaCl	Content (g)	LT ₅₀ (CI _{95%}) ^c
T2	C ₁₆ MImMeS	0.1	5.35 (5.10 – 5.60) b
T5	C ₁₆ MImMeS	0.01	5.73 (5.02 – 6.43) b
T8	C ₁₆ MImCl	0.04	5.48 (5.17 – 5.78) b
T10	C ₁₆ MImCl	0.01	5.40 (5.10 – 5.70) b
T12	C ₁₈ MImCl	0.1	5.32 (5.11 – 5.54) b
T15	C ₁₈ MImCl	0.01	6.60 (5.72 – 7.47) b
T17	NaCl	0.1	14.78 (14.22 – 15.32) a
T19	NaCl	0.02	12.00 (10.66 – 13.34) a
T21 - Control	-	-	13.93 (12.76 – 15.09) a
DF ^d			8
X ²			263.43
p ^e			< 0.001

^a See Table 1; ^b IS = imidazolium salt; ^c LT₅₀ = median lethal time (days). CI_{95%} = 95% confidence level. Means followed by the same lowercase letters in the column do not differ significantly from each other, whereas means followed by different letters indicate significant differences ($p < 0.001$). A multiple comparison procedure was used to isolate the group or groups that differ from the others. Multiple comparisons: All pairwise multiple comparison procedures (Holm-Sidak method); ^d DF = degrees of freedom; ^e p = probability value.

Considering the results obtained with the inorganic salt NaCl and the untreated control, it is possible to infer that not all salts exhibit insecticidal activity against the maize weevil. In contrast, the three IS evaluated (C₁₆MImCl, C₁₆MImMeS,

and C₁₈MImCl) demonstrated clear insecticidal activity against *S. zeamais*, whereas NaCl treatments did not differ statistically from the control, indicating that the observed mortality is associated with the specific properties of IS rather

than with the presence of salts in general.

According to Garcia (2014), insecticides intended for pest management should reach at least 80% control efficiency to be considered effective. From this perspective, the high mortality levels observed for the IS indicate their strong potential as control agents against *S. zeamais*. The rapid attainment of control efficiencies above this threshold, even at low concentrations and within a relatively short exposure period, suggests that these compounds may provide effective population suppression under storage conditions. Although C₁₆MImCl consistently showed complete mortality across concentrations, its performance did not differ statistically from that of C₁₆MImMeS and C₁₈MImCl, indicating that insecticidal activity is a shared property among the tested IS rather than a compound-specific anomaly. From an applied standpoint, the ability to achieve high control efficiency at reduced doses is particularly relevant, as it may translate into lower application costs and reduced chemical input in storage systems. Considering the long adult lifespan and high reproductive potential of *S. zeamais* (LORINI; SCHNEIDER, 1994), the rapid reduction of adult populations observed in this study may have important implications for limiting population growth and subsequent grain damage over time.

In the present study, insect mortality did not increase proportionally with increasing doses of the tested compounds (GRECO et al., 2024; RADÜNZ et al., 2024), as high control efficiencies were achieved even at the lowest concentrations evaluated, this may indicate that the minimum effective concentration was already reached at the lowest doses tested. This absence of a clear dose-response relationship suggests that the insecticidal activity of the IS against *S. zeamais* may be reached at relatively low application rates under laboratory conditions. Differences in dose-response patterns reported in other studies should be interpreted with caution, as they often involve distinct chemical classes, target organisms, and exposure routes. Therefore, direct comparisons are limited, and the results highlight that compound-specific properties and experimental context play a central role in determining insecticidal effectiveness.

The imidazolium salts C₁₈MImCl, C₁₆MImMeS, and C₁₆MImCl showed high efficiency in controlling *S. zeamais*, and over time this efficiency tends to increase. A study used *Aedes aegypti* larvae in an aqueous medium, applied the three IS tested in the present study, and reported an approximate control efficiency of 90% larval mortality after 48 h with C₁₈MImCl. This study with *A. aegypti* confirmed that IS have the potential to control pest insects (GOELLNER et al., 2018; SILVA et al., 2024). Similar results were observed by Pilz-Junior et al. (2023) when controlling *C. quinquefasciatus* larvae with C₁₈MImCl. Due to the small number of studies on these compounds to control insects, further research must be done to evaluate the effects of IS on the biological development of maize weevil. Also, to design good application logistics, the farmer needs to have safe conditions to put into practice the use of these substances in the control of stored grain pests.

The insecticidal activity observed for the IS against *S. zeamais* raises important considerations regarding their possible modes of action. Although the present study did not investigate mechanistic aspects directly, previous reports suggest that IS may act through multiple pathways, including disruption of cellular membranes, interference with ion balance, and impairment of digestive tissues, as observed for

mosquito larvae exposed to similar compounds (BICZAK et al., 2014; GOELLNER et al., 2018). Such mechanisms may explain the rapid mortality observed in adult weevils, even at low concentrations.

The high insecticidal efficiency achieved by the IS at low application rates is particularly relevant from both environmental and practical perspectives. The effectiveness observed at the lowest tested concentration (0.01 g per 20 g of maize grains) suggests a reduction in the chemical load required for pest control, which may contribute to lower environmental impact and improved safety for users and consumers when compared to conventional fumigant insecticides. From an applied standpoint, achieving high mortality at low doses may also translate into favorable cost-benefit ratios. Nevertheless, the practical implementation of these compounds in storage facilities would require appropriate formulation strategies to ensure homogeneous distribution, stability, and persistence under warehouse conditions, as well as further evaluation of potential residues in grains and effects on non-target organisms.

When compared with currently available alternatives, such as inert powders (e.g., diatomaceous earth) and essential oils, IS present distinct advantages. Diatomaceous earth, although effective, often requires high application rates and may cause abrasion of grains and dust-related issues. Essential oils, while attractive from a natural-product perspective, tend to exhibit high volatility, variable efficacy, and limited residual activity. In contrast, the IS evaluated here demonstrated rapid action and high efficacy at low concentrations, which position them as potentially competitive alternatives. Compared to fumigant insecticides, which are broadly toxic, volatile, and prone to resistance development, IS may offer a more targeted and controllable approach, although comprehensive safety and regulatory evaluations remain necessary (ANTUNES et al., 2013; SAKKA; ATHANASSIOU, 2021).

From a regulatory standpoint, the use of IS as insecticides is still at an early stage, and specific guidelines for their application in stored-grain systems are not yet established. Therefore, further studies addressing chronic toxicity, effects on natural enemies, environmental fate, and residue dynamics are essential before any large-scale implementation. Despite these gaps, the results obtained in this study highlight the potential of IS as promising candidates for the development of new, more sustainable strategies for the control of stored-grain pests.

The innovative character of this study lies in the evaluation of structurally tunable IS as insecticidal agents against *S. zeamais*, a major pest of stored maize, an approach that has been scarcely explored for stored-grain insects. The results demonstrate that high levels of control can be achieved at relatively low concentrations and short exposure times, suggesting a promising alternative for stored-grain pest control. From a prospective standpoint, these findings open avenues for the rational design of IS with optimized alkyl chains and counterions, as well as for further investigations addressing residual activity, grain quality, non-target effects, and performance under semi-field or storage-scale conditions.

CONCLUSIONS

The IS evaluated in this study demonstrated significant

insecticidal activity against adult *S. zeamais*, highlighting their potential as alternative control agents for stored maize pests. High mortality levels were achieved for all tested salts, even at relatively low concentrations and short exposure periods. These findings indicate that IS, as a class, may represent promising candidates for further investigation in stored-grain pest management strategies.

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