Mechanical stirring of bulk-stored maize in steel bins to suppress maize weevils and other beetle populations

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ABSTRACT
This study investigates the effectiveness of periodic stirring as a non-chemical approach to suppress maize weevils, Sitophilus zeamais, and other beetle populations in large-scale grain storage bins. The research was conducted in a farm steel bin with a diameter of 9.8 m holding 127 Mg of maize, and a control bin of diameter 7.3 m holding 102 Mg of maize. Both bins were loaded with maize at 13% moisture and infested at a commercial tolerance rate of 2 weevils/kg of maize. Probe traps monitored beetle populations except for S. zeamais before stirring was initiated. Maize samples were collected at depths of 0, 0.9, 1.8 and 2.7 m with a vacuum-probe sampler prior to stirring and at 10, 20, 30 and 40 days of continuous stirring machine operation. Stirring achieved 100% control of live S. zeamais while the control bin experienced an increase in its S. zeamais population after 40 days. The stirring process also led to a significant reduction in dominant beetle populations such as hairy fungus beetles, Typhaea stercorea, and foreign grain beetles, Ahasuerus advena. Although the quality of maize in both bins changed at different depths and storage times, the treatment bin had higher bulk density (732.7 ± 3.98 kg/m<sup>3</sup> to 768.9 ± 2.41 kg/m<sup>3</sup>), lower insect damage (0.02 ± 0.02% to 0.9 ± 0.28%), and higher allowable storage time (>249 days). Moisture content and molded kernels increased in the control bin, reaching 26.4 ± 1.29% and 3.2 ± 0.53%, respectively. The average percentage of broken corn and foreign material (BCFM) in the sweeps indicated that BCFM concentrations did not affect airflow. Stirring maize provides an alternative to the use of chemicals to control stored maize insect pests at a production scale.

1. Introduction

The maize weevil, Sitophilus zeamais (L.) (Coleoptera: Curculionidae), is a well-known and wide spread pest of stored maize, Zea mays (Poales: Poaceae), with its presence documented in more than 112 countries globally (López-Castillo et al., 2018). Although it has been observed as far north as Quebec and Ontario in Canada, S. zeamais is particularly prevalent in temperate zones and widely distributed in tropical regions around the world (Canada Grain Commission, 2019). In the southern part of the United States, specifically in the state of Georgia, S. zeamais can infest maize in the field and cause losses of up to 10% to the state’s $513 million maize crop (Toews, 2015). The infestation of weevils can initiate in standing drying corn, as flying adults of S. zeamais attack the crops from the field edges (Giles, 1969). Subsequently, during the storage phase, the developmental stages of S. zeamais are inadvertently introduced into the storage bins along with harvested maize. It has been observed that grain residues and dust present on the walls and ledges of farm steel grain bins may create favorable conditions for the survival and multiplication of S. zeamais (Hagstrum et al., 1999). Under suitable environmental conditions, the population of S. zeamais can increase by up to 15 times (Bbosa et al., 2014; Bell, 2014). The activity of S. zeamais within the grain stored in bins generates carbon dioxide (Aby and Maier, 2020) and leads to localized areas of increased temperature and moisture, which in turn facilitate mold growth (Sserunjogi et al., 2021; Sone, 2001).

The global focus on food safety and quality necessitates the...
elimination of *S. zeamais* from the food supply chain. Traditionally, chemical treatments have been widely employed to control and prevent *S. zeamais* and other insect infestations by applying insecticides directly to stored maize and surfaces of storage bins. Insecticide application is typically recommended prior to loading the bins, targeting any remaining life stages of *S. zeamais* along the bin walls, eaves, and perforated floor (Jones et al., 2012). Additionally, fumigation with toxic gases may be utilized during storage when insect populations are detected and, on the rise (Phillips et al., 2012). The use of chemical pesticides on grain has raised concerns related to environmental impact, consumer preferences, worker safety, and the development of resistance in *S. zeamais* to the active ingredients in these formulations (Tilley et al., 2007). Over the past decade, the demand for organic grains has surged, outpacing domestic supply, and resulting in increased imports of organic grains in the United States, particularly due to the expansion of the organic dairy and poultry sectors (ERS, 2018). It is important to note that the use of insecticides and fumigants is strictly prohibited on crops certified as organic under the USDA organic standards (U.S. Code of Federal Regulations, 2019). Therefore, there is a pressing need to explore non-chemical alternatives to effectively preserve the quality of stored maize while adhering to organic standards.

Physical disturbance of stored maize has emerged as an effective non-chemical approach to control *S. zeamais*, gaining significant interest in recent studies (Suerunyogi et al., 2021; Suleiman et al., 2016; Bhosa, 2014). While previous research focused on manual disturbance methods tailored for smallholder farmers, there is now a growing need to explore similar approaches on a larger scale or for advanced automated storage systems. In a study conducted by Joffe (1963) on a grain elevator, the practice of regularly turning the stored maize between storage bins every two weeks for a period of 8.5 months had a direct and detrimental effect on both adult and immature stages of *S. zeamais*. This turning process effectively disrupted localized hot spots within the grain and resulted in the crushing of external adult weevils as the maize was discharged from the bin into the truck, dropped into the receiving pit, passed through the cleaner, and conveyed back to the original bin. Another experiment evaluated the effectiveness of Sukup stirring augers (Sukup Manufacturing Company, Sheffield, Iowa, USA) on maize infested with *S. zeamais* (Rau et al., 2021). The laboratory study involved automated Sukup Fastir augers programmed to perform stirring every 12 h. The augers moved through one length (76 cm) of a stirred container over a 20-min period. After a storage period of 40 days, stirring using the Sukup augers achieved complete control (100%) of *S. zeamais* infestation.

Steel grain bins utilized for on-farm storage purposes offer the opportunity to employ stirring machines, which can be suspended from the bin roof and sidewalls. These machines typically consist of one or more vertical augers that extend through the grain mass, reaching nearly to the bin drying floor. The vertical augers rotate and engage in a circular motion around the grain, simultaneously moving back and forth along the bin radius from the center to the perimeter. This motion facilitates the mixing of the grain, effectively blending wet and dry maize and reducing the moisture gradient across different depths within the grain mass (Jones et al., 2012). Additionally, the stirring process helps to disrupt existing hot spots that may have developed due to insect infestation or mold spoilage.

To the best of our knowledge, the practice of stirring maize at the scale of a grain bin to suppress stored grain insect pests, has not been thoroughly explored. Therefore, the objective of the research presented in this study was to investigate the effects of stirring *S. zeamais*-infested maize within a farm-sized bin. The study aimed to assess both the impact on the population of *S. zeamais* and the quality of the maize following the stirring process.

### 2. Materials and methods

#### 2.1. Steel grain bins

This research was conducted from late July to early November 2019 at the Agricultural Engineering and Agronomy Research Farm of Iowa State University, Ames, Iowa. A steel grain bin of diameter 9.8 m (254 Mg of maize at full capacity), and cylindrical height of 4.9 m was equipped with a triple auger Sukup Fastir Plus stirring machine (Sukup manufacturing company, Sheffield, Iowa, USA) as the experimental treatment bin. Another steel grain bin of diameter 7.3 m (143 Mg of maize at full capacity), cylindrical height 5 m did not have a stirring machine and was designated the untreated control bin. The heights were measured from the drying concrete floor to the eave of the bin’s roof. The fan on the treatment bin was a Sukup axial fan (7.5–11.2 kW, 0.244 m/s) with a burner using liquid petroleum gas (LPG) (Sukup manufacturing company, Sheffield, Iowa, USA). The control bin had an axial fan (7.5 kW, 0.322 m/s) also with an LPG heater (Brock Grain Systems, Milford, IN, USA). Static pressure in the plenum of the bins was measured with a water manometer and airflows were computed using the University of Minnesota website for grain bin fan selection (bbefans.cnfs.umn.edu). Fan size and airflow were the basis for grain aeration using recommendations from Midwest Plan Service (MWPS), (1980). In early August (3rd and 4th), bin aeration resulted in grain temperatures reaching levels as high as 30 °C, creating suitable conditions for the activity and multiplication of *S. zeamais* within the grain bin. The grain temperature did not reach as high as 30 °C during the aeration in mid-October (17th and 18th) and with the warming fronts utilizing burners in late October (25th to 27th). To monitor the temperature and humidity levels within the bins and make informed decisions regarding aeration, a humidity and temperature meter from VAIASALA (Louisville, CO, USA) and OPI Blue temperature and moisture cables (OPISystems; Calgary, Canada) were installed in the control and treatment bins, respectively. These monitoring systems allowed for continuous tracking of temperatures and humidities, providing valuable data for managing aeration processes.

#### 2.2. Maize and *S. zeamais*

For this study, a mixture of several maize varieties was harvested using a combine harvester in October 2018 and stored in the treatment bin. Initially, approximately 102 Mg of maize was unloaded and conveyed to the control bin, while the treatment bin retained around 127 Mg of maize. The calculations for determining the targeted populations of *S. zeamais* in each bin were based on a commercial tolerance rate of 2 live *S. zeamais* per kg, as specified by the USDA agencies Grain Inspection, Packers and Stockyards Administration (GIPSA), and the Federal Grain Inspection Service (FGIS) guidelines (2013). Consequently, the treatment and control bins required that approximately 255,000 and 204,000 *S. zeamais* adults, respectively, be added to achieve the desired population size of weevils. To establish populations of *S. zeamais* for the study, weevils were bred in both 1 L glass jars and 19 L buckets covered with 3.2 mm screens to retain weevils but allow ventilation. These containers were kept at a temperature of 27 °C and a relative humidity of 65%. We estimated that after 60 days, the glass jars and buckets would house approximately 500 and 3000 live *S. zeamais*, respectively, following an initial infestation rate of 25 live *S. zeamais* per kg of maize (Bhosa et al., 2014). From August 1st to September 19th, 2019, colonies of *S. zeamais* were carefully released from their containers onto the top surface of each grain mass once every week. This artificial infestation, carried out prior to the application of artificial stirring, was intended to facilitate an exponential increase in the *S. zeamais* population within the bins.
2.3. Insect probe traps

To monitor the population sizes of beetles within the bins, we used unbaited cylindrical plastic WB II grain probe traps from Trécé Inc. (Adair, OK, USA). These tubular traps measured 44.5 cm in length, with a 3.8 cm internal diameter with 4 × 2 oval holes made through the cylinder’s wall at 3 × 2 mm spacing. Grain insects of various sizes that contact the trap will typically walk into the holes and fall down into the inside of the cylinder at a funnel at the bottom that is directed into a collection tip at the bottom closure. Following the method described by Toews and Nansen (2012), the perforated region of the traps was fully inserted below the surface of the maize grain mass. In each bin, traps were carefully removed from the grain mass, and the contents of each trap, including insects, debris, and broken corn and foreign material (BCFM), were emptied into labeled Ziplock bags for further analysis. The traps were left within the grain mass and monitored on a weekly basis to track changes in the insect population prior to the stirring process. At the end of each 7-day period, the probe traps were carefully removed from the grain mass, and the contents of each trap, including insects, debris, and broken corn and foreign material, were emptied into labeled containers for further analysis.

To fulfill the objective of detecting and monitoring the presence of other insect species, the maize samples from the treatment bin started on September 26th after the first sampling (0 d). Samples were drawn from specific locations within the bins, namely T1 to T5 for the treatment bin and C1 to C5 for the control bin, as illustrated in Fig. 1. Insect trapping commenced simultaneously with the infestation of the bins by S. zeamais. The traps were left within the grain mass and monitored on a weekly basis to track changes in the insect population throughout the experiment, allowing for consistent and continuous monitoring of the bins by S. zeamais. The traps were released back into the same bin. Beetles were frozen at −20 °C and later counted and identified as a species.

2.4. Experimental design

A total of 20 representative grain samples were collected from each bin on each sampling day using a Vac-A-Sample Pneumatic Sampler from Seedburo Equipment Co. (Des Plaines, IL, USA). These samples were then emptied into labeled Ziplock bags for further analysis. The experiment followed a 3-factorial design, incorporating two bins (treatment and control), four sampling depths (0, 0.9, 1.8, and 2.7 m), and five sampling days (0, 10, 20, 30, and 40). Maize stirring in the treatment bin started on September 26th after the first sampling (0 d). Samples were drawn from specific locations within the bins, namely T1 to T5 for the treatment bin and C1 to C5 for the control bin, as shown in Fig. 1. The stirring machines operated continuously in the treatment bin from day 0 to day 40 and were stopped briefly only during sample collections. This ensured that the stirring process was maintained throughout the experiment, allowing for consistent and continuous mixing of infested maize.

2.5. Insect counts and grain quality measurements

The data collection from the maize samples followed the established protocol outlined in the grain inspection handbook (USDA GIPSA FGIS, 2013). For the analysis of S. zeamais and other insect species, the maize samples were manually sieved using 12/64 in (4.8 mm) sieves and collected on the steel pan for counting. Inactive and dead insects were separated based on specific criteria described by Yakubu et al. (2011). Measurement was based on a kilogram of maize to determine the density of live S. zeamais in the bin population. This approach was adopted to account for the variations among vacuum sample sizes that were taken.

The quality of the maize was assessed based on various parameters, including moisture content, bulk density, broken corn and foreign material (BCFM), insect damage, and mold damage. The calculations for the allowable storage time of shelled maize followed the methodology described by Bern et al. (2002). During the unloading process of the control bin in the Spring of 2020, multiple loads of maize were sampled at different intervals to quantify the presence of BCFM in the various grain layers. Sampling was conducted on each quadrant of the bin floor in the cardinal directions of North East (NE), North West (NW), South East (SE), and South West (SW). The determination of BCFM in the screenings followed the protocol specified in the grain inspection handbook (USDA GIPSA FGIS, 2013).

2.6. Statistical analysis

The statistical analyses were performed using the Statistical Analysis System (SAS) software, specifically the PROC GLM (general linear model) module, in SAS version 9.4 (Copyright @ 2002–2012, SAS Institute Inc., Cary, NC, USA). A two-way ANOVA (analysis of variance) was conducted to analyze the mean differences between the bins at a 5% significant level. To address the non-normal distribution of data, a logarithmic scale transformation was applied on the variables of live S. zeamais per kg, as well as beetle populations in probe traps and vacuum probed samples, BCFM, and insect damage. Tukey-Kramer’s adjustment for pairwise comparison was used to obtain the correct p-values for comparing means. A paired t-test analysis compared the mean values of beetle population between the bins. The R Studio version 1.1.442 (Copyright @ 2009–2018 R Studio, Inc.) was utilized for generating plots of the variables.

3. Results

3.1. S. zeamais

The results of the statistical analysis indicate a significant difference in the live S. zeamais counts per kilogram of maize across time and depth between the treatment and control bins (F(65,14) = 3.09, P < 0.0001) (Fig. 2). The average number of live S. zeamais found in the maize samples from the treatment bin was consistently lower at each sampling time compared to the control bin. The paired t-test analysis revealed that the initial population of S. zeamais at all depths of maize in both bins was similar (P = 0.1403). After 10 days of continuous stirring, live S. zeamais were found only at depths of 0.9 (0.2 ± 0.14) and 2.7 (3.4 ± 0.16) m in the treatment bin, whereas the control bin had live S. zeamais at all depths. The unacceptable rating of 2 or more live S. zeamais per working sample was only at 2.7 (3.4 ± 0.16) m in the treatment bin, and at 0 (4.2 ± 0.59) and 1.8 (3.4 ± 0.30) m in the control bin at 10 days. S. zeamais population in the control bin decreased at the grain surface after 20 (1.4 ± 0.23) and 40 (1.0 ± 0.18) d. At 30 d, S. zeamais population increased at the grain surface (2.0 ± 0.32) and at 1.8 (1.8 ± 0.13) m depth of maize after pushing the warming front up through the grain mass with heated air at 30 °C (Table 1). A collapse of S. zeamais population at 0.9 (1.2 ± 0.28) m was observed in the control bin. The results indicate that stirring achieved 100% control of live S. zeamais by 40 days of maize storage.

3.2. Other beetles in probe traps and vacuum probed samples

Beetles found in the probe traps included the hairy fungus beetle (Typhaea stercorea), foreign grain beetle (Ahasuerus advena), minute mold beetle (Latridius spp./Cartodere spp.), rove beetle (Xylodromus...
spp.), booklice (*Psocids*), antlike flower beetle (*Anthicidae* spp.), flat grain beetle (*Cryptolestes* spp.), clown beetle (*Corcinops* spp.), red flour beetle (*Tribolium castaneum*), lesser grain borer (*Rhyzopertha dominica*), cereal bug (*Xylocoris* spp.), stored grain fungus beetle (*Litargus balteatus*), mold/plaster beetle (*Corticaria* spp.), larger black flour beetle (*Cynaeus angustus*), dried fruit beetle (*Carophilus hemipterus*), parastoid wasps (*Hymenoptera* spp.) and black fungus beetle (*Alphibitus diaperinus*). Beetles with highest populations in the probe traps are shown in Fig. 3, with *Ahasuerus advena* and *Typhaea stercorea* being dominant. It is likely that when maize was conveyed from the treatment bin to the control bin, it carried initial beetle populations with it. The beetle population between the bins was significantly different (*P* < 0.05) except for *Carophilus hemipterus*. The vacuum-probed samples (Fig. 4 (a)) had significantly higher populations of *Ahasuerus advena* than *Typhaea stercorea* in comparison to probe traps.

No population of *Ahasuerus advena* was found in the treatment bin after 40 d while *Cynaes angustus* and *Typhaea stercorea* were found only in the control bin (Fig. 4(a)). Similarly, *Cryptolestes* spp. was found only at 10 d in the treatment bin while *Litargus balteatus* and *Tribolium castaneum* were found only in the control bin. No populations of *Carophilus hemipterus* were found in the vacuum probed samples (Fig. 4(a) and (b)). The paired t-test analysis showed a significant difference in populations of beetles (*P* < 0.02) between the control and treatment bins.

### 3.3. Moisture content

The difference in the moisture content between the treatment and control bins was significant throughout the duration of maize storage (*F*<sub>35,144</sub> = 99.72, *P* < 0.0001). The average moisture content in the control bin at the grain surface reached 26.4 ± 1.29 % after 40 days and was significantly different with moisture content on other days of maize storage (Fig. 5). The largest variation in moisture content values within each bin was observed at 30 and 40 d (Fig. 5). Specifically, moisture content at a depth of 2.7 m was significantly reduced to values between 6.8 ± 0.38% and 7.8 ± 0.72% after warming maize in both bins. The average difference in moisture content between the bins was significantly different (*P* < 0.05) at all days of maize storage; 0 (1.7 ± 0.13%), 10 (2.5 ± 0.45%), 20 (2.0 ± 0.38%), 30 (2.6 ± 0.67%) and 40 (4.0 ± 1.3%) d. Although moisture content remained similar between 0.9 and 1.8 m depth of maize in both bins, there was a negative change in moisture points between the bins (Table 1). Calculations showed that the allowable storage time (AST) (Table 1) without spoilage of maize in the treatment bin exceeded 249 d, while in the control bin, the AST ranged between 32 and 249 d.

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>Grain Temperature (°C)</th>
<th>Moisture (% wet basis)</th>
<th>Diff (% points)</th>
<th>AST (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>treatment bin</td>
<td>Control bin</td>
<td>treatment bin</td>
<td>Control bin</td>
</tr>
<tr>
<td>0</td>
<td>31</td>
<td>31</td>
<td>13.5</td>
<td>15.2</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
<td>25</td>
<td>13.1</td>
<td>15.7</td>
</tr>
<tr>
<td>20</td>
<td>17</td>
<td>17</td>
<td>13.0</td>
<td>15.0</td>
</tr>
<tr>
<td>30**</td>
<td>23</td>
<td>22</td>
<td>12.9</td>
<td>16.4</td>
</tr>
<tr>
<td>40**</td>
<td>21</td>
<td>21</td>
<td>12.7</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Diff. = Difference in percentage points of moisture between the treatment and control bins. AST = Allowable Storage Time. ** Excluded moisture content at 2.7 m depth of maize in both bins because adding heat to the ambient air resulted in moisture loss of maize.
3.4. Bulk density

The mixing of maize from top to bottom by the mechanical augers resulted in significant differences in bulk density between the treatment and control bins at all days of maize storage ($F_{35,144} = 60.25$, $P < 0.0001$). The bulk density values in the treatment bin were consistently higher compared to the control bin (Fig. 6). Sserunjogi et al. (2021) observed similar results between disturbed and control jars of infested maize.
maize. Bulk density did not change significantly at each depth and sampling time, except at the grain surface of the control bin where a decrease in initial bulk density value from 707.4 ± 3.95 kg/m$^3$ to 616.2 ± 7.81 kg/m$^3$ at 40 d was observed. Conversely, reduction in bulk density was not observed at 0.9 (728.5 ± 1.45 kg/m$^3$) and 1.8 (734.3 ± 3.26 kg/m$^3$) m bin depths in the control bin which had more live S. zeamais counts at 40 d (Fig. 6). The differences in bulk density between the control and treatment bins were significant at 0 (24.5 ± 0.24 kg/m$^3$), 10 (36.0 ± 0.46 kg/m$^3$), 20 (24.5 ± 0.27 kg/m$^3$), 30 (29.6 ± 0.46 kg/m$^3$) and 40 (37.3 ± 0.87 kg/m$^3$) d.

3.5. Broken corn and foreign material (BCFM)

The highest average percentage of BCFM (22.8 ± 0.57%) was found in the treatment bin at a depth of 2.7 m after 10 d (Fig. 7). BCFM was significantly different at 2.7 m and 10 d ($P = 0.015$) between the treatment and control bins. The initial transfer of maize from the treatment bin contributed to the presence of BCFM in the samples taken from the control bin. A decreasing trend of BCFM was observed over time in both bins at 40 d. A significant difference in BCFM between the treatment and control bins at all days of maize storage was observed ($F_{35,144} = 6.58, P < 0.0001$). The trend of BCFM in the control bin align with the findings of Sserunjogi et al. (2021) who observed that BCFM in the control jars followed the change in populations of live S. zeamais. The average difference in BCFM in both bins was significantly different initially (0.3 ± 0.07%) and at 20 (2.9 ± 0.23%) d.

Table 2 shows the average BCFM from samples (loads 1 to 6) taken during unloading of the control bin, and from sampling the sweepings on the bin floor that the sweep augers passed over. The sweepings in the control bin had BCFM levels ranging from 0.6 to 3.0%, while in the treatment bin, the levels ranged from 5.9 to 10.9%. The BCFM levels on the floor of the treatment bin were nearly 6.5 times as much as those on the floor of the control bin. The calculated packing factor for the sweepings in the treatment and control bins were 1.2 and 1.4, respectively, using the method described by Grama et al. (1984). These values were close to the commonly assumed packing factor of 1.5 used in industries when grain conditions are unknown (Bern et al., 2013).

3.6. Insect and mold damage

Percentage insect damage between the treatment and control bins was significantly different at all days of maize storage ($F_{35,144} = 5.50, P < 0.0001$). Initially, the control bin had a significantly higher percentage of insect-damaged kernels at the grain surface (2.1 ± 0.36%) (Fig. 8). The change in insect damage was more significant in the control bin compared to the treatment bin at all sampling days. Infested kernels were introduced at the top layer of the grain mass during the bin infestation, but the stirring machines distributed them throughout the grain mass. Only at 40 d of the experiment did the insect damage in the control bin at 0.9 (1.7 ± 0.17%) and 1.8 (2.6 ± 0.34%) exceed that at the grain surface (Fig. 8). The differences in insect damage between the control and treatment bins were significant at 0 (0.6 ± 0.11%), 10 (0.4 ± 0.10%), 20 (0.4 ± 0.09%), 30 (0.6 ± 0.09%) and 40 (1.0 ± 0.17%) d. The highest recorded mold damage in the treatment bin was 1.7 ± 0.29%, which was approximately half of the highest mold damage observed in the control bin, 3.2 ± 0.53% at 40 d (Fig. 9). Percentage mold damage between the treatment and control bins was significantly different at all sampling days ($F_{35,144} = 3.65, P < 0.0001$).
4. Discussion

The calculations for bin infestation aimed to achieve the same initial number of *S. zeamais* based on the bin diameter and holding capacity. The increase in the number of *S. zeamais* at 2.7 m in the treatment bin may be attributed to the augers mixing the maize and relocating *S. zeamais* towards the bottom of the grain mass. The rotation of the augers might also explain the absence of *S. zeamais* in the treatment bin.
at a depth of 1.8 m after 20 days. The inconsistency in the trend of *S. zeamais* population at different depths in the control bin was influenced by the conditions required for insect growth in the grain mass. The decrease in the population of *S. zeamais* in the control bin at the grain surface can be attributed to the cool environment around the surface of the grain mass with ambient temperatures dropping below 17 °C in October (Table 1) providing unfavorable conditions for *S. zeamais* multiplication (FAO, 1994). The large variability in the populations of live *S. zeamais* observed in the control bin suggests that the samples collected may not have represented the entire bin accurately. The collapse of *S. zeamais* population at 0.9 m at 30 d might be due to *S. zeamais* that were missed from sampling at that depth. Besides, temperatures around 21 °C in the control bin favored the increase of *S. zeamais* populations at all depth of maize at 40 d. After 30 days of continuous stirring machine operation, almost no live *S. zeamais* were found in the treatment bin compared to the control bin. There is a possibility that the augers mixing the maize might have injured and killed live *S. zeamais*. Considering the *S. zeamais* life cycle, disturbance of maize is effective and likely disrupts the fecundity of female *S. zeamais*, resulting in fewer eggs laid per kernel and fewer kernels being subject to oviposition (Sserunjogi et al., 2021; Mathias et al., 2015; Throne, 1994).

![Fig. 7. Percentage (mean ± SE, n = 200) of BCFM from samples collected at four maize depths (0, 0.9, 1.8 and 2.7 m) in the control and treatment bins during the 40 d storage period.](image)

### Table 2

Mean percentage BCFM from samples taken during unloading of the treatment and control bins and samples collected from the sweepings at four cardinal locations in both bins.

<table>
<thead>
<tr>
<th>Quarter of the bin</th>
<th>Treatment bin</th>
<th>Control bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>North East (sweepings)</td>
<td>10.2</td>
<td>0.6</td>
</tr>
<tr>
<td>South East (sweepings)</td>
<td>8.6</td>
<td>1.0</td>
</tr>
<tr>
<td>North West (sweepings)</td>
<td>10.9</td>
<td>0.9</td>
</tr>
<tr>
<td>South West (sweepings)</td>
<td>5.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Loads 1 to 6 (Bin unloading)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>8.9</strong></td>
<td><strong>1.1</strong></td>
</tr>
</tbody>
</table>

The high moisture content at the grain surface in the control bin can be explained by both a drop in ambient air temperatures below 17 °C with condensation at the bin wall and moisture as a product of respiration from insect activity (Sserunjogi et al., 2021; Sone, 2001). Temperatures above 30 °C supplied from the plenum at 30 and 40 d of sampling over dried maize at the bottom of the bins, resulting in low moisture levels. This temperature increase caused *S. zeamais* to move up from the dry maize at lower depths towards the surface of the grain mass. Though the average temperature of maize in both bins was around 23 °C after 30 days, maize at the bottom of the bin was not cooled to regain moisture. The loss in moisture content at 2.7 m (Fig. 5) in the treatment bin is a
result of the stirring augers being too short to reach and disturb the bottom layer of the grain mass. This created similar conditions in both bins because of grain temperature and moisture content equilibrating with the prevailing air conditions in the plenum. Fans connected to each plenum remained unsealed allowing air exchange between the outside and inside of the bin as a function of ambient conditions and wind. Bern et al. (1982) stated that unlike in the control bin, stirring loosens caked grain by removing or mixing moist spots, allowing for more even air flow in the grain mass and achieving a more uniform moisture content in the aerated maize.

The decrease in bulk density at the grain surface of the control bin was likely a result of higher moisture, and as a rule of thumb, bulk density of maize decreases when its moisture content increases (Bern and Brumm, 2009). Adding weevils infested maize to the grain mass at the time of infesting the bin might have contributed to the lower bulk density in the top layer of the control bin. S. zeamais feeding on maize endosperm can lower kernel density (Sserunjogi et al., 2021). At 0.9 and 1.8 m depths where no significant reduction in bulk density in the control bin was observed in the presence of S. zeamais, it can be suggested that perhaps S. zeamais relocated to warmer depths below the grain surface after infesting maize from the top layers. This experiment spanned a single life cycle for S. zeamais activity with no substantial changes in maize bulk density at various sampling times and control bin depths.

BCFM concentrated in the lower layers of the treatment bin was attributed to the mechanical stirring process, which was unable to disturb the maize in those depths effectively. A decreasing trend of BCFM from both bins may be a result of sampling error perhaps due to repeated sampling from same location. It is possible that some amount of BCFM was likely consumed by the insects, but whether they consumed the difference in the measured amounts is speculative and probably unlikely. The increase in live S. zeamais at depths of 0.9 and 1.8 m of maize in the control bin (Fig. 2) likely caused the observed increases in BCFM. This experiment lasted for one insect life cycle which was not long enough to cause more significant changes in BCFM from S. zeamais activity. While the levels of BCFM were similar at other sampling days, the underlying causes for the presence of BCFM may have differed. The treatment bin acquired damage from the long-term mechanical stirring process, whereas the control bin developed BCFM due to insect damage. Accumulation of BCFM in the bottom layer of the grain mass can increase resistance to airflow, reducing the airflow rate (ASABE, 2016 – method ASAE D272.3 MAR 1996; Grama et al., 1984). Consequently, this can increase the time to move a cooling or warming front through the grain. However, stirring machines can mitigate this issue by reducing the static pressure drop throughout the grain mass, thereby facilitating faster grain drying and cooling (Bern et al., 1982).

The change in insect damage correlated with the observed trend of live S. zeamais populations. The increase in insect damage at a depth of 2.7 m in the treatment bin might indicate the further accumulation of kernels damaged by S. zeamais from the upper layers due to the operation of the stirring machines. When maize kernels, fungi, and S. zeamais respire, they generate heat and moisture, creating favorable conditions for fungal spores to grow and leading to the spoilage of maize. These biological activities contribute to self-heating and the development of hot spots which in turn promote mold growth and insect multiplication (Sserunjogi et al., 2021). The high initial populations of Typhaea sterncorea and Ahasuerus advena (Fig. 3) suggested the presence of moldy maize in the bins, as these insects are known to feed on mold (Hagstrum et al., 2012). Although we observed moldy kernels around the inner wall of the control bin, our grain quality data from the treatment bin align with the findings of Joffe (1963), who did not observe spoilage when grain was turned between elevators.

In conclusion, this study investigated the effect of stirring bulk stored maize to suppress S. zeamais and other beetle populations. After a period...
of 40 days, stirring effectively achieved 100% suppression of S. zeamais population in the treatment bin, while the number of live S. zeamais in the control bin continued to increase. Stirring also significantly reduced populations of other beetle species aside from S. zeamais. The quality of maize in both bins changed over time and varied with the depth of the grain mass and changes in beetle populations. The treatment bin exhibited higher bulk density and lower levels of insect damage compared to the control bin. The treatment bin also demonstrated a longer allowable storage time (>249 d) with minimal changes in maize quality, indicating the potential for extended storage periods without significant deterioration. In contrast, the presence of molded kernels and higher moisture content near the bin walls in the control bin reduced the allowable storage time for maize. Stirring machines used in the experiment concentrated BCFM near the bin floor, resulting in different packing factors between the treatment and control bins. On the floor of the treatment bin, BCFM levels were nearly 6.5 times higher than those observed on the floor of the control bin. The predicted packing factors were calculated to be 1.2 for the treatment bin and 1.4 for the control bin. Based on these findings, it is recommended that future research should investigate the effectiveness of stirring techniques with different types of grains and insects over multiple insect life cycles and storage periods. This would provide a more comprehensive understanding of the potential benefits and limitations of stirring as a method for insect control and grain quality preservation in various storage scenarios.

CRediT authorship contribution statement

M. Sserunjogi: Conceptualization, Formal analysis, Methodology, Software, Writing – review & editing. C.J. Bern: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. T.J. Brumm: Conceptualization, Methodology, Writing – review & editing. D.E. Maier: Conceptualization, Methodology, Writing – review & editing. T.W. Phillips: Conceptualization, Methodology, Supplying S. zeamais, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jspr.2024.102281.
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