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Use of IoT to Real-time Monitoring of Storage Silo and Ozone Gas Fungal Decontamination Strategy

Carlos Soares
Federal University of Santa Catarina
Department of Food Science
and Tecnology
Santa Catarina, Brazil

Eliza Gomes
Federal University of Santa Catarina
Department of Informatics and Statistics
Santa Catarina, Brazil

Fabiano Dahlke
Federal University of Santa Catarina
Department of Animal Science
Santa Catarina, Brazil

Carlos De Rolt
State University of Santa Catarina
Centre of Management
and Socioeconomic Science
Santa Catarina, Brazil

Patricia Plentz
Federal University of Santa Catarina
Department of Informatics and Statistics
Santa Catarina, Brazil

Mario Dantas
Federal University of Juiz de Fora
Department of Computer Science
Minas Gerais, Brazil

Vildes Scussel
Federal University of Santa Catarina
Department of Food Science and Technology
Santa Catarina, Brazil

ABSTRACT

During the food production process, qualitative losses are caused by biological contaminants (fungi, mycotoxins, and insects) and chemical contaminants (pesticide residues), widely found in grain storage. Several species of fungi, when they find ideal conditions for their development in the silos, cause damage to the grains (clod formation, grain heating, discoloration, loss of germination vigor, reduced nutritional value) and produce mycotoxins. With the advent of the new globalization, the demands for quality and sustainable products are becoming stronger. Thus, digital transformation is a differential for the productive market, inserting disruptive technologies, to become increasingly competitive. Therefore, monitoring of physical and biological conditions by intelligent systems in grain storage environments is required, as well as sustainable decontamination strategies (method-*green*). Therefore, in this article is proposed the use of IoT technology for monitoring and detecting the proliferation of different fungal species, having as parameters the temperature and humidity produced by fungal growth in (sites) of the grain storage silo. Besides, the use of ozone gas (GRAS - generally recognized as safe) is proposed as a useful alternative for fungal decontamination inside the storage unit silos and an automated real-time gas release system.

General Terms

Decontamination, Internet of Things

Keywords

Ozone gas, Real-time, Grain storage, Fungi, Monitoring environment

1. INTRODUCTION

Quantitative losses often occur during the food production process. Technical problems, such as harvester regulation, grain handling during harvest, as well as transportation, are factors that are associated with these losses [28, 7].

Food loss and economic impact are the main problems to be solved. On the other hand, qualitative losses, triggered by biological (insects, fungi and mycotoxins) and chemical (pesticide residues) contaminants are widely found in grain storage [19, 26].

Insects can cause damage to grains and usually carry fungi that eventually are responsible for spoilage of parts of the grains and seeds. Fungi develop in silos, causing clods, grain heating, discoloration, germination loss, odor changes, reduced nutritional value and affect product quality. In addition, they can produce mycotoxins, which makes the problem even more serious [5, 26].

Factors such as the high temperature associated with high air and grain humidity are crucial for the formation of clods. Alternatives such as systematic grain drying and continuous application of fungicides and pesticides are commonly applied in these cases. However, the high energy consumption produced by grain drying ventilation systems [24] and residual contamination generate economic losses for producers and concern for human health and the environment [27].

The practices described above meet the trends of the new globalization that is growing with digital transformation [18]. Bioeconomics has become an emerging strategy as it is a new economy based on biological resources and clean, renewable and sophisticated processes. In the concept of digital transformation, technological innovations are constant, as they introduce new benefits such as greater simplicity, convenience in use and lower cost. [30].

Thereby, disruptive technologies, such as the (Internet of Things - IoT), have been widely used in areas that need accurate control and continuous monitoring. In agroindustry, with smart agriculture, IoT is used to evaluate soil, air and biomass conditions of plants and animals [29]. The sensing systems implemented in Grain Storage Units (UAGs) are essential for controlling the internal temperature and humidity of the silos. Through control it is possible to prevent and combat the development of pest insects, fungi and bacteria.

Therefore, it is proposed in this research work the use of thermometry technique to detect the formation of clods produced by fungi filamentous in grain storage silos, respecting a time constraint. In other words, it is proposed to use temperature and humidity sensors for the preventive detection and elimination of clod-forming fungi, as well as the ozone gas O_3 application strategy for real-time decontamination of silos. Real-time in this context refers to the system response time. In this case, the system must meet with the activation time of the O_3 release mechanism and gas exposure time in the grain storage unit. For this, an IoT platform is used, similar to the FASTEN project [9], composed by open source software for silos monitoring and alerts generation for the user.

FASTEN (Flexible and Autonomous Manufacturing Systems for Custom-Designed Products) is a project carried out in cooperation between Brazil and Europe (H2020). The main goal of this project is to develop an open and standardized structure to produce custom-designed products that can function autonomously and provide products from low-cost additive manufacturing.

This article is organized as follows: in Section 2 we present concepts related to ozone gas and storage fungi. Section 3 is detailed the research proposal which consists of the use of IoT to detect fungal formation in storage silos through thermometry. In Section 4 is showed the environment configuration and the results of the first experimentation. Finally, in Section 5 is concluded our article and present indications for future works.

2. OVERVIEW

In Latin America approximately 127 million tons of food are wasted per year. Of this total, approximately 28 million tons are lost during the storage and handling steps. Some Mercosul countries have losses of up to 25% of their cereal production total, and fungi are among the main factors promoting these losses [17]. Most storage fungi can be toxigenic and produce toxins, leading to loss in the quality of grains directed for human and animal consumption [26].

Increasing consumer demand for food through increasingly sustainable production makes it impossible to apply fungicides to control and eliminate these microbiological contaminants. Developing agriculture for the new digital globalization requires balancing the three strands of sustainability: environmental, economic and social [18]. Given this, it is proposed in this research work a physical and computational infrastructure that meets the three aspects. Therefore, the use of ozone gas as a sustainable decontaminant is proposed, as well as the use of technological tools for prevention, detection and notification of fungal development, based on temperature and humidity conditions.

Ozone gas is considered a GRAS (*Generally Recognized as Safe* - FDA). The half-life of O_3 in atmospheric conditions is approximately 30 min and reduces with high temperatures and low pressures [22, 15].

In industry it is used as an effective tool in the control of insects, such as *Tribolium confusum and Oryzaephilus surinamensis*, genera of fungi *Aspergillus, Fusarium and Penicillium* their toxins and in the degradation of pesticide residues mainly of the pyrethroid group. [2, 1, 8].

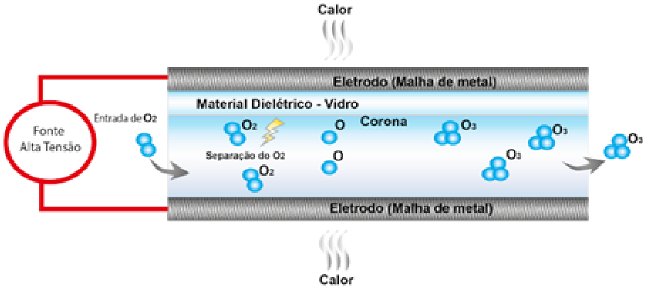


Fig. 1: Ozone production performed by electric discharge in an oxygen stream. Adapted from [4].

From the discovery of O_3 as a decontaminant, it was very difficult to use on a large scale due to the expensive ozone generators. The cellulose and paper industries needed to replace chlorine with O_3 for the bleaching process, new technologies made it possible to build ozone generators, lowering their generation costs. [16].

The O_3 production does not require high investments, it is performed by the process of electric discharge (corona discharge), which occurs through the tunnel between 2 electrodes subjected to a high potential difference of about 1000v (Figure 1). It is produced by the passage of air or pure oxygen between both electrodes. Oxygen molecules collide causing oxygen dissociation and the consequent formation of O_3 by the time electrons reach enough energy to dissociate [4].

Ozone gas can be utilized as an oxidizing agent and applied as a decontaminate to elioisinate living organisms (fungi, bacteria, viruses, protozoa, insects and mites) and / or degradation of toxic compounds such as pesticides and mycotoxins in food industries [3, 25].

Some articles, [20, 14, 21], utilized high concentrations of O_3 in short periods to eliminate larvae and adults of several beetle species responsible for intense damage to agriculture.

Low humidity content does not ensure storage efficiency. Some fungal species, such as *Aspergillus glaucus*, during their development release water and heat that can reach 40C [26]. Besides the formation of clods, these species compromise the quality of the grains (burnt grains) with high humidity content, 14.8% [6].

Species such as *A. restriticus* require humidity contents of 13.2 13.5% and temperatures of 30C to 35C for the development of their reproductive structures. [26].

Intelligent systems with sensors and micro-controllers are used to precisely monitor the development of reproductive structures in fungal cultures, utilizing the substrate temperature and humidity as parameters. [32].

In this context, the Internet of Things (IoT) is used in precision agriculture to monitor the temperature and humidity of silos, thereby preventing and detecting clod formation by fungi. IoT is a network of physical objects with sensors and actuators, connected to the Internet, that collect and transmit data and act when needed.

The FASTEN project IoT platform allows farmers to implement cost-effective technologies. The open source software allows the addition of economic and social sustainability. Besides to facilitating the dissemination of technological innovations for agriculture by the inclusion of digital transformation in agribusiness and the new competitive landscape.

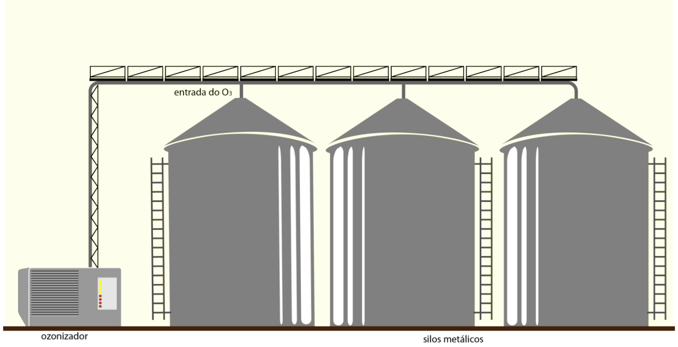


Fig. 2: Grain storage unit designed to receive ozone gas.

3. FUNGI DETECTION SYSTEM IN STORAGE SILOS

Grain storage has some climatic and biological barriers that cause great damage and hinder the flow of production. Therefore, it is proposed in this work a system for preventing and detecting the formation of clods produced in silos of grain storage units, as well as the use of O_3 gas for decontamination. The objective of this research is to reduce economic losses in grain silos using as a decontaminant a component considered as clean technology (*Green*). The research proposal presents three main contributions:

(1) *Projects for silos and ozone generator*: In order to use O_3 gas as a decontaminant, it is necessary to project the method as the gas will be inserted. The structure of the sensor presented is currently utilized.

(2) *Clod prevention and detection system*: development of a hardware and software infrastructure capable of preventing, detecting and notifying the user of clod development. In addition, the system will control gas release, concentration and release time according to the characteristics of the detected fungi.

(3) *Ozone gas concentrations and exposure time*: for each fungal species it is necessary to correlate the concentration and exposure time of the gas to get the whole process safe and effective.

3.1 Project of silos and ozone generator

Figure 2 shows the O_3 generator (ozonator) and grain storage unit structures that have input for gas insertion. The conduction of O_3 gas is accomplished through openings pipes that release O_3. In each silo there are three tubes with up to 36 openings (Figure 3).

Humidity and temperature sensors are inserted into the silos using cables. The silos are made up of 3 sectors, totalling a set of 45 sensors. Each sector consists of 15 temperature and 15 humidity sensors distributed in 5 points. A Figure 3 shows Sectors 1, 2, and 3, which consists in the provision of O_3 (1), in the O_3 inlet tubes (2), in the sensor cables (3), and the grain mass (4).

Figure 4 presents the silo structure with grain stocked (1), the sensor cables (2) and the O_3 gas release ducts (3).

The fungi detection process begins with measurements of humidity and temperature of the silo, since fungal development occurs with the association of these two factors. When the temperature rise in a particular part of the silo is detected, an alert is sent to the system (4). It will notify the user of fungal development and send a command to the actuator to release gas into the openings in the tubes underlying the sensor that detected the fungus. O_3 gas will be released according to the fungus infestation characteristics, at pre-established concentration and time, in real time (5).

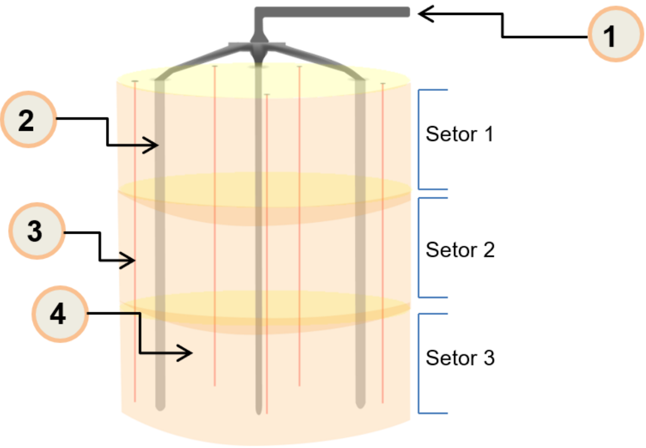


Fig. 3: Distribution of temperature and humidity sensors inside the grain silos.

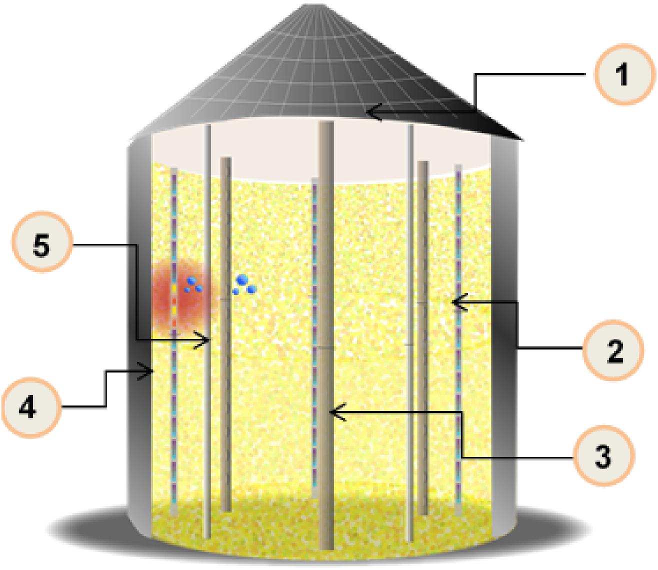


Fig. 4: Metal silo interior, local decontamination and detection scheme and real-time ozone application.

For each type of pest detected a specific concentration and release time is required. With this, the system, through the actuator, must adjust the concentration in the ozonator and control the O_3 release time.

3.2 Fungi contamination detection and prevention system

The computational platform is represented by Figure 5. As can be seen, it consists of a hardware layer (IoT Devices) and 3 software modules (IoT Core, Data Repository and Real-time BI).

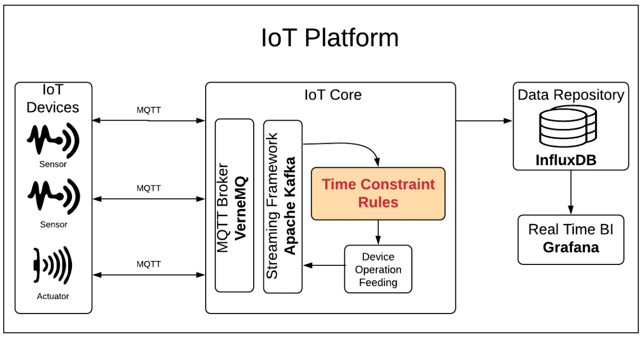


Fig. 5: IoT Platform for data processing [10].

- IoT Devices: consists of sensors and actuators. Sensors are responsible for capturing humidity and temperature data, and sending this data to processing core. Actuators have the role of triggering the ozonizer at the correct concentration and deactivating it when the gas release timeout is reached. Messages (data or commands from the actuators) are sent over a wireless network using the MQTT (Mensage Queuing Telemetry Transport) protocol [23]. This, in turn, is a connectivity protocol designed to carry messages from low latency IoT devices.
- IoT Core: it is a module composed of software responsible for receiving and processing the data sent by sensors. Initially data is received by a broker software. The software used to perform this function is the VerneMQ [31]. It uses the MQTT protocol for communication and its purpose is to provide a set of features related to scalability, reliability and high performance. After that, the data is processed in a data streaming framework. Apache Kafka [13] is a distributed messaging platform based on the publish / subscribe model that allows an application to act as a stream processor. Time Constraint Rules are responsible for controlling the O_3 gas release time and for sending commands to Device Operation Feeding which will send received commands to the actuators.
- Data Repository: is responsible for storing the data. The InfluxDB [12] database was used as it is a time-series database designed for storage of monitoring data, IoT sensors and instant analysis.
- Real-time BI: is responsible for data presentation and alerting. Grafana [11] is the software used as it performs time-series data analysis.

4. EXPERIMENTAL RESULTS

This section presents initial results of the elimination of fungi obtained in the laboratory, as well as the simulation of a monitored environment with temperature and humidity sensors.

4.1 Use of Ozone Gas in Grain Fungi Control

Utilizing low concentrations (10 ppm) of O_3 and time (60 min) to control fungal colonies in pilot silos show a reduction in fungal load. After treatment, the rice samples (n = 3) were for isolation and subsequent identification of genera in petri dishes after 7 days of cultivation at 25C. The control group (6a) (without gas treatment) presented three different genera of fungi, whereas (6b) (with treatment) obtained reduction in fungal count and also three different genera of fungi.

Research performed by [5] showed by scanning electron microscopy that beetle species (*Alphitobius diaperinus*) isolated in storage units are also vectors of toxigenic fungi, especially when they are dead. Figure 7 shows micrographs of the dead collected *A.diaperinus* beetle with high contamination by feed toxigenic fungi stored inside the poultry house. The head region (7a) was infected by fungal conidia. Figure (7b), in turn, shows the reproductive structures of the fungi *Pencillium* sp. dominating the beetles elytral suture.

Treatment with (60 ppm) 24 hour exposure gas was effective in eliminating *A. diaperinus* beetles in both the adult stage and larvae [5]. Further research on the application of ozone is needed since this pesticide-controlled beetle species remains dead in the environment as a substrate for fungi development.

4.2 Monitored Environment Simulation

One silo with three temperature sensors and three humidity sensors was used to perform the simulation. Six sensors belonging to 3 sectors of the silo were configured, with temperature values between 15C and 60C and humidity values between 40% and 100%. Three fungi filamentous species were considered: *Aspergillus flavus*, *Aspergillus restriticus* and *Aspergillus glaucus*. To identify the fungi, the following rules were inserted:

- *A. flavus*: the development of this fungi occurs when the temperature of the silo is between 20C and 29C and the humidity is 85%.
- *A. restriticus*: its development occurs when the silo temperature is between 30C and 35C and humidity is 70%.
- *A. glaucus*: this fungi develops when the silo temperature is between 30C and 35C and humidity is 73%.

The concentration and exposure time of O_3 gas was considered the same for all fungi species, as this research stage is under development.

4.3 Results Analysis

Synthetic data were generated according to the rules presented in the previous section, to simulate the proposed environment. Data is generated every 10 seconds and graphics and tables are updated every 5 seconds.

Figure 8 shows the dashboard of Grafana to be presented to the end user with the temperature and humidity graphs and the table with the detection of fungi the alerts generated.

Figures 9, 10, 11 present the graphs and the table separately. The graph in Figure 9 shows the temperature variation data in the silo sectors. The line in the graphic indicates that the temperature is acceptable up to its limit, that is, 20C. above these temperatures alerts are generated, because the chance of formation of fungus clods increases. These visual alerts enable the user to better assess the status of the silo.

Figure 10 presents the data obtained from the humidity sensors inserted in the sectors analyzed. As it can be seen, the limit value is 70 % humidity from this value alerts will be presented. alerts consist of a change in the screen of the graphics with red signals.

Finally, the table shown in Figure 11 shows presents the result of the association between the temperature and the humidity of the silo that contributes to the formation of fungi clods. As can be seen, the system detects and identifies the fungi which allow the user to have a real-time view of the silo situation.

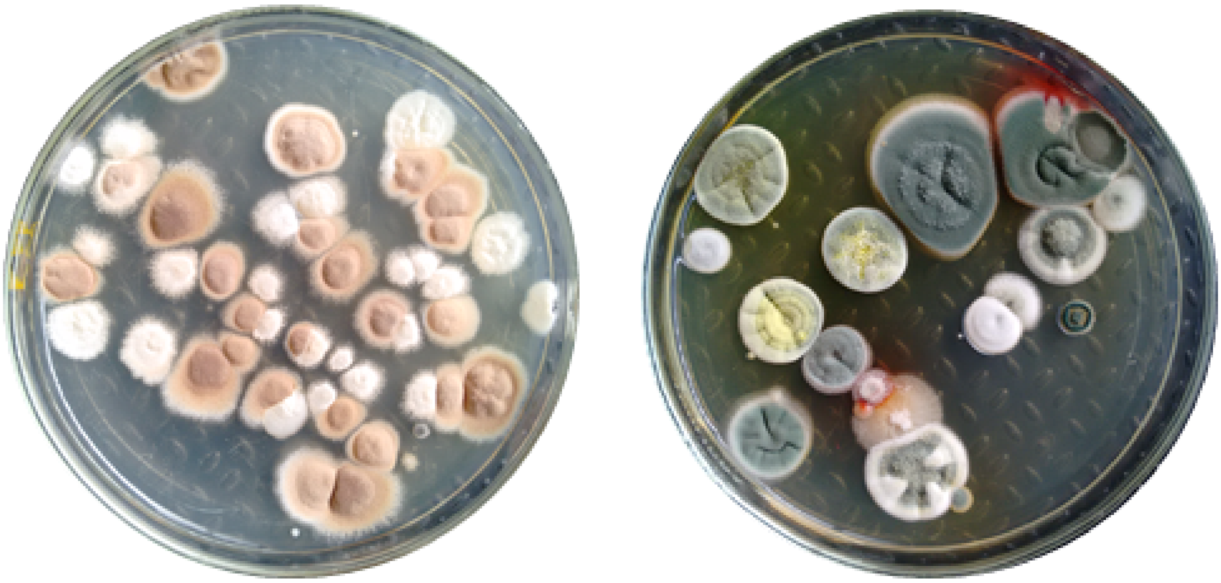
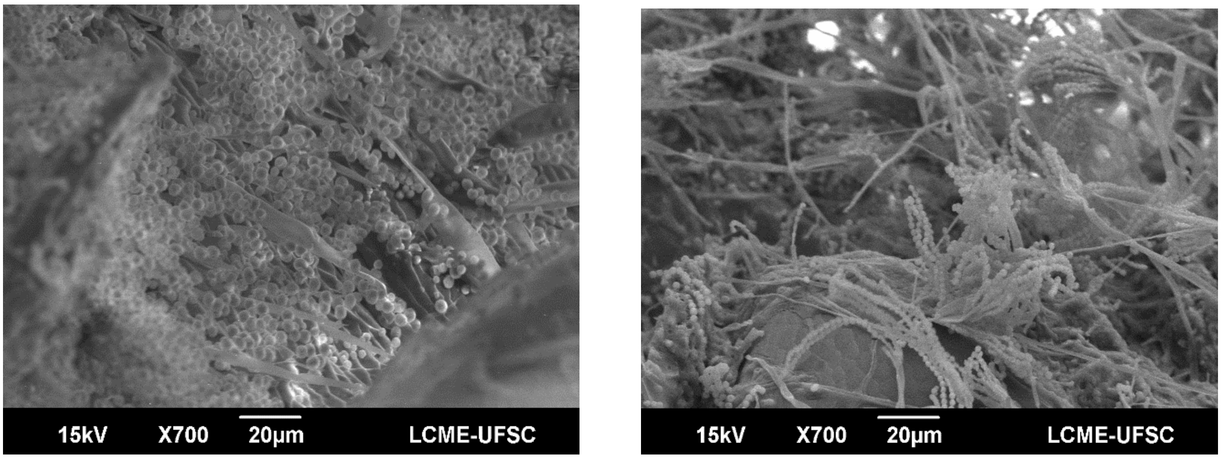

(a) (b)

Fig. 6: Fungal load colonies (a) untreated with ozone gas and (b) treated.



(a) (b)

Fig. 7: Reproductive structures of *Penicillium* sp in the head region and elitral beetle suture *A.diaperinus* [5].

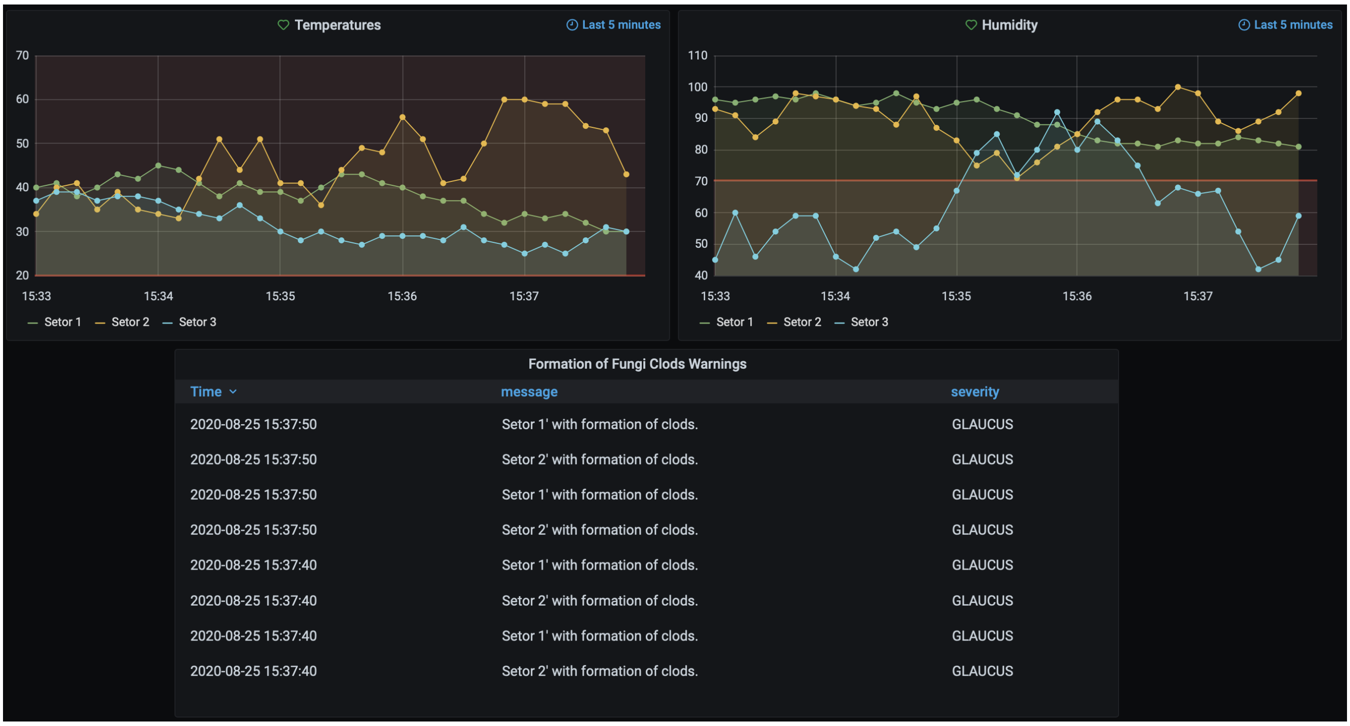
5. CONCLUSION

Technologies have been used to control and monitor humidity and temperature in grain storage units. The combination of these two factors is crucial for the development of biological contaminants such as fungi, mycotoxins and insects. However, the techniques used to control humidity and temperature and for decontamination are costly and release toxic residues in grains and do not eliminate all pathogens, making them resistant.

Therefore, this research work proposed the use of low cost technology for monitoring and control of formation of fungal clods in real time, as well as a clean method *(Green)* for decontamination of grain storage units.

A standard IoT platform was used to monitor and control grain storage units. The platform allows the user to know the situation (temperature and humidity) of the silo through graphical presentations and visual alerts. For decontamination, the use of O_3 gas was proposed. Studies have shown the efficiency of gas in eliminating pathogens such as fungi, mycotoxins and insects.

As a result, tests were performed that prove the significant reduction of toxigenic fungi. In addition, a simulation environment was designed to verify the system. The system was able to monitor and identify fungal species according to temperature and humidity of the silo. The use of the platform allows UAGs to be aware of the situation of their grain storage units and thus assists them in de-



Formation of Fungi Clods Warnings

Time	message	severity
2020-08-25 15:37:50	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:50	Setor 2' with formation of clods.	GLAUCUS
2020-08-25 15:37:50	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:50	Setor 2' with formation of clods.	GLAUCUS
2020-08-25 15:37:40	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:40	Setor 2' with formation of clods.	GLAUCUS
2020-08-25 15:37:40	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:40	Setor 2' with formation of clods.	GLAUCUS

Fig. 8: Silo temperature and humidity monitoring and fungi detection dashboard

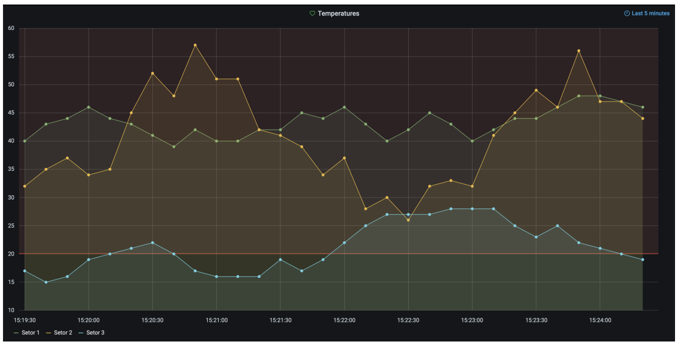


Fig. 9: Presentation of the silo temperature during the time

cision making. In addition, the use of a clean (I) method for decontamination adds value to products, which include it in the new globalization and, consequently, in the competitive market.
As future work, it is initially intended to refine the presentations by expanding the amount of silos and sensors. In the end, it is expected that the system will be able to present the humidity and temperature data of the silos, identify the developing fungi, enable the sound notification of the possible formation of clods by fungal, issue commands to the actuators (for the release of O_3), as well as control the concentration and exposure time to the gas.

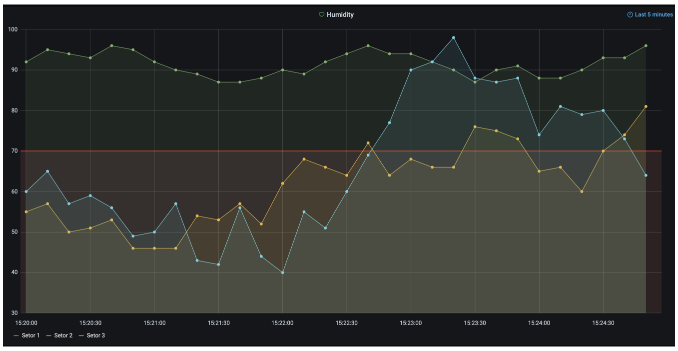


Fig. 10: Presentation of the silo humidity during the time

Formation of Fungi Clods Warnings

Time	message	severity
2020-08-25 15:37:40	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:40	Setor 2' with formation of clods.	GLAUCUS
2020-08-25 15:37:40	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:40	Setor 2' with formation of clods.	GLAUCUS
2020-08-25 15:37:30	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:30	Setor 2' with formation of clods.	GLAUCUS
2020-08-25 15:37:30	Setor 1' with formation of clods.	GLAUCUS
2020-08-25 15:37:30	Setor 2' with formation of clods.	GLAUCUS

Fig. 11: Fungi detection and identification table

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