

## Article

# CFD—Assisted Expert System for N<sub>2</sub>-Controlled Atmosphere Process of Rice Storage Silos

Phakkawat Angsrisuraporn <sup>1</sup>, Chawit Samakkarn <sup>1</sup>, Lertsak Lekawat <sup>1</sup>, Sasathorn Singkhornart <sup>2</sup>  and Jatuporn Thongsri <sup>1,\*</sup> 

<sup>1</sup> College of Advanced Manufacturing Innovation, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand; phakkawat.ang@gmail.com (P.A.); chawit.smk@gmail.com (C.S.); lertsak.le@kmitl.ac.th (L.L.)

<sup>2</sup> Department of Food and Nutrition, Faculty of Home Economics Technology, Rajamangala University of Technology Krungthep, Bangkok 10120, Thailand; sasathorn.s@mail.rmutk.ac.th

\* Correspondence: jatuporn.th@kmitl.ac.th

**Abstract:** Since organic rice storage silos were faced with an insect problem, an owner solved this problem using the expert system (ES) in the controlled atmosphere process (CAP) under the required standard, fumigating insects with an N<sub>2</sub>, reducing O<sub>2</sub> concentration to less than 2% for 21 days. This article presents the computational fluid dynamics (CFD) assisted ES successfully solved this problem. First, CFD was employed to determine the gas flow pattern, O<sub>2</sub> concentration, proper operating conditions, and a correction factor (K) of silos. As expected, CFD results were consistent with the experimental results and theory, assuring the CFD's credibility. Significantly, CFD results revealed that the ES controlled N<sub>2</sub> distribution throughout the silos and effectively reduced O<sub>2</sub> concentration to meet the requirement. Next, the ES was developed based on the inference engine assisted by CFD results and the sweep-through purging principle, and it was implemented in the CAP. Last, the experiments evaluated CAP's efficacy in controlling O<sub>2</sub> concentration and insect extermination in the actual silos. The experimental results and owner's feedback confirmed the excellent efficacy of ES implementation; therefore, the CAP is effective and practical. The novel aspect of this research is a CFD methodology to create the inference engine and the ES.

**Keywords:** control atmosphere; computational fluid dynamics; expert system; fumigation; inference engine; insect extermination; rice storage; sweep through purging; sustainable development goals; SDGs



**Citation:** Angsrisuraporn, P.; Samakkarn, C.; Lekawat, L.; Singkhornart, S.; Thongsri, J. CFD—Assisted Expert System for N<sub>2</sub>-Controlled Atmosphere Process of Rice Storage Silos. *Sustainability* **2024**, *16*, 2187. <https://doi.org/10.3390/su16052187>

Academic Editor: Hadi Bordbar

Received: 14 January 2024

Revised: 24 February 2024

Accepted: 4 March 2024

Published: 6 March 2024



**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Rice is Thailand's number one agricultural export product. The cultivation area is 43.7% of the country's total arable land from 5.1 million households. In 2022, Thailand has the 6th highest rice production globally, accounting for 3971 million USD, 4.0% of global rice production (after China, India, Bangladesh, Indonesia, and Vietnam, which account for 29%, 25.2%, 7%, 6.7%, and 5.2%, respectively) [1]. However, Thailand is the world's second-largest rice exporter, with a market share of 13.5%, behind India, with a market share of 38.8% [1]. Even though other countries produce a lot of rice, they export little due to high domestic consumption, indicating that Thailand is a leading country in rice production and export. For this reason, the rice storage in silos awaiting export is very important, making excellent rice quality and selling for a high price.

The rice owners' exporters' major problem with rice storage is insects such as moths, red flour beetles, etc. Its families feed on dry plantstuffs such as seeds and rice, leading to low rice quality and not exporting for a high price. In the past, exporters preferred to use phosphine (PH<sub>3</sub>) or methyl bromide to fumigate in silos that the 1987 Montreal Protocol abolished methyl bromide due to destroying the ozone layer as a carcinogen [2]. Unfortunately, PH<sub>3</sub> is a toxic gas, colourless, flammable, and hazardous to employees.

Additionally, continuous use of  $\text{PH}_3$  increases insect resistance, so insect extermination with  $\text{PH}_3$  needs more concentration, affecting manufacturing costs [3–5], so exporters pay attention to nitrogen ( $\text{N}_2$ ) use for export rice storage.

To encourage food safety production and rice storage, the controlled atmosphere process (CAP) method by  $\text{N}_2$  treating the atmosphere in the storage area to a low  $\text{O}_2$  concentration is a safer alternative to non-chemicals [4–6]. The CAP's importance is to maintain  $\text{O}_2$  to below 1% for 2–9 days [3] or below 2% for 21 days [7]; all life stages of insects cannot survive and propagate in the low  $\text{O}_2$  level atmosphere [4–8]. The difficulty of CAP is controlling  $\text{O}_2$  and  $\text{N}_2$  to a level that succeeds in insect extermination. The exporter previously employed a two-position controller (TPC), a typical control method using constant parameters: Min/Max  $\text{O}_2$ , which is insufficient for a high-efficacy CAP.

The expert system (ES), a main branch of intelligent control systems, is developing a computer system to emulate the decision-making ability of a human expert, which can be applied with various computer-assisted tools and mathematical models to increase the capability for achieving specific purposes [9,10]. The difference between the ES and a general computational application program, including the TPC, is that the first can be used in unknown environments with insufficient information or complex problems. On the other hand, the latter is employed for simple problems with sufficient information. The first performs more efficiently but is more difficult than the latter. The challenge of this work is that the essential parameters used in the ES for controlling both gas concentrations are complex depending on the real-time actual environment. To deal with this challenge, experiments and computational fluid dynamics (CFD) have been proposed and applied to determine the proper parameters for the ES to achieve the mentioned aim.

This article aims to develop ES for the CAP of organic rice at the silo, as shown in Figure 1, by monitoring and controlling  $\text{N}_2$  and  $\text{O}_2$  to levels sufficient that insects cannot survive and also replace the TPC. The novelties of this research are research methodology to apply the CFD and experiments to determine the essential parameters for developing the ES, which can actually be effectively used. First, a rice storage silo was surveyed to collect some parameters for simulation and validation. Next, the CFD and a Sweep-Through Purging (STP) principle were applied to determine the gas flow pattern and a correction factor, essential parameters depending on the environment and operating condition, in the silo. Then, the outcomes were analyzed, and a time inference equation for coding in the ES was determined. Last, the ES was implemented in the CAP, and its effectiveness was evaluated. Figure 1 shows Thai rice exporter silos as a case study in this research.



Figure 1. Rice storage silos.

## 2. Theoretical Background

This section describes the ES, CFD, and TPC.

### 2.1. Expert System (ES)

It is a computer program that combines knowledge of human expertise and rational thinking to create a knowledge base. It acts as an expert, advising users on how to solve complex problems. In addition, the ES is an interactive system that quickly responds to questions, gives advice, and helps in decision-making. Since the ES contains much more knowledge, it is more intelligent than a human and widely applied in many applications, such as engineering, manufacturing, medicine, management, military, education, and training [11]. Generally, the ES has three parts: user interface, inference engine, and knowledge base, summarized in Figure 2, described below.

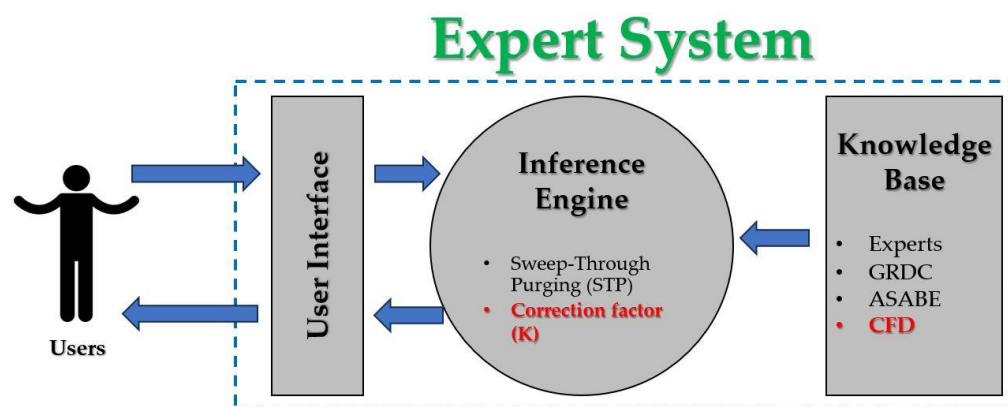


Figure 2. The expert system developed for the CAP.

#### 2.1.1. User Interface

It is a device's access point for human–computer interaction and communication. For example, in this research, users input data such as silo volume, rice weight, N<sub>2</sub> flow rate, the purification of N<sub>2</sub> from a nitrogen generator, Min/Max O<sub>2</sub> level required by users, etc. After that, the ES employed all data input to control the CAP.

#### 2.1.2. Inference Engine

It is the part that searches for information and relationships from existing databases, a key part to success in this research. Like experts, it can find answers, make predictions, validate results, evaluate data, etc. Since the shape, environment, and operating conditions of the silos in Figure 1 are complex, affect the CAP, and cannot determine or measure some essential parameters precisely, a Sweep-Through Purging (STP) principle was employed, and the concept can be described accordingly.

- Sweep-Through Purging (STP)

The STP is a process that purges N<sub>2</sub> into a silo and withdraws the mixed gas of N<sub>2</sub> and O<sub>2</sub> from the silo to the atmosphere, reducing O<sub>2</sub> concentration. Accordingly, the STP was employed in developing the ES for the CAP to control concentrations of both gases. The STP equation can be written as [12]

$$Qt = \frac{V}{K} \ln \left( \frac{C_1}{C_2} \right) \quad (1)$$

where  $Q$  is the volumetric flow rate of N<sub>2</sub>,  $V$  is the silo volume,  $C_1$  is the O<sub>2</sub> initial concentration,  $C_2$  is the O<sub>2</sub> final concentration,  $t$  is the process time, and  $K$  is the correction factor.

- Correction Factor ( $K$ )

The gas flow pattern inside the silo is a laminar flow because the Reynolds number is less than 300; the gas flow pattern due to Equation (1) is simple. Significantly,  $K$ , in other words, is an unknown parameter called mixing efficiency, which depends on the ventilation system, such as the source of supplied gas, obstructions, and the number of exhaust openings, which is no higher than 0.25 [13]. The proper  $K$  helps Equation (1) be

accurate when employed in the ES, leading to the high efficacy of the CAP. Table 1 reports  $K$  for the selected ventilation systems.

**Table 1.**  $K$  for selected ventilation systems [12].

| Source of Supply Gas                                | $K$ for Exhaust Openings |          |
|-----------------------------------------------------|--------------------------|----------|
|                                                     | Single                   | Multiple |
| Infiltration through cracks, open doors, or windows | 0.2                      | 0.3–0.4  |
| Power air supply through:                           |                          |          |
| - Grills and registers                              | 0.3                      | 0.5      |
| - Diffusers                                         | 0.5                      | 0.7      |
| - Perforated ceilings                               | 0.8                      | 0.9      |
| - Pipes and ducts                                   | 0.25 *                   | 0.25 *   |

\* Recommendation based on [13].

However, when the silo is stored with rice, and the gas flow in the rice space, rice will disturb and obstruct the gas flow; determination  $K$  is complex. Figure 3 shows a simulated gas flow pattern inside the silo: (a) without rice and (b) with rice storage, in which the arrows mimic the predicted gas flow directions.

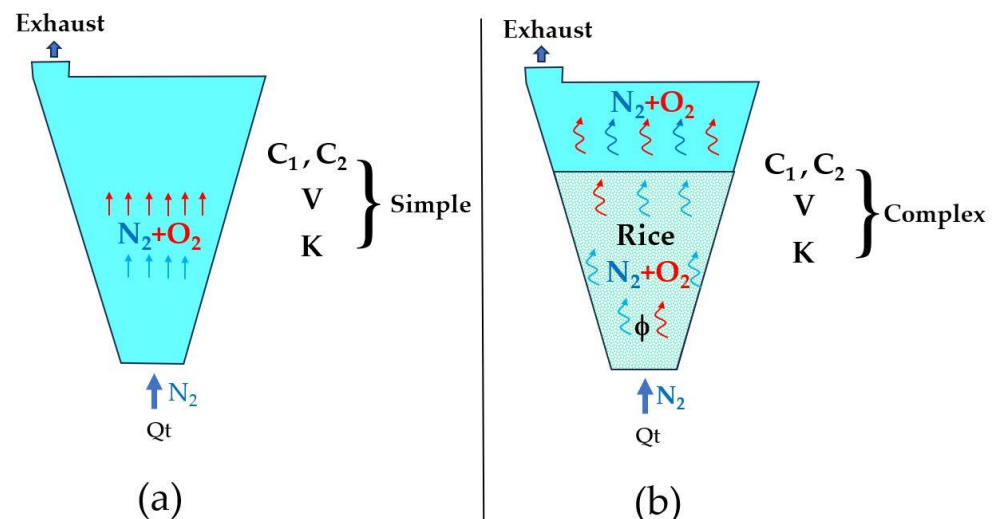


**Figure 3.** The simulated gas flow pattern inside the silo: (a) without rice and (b) with rice storage.

In Figure 3a, a simple case is shown an empty silo that has one opening inlet and one opening exhaust. Suppose  $N_2$  was supplied to the silo of volume  $V$  containing the air, a mixture of  $N_2$  and  $O_2$ . The supplying  $Q_t$  changes the  $O_2$ 's initial concentration from  $C_1$  to the final concentration of  $C_2$ . Since it is a simple case, one way to select  $K$  is from Table 1.

In Figure 3b, when the silo is fully loaded with rice, the gas flow pattern will not be as simple as in Figure 3a due to airflow resistance occurring related to porosity ( $\phi$ ), and the airflow resistance will increase according to the depth of the rice. In addition, the airflow resistance depends on the physical characteristics of each type of rice as well. Therefore,  $K$  is complex and is not consistent with Table 1. From the authors' experience,  $K$  from Table 1 led the CAP of the silo with unacceptable efficacy.

Accordingly, an accurate  $K$  determined using CFD and STP principles to suit the silo is key and novel presented in this research to developing better ES with high-efficacy CAP, explained in the next section.

### 2.1.3. Knowledge Base

It is a database for knowledge management. In this research, the knowledge base collects data and information from experts, ASABE, GRDC, and CFD, which are described accordingly.

- Experts

The experts are a manufacturer and operators who work with the silos. They provided essential information, such as environment, operating conditions, specifications, limitations, gas flow properties, etc. The authors arranged all this information to create the knowledge base to ensure the ES is usable, leading to high-efficacy CAP.

- American Society of Agricultural and Biological Engineers (ASABE)

The ASABE provides information on the airflow resistance equation regarding the airflow resistance of the grain [14]. This information was used to determine the effect of bulk density on airflow resistance, which was analyzed and transformed to suitable porosity in a CFD setting.

- Grains Research and Development Corporation (GRDC)

The GRDC is one of the world's leading grains research organizations, which aims to invest in research, development, and extensive to create enduring profitability for Australian grain growers. The GRDC suggested the silo, for example, how to prepare the silo, how to test the silo's efficiency, safety, etc. Importantly, it is strict that O<sub>2</sub> concentration should be below 2% at 25 °C for 21 days, a period that moths and insects, including eggs, larvae, and pupae, cannot survive [7]. Accordingly, the suggestion from GRDC has been included in the knowledge base and silo management.

- Computational Fluid Dynamics (CFD)

The CFD was used to determine the correction factor  $K$  from Equation (1) and the gas flow pattern. By changing the operating and environmental conditions, CFD reported results for each condition, which can be employed for the knowledge base. In addition, the gas flow pattern results can also be employed to assess the ES's effectiveness. Details and concepts of using CFD are reported next.

## 2.2. CFD

The CFD is a computer simulation to solve fluid flow, fluid-fluid, fluid-solid, or fluid-gas interaction problems using a numerical method based on the Navier-Stokes equations. For example, related to ventilation and airflow [15–19], CFD was employed to determine the ventilation and successfully develop technology and architectural design techniques [15], investigated the airborne transmission for medical and healthcare purposes [16], studied O<sub>3</sub> gas flow through a mass of rice grain and simulated of the O<sub>3</sub> gas injection in a silo with rice grain to control *S. zeamais* [17], designed a novel ultrasonic cleaning tank for jewellery factories [18], and investigated gas flow and ablation of a supersonic rocket nozzle to enhance the performance in missions [19]. All the mentioned works [15–19] confirm that CFD can simulate fluid flow in complex environments and provide accurate simulation results consistent with actual situations; therefore, CFD suits this research.

To determine  $K$  and gas flow patterns in the silo, Ansys Fluent 2021R1, an industry-leading CFD simulation software, was employed. After completing the boundary condition setting, the software solves the species transport equations, in which the CFD results were analyzed in terms of  $K$  and gas flow pattern. Significantly, solving the species transport equation yields the gas concentrations, which is important in this research for monitoring the CAP and determining  $K$ . The species transport equations for an unsteady condition without a reaction are given by [20,21]

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho U Y_i) = -\nabla \cdot J_i + R_i + S_i \quad (2)$$

$$J_i = -\left(\rho D_{i,m} + \frac{\mu t}{Sc_t}\right) \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \quad (3)$$

where  $\rho$  is species' density,  $Y$  is species' mass fraction,  $U$  is the three-dimensional velocity components,  $T$  is temperature,  $J$  is species' diffusion flux,  $S$  is species' source term, and subscript  $i$  is species' species type  $i$ . In addition,  $D_{i,m}$  is the species' mass diffusion coefficient

in the mixture  $i$ ,  $D_{T,i}$  is the thermal (Soret) diffusion coefficient,  $\mu_t$  is the turbulent viscosity, and  $Sc_t$  is the turbulent Schmidt number.

The equations' complete forms of conservation and  $k$ - $\epsilon$  turbulence equations are reported in references [18,19,22], respectively. Importantly, the  $k$ - $\epsilon$  turbulence model was applied in this work since it is suitable for the gas flow behaviour in silos and provides reliable CFD results under limited computational resources.

### 2.3. Two-Positions Controller (TPC)

The TPC or ON/OFF controller is a simple controller. There are two operating conditions: fully opened or completely closed, depending on the controlled variable related to the set value [23]. For example, when the controlled variable increases above the set value, the TPC switches from "OFF" to "ON" states. In contrast, when the controlled variable drops below the set value, the TPC switches from "ON" to "OFF" states. Previously, the rice exporter employed the TPC for the CAP with  $O_2$  Min of 0.1% and  $O_2$  max of 1.0%, in which the TPC operational flowchart is presented in Figure 4.

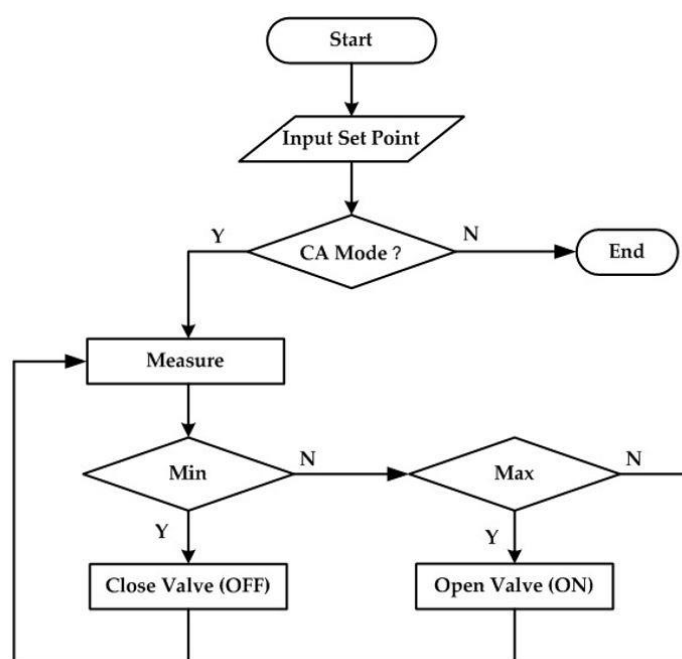


**Figure 4.** The two-position controller (TPC) operational flowchart.

This control does not fully consider data and resources in the actual system, and it is not good enough for controlling any process parameters where the system may change from equilibrium. Because it cannot automatically adjust the controlled values, it is not efficient enough for large storage silos with complex environments. In the case of CAP, poor control increases the risk of insect survival, decreasing the quality of the rice. From the authors' experience, the TPC can be developed more innovatively using the ES to increase the potential for superior control.

### 3. Methodology

As seen in Section 2.1, the ES consists of a user interface, inference engine, and knowledge base. The user interface and knowledge base have been successfully managed to be fully connected to the inference engine. Both are not novel; therefore, they are not presented here. In this research, the inference engine development based on CFD was focused on, briefly described below. Figure 5 shows the research methodology flowchart, consisting of CFD and ES development processes in yellow and blue boxes, respectively.

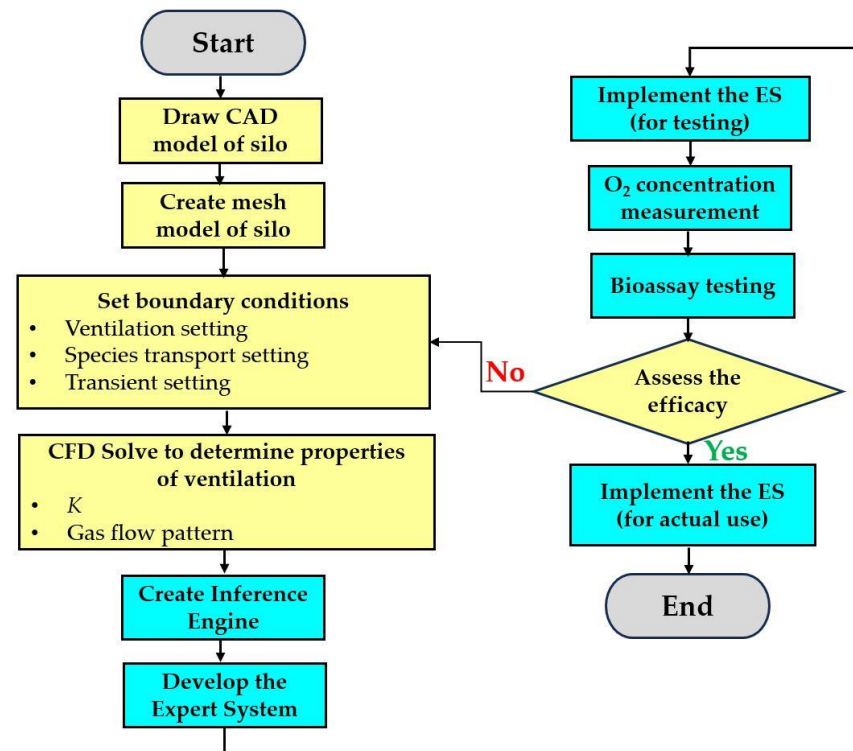


Figure 5. Research methodology flowchart.

### 3.1. CFD Process

#### 3.1.1. CAD Model

Figure 6 shows a CAD model of silos drawn and simplified from Figure 1 for (a) isometric view and (b) side view. A small picture on the left shows a  $2.0\text{ m} \times 2.0\text{ m}$  rectangle,  $\text{N}_2$ -released pipe of 0.1 diameter. In fact, this exporter has eight silos, as shown in Figure 1, and all silos have identical shapes and dimensions. Therefore, only one silo was chosen as a case study presented in this figure. It is a square indoor silo with a square cone base,  $5 \times 5 \times 17.95\text{ m}^3$  (about  $400\text{ m}^3$ ). The rice was stored until the silo was nearly full, leaving only 2.0 m of space from the silo cover. This storage contains about 265 tons of rice.

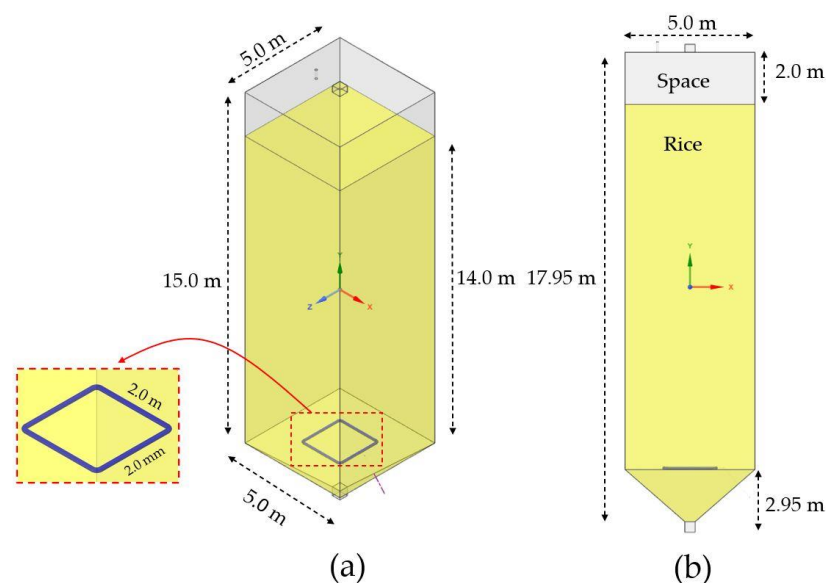


Figure 6. CAD model of the silo for (a) isometric view and (b) side view.

### 3.1.2. Mesh Model

Using the CAD model in Figure 6 as a prototype, since the silo has symmetry, the mesh model was created as a half model, shown in Figure 7: (a) isometric view and (b) side view. It consists of 417,296 nodes with 73,450 elements and is a polyhedron mesh type with sizing of 0.2–20 cm, created in Fluent meshing. The smallest mesh size is in the inlet and outlet. Fluent meshing with polyhedrons can increase the number of nodes and elements in some regions by automatically transforming element shapes and resizing in the model to automatically acquire accurate simulation results [24,25], which is more convenient and effective than mesh-independent analysis as employed in [18,19].

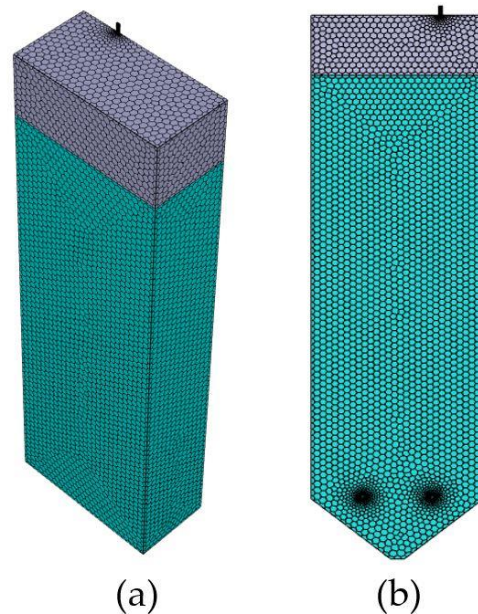


**Figure 7.** Mesh model: (a) isometric view and (b) side view.

### 3.1.3. Boundary Conditions

It consists of ventilation, species transport, and transient settings. All boundary condition settings were information from the knowledge base, as mentioned in Section 2.1, described below.

- Ventilation setting

Figure 8 presents the ventilation setting. The inlet was  $Qt/V$  with a temperature of 313 K at  $N_2$  released pipe, supplying  $N_2$  to the silo. Significantly, the inlet was a parameter that can be adjusted according to Equation (1) to determine  $K$ . The outlet was a pressure gauge of 0 Pa on the silo exhaust pipe presented in a small picture, releasing the gas mixture into the atmosphere. The porous zone was 0.4 porosity on the rice storage, where the gas mixture was between the rice space, causing airflow resistance. The  $N_2$  mass flow rate was  $50 \text{ m}^3/\text{h}$ ,  $V$  was  $153 \text{ m}^3$ ,  $t$  was a parameter depending on the CAP time, and  $k-\epsilon$  was the turbulence model with Scarable Wall Functions.

- Species transport setting

Figure 9 shows the species transport setting. All regions were assigned to the mixture materials: the gas mixture of  $O_2$  and  $N_2$ . The mixture material means the software will solve Equations (2) and (3) in these zones. The porous zone relates to air resistance due to the rice storage. The inlet pipe was also assigned a volume fraction with  $O_2$  of 0 and  $N_2$  of 1 since it was a  $N_2$ -released pipe. The gas properties used the default value from the software's engineering data.

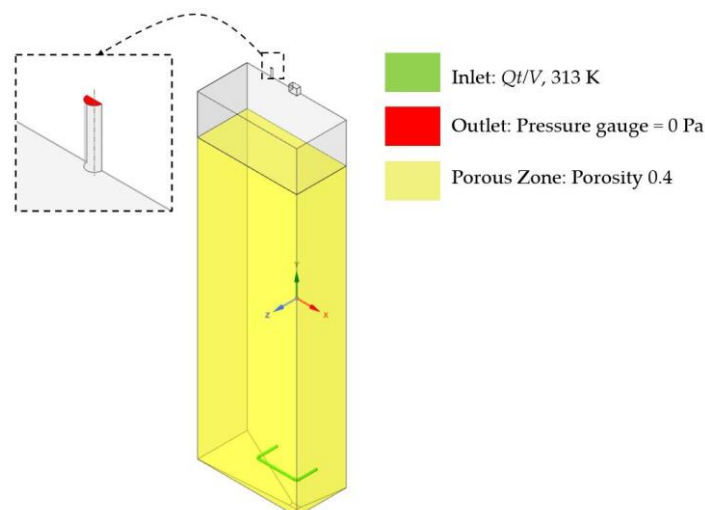


**Figure 8.** Ventilation setting.

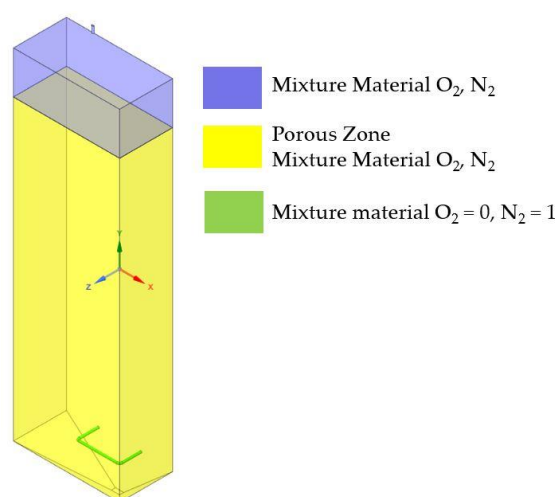


**Figure 9.** Species transport setting.

- Transient setting

The number of time steps was 720, and the time step size was 10 s with 25 iterations per time step. The continuity,  $k$ - $\epsilon$ ,  $O_2$ , and velocities residuals were 0.001, while the energy residual was  $10^{-6}$ . This setting revealed the results every ten seconds in two hours, from start to finish, providing accurate results for analysis.

After completing all the mentioned settings above, the software solved the CFD equations in Section 2.2 and then revealed the gas flow pattern, and  $K$  explained later in Section 4.1. Both results were employed to create an inference engine and develop the ES explained below.

### 3.2. ES Development Process

This section explains ES operation, including equipment employed in ES development and experiments to assess ES efficacy.

#### 3.2.1. ES Operation with Equipment

It begins with employing  $N_2$  gas ventilation and  $K$  results from CFD to create the inference engine, which is then installed in the ES, and some are used in the knowledge base. By ignoring unimportant equipment, Figure 10 shows the ES and equipment readily for actual use at the silo. The small pictures, for example, present some realistic images captured at the factory.

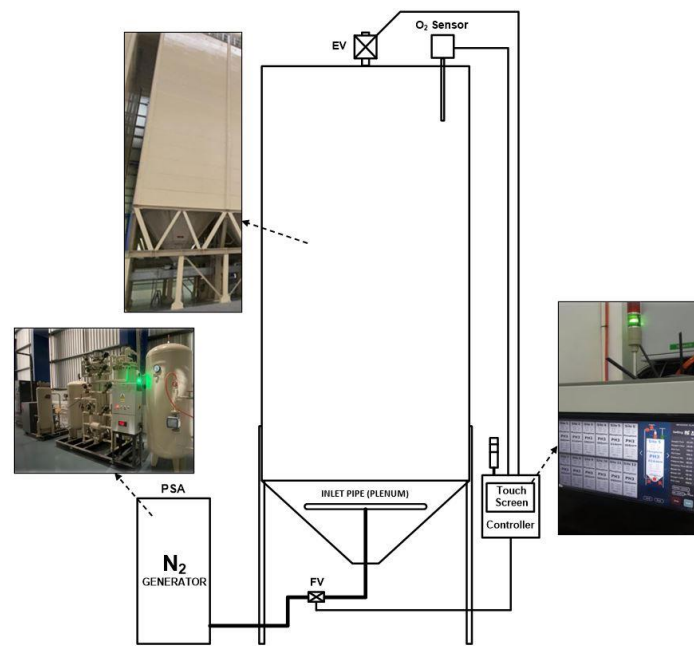


Figure 10. The ES and equipment.

Users can set the ES parameters and monitor  $O_2$  concentration via the touch screen. The sensor located on the top measures  $O_2$  concentration and reports results every 15 min on the touch screen, as presented in Figure 10. The  $N_2$  generator located on the floor produces  $N_2$  based on pressure swing adsorption (PSA) [26] with a purity of 99.999% and then supplies  $N_2$  into the silo via the inlet pipe (Plenum). The ES controls the  $O_2$  concentration by analyzing the results from the sensor and calculating  $t$  from the STP equation for opening the feeding valve (FV) and the exhaust valve (EV) or closing. Figure 11 shows the ES operational flowchart for the CAP. Significantly, the yellow box presents the CFD-assisted ES process, which is novel in this research and already explained in Section 2.1.2.

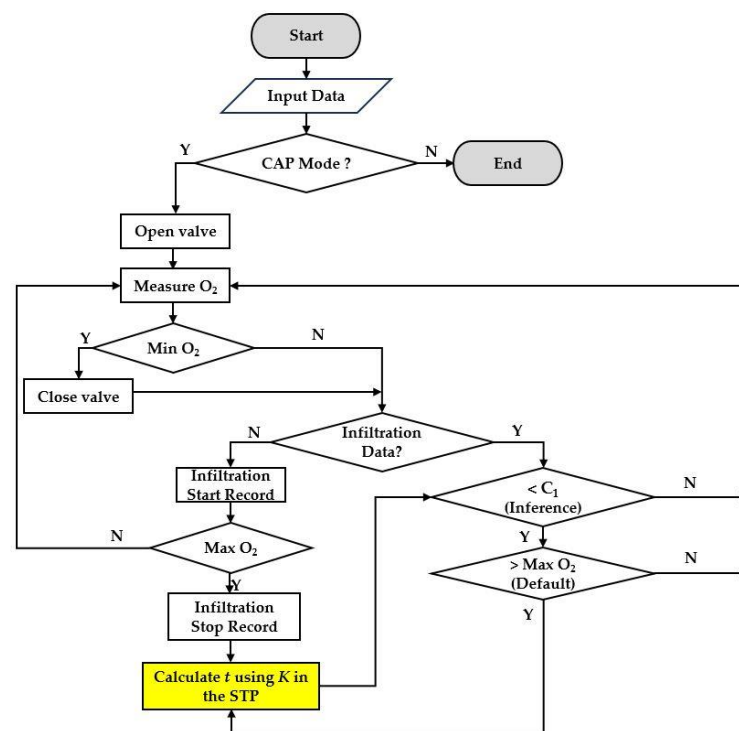


Figure 11. The ES operational flowchart.

### 3.2.2. Experiments

Two experiments were set to measure  $O_2$  concentration and assess the ES efficacy, briefly explained below.

- $O_2$  concentration measurement

The  $O_2$  concentration was measured by sampling at 1 m below the silo roof over the rice surface. The sensor specification includes a measurement range of 0–100%  $O_2$ , two decimal places, and a response time of less than 5 s. Accordingly, this sensor was set to report  $O_2$  concentration every 15 min on the touch screen for user monitoring and ES processing to control the values, as shown in Figures 10 and 11. This experiment measures  $O_2$  concentration before and after implementing the ES.

Figure 12 reports  $O_2$  concentration using the TPC before implementing the ES to CAP as an example of the results. The red line at 2%  $O_2$  concentration is the GRDC suggestion for killing insects, mentioned in 2.1.3, drawing to help analysis. Using the TPC, the  $O_2$  concentration fluctuated around 2%, meaning that insects may survive in the silo and also confirm that the TPC is not sufficient for the CAP, as expected.

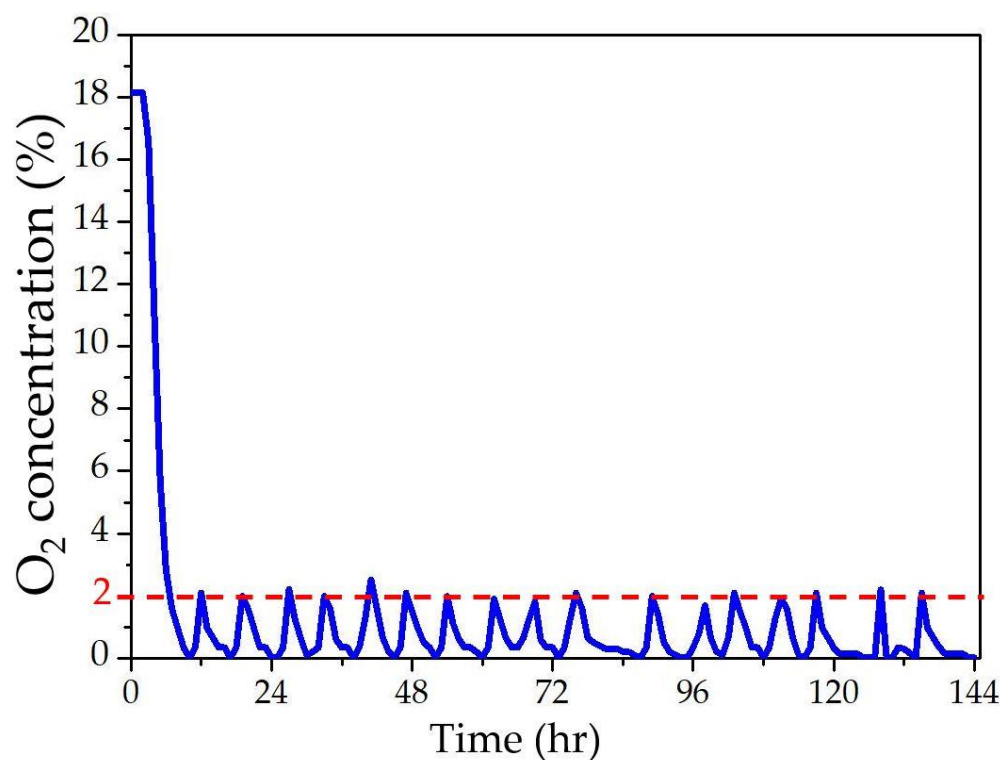


Figure 12.  $O_2$  concentration measurement before implementing the ES (using the TPC).

Similarly, this experiment measured  $O_2$  concentration after implementing the ES. The measurement results were recorded and shown on the touch screen for 21 days in a row to compare with the TPC, which will be reported and discussed in Section 4.

- Bioassay testing

The bioassay testing was set and explained according to the GRDC suggestion in Section 2.1.3. Four stages of Red Flour Beetles (*Tribolium castaneum*), including eggs (2 days old), larvae (14 days after eggs laying), pupae (21 days after egg laying), and adult (not more than two weeks old), were prepared and filled in bottles. Each bottle contains 100 beetles of each stage. A testing set combines egg, larvae, pupae, and adult bottles, a total of four bottles per testing set. Two testing sets were placed on the top, both left and right, of the silo. Similarly, eight bottles (two testing sets) were placed into the middle silo, and the other eight bottles in the bottom silo. The division into top, middle, bottom, left and right

locations is to distribute insect samples evenly in the silo. A total of 24 bottles are located inside the silo. All bottles contained sufficient food for samples alive in the silo for more than 21 days. Close the top cover and drill small ventilation holes to allow gas to pass in and out easily.

Red Flour Beetles were used as samples since their life cycle is 40 to 90 days, which makes them suitable for testing. The CAP begins by turning on the ES switch to release  $N_2$  into the silo to fumigant the rice. After that,  $O_2$  concentration was monitored to ensure it did not exceed 2% for 21 days. Finally, the ES was switched off. Took all bottles out of the silo and investigated the insect life using a microscope in a bioassay laboratory. Figure 13 shows the bioassay testing: (a) insect bottles and (b) bottle locations in the silo. In (a), samples of bottles contain 100 adult insects per bottle. In (b), the top, middle, and bottom levels are 3 m, 10 m, and 13 m from the silo cover, respectively, where the bottles were distributed evenly at the same level. The results after the microscope inspection are reported in Section 4.

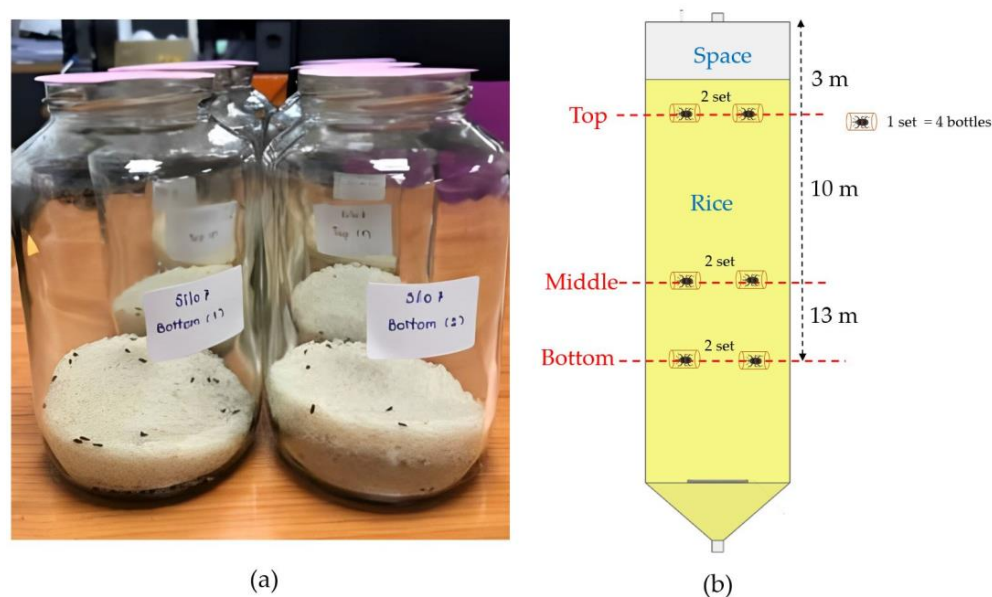


**Figure 13.** The bioassay testing: (a) insect bottles and (b) bottle locations in silo for testing.

#### 4. Results and Discussion

This section includes CFD-assisted ES, the ES efficacy developed, and suggestions, including future work. The first is to report CFD results with validation of  $K$  employed to assist the ES development, the next is to report the experiments to assess the ES efficacy, and the last is to suggest future work to improve the ES.

##### 4.1. CFD-Assisted ES

###### 4.1.1. Gas Flow Pattern and $O_2$ Concentration

Assuming that the silo starts with a 2%  $O_2$  concentration following the GRDC suggestion, from the ventilation setting in Figure 8, after 2 h of the CAP, CFD reveals the gas flow pattern shown in Figure 14. The silo has a central symmetry, which was divided into four zones, numbering 1–4, presenting 2D results in the middle plane of the silo to help with easy analysis. Note that rice was stored in zones 1, 2, and 3.

In Zone 1, central silo,  $N_2$  was released from the inlet pipe to the upper silo and purged  $O_2$  out of the silo via the exhaust pipe on the top, as expected. The purging is very good in this zone since the gas velocity is higher than in other zones, implying that  $O_2$  concentration in this zone reduces faster than in other locations.

In Zone 2, bottom silo, since the gas velocity is lower than in other zones, purging is the worst, implying that this zone requires the longest time to release  $N_2$  to control  $O_2$  concentration at below 2%.

In Zone 3, rim silo, since the gas velocity is moderate, lower than zone 1 but higher than zone 2, the purging is median.

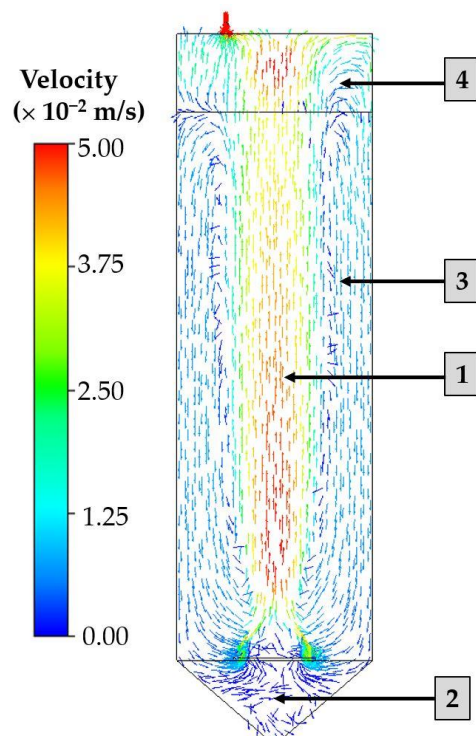


**Figure 14.** The gas flow pattern in the silo.

Look into Zone 4, the top silo above rice storage; the gas velocity is higher than in other zones since it is space below the roof without airflow resistance due to rice storage; therefore, the gas can flow freely in this zone, as expected.

Significantly, the maximum velocity of gas was about 0.05 m/s, consistent with the operators' measurement data, confirming the credibility of the CFD results. Additionally, Figure 14 implies the purging performance in the silo, depending on the zones. However, it does not indicate the  $O_2$  concentration critical to the CAP.

In chemistry, the mass fraction measures the concentration of component substances in a mixture substance, commonly measured in percentage (%), while the concentration measures how much of a given substance there is in a given mixture of substances. Both seem similar. Since CFD cannot report  $O_2$  concentration, the CFD  $O_2$  mass fraction ( $O_{2,mf}$ ) was reasonably reported and analyzed. Figure 15 presents the CAP's  $O_{2,mf}$  from 0 to 120 min (2 h). As expected,  $N_2$  was released from the inlet pipe, reducing  $O_{2,mf}$  from 2% at the start of 0 min to 1% at the end of 2 h. Compared this figure to Figure 14, the  $O_{2,mf}$  is the lowest in zone 1, moderate in zone 3, and the highest in zone 2, consistent with the gas flow pattern discussed previously. The  $O_{2,mf}$  is the highest in zone 2 since this zone is located below the inlet pipe, so  $N_2$  arrived the slowest. Accordingly, zone 2 needs more time for  $N_2$  purging to reduce the  $O_{2,mf}$  to the same level as other zones.

Since the  $O_{2,mf}$  is ununiform inside the silo; Figure 16 reports the  $O_{2,mf}$  volume average from 0 to 2 h, calculated using CFD. As expected, the  $O_{2,mf}$  volume average decreases with increasing time for the CAP. The reduction decreases rapidly for the first 5 min and slows down until the end. Importantly, the  $O_{2,mf}$  is lower than 2% every time, implying that  $O_2$  concentration is also less than 2% during this period in all zones; hence insects cannot survive in this fumigated silo atmosphere. The animation clip that helps analyze Figures 15 and 16 was attached in Supplementary Materials, named Additional-Figs15\_16.mp4.

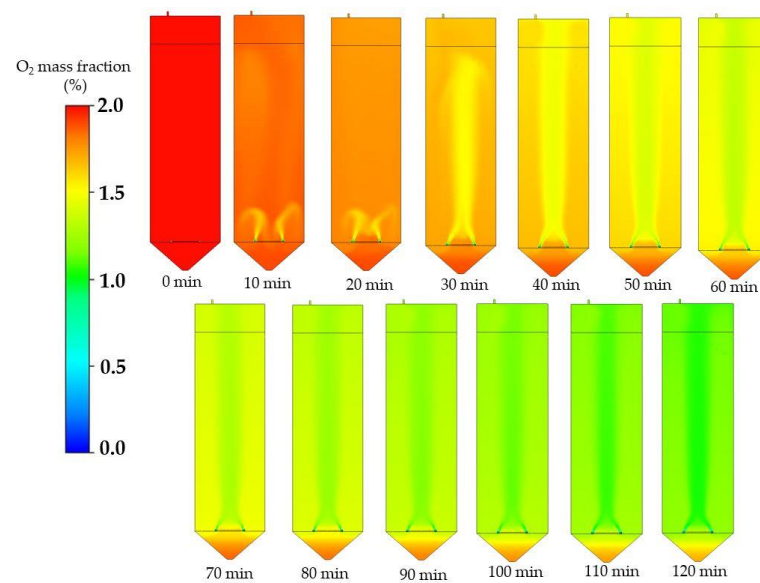


Figure 15. O<sub>2</sub> mass fraction inside the silo from 0 to 2 h.

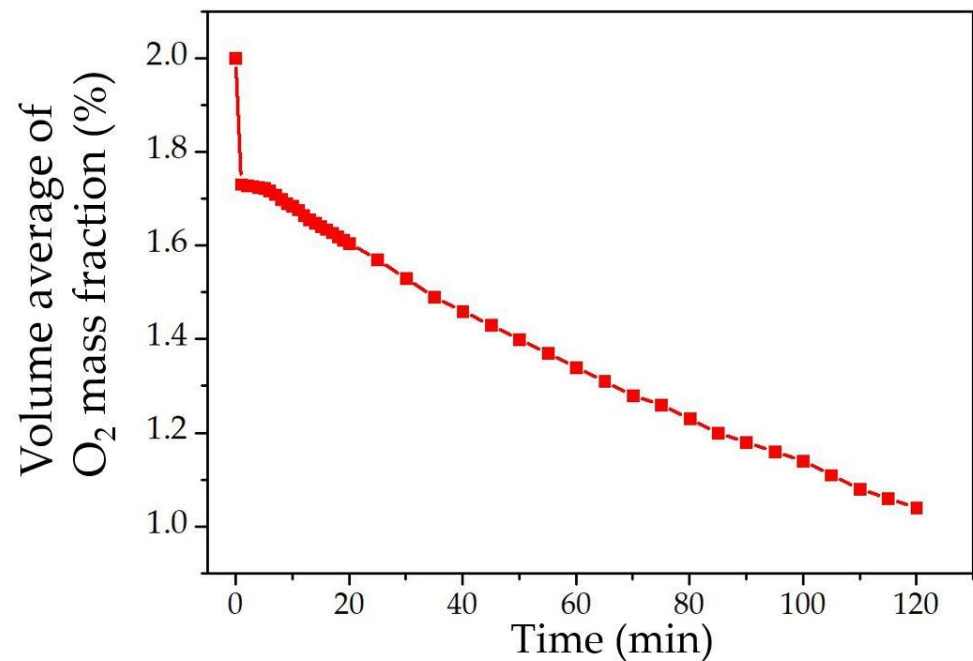


Figure 16. The volume average of O<sub>2</sub> mass fraction inside the silo from 0 to 2 h.

In sum, CFD results from Figures 15 and 16 reveal O<sub>2</sub> concentration and proper operating conditions for the CAP, consistent with the actual situation authors observed at the silo; therefore, CFD results and methodology employed in this research are reliable and can be applied to the knowledge base described in Figure 2 accordingly.

#### 4.1.2. Correction Factor $K$

As described in Section 2.1.2,  $K$ , a key parameter in the inference engine, is an unknown to be determined depending on the depth of rice storage, operating conditions, and environment. This section applied the CFD to determine  $K$ , as explained below.

Equation (1) of the STP has proved that  $K$  is a slope of a linear function between  $Qt/V$  plotted on the x-axis and  $\ln(C_1/C_2)$  plotted on the y-axis. Accordingly, using the CFD setting in Section 3.1.3 and varying  $Qt/V$  from 0 to 0.65,  $\ln(C_1/C_2)$  can be plotted in terms of O<sub>2,mf</sub> volume average at the initial and final times, which are reported in Figure 17. It

was found that  $\ln(C_1/C_2)$  is a linear function of  $Qt/V$ , as expected. The  $\ln(C_1/C_2)$  increases with increasing  $Qt/V$ . The slope  $K$  is 0.79 with a y-interception of 0.08. In theory, this graph should pass the origin without a y-intersection. The y-interception may come from CFD boundary condition settings in Section 3.1.3. For example, the porosity of 0.4 and  $Q$  of 50 m<sup>3</sup>/h are suggestion values, which were estimated by the operators who work daily with the silo. If the authors have the accurate value of porosity and  $Q$  supported by the experiment, the y-interception has vanished, increasing the credibility of CFD results. However, the y-intersection is too tiny with the coefficient of determination ( $R^2$ ) of 0.999, confirming that the line is linear as expected, obeying the theory. Comparing this  $K$  of 0.79 calculated using CFD with some  $K$  in Table 1, the  $K$  in this research is much higher than in Table 1 because of the air resistance from rice storage in silo, as expected.

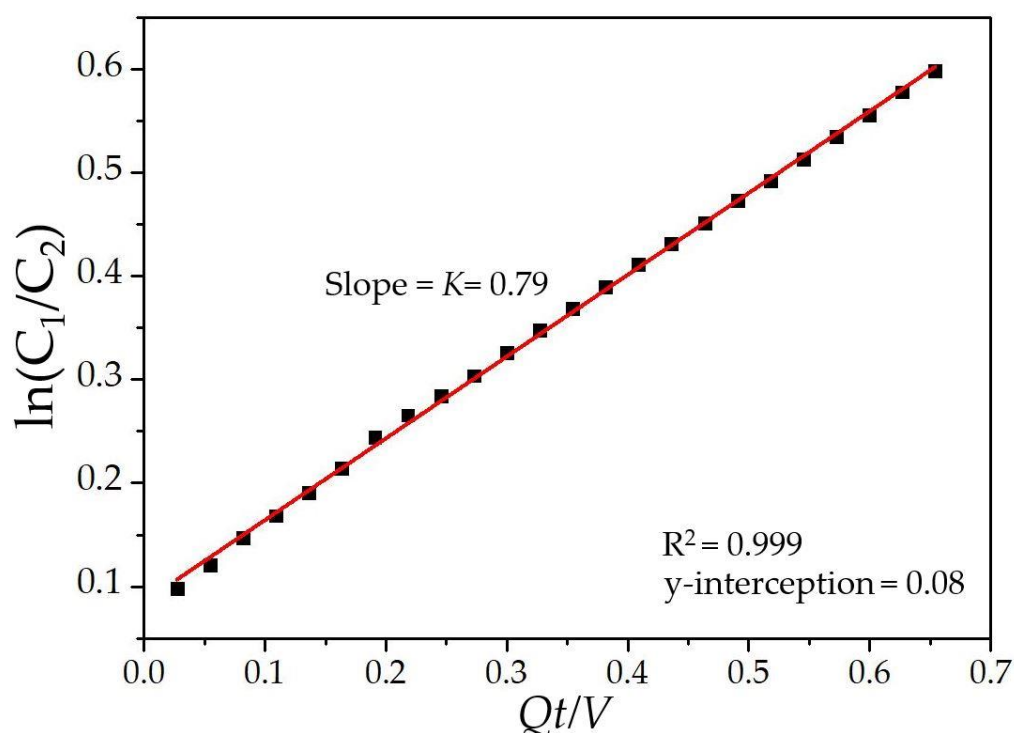


**Figure 17.** The relationship between  $Qt/V$  and  $\ln(C_1/C_2)$  using CFD.

Consequently,  $K$  calculated using CFD is 0.79, was employed with the STP to find  $t$  in Figure 11, creating the inference engine, as mentioned in Figure 2.

#### 4.2. ES Efficacy

The CFD results reported in Section 4.1 were employed to develop the ES. After finishing the development, the ES was implemented in the silo and assessed the usage efficacy by the O<sub>2</sub> measurement and bioassay testing mentioned in Section 3.2.2, reported below.

##### 4.2.1. O<sub>2</sub> Concentration Measurement

Figure 18 reports the O<sub>2</sub> concentration measurement versus the time of the CAP after implementing the ES, from the 1st to the 6th day. In the beginning, the O<sub>2</sub> concentration inside the silo was 18.5%, which is almost equal to the O<sub>2</sub> concentration in a typical environment. Then, the CAP's ES released N<sub>2</sub> to the silo, reducing O<sub>2</sub> concentration to lower than 2% within 7 h. N<sub>2</sub> continued to be released, reducing O<sub>2</sub> concentration to 0.02% after passing 14 h. Next, the O<sub>2</sub> concentration increased to 2.21% in 19 h, over the requirement. The increase may be due to the silo having small openings or leak holes, allowing O<sub>2</sub> from the outside to percolate into the inside. After that, the FV controlled by the ES was automatically opened, and N<sub>2</sub> was fed into the silo, reducing O<sub>2</sub> concentration to 0.02% again in 30 h. At this time, the ES closed the FV and stopped feeding N<sub>2</sub>, so the O<sub>2</sub>

concentration was stable at 0.02%. However, because of the small opening and leak holes, the O<sub>2</sub> concentration increased again after 38 h to 43 h with about 1.67% O<sub>2</sub> concentration. Simultaneously, the ES operated again to control O<sub>2</sub>, not to exceed 2%; therefore, the feeding N<sub>2</sub> reduced O<sub>2</sub> concentration to 0.02%, which was in the GRDC suggestion. Last, after 48 h, two days after starting the CAP, O<sub>2</sub> concentration slightly fluctuated, not over 0.05%, because the ES operated at all times.

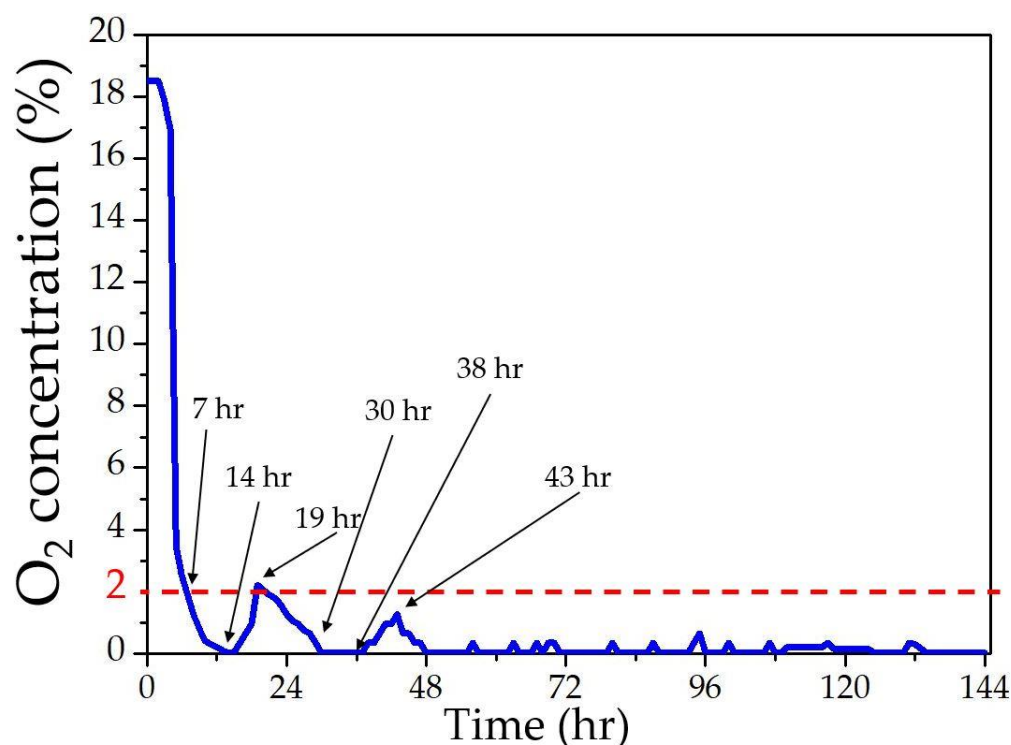


**Figure 18.** The O<sub>2</sub> concentration measurement after implementing the ES.

By comparing Figure 18 with Figure 12, it can be noticed that the ES can control O<sub>2</sub> concentration better than the TPC since the ES is more complex than the TPC, presented in the operational flowchart Figures 4 and 11. Significantly, after implementing the ES after 19 h of the CAP, O<sub>2</sub> concentration was never over 2% as intended. In contrast, O<sub>2</sub> concentration was frequently over 2% using the TPC, which was insufficient for killing insects. Therefore, the ES helps increase the CAP efficacy in controlling O<sub>2</sub> concentration as expected.

#### 4.2.2. Bioassay Testing

After passing 21 days of the CAP controlled by ES, Red Flour Beetles, as insect samples mentioned in Section 3.2.2, were investigated. More specifically, the amount of dead and alive beetles was observed using a microscope and approximately counted with the naked eye. Table 2 reports the bioassay testing results in the number of insects: dead, alive, and the percentage of dead. Note that the total number of insects for each silo location level: top, middle, and bottom, is 800 from eight bottles (marked in the bracket with an asterisk); therefore, the total number of dead insects for each column should not exceed 800 beetles, but the table shows otherwise. The reason behind this difference can be explained as follows. The insect grew up from eggs to larvae, pupae to adults, etc. Some insects may relocate positions within the silo. In addition, some insects already living in the rice in the silo joined the samples and increased the number of insects in the testing since the silo is actually rice storage.

**Table 2.** Bioassay testing results.

| Stage         | Top  |       |       | Middle |       |       | Bottom |       |       |
|---------------|------|-------|-------|--------|-------|-------|--------|-------|-------|
|               | Dead | Alive | %Dead | Dead   | Alive | %Dead | Dead   | Alive | %Dead |
| Egg (200)     | N/A  | N/A   | N/A   | N/A    | N/A   | N/A   | N/A    | N/A   | N/A   |
| Larvae (200)  | 203  | 0     | 100   | 160    | 0     | 100   | 149    | 0     | 100   |
| Pupae (200)   | 433  | 0     | 100   | 385    | 0     | 100   | 76     | 0     | 100   |
| Adult (200)   | 355  | 0     | 100   | 402    | 0     | 100   | 323    | 0     | 100   |
| Total (800 *) | 991  | 0     | 100   | 947    | 0     | 100   | 548    | 0     | 100   |

\* The sum of the number in the above brackets.

Taking into account Figures 13 and 15, and Table 2, it can be concluded that the lowest number of dead insects were observed in the bottom of the silo because this position is near the inlet pipe and has the lowest O<sub>2</sub> concentration. Consequently, the insects might find it hard to live at the bottom, so they fled to the middle and top, where the O<sub>2</sub> concentration was higher, to survive. Last, they died in that positions, increasing the number of dead insects in the middle and top of the silo.

Significantly, the egg results are not applicable (N/A) because they grew to the elder stage: larva, pupae, or adults. However, whether the focus is on live or dead insects, the increase in their number is negligible. Figure 19 shows examples of (a) larvae, (b) pupae, and (c) adults, which are dead because of the CAP, investigated by the microscope. Note that no picture of eggs is shown here as they grew up to the elder stages, and (a)–(c) are not on the same scale of microscope magnification.

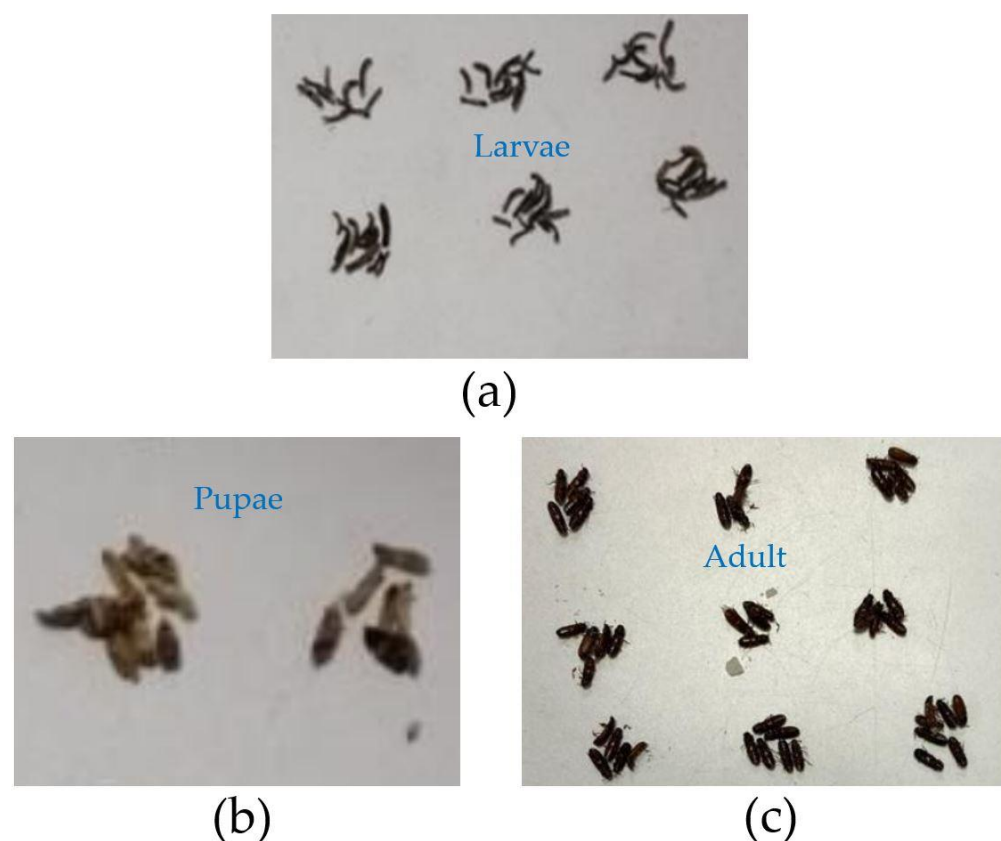


**Figure 19.** Red Flour Beetles in stages: (a) larvae, (b) pupae, and (c) adult, dead after 21 days of the CAP, pictured by the microscope.

By comparing the results for the two applied methods, TPC and ES, it can be concluded that the ES method helps the exporter save time and money, obtain high-quality rice, and thus achieve a higher price. Indeed, the ES had excellent feedback from the operators since N<sub>2</sub> is approximately 78% of the air in the atmosphere; even leaking out of the silo into the

factory is not harmful to all operators, environmentally friendly. When analyzing feedback and results from Section 4.2, the authors concluded that the ES assisted using CFD had excellent efficacy for the CAP.

#### 4.3. Suggestions and Future Work

Figures 14 and 15 show that the CAP efficacy is low in zone 2; therefore, the new inlet pipe design with proper operating conditions is a solution. For example, the inlet pipe can be designed to be with a larger outer surface. This method helps  $N_2$  distribute into the silo quickly on a broader volume, enhancing the CAP efficacy in zone 2. Fortunately, CFD is also a proper tool to succeed in this method.

Since the ES was developed based on the model shown in Figure 6, it has limitations in actual use. For example, when the amount of rice is much lower than in this model, the CAP efficacy drops. Consequently, the operators try to make the amount of rice similar to the employed model to make the CAP consistently highly efficacious. An alternative solution is to upgrade the CAP with a digital twin [27,28]. By varying the amount of rice and operating conditions defined in the model, CFD results will be applied with data management and data analytics, real-time monitoring, and managing in the digital twin to increase the CAP efficiency. These two methods are the authors' intended future work.

Additionally, the ES developed in this research helps to protect rice from insects in an environmentally friendly way with a highly innovative solution consistent with Sustainable Development Goals (SDGs) in Goal 9: industry, innovation, and infrastructure, including Goal 12: responsible consumption and production [29,30].

### 5. Conclusions

To kill insects in organic rice storage silos waiting for exporting abroad, the ES was developed for the CAP following the GRDC suggestion. This suggestion controls CAP with an  $O_2$  concentration of less than 2% for 21 days. In the CAP,  $N_2$  was supplied into the silo, reducing  $O_2$  concentration until  $O_2$  was less than 2%. Previously, the rice owner used TPC for the CAP, leading to low efficacy CAP. The key to success in high-efficacy CAP is employing CFD to create the knowledge base and inference engine, both ES parts. First, CFD was employed to determine the gas ventilation properties,  $O_2$  concentration, and  $K$  under the actual operating conditions of CAP. CFD results revealed uneven gas flow, implying that the CAP efficacy for the rice storage was the best at the central, moderate at the rim, and the worst at the bottom silo zones. Then, using the STP principle and CFD,  $K$  was 0.79 calculated from the linear function between  $Qt/V$  and  $\ln(C_1/C_2)$ , consistent with the theory, as expected. In addition, CFD results also indicated that  $K$  depends on the CAP operating conditions and environment, as also expected. Next, the CFD gas flow pattern and  $K$  results were employed to create the knowledge base and inference engine, developing the ES. Last, after the ES and CAP were implemented in the silo, the experimental results confirmed that the ES was more effective and practical than the TPC since it can control  $O_2$  concentration in the CAP and can kill 100% of all Red Flour Beetles samples within 21 days. The ES helps save time and cost by increasing the CAP efficacy and receiving excellent feedback from the rice exporter. The novel of this research is a CFD methodology to assist the ES presented step-by-step, from the start to the end, in this article.

### 6. Patents

The Thailand parent application number 2101002275, an expert system for controlling the atmosphere in agricultural product storage areas to eliminate pests and maintain quality, is an outcome of this research.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su16052187/s1>, The animation clip used to support the discussions in Figures 13 and 14 is included in the Supplementary Materials.

**Author Contributions:** Conceptualization, P.A. and J.T.; methodology, P.A. and J.T.; software, P.A., C.S. and J.T.; validation, P.A., C.S. and J.T.; formal analysis, J.T.; investigation, J.T.; resources, P.A. and J.T.; data curation, P.A. and C.S.; writing—original draft preparation, J.T.; writing—review and editing, P.A., J.T., L.L. and S.S.; visualization, P.A., C.S. and J.T.; supervision, J.T.; project administration, J.T.; funding acquisition, J.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the College of Advanced Manufacturing Innovation, King Mongkut's Institute of Technology Ladkrabang, grant number 2566-02-10-003.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Acknowledgments:** The financial support mentioned in the Funding part is gratefully acknowledged.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Nomenclature

|            |                                                           |
|------------|-----------------------------------------------------------|
| ASABE      | American Society of Agricultural and Biological Engineers |
| CAP        | control atmosphere process                                |
| CFD        | computational fluid dynamics                              |
| $K$        | correction factor                                         |
| $C_2$      | oxygen final concentration                                |
| $C_1$      | oxygen initial concentration                              |
| $O_{2,mf}$ | oxygen mass fraction                                      |
| ES         | expert system                                             |
| EV         | exhaust value                                             |
| FV         | feeding value                                             |
| GRDC       | Grain Research and Development Cooperation                |
| $V$        | silo volume                                               |
| STP        | sweep through purging                                     |
| $t$        | time                                                      |
| TPC        | two-positions controller                                  |
| UI         | user interface                                            |
| $Q$        | volumetric flow rate                                      |

## References

1. Business/Industry Trends 2023–2025: Rice Industry by Chaiwat Sowcharoensuk. Available online: <https://www.krungsri.com/th/research/industry/industry-outlook/agriculture/rice/io/io-rice-2023-2025> (accessed on 8 December 2023). (In Thai).
2. The Montreal Protocol on Substances that Deplete the Ozone Layer. Available online: <https://ozone.unep.org/treaties/montreal-protocol/montreal-protocol-substances-deplete-ozone-layer> (accessed on 9 December 2023).
3. Sakka, M.K.; Gatzali, F.; Karathanos, V.T.; Athanassiou, C.G. Effect of Nitrogen on Phosphine-Susceptible and-Resistant Population of Store Product Insects. *Insects* **2020**, *11*, 885. [CrossRef] [PubMed]
4. Navarro, S.; Athanassiou, C.G.; Varnava, A.; Vroom, N.; Yiassoumis, D.; Leandrou, I.; Hadjioannou, S. Control of stored grain insects using nitrogen in large concrete silos in Cyprus. In Proceedings of the 9th International Conference of Controlled Atmospheres and Fumigation in Stored Products, Antalya, Turkey, 15–19 October 2012; pp. 478–487.
5. Sadeghi, G.R.; Pourmirza, A.A.; Safarralizade, M.H. Effect of Nitrogen and Phosphine mixture on Stored Product Insects' Mortality. *Afr. J. Biotechnol.* **2011**, *10*, 6133–6144.
6. Navarro, S. The use of modified and controlled atmosphere for the disinfestation of stored products. *J. Pest Sci.* **2008**, *81*, 301–322. [CrossRef]
7. GRDC Grownotes. Available online: [https://grdc.com.au/\\_data/assets/pdf\\_file/0022/429502/GRDC-GS-GrowNotes\\_1.6.20-PDF\\_for-GRDC-approval-website-version.pdf](https://grdc.com.au/_data/assets/pdf_file/0022/429502/GRDC-GS-GrowNotes_1.6.20-PDF_for-GRDC-approval-website-version.pdf) (accessed on 8 December 2023).
8. Carpaneto, B.; Bartosik, R.; Cardoso, L.; Manetti, P. Pest Control treatments with phosphine and controlled atmospheres in silo bags with different airtightness conditions. *J. Stored Prod. Res.* **2016**, *69*, 143–151. [CrossRef]
9. Trematerra, P. Aspects Related to Decision Support tools and Intergrated Pest Management in Food Chains. *Food Control.* **2013**, *34*, 733–742. [CrossRef]
10. Jing, Z. Application and Study of Expert PID Intelligent Control. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *563*, 042084. [CrossRef]

11. Tan, C.F.; Wahidin, L.S.; Khalil, S.N.; Tamaldin, N.; Hu, J.; Rauterberg, G.W.M. The Application of Expert System: A Review of Research and Applications. *ARPN J. Eng. Appl. Sci.* **2016**, *11*, 2448–2453.
12. Kinsley, G.R. Properly purge and inert storage vessels. *Chem. Eng. Prog.* **2001**, *12*, 57–61.
13. National Fire Prevention Association. *Standard on Explosion Prevention Systems*; National Fire Prevention Association: Quincy, MA, USA, 1997.
14. American Society of Agricultural and Biological Engineers (ASABE). *Resistance of Airflow of Grains, Seeds, Other Agricultural Products, and Perforated Metal Sheets*; American Society of Agricultural and Biological Engineers (ASABE): St. Joseph, MI, USA, 1996.
15. Cuce, E.; Sher, F.; Sadiq, H.; Cuce, P.M.; Gucle, T.; Besir, A.B. Sustainable Ventilation Strategies in Building: CFD Research. *Sustain. Energy Technol. Assess.* **2019**, *36*, 100540. [\[CrossRef\]](#)
16. Tsang, T.W.; Mui, K.W.; Wong, L.T. Computational Fluid Dynamics (CFD) Studies on Airborne Transmission in Hospital: A Review on the Research Approaches and the Challenges. *J. Build. Eng.* **2023**, *63*, 105533. [\[CrossRef\]](#)
17. Silva, M.V.A.; Farono, L.R.A.; Martins, M.A.; Sousa, A.H.; Bustos-Vanegas, J.D. CFD Simulation of ozone gas flow for controlling *Sitophilus Zeamais* in Rice Grains. *J. Stored Prod. Res.* **2020**, *88*, 101675. [\[CrossRef\]](#)
18. Tangsopa, W.; Thongsri, J. A Novel Ultrasonic Cleaning Tank Developed by Harmonic Response Analysis and Computational Fluid Dynamics. *Metals* **2020**, *10*, 335. [\[CrossRef\]](#)
19. Thongsri, J.; Srathonghuam, K.; Boonpan, A. Gas Flow and Ablation of 122 mm Supersonic Rocket Nozzle Investigated by Conjugate Heat Transfer Analysis. *Processes* **2022**, *10*, 1823. [\[CrossRef\]](#)
20. Ansys Inc. Chapter 7 Species Transport and Finite-Rate Chemistry. In *Ansys Fluent 17.1, User's Guide*; Ansys Inc.: Canonsburg, PA, USA, 2016.
21. Welahettige, P.; Vaagsaether, K. Comparison of OpenFoam and ANSYS Fluent. In Proceedings of the 9th EUROSIM & the 57th SIMS, Oulu, Finland, 12–16 September 2016. [\[CrossRef\]](#)
22. Ansys Inc. Chapter 4 Turbulence. In *Ansys Fluent 17.1, User's Guide*; Ansys Inc.: Canonsburg, PA, USA, 2016.
23. Stanbury, P.F.; Whitaker, A.; Hall, S.J. Chapter 8—Instrumentation and Control. *Principle Ferment. Technol.* **2017**, *3*, 487–536. [\[CrossRef\]](#)
24. Thongsri, J.; Tangsopa, W.; Kaewbumrung, M.; Phanak, M.; Busayaporn, W. Derosion Lattice Performance and Optimization in Solving and End Effect Assessed by CFD: A Case Study in Thailand's Beach. *Water* **2022**, *14*, 1358. [\[CrossRef\]](#)
25. Chaparro, D. A Comparison of ANSYS Fluent Meshing and Ansys Meshing for CFD. Available online: <https://www.padtinc.com/2021/05/11/comparison-ansys-fluent-meshing-ansys-meshing-cfd/> (accessed on 13 February 2024).
26. Sircar, S. Pressure Swing Adsorption. *Ind. Eng. Chem. Res.* **2002**, *41*, 1389–1392. [\[CrossRef\]](#)
27. Botín-Sanabria, D.M.; Mihaita, A.-S.; Peimbert-García, R.E.; Ramírez-Moreno, M.A.; Ramírez-Mendoza, R.A.; Lozoya-Santos, J.d.J. Digital Twin Technology Challenges and Applications: A Comprehensive Review. *Remote Sens.* **2022**, *14*, 1335. [\[CrossRef\]](#)
28. Liu, M.; Fang, S.; Dong, H.; Xu, C. Review of Digital Twin about Concepts, Technologies, and Industrial Applications. *J. Manuf. Syst.* **2021**, *58*, 346–361. [\[CrossRef\]](#)
29. United Nations Development Programme. What Are the Sustainable Development Goals. Available online: <https://www.undp.org/sustainable-development-goals> (accessed on 8 February 2024).
30. Cordova, M.F.; Celone, A. SDGs and Innovation in the Business Context Literature Review. *Sustainability* **2019**, *11*, 7043. [\[CrossRef\]](#)

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.