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Development of automated fumigation chamber for treatment of grapes with SO_2 and CO_2

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Abstract

The export of grapes from one country to another is dependent on the grape's quality that should pass the strict phytosanitary requirements of the importing country. There is a requirement of fumigation of grapes with CO_2 and SO_2 at specified concentrations for a certain period besides the other pack-house protocols and export standards. This study was focused to develop and establish an electronically controlled model fumigation chamber for the treatment of grapes in the grapes-producing region. The gas injection and evacuation systems are electronically operated, and the fumigant concentration can be varied according to the requirement. Heaters of 2 kW are fitted inside the chamber to maintain the treatment temperature above 16°C for grapes fumigation. The fumigation chamber was found leak-proof during pressurized helium leak testing. The CO_2 and SO_2 gas concentrations can be maintained between 600 and 60,000 ± 100 ppmv and 10 and 10,000 ± 2 ppmv, respectively, for 1–90 min (1% is equivalent to 10,000 ppmv). The fumigation of grapes with 6% CO_2 for 30 min followed by fumigation with 1% SO_2 for 30 min ensured 100% mortality of the adult fruit fly (*Drosophilla melanogaster*). This chamber may also be used for the fumigation treatment of other fruits, vegetables, nuts, and so on, as per the time and concentration of gases required for the 100% mortality of target pest. Nevertheless, the protocol for such treatments should be developed for other fruits, and the effect of the gases on the quality of the products should be studied.

Practical Applications

The developed automated fumigation chamber for treatment of grapes with CO_2 and SO_2 is an effective measure for disinfesting the grapes from invasive pests like *Drosophilla suzukii*, spiders, and so on. This would help in overcoming phytosanitary measures put in place by many grapes importing countries like New Zealand, Australia, and so on. These countries offer huge market potential for export of Indian grapes, and if the trade barriers are overcome, it would lead to earning huge foreign exchange. Furthermore, the developed automated fumigation chamber can be used as an integral part of horticultural pack houses both for domestic as well as international trade as it would eliminate most of the adult field pests at preliminary stages before pack-house operation.

1 | INTRODUCTION

Invasion of insects, pests, and pathogens results in severe quantitative losses, and if not managed, the quality of the food products deteriorates to a considerable extent (Jha, Vishwakarma, Ahmad, Rai, & Dixit, 2015). The introduction of invasive unknown pests into a country resulted in severe damage to the plants and ecosystem in the past (Schrader & Unger, 2003). Therefore, the efforts were made in the past to develop measures and protocols against invasive insects. In this context, International Plant Protection Convention (IPPC) is the umbrella for phytosanitary activities worldwide and defined regulated articles as "any plant, plant product, storage place, packaging, conveyance, container, soil and any other organism, object or material capable of harboring or spreading pests deemed to require phytosanitary measures, particularly where international transportation is involved" (IPCC, 1997). Commonly found insects/pests in a country are not regulated, and their presence is permitted to a certain level. However, quarantine pests are alien-invasive species as they are unknown to a specified region and threaten ecosystems, habitats, or species (Schrader & Unger, 2003). These include direct pests (pathogens, parasites, herbivores) of plants and their products, indirect pests (invasive plants such as weeds), and other organisms affecting plants.

India exports grapes to many countries; however, New Zealand and Australia are not importing grapes from India because of their specific phytosanitary requirements. *Drosophila suzukii* has been considered as an invasive insect in these countries, and reports indicated their presence in the temperate region of India viz. Uttarakhand, Jammu & Kashmir, and Karnataka (Australian Government, DAFFB, 2013). However, no record is available regarding its presence in other major grape-growing regions of India. Nevertheless, quarantine pests must be eradicated prior to the export of grapes as per the requirement of importing countries, and fumigation is one of the most effective methods to eliminate *D. suzukii*.

Fumigation is one of the most effective ways of quarantine pest management for any fruits and vegetables. Several fumigants are used to kill the target pests, such as methyl bromide, phosphine, SO_2, and so on. SO_2 is widely used as a fumigating agent for table grapes to prevent decay during storage by either initial fumigation of fruit from the field followed by weekly fumigation of storage rooms or slow release in package pads containing sodium metabisulfite (Palou, Serrano, Martinez-Romero, & Valero, 2010). Cantín et al. (2012) observed that SO_2 fumigation followed by controlled atmosphere storage is a promising strategy for fresh blueberries to reduce decay, extend shelf life, and maintain high nutritional value. Rivera, Zoffoli, and Latorre (2013) reported that SO_2 is an effective and practical technique for reducing the risk of blueberry gray mold decay during storage and could be used for the export market. Gray mold and botrytis rot are reported to be controlled by fumigation with SO_2 and CO_2 in table grape (E. Mitcham & Leesch, 2004). Pretel, Martinez-Madrid, Martinez, Carreno, and Romojaro (2006) reported that a slightly CO_2 enriched atmosphere along with SO_2 fumigation can extend the storage life of late-harvested "Aledo" table grapes without relatively affecting its quality.

Liu (2019) reported that SO_2 treatment of table grapes obtained 100% mortality of eggs and nymphs/adults of vine mealybug. Fumigation with 1% SO_2 combined with 6% CO_2 at 19.5°C is used to control the black widow spiders on table grapes (E. Mitcham et al., 2005). However, in an earlier study, 30-min fumigations with 2500, 5000, and 7500 ppmv SO_2 at 20°C resulted in 18, 73, and 100% mortalities of grape mealybug crawlers (E. J. Mitcham & Zhou, 1998), indicating that SO_2 has the potential to be used as a fumigant for pest control. USDA (2020) provided a protocol supporting a combination treatment of SO_2/CO_2 fumigation followed by a cold disinfestation treatment as a measure to manage *D. suzukii* in the fresh table grapes.

Thus, various other risk management measures may be suitable to manage the risk of *D. suzukii* in the pathways associated with the import of host fruit into New Zealand and Australia; however, a combination treatment of CO_2 (6%) and SO_2 (1%) fumigation at a pulp temperature of 15.6°C or greater followed by 6 days cold disinfestation treatment at a pulp temperature of -0.5 ± 0.5°C is found to be the most promising and recommended methods in fresh table grapes (Australian Government, DAFFB, 2013; USDA, 2020; Walse & Bellamy, 2012).

Doses of fumigant, duration of treatment, environmental conditions for fumigation, and effect of fumigant on quality and safety of the product are widely studied and standardized. However, the commercial application of such fumigation treatment requires a complete fumigation system to conduct safe fumigation operation according to the standard procedures. Although many fumigation systems are used for the treatment of fruits and vegetables, gas-tight fumigation chambers, efficient circulation and exhaust of fumigants, a dispensing system for the fumigant, refrigeration or heating system, safe, practical operation of the fumigation facility, and so on are the basic features for the design and construction of such fumigation systems (USDA, 2020). However, in the present context, automated operation of the fumigation facility along with sensor-based measurements of fumigant doses and operation controls is essential while using hazardous gases like SO_2.

In fact, CO_2/SO_2 fumigation facility for the treatment of fruits and vegetables is not available in India. Therefore, the present study was taken up to develop an automated and electronically controlled model fumigation chamber for the treatment of grapes to cater the surmounting phytosanitary requirements and gain access to the new export markets for Indian grape farmers.

2 | MATERIALS AND METHODS

2.1 | Design criteria and materials

The fumigation chamber and its operation were conceived in a complete gas-tight chamber, automated injection of the desired dose of fumigant gases, uniform and rapid distribution of gases, treatment at controlled temperature, monitoring and controlling the fumigation dose during the treatment period, quick evacuation of fumigant gases to safe limits, and safe disposal of fumigants. Due to the higher

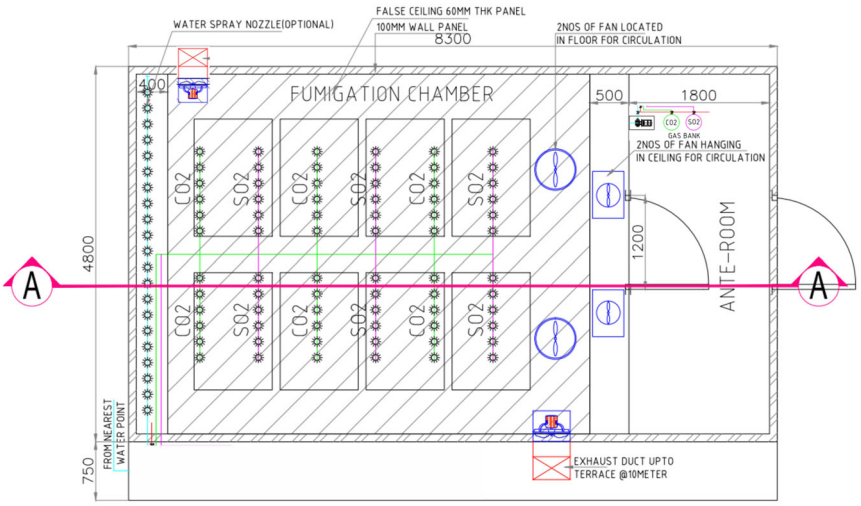

FIGURE 1 Top view of fumigation chamber

toxicity of SO_2 gas, all the fumigation operations were controlled electronically. The treatment durations were specified for grapes, and batch treatment operation was envisaged to ensure safety and effective fumigation.

Masonry/brick wall and concrete roof with concrete floor may be the most suitable material for the construction of a gas-tight fumigation chamber; however, in the present study, polyurethane foam-filled (PUF) panels with pre-painted MS sheets were selected for the construction of the chamber because of its smaller size of 8300 mm × 4800 mm × 3300 mm (1500 kg grapes per batch). In higher capacity chambers, longer PUF walls may buckle due to gaseous pressure (1.07 atm) upon injection of fumigants, and hence reinforcement may be required.

The chamber was divided into two sections, namely fumigation chamber and ante-room. The fumigation chamber was closed from all sides and connected with the ante-room through an electronically controlled door (Figure 1). Another door was provided in the ante-room that opens outside. Both the doors envisaged to operate through a control panel mounted outside of the chamber. The main purpose of the ante-room was to place the gas cylinders, control the gas flow, and stop the gas flow immediately and safely in emergency situations, which might not be possible if the gas cylinders were placed in the fumigation chamber.

For injection of gases inside the fumigation chamber, the perforated gas pipes were mounted at 600 mm below the roof, and separate pipes were installed for each gas. The gas flow was controlled using gas regulators, and flow was controlled through electronically controlled solenoid valves. The gases were circulated inside the camber using three high-velocity blast fans mounted on a separate false sealing inside the camber.

The fresh air entry port along with an electronically actuated damper gate was placed near the top of one corner of the fumigation chamber. The exhaust port with an exhaust fan and electronically actuated damper gate was mounted near the bottom of the opposite corner of the chamber (Figure 2). This arrangement ensured that the fumigant would be replaced with fresh air efficiently because the SO_2 gas is heavier than air and a higher concentration was expected near the chamber floor.

Windows were not provided inside the chamber for lighting to avoid joints on the walls. Therefore, the lights were placed inside the chamber using feed-through connectors. The CO_2, SO_2, and temperature sensors were fitted on one wall of the chamber, and connections were made using feed-through connectors to ensure no gas-tight joints.

2.2 | Design calculations of fumigation chamber

The fumigation chamber was designed for the treatment of 1500 kg grapes at a time. The treatment was supposed to be done immediately after receiving the fresh grapes from the field for packaging; however, treatment of grapes after punnet packaging may also be done. The grapes were received from the field in the plastic crates. The basic data for the design was collected, and design calculations were made as below.

2.3 | Chamber size

The size of one standard plastic crate used for transporting freshly harvested grapes from the field was 600 mm × 400 mm × 165 mm ($L \times W \times H$), and each crate contained 5–6 kg grapes. Thus, a total of 300 crates were required for the treatment of one batch. The chamber must have more than 60% empty space for effective treatment (Anon, 2008); therefore, the calculation was made with 66% of empty space of the total chamber volume, and minimum volume of fumigation chamber was calculated as 36 m^3.

A space of 1000 mm was kept on all sides of the chamber for the movement of workers to load and unload the crates in the chamber. Furthermore, an overhead space of 600 mm was kept for the fitting of lights and gas pipes. An additional space of 500 mm was kept toward the entry gate for the fitting of heaters and circulating fans on

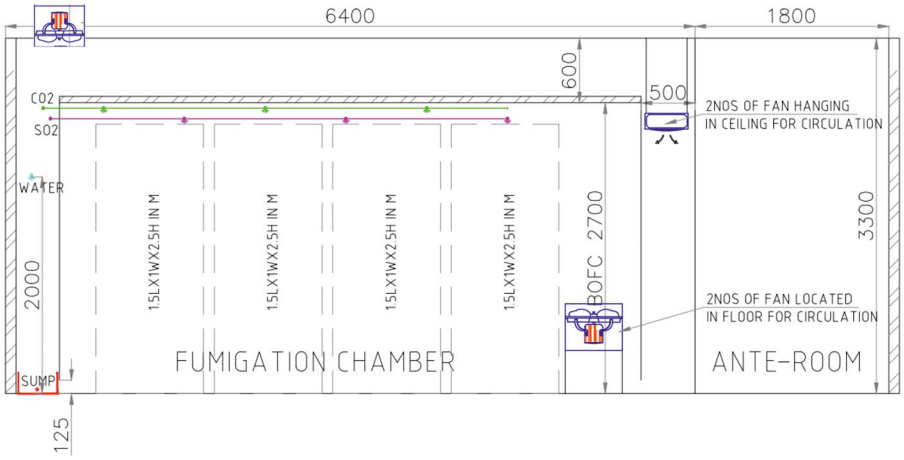

FIGURE 2 Drawing of the fumigation chamber: Section AA

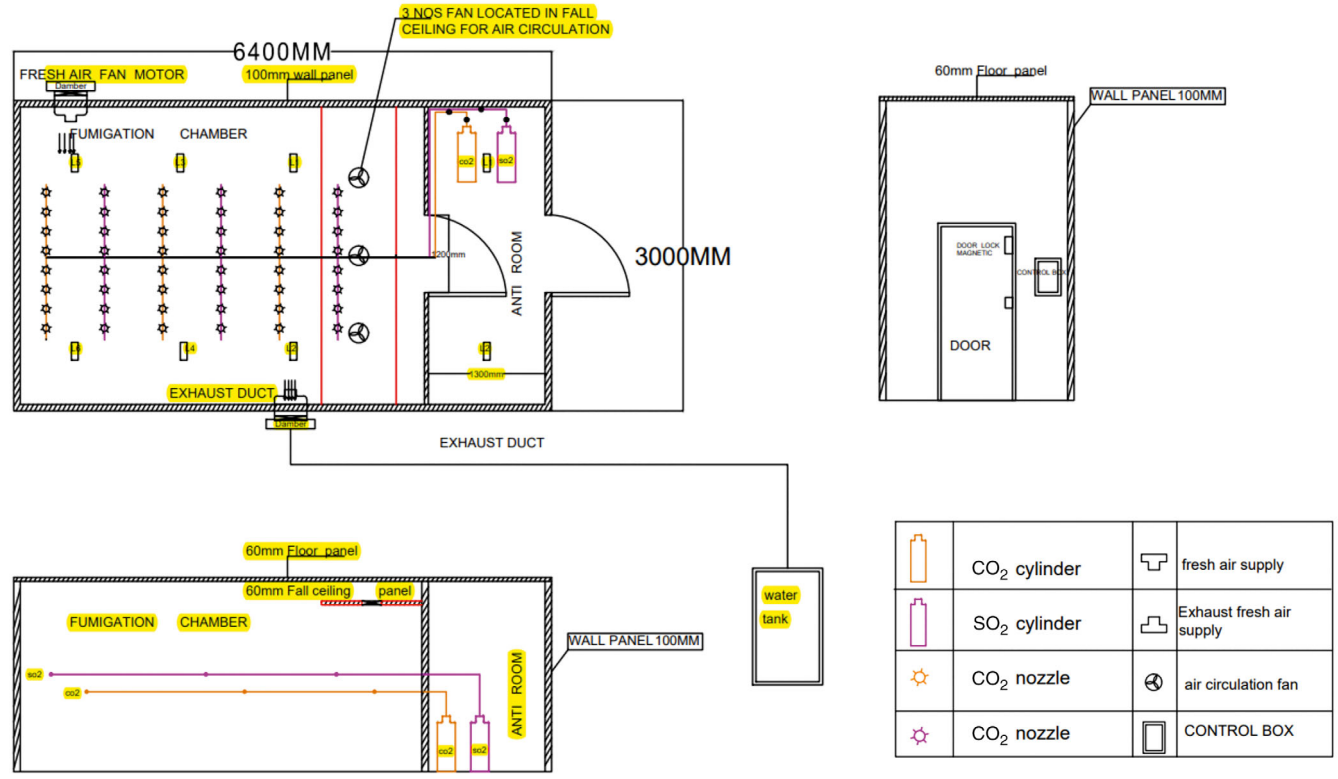

FIGURE 3 Floor plan with gas injection and circulation system

a false roof. Thus, the overall dimensions of the fumigation chamber were 6800 mm × 4800 mm × 3300 mm ($L \times W \times H$) (Figure 1).

The dimensions of ante-room were decided based on the basis of space required for opening of the door connecting the fumigation chamber and ante-room. As the door size was kept 1200 mm × 2200 mm ($W \times H$), the width of ante-room was kept as 1,800 mm.

The overall dimensions of the complete fumigation chamber system were 8300 mm × 4800 mm × 3300 mm ($L \times W \times H$). Wall and ceiling were fabricated by using 100-mm thick PUF panel (prefabricated, pre-engineered sandwich PUF insulation panel). All the dimensions of the chamber and placement of fittings are shown in Figures 1–3.

2.4 | Stacking plan of grapes in the chamber

The stacking of crates was done on the wooden pallets of 1200 mm × 1000 mm × 150 mm size ($L \times W \times H$). A total of eight pallets were placed in the fumigation chamber. A space of 150 mm was maintained between two pallets from each side for proper circulation of fumigants. A total of five trays were placed on each pallet in one layer. On

the basis of the strength of the crates and ease of manual loading/unloading of crates, 10 crates could be placed one over the other (up to 1650 mm height) for fumigation treatment. This height may be increased for high-capacity chamber where movement of forklift is possible.

2.5 | Fittings in the chamber

The gas and temperature sensors were fitted on one wall of the chamber at 1,000 mm height from the ground level. Lights were fitted on the roof of the chamber, and gas injection line and pipes were fitted 600 mm below the roof. A false roof of 600 mm width was made on the wall of ante-room side for mounting the heaters and circulating fans. Construction of false roof on any other wall may obstruct the gas pipe fitting and hinder the loading/unloading of crates.

CO_2 sensor (0–60 000 ppmv; least count: 100 ppmv, M/s Dwyer Instruments, Inc., MI) and SO_2 sensor (0–10 000 ppmv; least count: 2 ppmv, M/s Riken Keiki, Japan) were installed on one wall inside the chamber. The sensors were connected with the control panel to regulate the gas concentration during the treatment.

2.6 | Fittings in the ante-room

Gas cylinders, solenoid valves, gas regulators, and gas transmission lines were placed in the ante-room (Figures 2 and 3). The ante-room was also used for storing gas mask, aprons, safety gloves, and other safety devices, which were taken out prior to the operation of the chamber.

The CO_2 gas cylinder of 60 kg capacity and SO_2 gas cylinder of 10 kg capacity were used for this chamber. Each gas cylinder had a separate gate valve, pressure regulator, and solenoid valve. The gas pipes in the ante-room were installed near the roof and connected with the fumigation chamber using feed-through sealed connectors.

2.7 | Control panel

All the operations of the fumigation system were controlled from an electronic control panel fitted outside the chamber. The gases concentration, temperature, operation time, operation of solenoid valves, status of doors, operation of exhaust fans, run time for each gas, and so on were displayed through LED displays and controlled by a Building management and control system (BMCS) program specifically prepared for this fumigation system. The control panel was operated by an human machine interface (HMI) touch screen. Any requisite concentration of both fumigants along with the treatment time can be programmed prior to operation of the chamber, and changes can also be incorporated during the operation.

2.8 | Construction of fumigation chamber

The PUF panels were joined together by meshing/interlocking them. All the joints were filled with high-quality polyurethane sealant from inside as well as outside of the chamber. Extreme Sealing Tape (75 mm wide 3 M™) was placed on the joints of the panel inside the chamber to ensure no leakage.

The doors were fitted with magnetic locks and operated from the control panel. Both doors could be opened individually using the control panel. The door locks were controlled in a way that the lock would open only when the concentration of gases reached the safe limit during operation.

Both the fans (exhaust and fresh air entry) were fitted with electronically controlled actuators to open or close the dampers during the operation. The dampers were controlled from the control panel. Outlet of the exhaust fan was connected with flexible, reinforced polyvinyl chloride (PVC) pipe, which was dipped into water for absorption of SO_2 gas. In a high-capacity chamber, the gases may be released in the water through a network of perforated pipes placed at the bottom of a water tank.

Fumigation chamber floor was covered with a 10-mm thick PVC sheet, and the extreme sealing tape was placed on the wall and floor joint to prevent gas leakage.

The false-roof panel was placed 450 below the roof. Two fin-type electric heaters of 1 kW capacity were fitted on this panel. Circulating fans were placed at the bottom side of the false panel (Figure 4). The heaters were operated from the control panel using proportional–integral–derivative (PID)-controlled temperature controller cum indicator and came into operation only when the temperature of the chamber was less than 16°C. For heating of fumigation chamber, the control panel was programmed in a way that fumigant would not be released in the chamber unless the environmental temperature is above 16°C. The circulating fans were operated through a separate on–off switch placed near the control panel.

A total of six lights are fitted on the roof of the chamber. The electrical wiring inside the chamber was connected using feed-through sealed connectors.

The materials used for the construction of the fumigation chamber and their functions are given in Table 1.

FIGURE 4 Internal view of fumigation chamber showing false-roof panel, heaters, and circulating fans

TABLE 1 Details of construction materials used for construction of fumigation chamber

Construction materials/ tools	Description	Function
Walls and roof	Panels having PUF insulation of 100 mm thickness sandwiched between 0.4 mm pre-painted GI sheet	Structure of the chamber
Doors (02)	Type: Hinged type; 1200 × 2,000 mm Door gasket: Silicon rubber (continuous) Controlled by magnetic actuators from control panel	Loading and unloading of chamber for treatment
Sealant	3M, 500 series polyurethane construction sealant 75 mm wide 3M Extreme Sealing Tape on the joints after filling with PU sealant sealant	To make the chamber gas-tight by filling the joints
Lights (06)	LED lights of 20 W	Light in the chamber for operation
Fumigation pipe nozzles for CO_2 and SO_2	SS made to inject the gases into chamber Total 48 nozzles connected with SS pipes inside the chamber	Gas supply in the chamber for treatment
CO_2 cylinder (01)	Capacity: 60 L placed in ante-room Fitted with gas regulator, gate valve and solenoid valve	Start/stop gas flow, changing gas flow rate
SO_2 cylinder (01)	Capacity: 10 L; placed in ante-room Fitted with pressure regulator, gate valve, and solenoid valve	Start/stop gas flow, changing gas flow rate
Fresh air supply fan (01)	Fan with damper and actuator; placed near the roof at far end of the chamber	To supply fresh air during evacuation of fumigants
Exhaust fan	Fan with damper placed near the bottom of the chamber at the opposite corner of fresh air port	To remove fumigant from the chamber
Gas circulating fans (03)	High-capacity fans Fitted on a separate false-roof panel inside the chamber	Mixing of fumigants and circulate during treatment
Heating system	2 kW heater; strip type	Maintain environmental temperature inside the chamber >16°C
Chambers (02)	Fumigation chamber for fumigant application Ante-room for gas cylinders and safety area	Grapes treatment area Gas supply and ancillary equipment storage
Sensor of CO_2	Range: 0–60,000 ppm; least count: 100 ppm Placed inside the chamber at 1.5 m above the floor	Measure the concentration of CO_2 continuously
Sensor of SO_2	Range: 0–10,000 ppm; least count: 1 ppm Placed inside the chamber at 1.5 m above the floor	Measure the concentration of SO_2 continuously
CO_2 and SO_2 regulators	Flow rate up to 40 cfm	Increase or decrease the gas flow rate
BMCS	Control panel, fitted outside the chamber near entry gate	To control all parameters (temperature; gas flow rate; regulators; doors opening and closing; fans; heaters; circulating and exhaust fans; fresh air supply fan; etc.) for automated operation

Abbreviations: BMCS, building management and control system; GI, galvanized iron; PU, polyurethane; PUF, polyurethane foam; SS, stainless steel.

2.9 | Pressure leakage test of chamber

Pressurized helium leakage test of fumigation chamber was conducted by a third party to identify the leakage points and ensure a leak-proof chamber. Helium gas used for this purpose was of >95% purity. All the joints and possible leakage points of the chamber were covered with polyethylene film to form an envelope (hood). Helium gas was injected inside the fumigation chamber until the concentration reached to 10 000 ppmv. Mass Spectrometric Leak Detector (MSLD, M/s ADIXEN, France; Model ASM 310) for helium was used to measure the concentration that was connected with a sniffer probe (M/s ADIXEN, France). Initially, the leak detector was standardized (Helium Standard Leak 1 for Instrument calibration, M/s VIC). Thereafter, the probe was calibrated (Helium Standard Leak 2 for Probe calibration, HINDHIVAC, India). The background Reading (X, typically about 5.0×10^{-7} mbar l/s, which corresponded to 5 ppmv concentration in the ambient atmosphere) was recorded with elapsed time. The sniffer probe was then introduced into the hoods made at different locations, and concentration of He was recorded using Leak Detector (Y). The helium leak rate at the joint was presented as ($Y - X$). The corresponding SO_2 leakage was calculated by dividing the observed helium leakage concentration in 30 min by the factor 8.

2.10 | Gas concentration at no load

To test the gas-tightness and operation of the chamber, two levels of CO_2 (3.2% and 6%) and SO_2 (0.13% and 1%) concentrations were

filled initially in the chamber. Thereafter, the gas regulator and solenoid valves were closed to prevent entry of gas during the operation. The variations in concentration of both the gases were recorded for 30 min of continuous operation.

2.11 | Operation of chamber

Before starting the fumigation treatment, each component was checked for their functioning. Thereafter, the grape trays were loaded into the chamber, and the inner door was closed. The regulators of both gas cylinders were opened, and the outer door was closed. The circulating fans were then operated. Operating parameters, such as temperature, CO_2/SO_2 dose level, duration of fumigation, safe limits of gases for opening the lock of doors, and fresh air inlet/exhaust fan actuators were entered in the software of control panel. Then the system was operated. The doors were locked initially, and then dampers of fresh air inlet and evacuating outlet fans were closed. Then heaters were operated to maintain the desired temperature. Thereafter, the CO_2 gas was released till the requisite concentration was achieved and then the treatment duration started. Thereafter, SO_2 gas was released to a requisite concentration and maintained for a specified duration. After completion of the treatment time, the control panel closed the solenoid valves and opened dampers of the inlet and exhaust as per the program. The fans run till the CO_2 concentration reached <1,000 ppmv and SO_2 concentration < 5 ppmv. Thereafter, the doors were unlocked. The gas regulators were closed, and the workers were allowed for unloading the fumigated grapes.

A standard operating procedure (SOP) for the fumigation chamber was developed for safe and efficient operation of the system.

2.12 | Evaluation of fumigation system and development of protocol for fruit fly management

The incidence of even a single adult insect or maggot was considered as a failure of the treatment for 100% insect-free grapes for export. Therefore, to evaluate the effectiveness of the fumigation system and ensure 100% mortality, a vineyard in the Pune region was selected in which the attack of fruit fly (*Drosophila melanogaster*) was observed. The infested grapes (variety *Sharad* Seedless) were harvested from a vineyard at Bori, Pune, and India.

The grapes were sorted, graded, and packed in perforated punnets of 500 g each as per the standard packaging protocol. Thereafter, the punnets were placed in the perforated corrugated fiberboard (CFB) boxes without cover. In each CFB box, five punnets of fruit fly infested grapes and five punnets of healthy grapes were kept. The boxes were covered with muslin cloth, and the joints were sealed using cello tape so that the adult flies could not escape from the boxes.

Fumigation treatment of the grapes packed into perforated CFB boxes (without cover) was done as per the fumigation process protocol adopted and developed in this study (USDA, 2020; Walse & Bellamy, 2012). The fumigation treatment comprised injection of 6% CO_2 in the chamber and maintaining the concentration for 30 min followed by injection of 1% SO_2 and maintaining the concentration for 30 min (USDA, 2020; Walse & Bellamy, 2012). Thereafter, the fresh air was flushed till the concentration of fumigants reached to the safe limit. The boxes were then taken out and precooled immediately, and the number of live adults and dead adults was recorded by opening one box of each treatment.

2.13 | Large-scale operation of chamber

A large-scale fumigation treatment of the fresh grapes was conducted in March 2021 to verify the operational protocol of the chamber. A total of 280 crates containing about 5–6 kg grapes in each crate were placed in the fumigation chamber, and CO_2 (6% for 30 min) and SO_2 (1% for 30 min) treatments were applied (USDA, 2020). Then, the chamber was flushed with fresh air, and the efficacy of treatment was observed by taking five crates from different locations.

3 | RESULTS AND DISCUSSION

The fumigation chamber was established at M/s Sahyadri Farmers Producer Company, Ltd., Survey Nos. 314/1 & 314/2, A/P Mohadi, Nashik, India, which is a leading company in the grapes export business.

Fabrication of the chamber was done as per the drawings shown in Figures 1–3 using the materials given in Table 1. Thereafter, the silicon sealant was filled, and extreme tape was applied on the possible leakage points and joints. Electronic control panel was fitted outside the chamber and programmed for the automatic operation.

3.1 | Leakage test

The helium leakage in the first 5 min of the test was less than 1 ppmv from any of the possible leakage points (wall joint, near the door, electrical cable, air inlet damper, and exhaust pipe). Furthermore, after 30 min, the helium leakage was ≤5 ppmv from wall joints, near the door, and electrical cable 54 ppmv from air inlet damper and 155 ppmv from the exhaust pipe. The equivalent SO_2 gas leakage at 1% concentration for 30 min of operation was <0.18 ppmv from all the wall joints, <0.125 ppmv near the door, <0.7 ppmv through the electrical power cable entering path, <7 ppmv through the air inlet damper, and <20 ppmv through the damper at the exhaust.

3.2 | Test at no load

Variation of CO_2 and SO_2 concentrations in the empty chamber with time is reported in Table 2. No significant change in the gas concentration was observed during the entire test period. It may, therefore,

TABLE 2 Variations in fumigants concentration inside the chamber with time at no load

S. No.	Time (min, after infusion of fumigant in the chamber)	Concentration of fumigants (PPM)			
		CO_2 (initial conc. 32,000)	CO_2 (initial conc. 60,000)	SO_2 (initial conc. 1,300)	CO_2 (initial conc. 10,000)
1	0	32,458	60,000	1,282	10,000
2	5	32,438	59,800	1,292	10,000
3	10	32,087	59,900	1,296	10,000
4	15	31,456	59,900	1,296	10,000
5	20	31,000	59,900	1,299	10,000
6	25	30,894	60,000	1,305	10,000
7	30	31,719	59,900	1,308	10,000

be inferred that the leakage of gases from any point of the chamber was not significant, and the chamber may be safe for fumigation treatment with CO_2/SO_2 gases.

3.3 | SOP of chamber

The SOP of the fumigation chamber is reported in Figure 5. All the unit operations were performed in a sequential manner by the BMCS program to prevent unsafe operation and ensure proper treatment. It must be ensured that the doors are locked properly and dampers of fresh air inlet and exhaust are closed prior to starting the gas injection. Similarly, at the end of the treatment period and flushing the chamber with fresh air, it must be ensured that the dampers are open, and fans are running. Furthermore, the temperature of the chamber must be checked and ensured that it is >16°C prior to injection of gases.

The gas concentration and treatment time can be varied by entering the requisite data in the control panel. Furthermore, both the gases might be injected simultaneously in the chamber because separate supply lines were provided for both the gases. Thus, the total treatment period might be reduced by 30 min. All the safety devices, such as gas mask with correct filters, gloves, self-contained breathing apparatus, and so on, must be in place and in working condition.

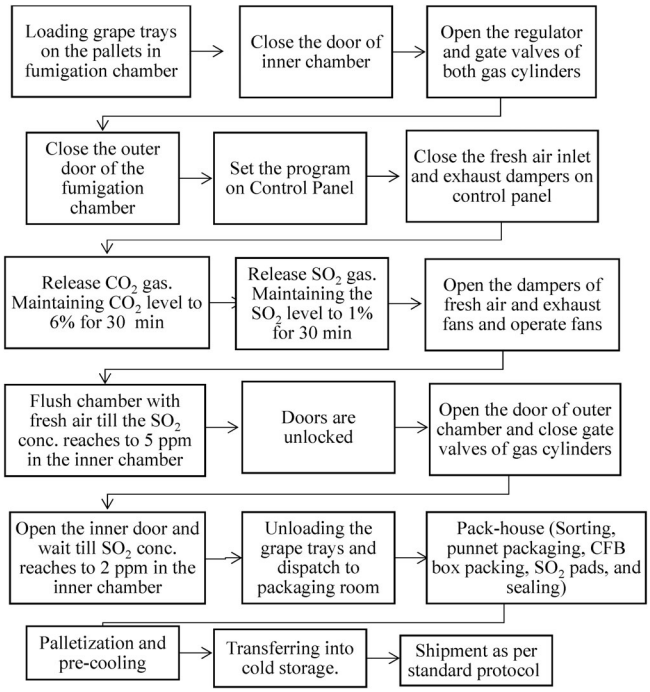

FIGURE 5 Standard operating procedure for fumigation treatment of grapes

3.4 | Effect of fumigation on mortality of insects

The temperature and relative humidity (RH) inside the chamber at the time of treatment was 23°C and 45%, respectively. The pulp temperature of berries received for the treatment was 21 ± 2°C. Therefore, the heating of the system was not required at the time of treatment. Live adults were not observed immediately after the fumigation treatment. It indicated that the fumigation treatment ensured 100% mortality of adult fruit flies. No further infestation of the healthy berries was observed after fumigation. Thus, the fumigation treatment ensured that the healthy berries would not be infested further. However, the maggots present inside the berries probably may not destroy during fumigation and may convert in adults during storage at normal temperature. It was concluded in earlier studies that the fumigation followed by storage at ±0.5°C for ≥6 days can ensure 100% mortality of maggots (USDA, 2020; Walse & Bellamy, 2012). The fumigation destroys the adult forms while cold treatment is a possible cause for inhibiting the growth of maggots. Based on the results of the present study, it may be inferred that the fumigation treatment killed all the adult insects even after packaging in perforated punnets.

3.5 | Large-scale experiment

The temperature and RH inside the chamber at the time of treatment were 25°C and 55%, respectively. The pulp temperature of berries received for the treatment was 23 ± 2°C. The temperature inside the chamber Fumigation treatment of fresh grapes (about 1,500 kg) was

done as per the SOP of the fumigation chamber and operated by the electronic control panel. It was observed that all the operations worked satisfactorily during the treatment. The chamber was loaded with grapes manually in 15 min. Thereafter, the chamber was closed and operated. The CO_2 concentration of 6% was achieved in 10 min and then treatment duration started and continued for 30 min. Thereafter, the control panel actuated the SO_2 solenoid valve, and the 1% concentration was reached in 4 min. The treatment period of SO_2 was displayed on the control panel and treatment continued for 30 min. Thereafter, both the dampers opened automatically as per the BMCS program and flushing of the chamber with fresh air took about 20 min to reach SO_2 concentration of 5 ppmv. Then the doors were unlocked by the control panel, and unloading of the chamber was done. Thus, the total treatment time for one batch was found to be 2 h approximately. It was observed that the BMCS was working satisfactorily, and each operation took place without any manual intervention.

The analysis of samples showed that all the insects (spiders, fruit flies, flies, insects of other species, etc.) that came with the grape bunches were died. No visual change in color of the grapes was observed. It may be inferred that the developed fumigation chamber worked effectively and operated automatically through the electronic control panel.

The exhaust pipe coming out from the chamber was dipped in the water and pH of water reached to 6 in one batch of operation. This water was slightly acidic and might be disposed of in the sewer line. However, using the same water for second batch treatment resulted in slow evacuation of SO_2 and evacuation time increased substantially.

4 | CONCLUSION

The fumigation chamber designed and evaluated in this study was leak-proof and controlled all the operations through electronic control panel. Fumigation treatment of grapes with CO_2 (6%) SO_2 (1%) concentrations followed by pre-cooling and 6 days cold storage at 1°C ensured 100% mortality of adults and maggots of fruit fly. The fumigation treatment with CO_2/SO_2 can be performed in this chamber for various fruits, vegetables, nuts, and so on, depending upon the dose and duration of treatment. However, the protocol for such treatments should be developed, and effect of the gases on the quality of the products should be studied to ensure food safety. Such chambers may be constructed in higher capacities with complete mechanized operation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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