Int. J. Plasma Environ. Sci. Technol. 18 (2024) e02003 (13pp)

International Journal of Plasma Environmental Science and Technology

Regular Paper

DOI: 10.34343/ijpest.2024.18.e02003

Ozone nano-mist disinfection of insect pests and automatic spraying system based on deep learning technology

Kenji Ebihara[1,2,*], Fumiaki Mitsugi[2], Shin-ichi Aoqui[3], Oleksandr Boiko[4], Henryka D. Stryczewska[4], Yoshitaka Yamashita[5], Seiji Baba[6]

[1] Environment and Energy Laboratory, Suizenji-Park 25-39, Kumamoto 862-0956, Japan
[2] Faculty of Advanced Science and Technology, Kumamoto University, Kurokami 2-39-1, Kumamoto 860-8555, Japan
[3] Faculty of Computer and Information Sciences, Sojo University, Ikeda 4-22-1, Kumamoto 860-0082, Japan
[4] Department of Electrical Engineering and Electrotechnologies, Lublin University of Technology, 38A Nadbystrzycka Str., 20-618 Lublin, Poland
[5] Sanwa hi-tec Co.Ltd., Yoshitomi 210-29, Shisuimachi, Kikuchi City, Kumamoto 861-1201, Japan
[6] Densoken Co.Ltd., Hanamigawa 7-9-405, Chiba City, Chiba 262-0046, Japan

* Corresponding author: ebihara@environment-lab.com (Kenji Ebihara)

Received: 1 October 2023
Revised: 5 May 2024
Accepted: 28 May 2024
Published online: 1 June 2024

Abstract

We propose an ozone nano-mist spraying system which is composed of an ozone nano-mist generator and an automatic spraying system in agriculture. The highly dense ozone generated by dielectric barrier discharges is injected into water nano-mist flow ejected from an ultrasonic humidifier(1.7Mhz). This disinfection system is controlled to spray in real time the ozone nano-mist on the detected pests in response to the treatment conditions given by the deep learning technology. Six species of insect pests (aphid, moth, beetle, fly, whitefly and ant) were selected to study control performance of the disinfection spraying on these pests in the greenhouse. The disinfection rates of the 6 species of insect pests were measured in advance at various nano-mist conditions. The YOLO object detection architecture based on deep learning is adopted to acquire information about insect species and their number of the target insect pests appeared on the photo images. The automatic nano-mist spraying system is operated by the signals from the Raspberry Pi which communicates remotely with the main computer using Wi-Fi. In these processes of the training and validation of the pest dataset, mean average precision values of 96.8% (mAP@0.5) and 70.1% (mAP@0.5:0.95) were achieved for all classes(species). The computing time for this training and the validation was 6 minutes. When the object targets are winged insect pests such as moths, flies and whiteflies, the testing time was 11−12 sec and the consuming time for the following spraying procedure was 30 sec at an ozone flow rate of 110 g-O_3 m^{-3}. The disinfection rate at this spraying process was near 100% and closed to the rate of the conventional chemical pesticide treatment. The results suggest that the proposed ozone nano-mist disinfection system can be used practically to disinfect remotely winged insect pests in greenhouses.

Keywords: Ozone nano-mist, dielectric barrier discharge (DBD), automatic insect pest disinfection, YOLO object detection, Raspberry Pi.

1. Introduction

Ozone is a powerful oxidizing agent and an effective alternative to chemical pesticides. Combining ozone with other materials such as water-mist produces a very reactive intermediate, hydroxyl free radical (•OH) which is stronger oxidizing agent than ozone itself. Ozone mist mixture consisting of ozone gas and water mist is one of alternative pesticides which contribute to protect global environment. In view of present global environmental issues, we propose an ozone nano-mist disinfection system which can be applied to disinfect insect pests in agricultural fields. Highly ozone concentrations are needed to complete disinfection procedures for insect pests in short treatment-time at agricultural fields. In this study the dielectric barrier discharge is used to generate highly dense ozone concentration of about 110-g O_3 m^{-3}. This treatment utilizes nano-meter size mist generated by irradiation of MHz ultrasound on water and the particle diameters are in the range 200 nm–1250 nm. Ozone nano-mist mixture is produced by injecting gaseous ozone into the water nano-mist atmosphere. The ozone nano-mist treatment can be expected to be effective in killing many kinds of insect pests.

When information about pest species and the densities can be provided in a timely and accurate way, the over-use of chemical pesticides and the pesticide residue in foods and soil partly can be reduced. The image-based method takes clear images of insect pests and then recognizes and counts the pests. The Deep Learning (DL) method based on the convolutional neural networks (CNNs) has shown high performance for task such as detection and classification of insect pests in agricultural fields.

This study aims to develop an automatic ozone nano-mist spraying system on the base of the DL technology for the remote detection and identification of insect pests in agricultural fields. We previously developed a portable ozone mist disinfection system in which the water mist generated using conventional spray nozzles has micro-mist size of 130–200 μm. The ozone micro-mist disinfection systems have been studied to clarify the disinfection effect on several pest species in the fields [1–9]. In the ozone nano-mist disinfection system proposed here, the Raspberry Pi (single-board computer) is introduced to control the ozone nano-mist disinfection system which is set in the greenhouse. The output power from the Raspberry Pi can activate automatically the ozone nano-mist disinfection system when insect pests are observed in the field. The developed system is composed of consecutive procedures including image acquisition, YOLO detection, optimal treatment conditions and automatic ozone nano-mist spraying. This system is operated practically to evaluate disinfection performance of insect pests in the greenhouse.

2. Literature review

2.1 Ozone mist disinfection in agriculture

Recently, ozone has been used in agriculture for soil remediation [9] and in the food industry for drinking water disinfection, wastewater treatment, medical disinfection and air refreshing [10–12]. We have proposed the ozone micro-mist spray system for pest control in agriculture [1–9]. Highly dense ozone of 70-g O_3 m^{-3} was generated by dielectric barrier discharges on surface electrodes placed on the dielectrics Al_2O_3. High frequency power (15 kHz, $V_{p\text{-}p}$ = 8 kV) is applied to the electrodes. The ozone was injected into water micro-mist atmosphere produced by spray nozzles. The ozone micro-mist was applied to study the disinfection rate for several insect pests (aphid, tobacco worm, green rice leaf hopper, caterpillar) and biological damages on plants.

On the other hand, ozone nano-mist is also expected to enhance the disinfection effect on insect pests. The nano-mist produced by ultrasonic energy has been used in a wide range of field including material processing, medical/sanitary treatment, food industry and environment technology [13]. However apart from a few information about ozone micro/nano bubble water and in the fields of medical treatment and biology [14–17], little is known about the pesticide effect of ozone nano-size mist on insect pests in the agricultural fields.

2.2 Pest recognition by YOLO object detection

The practical and effective operation of an ozone nano-mist disinfection system in agricultural farms needs to monitor the performance of insect pests. Accurate detection of the selected pests plays an important role of the precision agriculture based on the information technology.

Yellow sticky traps are usually used to collect insect pests in farms. This method can get clear images compared with the direct shoot setting. Cho *et al.* collected thrips, whiteflies and aphids on the yellow traps and carried out automatic identification of the pests using algorithms for image processing where various morphological features (size and color components) of specimens were extracted and analyzed [18]. Zhong *et al.* installed a yellow sticky trap in the surveillance area and a camera was set up in front of the trap to capture clear images of flying insects [19]. They adopted the detection method based on the YOLO object detection to identify flying pests captured on the yellow sticky trap.

The YOLO object detection [20] is based on deep learning and is adapted to the recognition and classification of flying and parasitic insect pests. The most widely used object detection algorithms are divided into classification-based object detectors (two-stage detectors: R-CNN, Faster R- CNN) and regression-based object detectors (one-stage detectors: YOLO, SSD) [21,22]. The YOLO has reduced computing time compared with the R-CNN series. Önler *et al*. developed the detection system to detect the thistle caterpillar in real time via video using the YOLO architecture [23]. In the work the direct shooting was available to take images of the caterpillar moving slowly on the plants. Ahmad *et al*. invested the diagnosis of pest infestation on a real-time recognition of beneficial insects such as honeybees in agricultural fields [24].

Most of current studies on the pest detection have been performed using pest images collected in the indoor (ideal lab experiment) without implementation in the agricultural fields. They used the internet to search the pest images from different databases and search engines, and studied an accuracy of pest detection based on various deep learning methods [18, 25–27]. In this work our pest dataset consisting of the series of insect pests which cause fatal harm to vegetables were mostly collected in the greenhouse and farms.

2.3 Automatic pesticide spraying system

Our ozone nano-mist spraying system proposes an automated approach to identify the insect pests and spray in real time the ozone nano-mist on insect pests in the greenhouse. There are a few research on the automatic pesticide spraying system which is controlled timely referring the identification of insect pests and diseases. Mohiddin *et al*. developed an automatic pesticide using Raspberry Pi [28]. A webcam connected to the Raspberry Pi captured the real time images of pests in the field. If any pest was detected in the field the relay turned on so that the pesticide pump started to operate on the programmed code. Kotkar *et al*. developed a robot system for CNN identification, monitoring, and detection of crop diseases, and according to the information the Raspberry Pi controlled the spraying mechanism (DC stepper motor) [29]. There are some automatic pesticide spraying robots designed to lessen the treatment-time and prevent hazards involved in spraying toxic chemicals [30–32]. Our automatic spraying system has a superior advantage that the nano-mist spray is managed under the optimal disinfection conditions of the ozone concentration of the nano-mist and the treatment-time suitable to the target insect pests.

3. Materials and methods and discussion

Our proposed approach is based on the development of an ozone nano-mist spraying system and an automatic remote operating system by using the YOLO object detection architecture.

3.1 Automatic ozone nano-mist disinfection spray

Fig. 1 shows the outline of the automatic ozone nano-mist disinfection spraying system. This system is composed of an ozone generator equipping with an oxygen cylinder, a water nano-mist humidifier and the Raspberry Pi microcomputer Board. Atmospheric pressure plasma of dielectric barrier discharges was generated in the cylindrical dielectric tube (high purity aluminum oxide) with outer and inner electrodes (316L stainless steel) (KHT-40GWO). The power applied between the electrodes was 3.8–4.2 kV with a frequency of 6 kHz. Maximum concentration of 110 g-O_3 m^{-3} was produced an oxygen flow rate of 0.5 L min^{-1}. The ozone density at the outlet of the ozone generator was measured using an ozone monitor (ED-OA-1).

The ultrasonic humidifier adopted in this work used a piezoelectric transducer vibrating at an ultrasonic frequency 1.7 MHz to create the nano-mist of the size in the range 200 nm–1250 nm [33]. The water nano-mist reacts immediately with the flow originating in the ozone generator to form the ozone nano-mist. When ozone reacts with water nano-mist particles, highly unstable and rapid decomposition occurs.
The elementary reactions in the ozone nano-mist are expressed by.

$$OH^- + O_3 \rightarrow \bullet HO_2 + \bullet O_2^- \quad (1)$$

$$\bullet HO_2 \rightarrow H^+ + \bullet O_2^- \quad (2)$$

$$\bullet O_2^- + O_3 \rightarrow O_2 + \bullet O_3^- \quad (3)$$

$$\bullet O_3^- + H^+ \rightarrow HO_3 \quad (4)$$

$$HO_3 \rightarrow O_2 + \bullet OH \quad (5)$$

$$O_3 + \bullet OH \rightarrow \bullet HO_2 + O_2 \quad (6)$$

Initial formation of the superoxide ion radical ($\bullet O_2^-$) and the hydroperoxide radical ($\bullet HO_2^-$) leads to the generation of the highly reactive hydroxyl radical (•OH). The •OH reactive radical has stronger oxidation potential than that of ozone: •OH (2.86 V) and O_3 (2.07 V). The ozonide radical ion ($\bullet O_3^-$) is formed as an intermediate product [34].

As a result, the ozone nano-mist is composed of residual ozone, reactive hydroxyl radical(•OH) and other radicals. Water nano-particles still remain in the mist. Insect pests are exposed by these complexly decomposed elements and water particles in spraying processes. Gaseous ozone and the free radical species as mentioned above are directly taken into the pest body through spiracles, travel via the tracheae and reach the cells. The ozone nano-mist provides specified behavior at the spiracles of the insect pests, thereby can enhance the disinfection effect on the pests. Oxidizing agents including ozone and the radicals react many macromolecules in cell such as proteins, DNA and RNA to collapse their structure.

Spiracles ranges from 27 μm^2 for the giant beetle to only a few micrometers area for small pests. The outside of the spiracle is mostly filtered with hair or covered with a filter to help resist entry of dust, water or parasites. The spiracles open into large tracheal tube that leads to tracholes, eventually penetrate to every region of the insect. Considering the remarkable differences of mist sizes of the nano-mist and the micro-mist, above properties of the spiracles suggest that the nano-mist causes lower effect on the obstruction in delivery functions of gaseous ozone and free reactive radicals comparing with water micro-mist spraying. In this work the ozone concentration measured at the outlet of the ozone generator is defined as one of the treatment parameters because microbiological phenomena of the cells absorbing the ozone mixture is so complicated to measure *in-situ* concentration of ozone and related radicals near the pests.

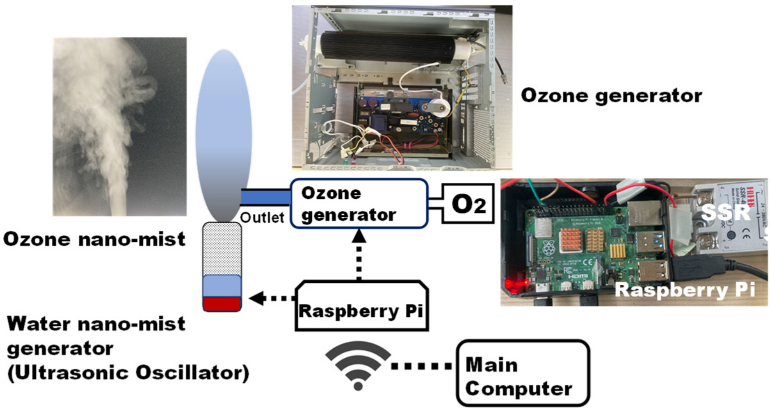


Fig. 1. The outline of automatic ozone nano-mist disinfection system.

3.2 Automatic ozone nano-mist disinfection processes

The proposed processes consist of 4 consecutive steps as follows: (1) image acquisition; (2) detection, classification and counting number; (3) optimal disinfection conditions; (4) automatic remote operation of the ozone nano-mist spray in real time.

Fig. 2 shows a schematic representation of insect pest acquisition, pest detection and the automatic ozone nano-mist disinfection system. Six specie of insect pests including aphids, moths, beetles, flies, whiteflies and ants were selected to study the detection and classification of the pest images in the greenhouse. Yellow sticky traps were used to collect flying insects in the greenhouse (W:2.8 m D:4 m H:2 m) because they are always moving and it is difficult to get clear images directly. Other insects whose images we were not able to catch using the sticky traps were captured using an insect capture net and a UV-light sensor-based bucket trap. The digital Wi-Fi camera (Nikon D7200: effective pixels 24.2 million, image 23.5 × 15.6 mm CMOS) was applied to take *in-situ* images of insect pests under natural solar irradiation. The CMOS image sensor with the IR cut filter has a spectral sensitivity of a peak intensity of around 550 nm. The pest images of the camera-equipped Wi-Fi were transferred to the main computer via a commercial Wi-Fi network (2.4 GHz,5 GHz). The original image was cropped and scaled to a size of 640 × (426–640) pixels to reduce the computing amount. The image annotation tool LabelImg (Ver. 1.8.0) was used to mark the categories and rectangular bounding boxes of the images.

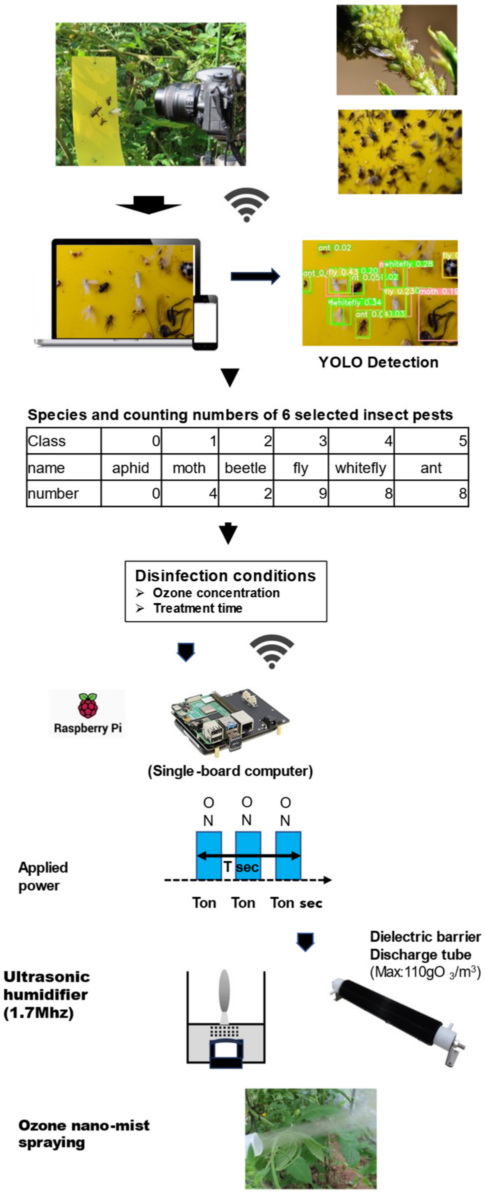


Fig. 2. The schematic representation of disinfection steps: image acquisition, YOLO detection, optimal disinfection conditions, Raspberry Pi, ozone nano-mist generation, Ultrasonic humidifier, automatic ozone nano-mist spraying.

The YOLOv5 object detection, based on deep learning, is adopted here to enable the detection and classification of selected pest insects. The models in YOLOv5 prove to be significantly smaller, faster to train, and more accessible to be used in practical applications. The YOLOv5 can simultaneously provide the bounding boxes and the confidences for these pest images. A pandas which is one of Python packages can convert the YOLO detection images to the expressive data structures (table embedded in Fig. 2). The YOLO object detection was implemented in Google Colaboratory which provides access for running computer job in the cloud.

When target pests are identified by the object detection process of the pest images, the class, species name and the counting number are obtained. Then the disinfection condition of ozone concentration and treatment time is known for each target pest of the images. The resulting disinfection conditions for the target pests are sent to the Raspberry Pi. Raspberry Pi is implemented using Python language and communicates remotely with the main computer using Wi-Fi.

The Raspberry Pi 4 model B used here has 40 GPIO(General Purpose Input Output) pins. A couple of GPIO pins is connected to the Solid State Relay (SSR) that turns on when the input signal of the Raspberry Pi is on. The ozone generator is controlled by the output signal (3.3 VDC) of the SSR depending on the ozone disinfection conditions for the target insect pests.

In the case of practical disinfection processes, the nano-mist sprays will be placed at proper sites in the greenhouse considering behaviors of pests (winged or wingless) and characteristics of plant species.

4. Results and discussion

4.1 Optimal ozone concentration of ozone nano-mist spraying

Characteristics of dielectric barrier discharges (DBD) are closely related with the high frequency power applied between electrodes. The conventional technologies to control the ozone concentration of DBD is based on the methods such as the amplitude adjustment and phase control of the waveform of the applied power. However, these electronic methods are considered not to be suitable to the Raspberry Pi operation because the ozone control using the above methods requires complex technology in the practical usage. Considering the above, we chose the method to control the ozone concentration by adjusting the operating time of the input AC power. The ozone concentration at the outlet of the ozone generator was varied by means of the switching modification of the applied power. An ozone concentration in the mist should be maintained at a specific value such as 110 g-O_3 m^{-3} during the treatment. Our experimental apparatuses such as an O_2 cylinder, a humidifier, an ozone generator and an ozone monitor were operated in advance to keep a stable value of ozone concentration in the mist. The generated mist was exhausted to another discharge container. When we measure disinfection rates of pests on plants and exposure on pests enclosed in a mesh-net container, a head of the spray nozzle was shifted to target plants or the mesh-net container. This moment when the mist spray starts to treat target pests is defined as the time- zero ($t = 0$). The spraying time (T_{on}) indicates the time period while ozone nano-mist is supplied to target pests.

Fig. 3 shows temporal profiles of the ozone concentration at oxygen flow rates of 0.5 L min^{-1} and 1 L min^{-1} when the ozone nano-mist was supplied during the spraying time (T_{on}) of 30 sec and then was turned off. The ozone concentration at the outlet of the ozone nozzle falls down with time and then disappear near 60 sec. As a result, the nano-ozone mist generated by the mixture reaction between the gaseous ozone and the nano-water particles is considered still to keep the disinfectant effects on target pests near 60 sec.

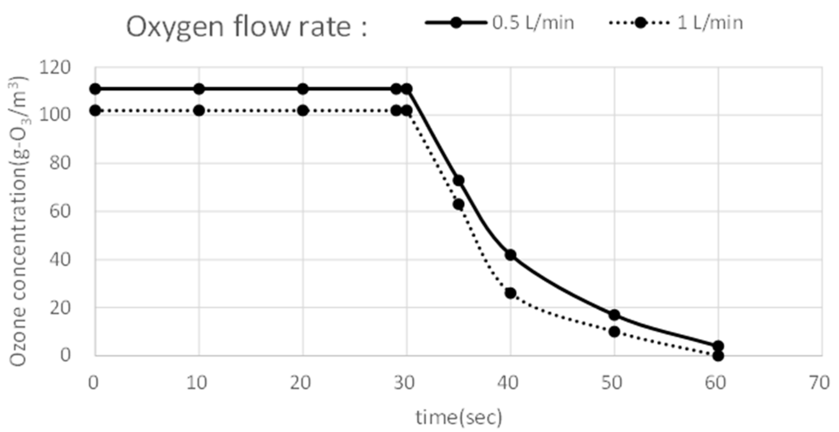


Fig. 3. Change of ozone concentration after the spray operates during T = sec (T_{on} = 30 sec) at oxygen flow rates of 0.5 L $min^{-1}$and 1.0 L min^{-1}.

In order to reduce plant damages ozone concentrations should be kept as low as possible maintaining the range of the concentration-spraying time product suitable to the target pest. A product of the concentration of ozone multiplied by the treatment time has been used as an indicator of ozone disinfection effect. In our spraying system a variety of ozone concentration can be provided by controlling a time interval while the high voltage (3.8–4.2 kV, 6 kHz) is applied between the electrodes.

Fig. 4 presents a typical change of the ozone concentration when the voltage is applied again after the turn-off time (T_{off}) of 10 sec. It is shown that the concentration of an oxygen flow rate of 0.5 L min^{-1} recovers in a few seconds to the original value after a minimum vale of 42 g-O_3 m^{-3}. In the case of the flow rate of 1 L min^{-1} the concentration gradually approaches the original value at 60 sec after a minimum concentration (10 g-O_3 m^{-3}) at 45 sec. The behavior suggests that the contents of ozone and the reactive radicals in the ozone nano-mist can be controlled remotely by adjusting T_{on} and T_{off}. In the following study, in order to reduce the consuming time in the spraying process, high ozone concentrations of 110 g-O_3 m^{-3} (0.5 L-O_2 min^{-1}) and 100 g-O_3 m^{-3} (1L-O_2 min^{-1}) were mostly used under a condition of T_{off} = 0.

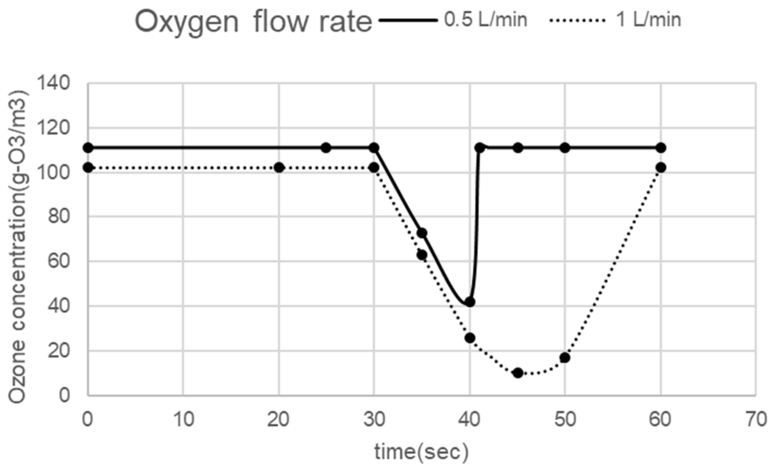


Fig. 4. Temporal profiles of ozone concentration when the spray operates during T_{on} = 30 sec and reoperates after the 10 sec T_{off}.

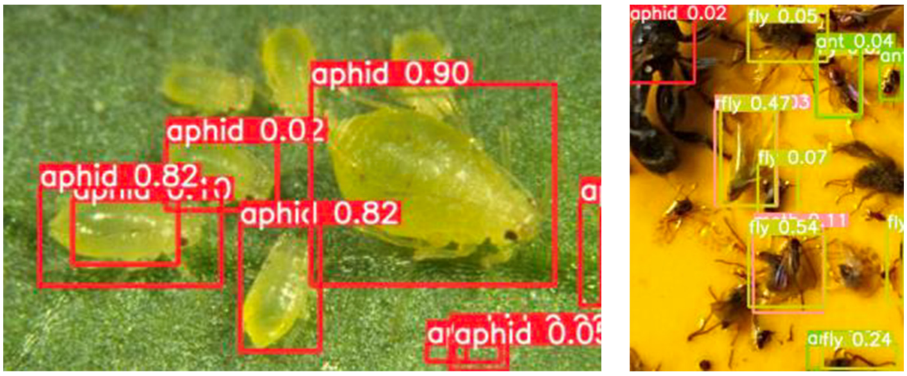
4.2 Training and identification of insect pests

In this work, six species of insect pests (aphids, moths, beetles, flies, whiteflies, and ants) were selected to train and test the object detection system. We collected 53 images of pests including 87 instances (42 aphids, 15 moths, 7 beetles, 8 flies, 6 whiteflies, and 9 ants). We used the image set for training and validation of the object detection system. The YOLO was trained at batch size of 20 with 100 epochs. The training loss is a metric that measures how well a deep learning model matches the training data. In our training the training loss curves decrease rapidly as number of epochs increases and converge on the stable values after 100 epochs. The final values with the bounding box loss (box_loss) of 0.02902, the object loss (obj_loss) of 0.0185 and the class loss (cls_loss) of 0.09385 were achieved. The box_loss is the error between the predicted bounding boxes and the ground truth boxes. The obj_loss indicates the probability that the detected object belongs to a certain category. The cls_loss is a loss that measures the correctness of classification of each predicted bounding box. This performance means that accurate results are trained. Table 1 shows the evaluation of the detection performance of YOLOv5 architecture. The mAP@0.5 means the average precision when the IoU > 0.5, and the mAP@0.5:0.95 denotes the average precision when the IoU has taken 10 values between 0.5 and 0.95. The IoU(Intersection Over Union) is a fundamental metric used to compare object detection systems. It means how good are the real object bounding area in an image and the pest bounding area generated by the algorithm [24,25].

The validation test results showed that in the case of all classes, the mAP@0.5 of 0.968 and mAP@0.5:0.95 of 0.71 were obtained. For each pest the mAP@0.5 was in the range between 0.923 and 0.995 and the mAP@0.5:0.95 was the lower value between 0.532 and 0.79. There are some pest detection experiments based on YOLOv5 in order to perform pesticide spraying. Their validation performances are mAP@0.5 = 0.59 for thistle caterpillars [23] and mAP@0.5 = 0.74 for oilseed rape pests [25]. These results suggest that our method using the selected pest dataset shows better performance to detect insect pests with good precision.

Table 1. YOLO detection performance for different species.

Class	Instances	mAP@0.5	mAP0.5:0.95
All	87	0.968	0.701
Aphid	42	0.995	0.730
Moth	15	0.976	0.755
Beetle	7	0.995	0.790
Fly	8	0.923	0.532
Whitefly	9	0.995	0.720
Ant	6	0.927	0.680



(a) (b)

Fig. 5. Typical detection images in the training process of pests (pirilla) on a leaf (a) and a sticky trapped sheet (b).

Typical bounded images in the present training process are shown in Fig. 5. Each bounding box consists of confidence and the point information of the box (coordinate: x, y; w (width), h (height)). The confidence is defined by the probability that a detected object belongs to a particular class (pest species). The numerical decimal values of each box indicate the confidence of insect pests. Maximum confidence of 90% is obtained for the aphid(pirilla) on the leaf (Fig. 5.a). Lower confidence below 54% for the pests captured by sticky traps (Fig. 5.b) is due to the fact that the shapes of some flying pests caught in adhesive glue were deformed.

These results showed that pest monitoring is possible using the present YOLOv5 method. The number of 53 images for present object detection is chosen to lessen the time consumed in the computing processes. The computing time for the training and the validation of the YOLO was about 6 minutes at our main computer (Windows11, Core i7, 2.92, 16GB RAM). A deep learning technique included Raspberry Pi can be applied to control ozone-mist disinfection system based on the real-time detection and identification of insect pests in the field.

4.3 Disinfection rates for selected insect pests

The disinfection rates for insect pests are needed to operate the ozone nano-mist spray. Effect of ozone and related radicals on the pest disinfection in the mist depends on both the ozone concentration and the treatment time ($T = T_{on} + T_{off}$). Here we measured the disinfection rates for the selected species. We tried two types of spraying methods: a direct exposure on pests living on plants and an exposure on pests enclosed in a mesh-net container (100 × 80 × 250 mm). Fig. 6 shows images of aphids (perilla) after the nano-mist treatment under the conditions of T = 120 sec (T_{on} = 120 sec, T_{off} = 0) at an oxygen flow rate of 0.5 L min^{-1}. The mist was directly sprayed on the samples placed on the wire mesh. Aphids including flightless and winged species live on plants as a colony. It is shown that most of the aphids left the vegetable leaves to die.

Fig. 6. Images of aphids(perilla) treated by nano-mist of 110 g-O_3 m^{-3} during T = 120 sec (T_{on} = 120 sec, T_{off} = 0) at an oxygen flow rate of 0.5 L min^{-1}.

We implemented disinfection treatments for other insect pests and typical results are shown in Fig. 7. The nano-mist was led to the mesh-net container which enclosed insect pests. The disinfection time was T = 30 sec (T_{on} = 30 sec at T_{off} = 0 sec). Moths (order:Lepidoptera) and whiteflies (order:Hemiptera) having wings take quickly ozone and its derivative radicals into the cell through spiracles. Their treatment time of T = 30 sec is shorter than that of aphids because of biological differences of spiracle functions. Aphids which damage a huge variety of plants by sucking the juices from leaves and stems are among the most harmful pests for corps and complex to control [32].

The winged insect pests flying in the container are directly exposed to the ozone nano-mist and consequently gaseous ozone, ozonated nano-particles and water nano-particles are carried through spiracles to their bodies. The gaseous elements such as ozone, oxygen and reactive radicals can contribute to enhance insecticidal effect. On the other hands, most of the ozone-nano-mist deposits to form the droplets on the wall of the container which fall down on the bottom of the container. The accumulated water was measured using the pH meter (Fujiwara:PRN-41) . As a result, the pH value of 5.29 was obtained for the spraying by use of 110 g-O_3 m^{-3} at an oxygen flow rate of 0.5 L min^{-1}. The pH is slightly acidic and this result is probably due to the fact some parts of the gaseous reactive components are exhausted outside and not contained in the water. Because the insect pests which move at the upstream central part in the nano-mist with high ozone concentration directly take the reactive radical components into their body, higher disinfection affects the pests.

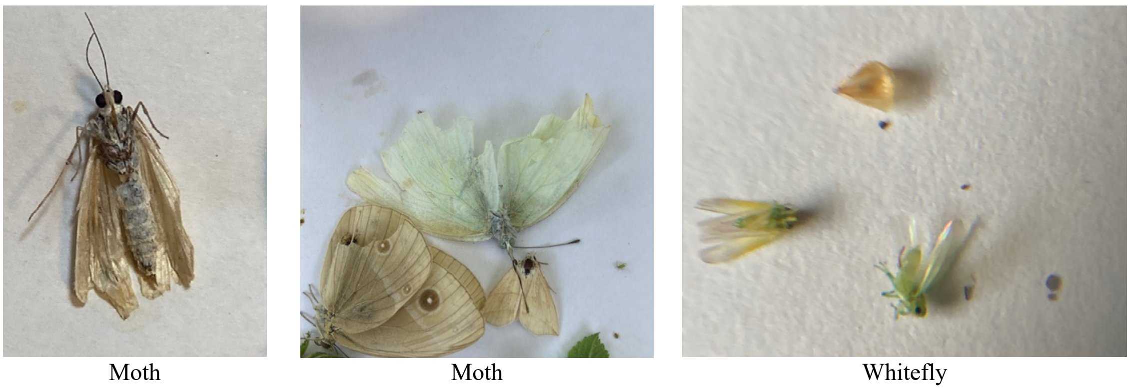


Fig. 7. Images of insect pests after treatment in the mesh-net container at T = 30 sec (T_{on} = 30 sec, T_{off} = 0).

We also carried out the experiments to get disinfection conditions for other pests and summarized the results in Table 2. The disinfection conditions obtained using ozone micro-mist generated by the water spray nozzles are added to this Table 2 [1, 5]. It is shown that treatment times and disinfection rates for the winged pests (moth, whitefly) are similar values for both disinfection systems. The large deference in the case of aphids is mostly due to the disinfection characteristics of the nano- and micro-mists on aphides. Chemical insecticides and spiracle-blocking insecticides have been widely used to disinfect aphides. Considering the results about aphids in Table 2, the chemical disinfection based on ozone reactive radicals is dominant in nano-mist treatments and the shorter treatment time (T = 10 sec) in a micro-mist process means that the spiracle-blocking by water droplets is superior at micro-mist spraying.

Table 2. Disinfection rates of selected species of insect pests.

Ozone nano-mist spray 110 g-O_3 m^{-3} (0.5 L-O_2 min^{-1}, 4.2 mL-water min^{-1}				References [1, 5]; Ozone micro-mist nozzle spray 70 g-O_3 m^{-3} (1 L-O_2 min^{-1}, 300 mL-water min^{-1}
Class	Name	Treatment time (T_{on})	Disinfection rate (%)	Ozone micro-mist nozzle spray
0	Aphid	120	90-100	Green aphid: T = 10 s, 80-90%
1	Moth	30	100	T = 30 s, 90-100%
2	Beetle	1200	50-80	
3	Fly	30	100	
4	Whitefly	30	100	T = 20 s, 90%
5	ant	120	90-100	

4.4 Remote automatic disinfection of insect pests in the greenhouse

The automatic nano-mist spraying system is placed in the greenhouse. The main computer (Windows11) set at the station can remotely control the Raspberry Pi with Wi-Fi. Insect pest picture images (the yellow stick traps or direct shots) taken by the Wi-Fi-equipped camera in the greenhouse are sent to the main computer. The main processes to disinfect insect pests involve 4 consecutive steps as shown in section 3.2. The overall processes of the automatic ozone nano-mist operation were completely accomplished and the experimental results of total consuming time for each species are shown in Table 3. The initial process of the YOLO detection including train and validation consumed about 6 minutes as shown in section 4.2. The next testing process of the object target pests needs 11−12 seconds depending on the conditions (figure, size, numbers) of the selected picture image. Finally, the ozone nano-mist was exposed on the detected pests during the treatment time. Fig. 8 shows pest images disinfected by automatic nano-mist spraying processes at 110 g-O_3 m^{-3}. Moths and whiteflies were disinfected within 30 sec (Fig. 8 (a)) and aphids and beetles need longer treatment time (Fig. 8 (b)). Here, the distance between the target pests and the head of the spray nozzle is about 100mm. In order to increase the effectiveness of the disinfection, a direct spot spray will be adopted and also the distance between the objects and the mist nozzle head will be adjusted automatically by introducing a remote driving system of the spray head.

It is clarified that the developed automatic ozone nano-mist spraying system could be used practically to disinfect winged insect pests at high disinfection rate comparable to chemical pesticide treatments used commonly.

In addition, this nano-mist spray can reduce the volume of processed water (4.2 mL min^{-1}) comparing with the water nozzle micro-mist spray operated at 300 mL min^{-1}. This is another advantage to solve the ubiquitous problems of chemical pesticides in aquatic environment.

Table 3. Consuming time of remote automatic spraying system.

Species	Winged	Parasite	
	Moth, fly, whitefly, ant	aphid	beetle
Train and variation	6 min		
Testing	~ 12 sec		
Raspberry Pi spraying	30 sec	120 sec	1200 sec
Total consuming time	6 min 42 sec	8 min 12 sec	26 min 12 sec

(a) Winged pests: Treatment time T = 30 sec (T_{on} = 30 sec, T_{off} = 0)

(a) Aphids: Treatment time T = 120 sec (T_{on} = 120 sec, T_{off} = 0)

Fig. 8. Pest images disinfected by automatic nano-mist spraying processes at 110 g-O_3 m^{-3}.

5. Conclusion

We developed an automatic ozone nano-mist disinfection system which can be applied remotely to kill insect pests in a greenhouse. The ozone nano-mist was produced by injecting the highly dense ozone of a concentration of 110 g-O_3 m^{-3} into the water nano-mist generated using an ultrasonic humidifier. YOLO object detection was adopted to make the detection and classification of six species of harmful insect pests in the greenhouse. In order to realize an unmanned disinfection management, Raspberry Pi was set in the green house and communicated remotely with the main computer.

This study is summarized as follows:

(1) The overall processes were completely accomplished to implement the ozone nano-mist disinfection in the greenhouse.

(2) The ozone nano-mist spraying is an alternative approach to replace pesticides and its disinfection rates are clarified for selected insect pests.

(3) The YOLO model performed with the mAP@0.5 of 0.968 and the mAP0.5:0.95 of 0.71 for all classes of the selected species. This method using the custom pest dataset shows better performance to detect insect pests with good precision.

(4) The testing stage to classify the object species takes the computing time of 11–12 sec. The ozone nano-mist spraying during 30 sec almost killed winged insect pests and small larva of aphids.

It is concluded that the automatic ozone nano-mist spraying system can be remotely managed by use of disinfection conditions predicted in advance by the YOLO object detection. The nano-mist disinfection can reduce significantly the volume of processed water compared to other disinfection methods. The proposed disinfection system has great potential for practical applications as an alternative to chemical pesticides in agricultural practices.

Acknowledgements

This work was funded by the Polish National Agency of Academic Exchange (NAWA) under the project “POL-JAP ENERGO-ECO”, Grant PPI_APM_2019_1_00009 as well as Lublin University of Technology Grants FD-20/EE-2/416, FD-20/EE-2/401 and 5/GnG/2022.

References

[1] Ebihara K., Mitsugi F., Ikegami T., Nakamura N., Hashimoto Y., Yamashita Y., Baba S., Stryczewska H. D., Pawlat J., Teii S. and Sung T-L., Ozone-mist spray sterilization for pest control in agricultural management,” *EPJ Appl. Phys.*, Vol 61 (2), 24318, 2013.

[2] Stryczewska H. D. and Boiko O., applications of plasma produced with electrical discharges in gases for agriculture and biomedicine,” *Appl. Sci.*, Vol. 12 (9), 4405, 2022.

[3] Stryczewska H. D., Stępień M. A. and Boiko O., Plasma and superconductivity for the sustainable development of energy and the environment," *Energies*, Vol. 15 (11), 4092, June 2022.

[4] Ebihara K., Baba S., Mitsugi F., Ikegami T., Yamashita Y., Aoqui S. and Stryczewska H.D., Ozone-mist sterilization and web-based management for greenhouse agriculture, in *Proc. 2017 Int. Conf. Electromagn. Devices Process. Environ. Prot. with Semin. Appl. Supercond. (ELMECO & AoS)*, pp. 1− 4, 2017.

[5] Ebihara K., Mitsugi F., Aoqui S., Yamashita Y., Baba S., Stryczwska H.D., Deep learning technology for remote identification of insect pest and plant growth in ozone-mist sterilization", in *Proc.2022 Int. Conf. Electromagn. Devices Process. Environ. Prot.(ELMECO -10),* May 2022.

[6] Stryczewska H.D., Ebihara K., Aoqui S., Mitsugi F., and Boiko O., Review of plasma technologies application in agriculture, biomedicine, power and environmental engineering, in *Proc.2022 Int. Conf. Electromagn. Devices Process. Environ. Prot. (ELMECO -10),* May 2022.

[7] Stryczewska H.D., Ebihara K., Aoqui S., Mitsugi F., Boiko O., Review of plasma technologies application in agriculture, biomedicine, power and environmental engineering, in *Proc.2022 Int. Conf. Electromagn. Devices Process. Environ. Prot. (ELMECO -10),* May 2022.

[8] Stryczewska H.D., and Ebihara K., Advanced Technologies for Energy and Environment, Politechnika Lubelska, Lublin 2023.

[9] Mitsugi F., Nagatomo Y., and Stryczewska H.D., Characteristics on filtrates from soil treated by ozone, *IEEE Trans. Plasma Sci*., Vol. 51, pp. 421−428, 2023.

[10] Diaz-Lopez M., Siles J.A., Ros C., Bastida F., and Nicolas E., The effects of ozone treatments on the agro-physiological parameters of tomato plants and the soil microbail community, *Sci. Total Environ*., Vol. 812, 15142, 2022.

[11] Mohanapriya R., Kalpana R., and Aravinth K.V., Role of ozone in food industry and agriculture-Review, *The Indian J. Nutrition and Dietetics*, Vol. 59 (2), pp. 232−249, 2022.

[12] Kim H.H., Abdelaziz A.A., Teramoto Y., Nozaki T., Kim D-Y., Brandenburg R., Schiorlin M., Hensel K., Song Y-H., Lee D-H., Kang W-S., Mizuno A., Revisiting why DBDs can generate O_3 against thermodynamic limit, *Int. J. Plasma Environ. Sci. Technol*., Vol. 17 (2), e020004, 2023.

[13] Saenmuang S., Al-Haq M.I., Makino Y., Kawagoe Y., and Oshita S., Particle size distribution of nano-mist in a spinach-storage atmosphere and its effect n respiration and qualities, *J. Food Eng*., Vol. 112 (1−2), pp. 69−77 2012,.

[14] Saijai S., Thonglek V., and Yoshikawa K., Sterilization effects of ozone fine(micro/nano) bubble water, *Int. J. Plasma Environ. Sci. Technol*. Vo.12 (2), pp. 55− 58, 2019.

[15] Seridou P., and Kalogerakis N., Disinfection applications of ozone micro- and nanobubbles, *Environ. Sci. :Nano*, Vol. 8, pp. 3493−3510, 2021.

[16] Tanuwidjaja I., and Fuka M., Ozone in droplets and mist in inhibition of phytopathogenic microbiota, *Agriculture*, Vol. 12 (11), 1875, 2022.

[17] Epelle E.I., Macfarlane A., Cusack M., Burns A., Okalie J.A., Vichare P., Rolland L., and Yaseen M., Ozone decontamination of medical and nonmedical devices: An assessment of design and implementation considerations, *Ind. Eng. Chem. Res*., Vol. 62, pp. 4191−4209, 2023.

[18] Cho J., Choi J., Qiao M., Ji C−W., Kim H-Y., Uhm K-B., and Chon T-S., Automatic identification of whiteflies, aphids and thrips in greenhouse based on image analysis, *Int. J. Mathematics Comput. Simulat.*, Vol.1 (1), pp. 46−53, 2007.

[19] Zhong Y., Gao J., Lei Q., and Zhou Y., A vision-based counting and recognition system for flying insects in intelligent agriculture, *Sensors*, Vol. 18 (5), 1489, 2018.

[20] Redmon J., Divvla S., Grrshick R., and Farhadi A., You only look once: unified, real−time object detection, in *Proc. 2016 IEEE Conf. Comput. Vis. Pattern Recog. (CVPR)*, pp. 779−788, 2016.

[21] Girshick R., Donahue J., Darrell T., and Malik J., Rich feature hierarchies for accurate object detection and semantic segmentation, *Proc. 2014 IEEE Conf. Comput. Vis. Pattern Recog. (CVPR)*, pp. 580−587, 2014.

[22] Girshick R., Fast R-CNN, *Proc. 2015 IEEE Conf. Comput. Vis. Pattern Recog. (CVPR)*, pp. 1440−1448, 2015.

[23] Önler E., Real time pest detection using YOLOv5, *IJANS*, Vol. 14 (3), pp. 232−246, 2021.

[24] Ahmad I., Yang Y., Yue Y., Ye C., Hassan M., Cheng X., Wu Y., and Zhang Y., Deep learning based detector YOLOV5 for identifying insect pests, *Appl. Sci.*, Vol. 12 (19), 10167, 2022.

[25] He Y., Zeng H., Fan Y., Ji S., and Wu J., Application of deep learning in integrated pest management: A real-time system for detection and diagnosis of oilseed rape pests, *Mob. Inf. Syst.*, Vol. 2019, 4570808, 2019.

[26] Hong S. J., Nam I., Kim S. Y., Kim E., Lee C. H., Ahn S., Park I. K., and Kim C., Automatic pest counting from pheromone trap images using deep learning object detectors for matsucoccus thunbergianae monitoring, *Insects*, Vol. 12 (4), 342, 2021.

[27] Kamath R., Balachandra M., and Prabhu S., Raspberry Pi as Visual Sensor Nodes in Precision Agriculture: A Study," *IEEE Access*, Vol. 7, pp. 45110−45122, 2019.
[28] Mohiddin T. M. D., Gopinadh P., Chandra P. S. and Sowmya V., Pest detection and automatic pesticide spraying using raspberry pi," *Int. J. Innov. Res. Multidiscip. Field*, Vol. 6 (5), pp. 274−280, 2020.
[29] Kotkar V. A., Ghute A. ABhosale., S. A., and Hajare K. H., An automatic pesticide sprayer to detect the crop disease using machine learning algorithms and spraying pesticide on affected crops, *TURCOMAT*, Vol. 12 (1S), pp. 65−72, 2021.
[30] Jiwtode Y.D., Ukani N.A., Sonaskar S.S., Chakole S.S., Smart pesticide spraying robot*, Int. Res. J. Eng. Technol. (IRJET)*, Vol. 9, pp. 706−710, 2022.
[31] Li Y., Xia C., and Lee J., Vision-based pest detection and automatic spray of greenhouse plant, *Proc. IEEE Int. Symp. Ind. Electron.*, pp. 920−925, Jul. 2009.
[32] Lacotte V., Nguyen T., Sempere J.D., Novales V., Dufour V., Moreau R., Pham M.T., Rabennorosoa K., Peignier S., Feugier F.G., Gaetani R., Grenier T., Masenelli B., Silva P.d., Heddi A., Leleve A., pesticide-free robotic control of aphids as corp pests, *AgriEng*., Vol. 4, pp. 903−921, 2022.
[33] Hung D.V., Tong S., Nakano Y., Tanaka F., Hamanaka D., Uchino T., Measurements of particle size distributions produced by humidifiers operating in high humidity storage environments, *Biosys. Eng*., Vol. 107 (1), pp. 54−60, 2010.
[34] Khadre M.A., Yousef A.E., and Kim J.G., Macrobiological aspects of ozone application in food: A Review, *J. Food Sci*., Vol.66, pp. 1242−1252, 2001.