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An Exploration of the Influence of ZnO NPs Treatment on Germination of Radish Seeds under Salt Stress based on the YOLOv8-R Lightweight Model

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Abstract
Background: Since traditional germination test methods have drawbacks such as slow efficiency, proneness to error, and damage to seeds, a non-destructive testing method is proposed for full-process germination of radish seeds, which improves the monitoring efficiency of seed quality.

Results: Based on YOLOv8n, a lightweight test model YOLOv8-R is proposed, where the number of parameters, the amount of calculation, and size of weights are significantly reduced by replacing...
the backbone network with PP-LCNet, the neck part with cross-scale feature fusion module CCFM, the original C2f of the neck part with OREPA, and the original SPPF with FocalModulation. The ablation test and comparative test prove the performance of the model. With adoption of germination rate, germination index, and germination potential as the three vitality indicators, the seed germination phenotype collection system and YOLOv8-R model are used to analyze the full time-series sequence effects of different ZnO NPs concentrations on germination of radish seeds under varying degrees of salt stress.

**Conclusions:** The results show that salt stress inhibits the germination of radish seeds and that the inhibition effect is more obvious with the increased concentration of NaCl solution; in cultivation with deionized water, the germination rate of radish seeds does not change significantly with increased concentration of ZnO NPs, but the germination index and germination potential increase initially and then decline; in cultivation with NaCl solution, the germination rate, germination potential and germination index of radish seeds first increase and then decline with increased concentration of ZnO NPs.

**Keywords:** radish seeds, YOLO model, germination test, ZnO NPs, salt stress

**1 Background**

As the basic means of plant reproduction and dissemination, seeds are an important means of agricultural production, as their quality directly affects the yield and quality of crops (Zhang et al., 2020; Abebe and Alemu, 2017). The germination of seeds is an important indicator of seed quality. The monitoring of seed quality can lay the foundation for cultivating high-quality seeds and increasing food production (Feng et al., 2019; Xia et al., 2019).
Radish is a root vegetable which originated from the cruciferous radish family in Europe (Li et al., 2021). It has high edible and medical value with delicious taste (Curtis, 2011). Due to environmental degradation, climate change, etc., the abiotic stress on growth and productivity of plants has been aggravated (Chieb and Gachomo, 2023). Salt stress is a major abiotic stress that interfere with the growth and development of plants. Zinc oxide nanoparticles (ZnO NPs) is one of the most widely used engineering nanomaterials (Kalpana and Devi Rajeswari, 2018) with certain biological toxicity (Wang et al., 2016). With the advancement and widespread application of nanotechnologies, the release of ZnO NPs into environment has been inevitable, which poses a continuous threat to the ecological safety of plants (Kang et al., 2024). Yang et al. (2015) found that ZnO NPs with a mass concentration of 2000 mg/L significantly inhibited the elongation of root systems of corn and rice. At the same time, however, ZnO NPs also has many positive effects on growth of plants. Li et al. (2021) found that the application of ZnO NPs can reduce the toxicity of Cd to rice seedlings, and promote the increase of seedling weight, total fresh weight, and root-to-crown ratio. However, the effect of ZnO NPs treatment on the salt resistance of radish seeds has rarely been reported. The exploration of the effects of single zinc oxide nanoparticles treatment and single salt stress on the germination of radish seeds, and the effects of zinc oxide nanoparticles treatment on the resistance of radish seeds can provide a test basis for cultivating stress-resistant varieties and a scientific basis for rational use of nanomaterials in agriculture, thereby laying the foundation for sustainable agricultural development.

Traditional germination testing of seeds requires manual counting, which has problems such as slow efficiency, strong subjectivity, and proneness to error. What’s more, some chemical testing methods are destructive to seeds and cause infection, etc. (He et al., 2019), such as staining method (Hampton et al., 1999), conductivity method (Aosa, 1983), enzymatic method
(Guzmán-Ortiz et al., 2019). At present, there are many tests for the determination of seed vitality. Hampton et al. (1999) invented the rapid tetrazole staining method, where the germination and emergence ability of seeds are determined based on the strength of metabolism judged through differences in red characteristics due to dehydrogenation and reduction reaction and the inaccurate judgment caused by seed dormancy is avoided. Borji et al. (2007) tested the conductivity of soybean leaching solution and found that there is a very significant negative correlation between conductivity and germination rate; Wang et al. (2016) adopted artificial accelerated aging method, it was found that the control of moisture content of wolfberry seeds near (5.70±1)% can maintain high vitality and anti-aging ability of seeds stored at low temperature.

In recent years, non-destructive testing of seed germination has been a trend (Xia et al., 2019), including include near-infrared spectroscopy (He et al., 2019), infrared thermal imaging (Kranner et al., 2010), electronic nose (Zhang et al., 2017), laser speckle technology (Braga et al., 2003), etc. X. He et al. He et al. (2019) used near-infrared spectroscopy to identify the vitality of 2,400 rice seeds harvested in three different years with a high classification accuracy of 93.67%, thereby developing a fast and cost-effective industrial online seed sorting system; Zhang et al. (2017) optimized the electronic nose-based sensor array, and used the sensors to classify 5 kinds of sweet corn seeds with different vitality, where the accuracy of the training set and the verification set reached 98.55% and 96.67%, respectively.

Owing to the rapid development of computers, deep learning-based image processing based has been widely used in detecting seed vitality. Zhao et al. (2023) developed a convolutional neural network (YOLO-r) that can detect the germination status of rice seeds and allows automatic evaluation of the total number of germinations, with an average accuracy of 0.9539. The average test time of a single image was 0.011s, and the average absolute error in prediction of germination
rate was within 0.1. Zhang et al. (2023) proposed a mask R-CNN model trained with microscopic images of tree peony pollen for fast testing of the pollen germination rate and pollen tube length. The R2 value of the linear regression model of tested pollen germination rate and ground conditions was 0.909, and the R2 value of the average pollen tube length was 0.958. By combining machine vision technology and deep learning, Bai et al. (2023) constructed a seed germination discrimination model DB-YOLOv5 based on YOLOv5, which was used for fast testing of germination rate, germination potential, germination index and average germination days of wheat seeds. The accuracy rate of the DB-YOLOv5 model for wheat seed germination discrimination was 98.5%. Jiang et al. (2023) proposed a YOLOv8-Peas model whose number of parameters, amount of calculation, and weight file sizes were 1.17M, 3.2g, and 2.7MB, respectively. Compared with YOLOv8, they decreased by 61.2%, 61%, and 56.5%, respectively. PEG6000 was used to simulate different drought environments to analyze the germination of peas of different genotypes, and the pea varieties with the best drought resistance were selected.

In summary, the traditional testing of seed vitality cannot cater agricultural automation due to the disadvantages. Therefore, a future trend is to develop lightweight deep learning network models that allow fast and accurate measurement of the effects of different abiotic stresses on seed germination. In this paper, an improved YOLOv8n-based lightweight YOLOv8-R model is proposed. This model significantly reduces the amount of calculation and improves the testing speed while basically maintaining the accuracy through replacement of backbone network with PP-LCNet, the original C2f of the head with OREPA and the original SPPF with FocalModulation and the adoption of cross-scale feature fusion module (CCFM) at the neck. The germination tests of radish seeds were carried out under salt, drought and zinc oxide nanoparticle conditions, with the use of seed germination phenotype collection system to achieve the full time-series sequence
tracking of germination rate, germination index and germination potential. Then, based on the acquired seed germination image and YOLOv8-R model, the change law of radish seed germination index under different conditions was analyzed.

2 Methods

2.1 Seed Germination Phenotypic Collection System

The experimental seed germination phenotypic acquisition system can be divided into seed cultivation module, environmental control module, image data acquisition module, man-machine interaction module, and phenotypic data analysis module according to functional partitions.

In the seed cultivation module, germination test of radish seeds can be carried out in a 3D-printed 16-cell seed germination petri dish; the environmental control module can realize real-time control of dynamic temperature and humidity of the incubator, where the temperature range is 10°C to 75°C, the humidity range is 30% to 70%. What’s more, the light in the box can also be adjusted by switching; the image data acquisition module consists of an X track and a Y track which are 160mm above the petri dish, as well as a fixed-focus RGB imaging sensor moving on the tracks. During shooting, the external LED lighting ring is automatically turned on to ensure the clarity of the pictures. The PLC program controls the imaging sensor to collect images of 16 cells in sequence at regular intervals; the human-computer interaction module allows the control of temperature, humidity, shooting interval, and camera movement through the touch screen on the incubator; the phenotypic data analysis module allows the transmission of collected images to the PC for processing through GigE gigabit network high-speed interface.

2.2 Data Set Construction
320 full-grain short-leaf early radish seeds without pests or damage were chosen for germination experiments. The germination process is shown in Figure 2 (a), and the test parameters are shown in Figure 2(b). The camera collected one image of each of the 16 cells at an interval of 15 minutes. The experiment lasted for 48 hours, and a total of 3072 images were collected. Some of the collected images are shown in Figure 2(c). It can be seen that the germinated of seeds in the first 12h was not obvious. Therefore, the 768 images collected in the first 12h were deleted because they were of little help to the training model, and 2304 original images were left. Next, the data set was build, as shown in Figure 2 (d).

Germinate was judged by “whitening” of the radish seeds. LabelImg was used to mark the collected pictures as “sprout” or “not sprout”. Then, an xml file containing the image size, the quadrangular coordinates of the label box, and the name of each label box was generated. In order to improve the robustness and generalization of the network model, the collected original images were enhanced to increase the number and diversity of samples. The enhancement methods in the experiment include: Add, Multiply, GaussianBlur, CoarsePepper, GammaContrast, and GaussianNoise. After the enhancement, a total of 5881 images, including the original images, were obtained. Next, all xml files were converted into txt files corresponding to the YOLO model. Finally, the jpg files and the corresponding txt files were randomly divided into training sets, test sets, and verification sets in an 8:1:1 ratio to form the data set used in the training model.

2.3 YOLOv8n-based Lightweight Structure Design (YOLOv8-R)

The YOLO series has achieved great success in the field of computer vision. As the latest target test model of YOLO series, YOLOv8 exhibits excellent robustness and strong learning ability, being the fastest and most accurate target testing model in this series (Terven and Cordova-Esparza, 2023). In the actual agricultural production, due to the problems such as limited computing power of
equipment, it is necessary to reduce the number of parameters and computational complexity of the model while maintaining high precision, so that the model can be deployed on embedded or mobile platforms. Based on YOLOv8n which balances detection accuracy and model complexity, a YOLOv8-R model for testing the germination of radish seeds is proposed. Its network structure is shown in Figure 5(a), and the specific improvements are as follows:

(1) Replacement of backbone network (P-YOLOv8) with PP-LCNet: The backbone network is a key component for extracting data features. The original backbone network structure of YOLOv8n is complex, which resulted in excessive parameters and increased calculations. In PP-LCNet (Cui et al., 2021), DepthSepConv (Howard et al., 2017) is used instead of ordinary convolution as the basic module. Since there is no skip connection, this module will not be a significant impact on the inference speed of the model. The network structure of DepthSepConv is shown in Figure 5(b). It is a fusion of deep convolution (DWConv) and point convolution (PWConv). The use of H-Swish (Howard et al., 2019) in activation functions of PWConv and DWConv can avoid a large number of exponential operations. The activation functions used in the SE (Hu et al., 2018) layer are ReLU and h-sigmoid. The image input trunk passes through the 3×3Conv module, the 3×3DepthSepConv module and the 5×5DepthSepConv module for feature extraction. After testing, it was found that replacement of the convolution module of the neck with DepthSepConv can reduce the number of parameters by 0.16M and the amount of calculation by 0.2G.

(2) Adoption of cross-scale feature fusion module CCFM (PC-YOLOv8) in the neck: CCFM (Lv et al., 2023) is proposed in the RT-DETR model, and jointly constitutes the encoder of the RT-DETR model with attention-based intra-scale feature interaction (AIFI). The main principle of CCFM is to enhance the model’s adaptability to scale changes and the ability to detect
small-scale objects through the fusion of the features of different scales. The effective integration of
detailed features and contextual information improves the overall performance of the model. CCFM
can address the computational redundancy in the encoder to achieve lightweight RT-DETR model.
After reproduction of it in YOLOv8n, it was found in the tests that the number of parameters and
amount of calculation of YOLOv8n are also significantly reduced.

(3) Replacement of C2f (PCO-YOLOv8) of the neck with OREPA: OREPA (Hu et al.,
2022) reduces the cost and complexity of model training through online convolution
re-parameterization, which is divided into two stages: block linearization and block extrusion.
Block linearization is to remove the nonlinear blocks from the prototype re-parameterization blocks,
leaving only the convolution layer and the batch normalization (BN) layer, and a scaling layer is
added to optimize the performance. Block extrusion is to merge a series of convolutional layers,
pooling layers, scaling layers, and frequency prior layer into a single convolution (OREPAConv).
No matter how complex the model is during training, they will be eventually be compressed into a
single 3×3OREPAConv, thereby reducing resource loss. Through the dynamic adjustment of the
weight of the convolutional layer, OREPA greatly reduces the complexity of the model while
ensuring the accuracy. Its structure and the process of block extrusion are shown in Figure 5(c).

(4) Replacement of SPPF (YOLOv8-R) with FocalModulation: FocalModulation (Yang et
al., 2022) is a feature enhancement method that adopts an attention mechanism to focus on key
areas of an image, thereby improving the model’s ability to recognize these areas. In
FocalModulation, the input is first processed through the linear layer. Then, the information is
aggregated selectively through Hierarchical contexalization (Yang et al., 2021) and Gated
aggregation (Liang et al., 2019). Finally, the output is generated through interaction between the
modulator and query. Hierarchical contexalization is to extract contextual features of different
granularity levels through stacking of DWConv layers, while gated aggregation is to aggregate contextual features into a modulator. FocalModulation technology is used to replace the original spatial pyramid pooling-fast (SPPF), which improves the accuracy of the network model without changing the number of parameters and amount of calculation. It is a spatial pyramid pooling with higher accuracy. The structure of FocalModulation and the aggregation process are shown in Figure 5(d).

2.4 Model Training Parameters and Evaluation Indicators

In this experiment, Windows 11 operating system was adopted. The computer was equipped with Intel (R) Xeon(R) Gold 6248R@3.00GHz processor, 30GB memory, NVIDIA GeForce RTX3090 graphics card and 24GB video memory. The development language was Python3.8. The deep learning model framework was Pytorch2.0.0, and the CUDA version was 11.7. The settings of model training parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoch</td>
<td>100</td>
</tr>
<tr>
<td>Batch Size</td>
<td>16</td>
</tr>
<tr>
<td>Image Size</td>
<td>640×640</td>
</tr>
<tr>
<td>Optimizer</td>
<td>Adam</td>
</tr>
<tr>
<td>Learning Rate</td>
<td>0.01</td>
</tr>
<tr>
<td>Weight Decay</td>
<td>0.0005</td>
</tr>
<tr>
<td>Momentum</td>
<td>0.937</td>
</tr>
<tr>
<td>Workers</td>
<td>8</td>
</tr>
</tbody>
</table>

In order to comprehensively evaluate the effectiveness of the model in testing the germination of radish seeds and its satisfaction of the lightweight requirements on low cost and high efficiency, the precision rate (P), recall rate (R), and mean average precision (mAP) were used as indicators to
evaluate the accuracy of the model; the number of parameters (Params), and floating-point Operations Per second (FLOPs), and weight size (Weight Size) were used as indicators to evaluate the complexity of the model.

The precision rate is the proportion of the correct prediction in all the results predicted by the model; the recall rate is the proportion of the correct prediction in all positive samples; mAP is the mean value of AP of each class, including the trade-off between precision and recall rate; the parameter quantity is the number of all parameters of the model; the amount of calculation is the total number of floating-point calculation of the model; the weight file contains the weight and bias in each layer of the model and other parameters. All three indicators are used to reflect the degree of lightness of the model. The specific calculation formula is shown below.

\[
P = \frac{TP}{TP + FP} \tag{1}
\]

\[
R = \frac{TP}{TP + FN} \tag{2}
\]

\[
mAP = \frac{1}{C} \sum_{i=1}^{C} AP_i \tag{3}
\]

\[
Params = C_{in} \times K^2 \times C_{out} \tag{4}
\]

\[
FLOPs = 2 \times H \times W(C_{in}K^2 + 1)C_{out} \tag{5}
\]

Where, true positives (TP) means the number of germinated and non-germinated seeds correctly detected by the model; false positives (FP) means false identification of non-seed areas as the number of seeds marked “sprouted” or “not sprouted” by the model; false negatives (FN) means the actual number of germinated or non-germinated seeds that are not detected by the model; C means the number of categories; C_{in} and C_{out} mean the number of input and output channels; H and W mean the spatial size of the output feature map; and K means the convolution kernel size.

2.5 Ablation Tests

In order to verify the feasibility of the proposed improved model YOLOv8-R in terms of
performance, and reflect the impact of different improved modules on its detection performance. Ablation tests were carried out based on YOLOv8n. In each training, all parameters were consistent except the improvement of modules. The ablation test results are shown in Table 2.

Table 2 Ablation test results

<table>
<thead>
<tr>
<th>Model</th>
<th>P/%</th>
<th>R/%</th>
<th>mAP50/%</th>
<th>Params/M</th>
<th>FLOPs/G</th>
<th>Weight Size/MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>YOLOv8n</td>
<td>99.0</td>
<td>99.3</td>
<td>99.2</td>
<td>3.01</td>
<td>8.1</td>
<td>6.2</td>
</tr>
<tr>
<td>P-YOLOv8</td>
<td>96.6</td>
<td>98.0</td>
<td>98.8</td>
<td>1.69</td>
<td>5.0</td>
<td>3.4</td>
</tr>
<tr>
<td>PC-YOLOv8</td>
<td>96.9</td>
<td>98.0</td>
<td>98.7</td>
<td>0.75</td>
<td>3.6</td>
<td>1.7</td>
</tr>
<tr>
<td>PCO-YOLOv8</td>
<td>96.4</td>
<td>97.7</td>
<td>98.7</td>
<td>0.94</td>
<td>3.2</td>
<td>2.1</td>
</tr>
<tr>
<td>YOLOv8-R</td>
<td>98.0</td>
<td>98.8</td>
<td>99.1</td>
<td>0.93</td>
<td>3.2</td>
<td>2.0</td>
</tr>
</tbody>
</table>

As shown in Table 2, after the backbone network is replaced with PP-LCNet, the presence of DepthSepConv reduced a large number of operations. The number of parameters, amount of calculation, and weight file size of P-YOLOv8 were reduced by 43.9%, 38.3% and 45.2%, respectively, but the detection accuracy was sacrificed. After adoption of CCFM in the neck part, the computational redundancy was effectively eliminated, which further reduced the number of parameters, amount of calculation, and weight file size of PC-YOLOv8 by 55.6%, 28% and 50%, respectively while basically maintaining the precision. After the C2f of the neck part was replaced with OREPA, the complex structure can be compressed into a single convolution. The number of parameters and weight file size of PCO-YOLOv8 slightly increased, but the amount of calculation was reduced by 11.1% without the detection of precision. After FocalModulation was replaced with SPPF, the model complexity of YOLOv8-R remained basically the same, but the precision was improved. In summary, YOLOv8-R significantly reduces the complexity of the model, with excellent performance in terms of lightweight. At the same time, YOLOv8-R maintains the high-precision performance of the basic model YOLOv8n, which reflects its feasibility in testing the germination of radish seeds and its potential to be deployed on embedded devices.
**2.6 Comparative test**

In order to further verify the superiority and effectiveness of YOLOv8-R, it is compared with the currently widely used target detection models such as RT-DETR-x, YOLOv3, YOLOv3-tiny, YOLOv5s, YOLOv6-v3.0, YOLOv7, YOLOv7x, YOLOv7-tiny, and YOLOv8s. All parameters were consistent during the experiment, and the results are shown in Table 3.

**Table 3 Comparative test results**

<table>
<thead>
<tr>
<th>Model</th>
<th>P/%</th>
<th>R/%</th>
<th>mAP50/%</th>
<th>Params/M</th>
<th>FLOPs/G</th>
<th>Weight Size/MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT-DETR-x</td>
<td>94.6</td>
<td>94.5</td>
<td>95.2</td>
<td>65.47</td>
<td>222.5</td>
<td>129.1</td>
</tr>
<tr>
<td>YOLOv3</td>
<td>97.4</td>
<td>98.1</td>
<td>98.8</td>
<td>103.69</td>
<td>283.0</td>
<td>198.1</td>
</tr>
<tr>
<td>YOLOv3-tiny</td>
<td>96.6</td>
<td>97.9</td>
<td>98.7</td>
<td>12.13</td>
<td>18.9</td>
<td>23.2</td>
</tr>
<tr>
<td>YOLOv5s</td>
<td>97.9</td>
<td>98.8</td>
<td>98.7</td>
<td>9.11</td>
<td>23.8</td>
<td>17.7</td>
</tr>
<tr>
<td>YOLOv6-v3.0</td>
<td>96.3</td>
<td>97.1</td>
<td>98.5</td>
<td>4.23</td>
<td>11.8</td>
<td>8.3</td>
</tr>
<tr>
<td>YOLOv7</td>
<td>98.6</td>
<td>98.4</td>
<td>98.9</td>
<td>37.20</td>
<td>105.1</td>
<td>74.8</td>
</tr>
<tr>
<td>YOLOv7x</td>
<td>98.4</td>
<td>98.3</td>
<td>98.7</td>
<td>70.03</td>
<td>188.9</td>
<td>142.1</td>
</tr>
<tr>
<td>YOLOv7-tiny</td>
<td>87.2</td>
<td>96.7</td>
<td>97.7</td>
<td>6.02</td>
<td>13.2</td>
<td>12.3</td>
</tr>
<tr>
<td>YOLOv8s</td>
<td>99.3</td>
<td>99.6</td>
<td>99.2</td>
<td>11.13</td>
<td>28.7</td>
<td>21.5</td>
</tr>
<tr>
<td>YOLOv8-R</td>
<td>98.0</td>
<td>98.8</td>
<td>99.1</td>
<td>0.93</td>
<td>3.2</td>
<td>2.0</td>
</tr>
</tbody>
</table>

It can be seen from Table 3 that, RT-DETR-x has no advantages in terms of both precision and complexity; YOLOv3, YOLOv3-tiny, YOLOv5s, and YOLOv6-v3.0 exhibited high precision, but YOLOv3 involves a huge amount of calculation and parameters; compared with YOLOv7 and YOLOv7x, YOLOv7-Tiny is lighter, but partial detection precision is sacrificed; compared with the previous YOLO version, YOLOv8s has fewer parameters but better detection performance; the mAP50 of YOLOv8-R is second only to YOLOv8s, and the model complexity is much lower than other models. In order to more intuitively demonstrate the advantages of YOLOv8-R, 6 lightweight models were further compared, including YOLOv3-tiny, YOLOv5s, YOLOv6-v3.0, YOLOv7-tiny, YOLOv8s, and YOLOv8-R. Figure 4 (a) is the detection result of the six models at the five
moments of radish seed germination. Where, yellow means repeated detection and green means erroneous detection. At time I, the seeds had not yet germinated, and there was repeated detection of YOLOv3-tiny, YOLOv5s, and YOLOv7-tiny; at time II, the seeds began to germinate, and there was repeated detection of YOLOv7-tiny; at time III, a small part of the seeds were germinated, and there was repeated detection of YOLOv5s, YOLOv7-tiny, and YOLOv8-R; At time IV, most of the seeds were germinated, and there was repeated detection of YOLOv5s and YOLOv6-v3.0. There was erroneous detection of YOLOv7-tiny and YOLOv8s; At time V, all seeds were basically germinated, and repeated detection is found except YOLOv8s. Figure 4(b) more intuitively shows the performance comparison of the above six models. In summary, YOLOv8-R well balance the precision and complexity, and has high overall performance and use value.

3 Results and Discussion

3.1 Experimental Design

Based on the seed germination collection system and the improved target detection model YOLOv8-R, the 48h full time-series sequence change law of the dual variables of zinc oxide nanoparticles treatment and salt stress on the germination of radish seeds was analyzed. The experimental design is shown in Table 4. The NaCl solution was used to simulate salt stress, and a 2-factor randomized block design was adopted. There were a total of 25 treatments, each of which was done in 4 cells at a time, with a repetition of 3 times. The experimental process is shown in Figure 5, where the particle size of ZnO NPs was 20~30 nm.
### Table 4 Experimental design

<table>
<thead>
<tr>
<th>NaCl/mmol·L⁻¹</th>
<th>Concentration of ZnO NPs/mg·L⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 (CK) 200 (A) 400 (B) 600 (C) 800 (D)</td>
</tr>
<tr>
<td>0 (CK)</td>
<td>CK</td>
</tr>
<tr>
<td>30 (T1)</td>
<td>T1</td>
</tr>
<tr>
<td>60 (T2)</td>
<td>T2</td>
</tr>
<tr>
<td>90 (T3)</td>
<td>T3</td>
</tr>
<tr>
<td>120 (T4)</td>
<td>T4</td>
</tr>
</tbody>
</table>

### 3.2 Evaluation indicators of germination

The germination rate, germination potential, and germination index were used as the evaluation indicators of the germination of radish seeds. The germination potential reflects the germination speed and neatness of seeds, and the germination index can also reflect the germination speed of seeds. The specific calculation formula is as follows:

\[
Germination\ rate = \frac{N_t}{N} \times 100\% \tag{7}
\]

\[
Germination\ energy = \frac{N_{32}}{N} \times 100\% \tag{8}
\]

\[
Germination\ index = \sum \frac{G_t}{D_t} \tag{9}
\]

Where, \(N_t\) means the number of seeds germinated after \(t\) hours; \(N\) means the number of tested seeds; \(N_{32}\) means the number of seeds germinated within 32 hours before the peak of germination; \(G_t\) is number of seeds germinated after \(t\) hours of culture; \(D_t\) is the corresponding during of culture.

### 3.3 Effects of different concentrations of ZnO NPs on the germination of radish seeds under salt stress

Salt stress is a key factor that affects growth and yield of crops. Saline soil can cause physiological and metabolic disorders of plants and affect seed germination (Jouyban, 2012). At present, the widespread application of nanotechnologies in materials, energy, medicine, and other fields has
brought fundamental changes to many aspects of modern society, and its rapid development in biotechnology and agriculture has also been witnessed (Siddiqui et al., 2015). However, the influence of ZnO NPs on the germination of radish seeds under salt stress is not yet clear. According to Table 4, the germination rate, germination potential, and germination index of radish seeds treated with ZnO NPs of NaCl concentrations of 0, 30mmol·L$^{-1}$, 60mmol·L$^{-1}$, 90mmol·L$^{-1}$, and 120mmol·L$^{-1}$ were tested and compared to explore the effect of ZnO NPs treatment on the germination of radish seeds under salt stress, thereby providing a test basis for cultivating salt-tolerant varieties.

(1) The effects of treatment with different concentrations of ZnO NPs on the germination of radish seeds. The germination test of radish seeds treated under CK, A, B, C, and D were carried out, as shown in Table 4, and the germination images within 48h were obtained, as shown in Figure 6; the YOLOV8-R model was used to detect the germination images, thereby obtaining the germination rate, germination potential and germination index of radish seeds treated with different concentrations of ZnO NPs, as shown in Figure 7.

Figure 7 (a) shows the change in germination rate of radish seeds soaked in different concentrations of ZnO NPs with the advancement of time. Taking the data of Dt=28.25h-32h as an example, the Mean Value line segment represents the mean germination rate of the three groups of repeated tests during 28.25h-32h. As can be seen from Figure 7 (a), with the advancement of germination Dt, the germination rate of radish seeds soaked in different concentrations of ZnO NPs showed an increasing trend. With the increase of ZnO NPs concentration, the germination rate of all radish seeds were above 95% without significant difference, but the initial germination time showed a trend of delay and postponement. Within the germination Dt=44.25-48h, the germination rates of radish seeds soaked in deionized water (CK), 200mg·L$^{-1}$, 400mg·L$^{-1}$, 600mg·L$^{-1}$, and
800mg·L⁻¹ ZnO NPs in the control group were 97.50%, 97.50%, 96.67%, 96.67% and 95.83%, respectively. It can be seen that with the increase of ZnO NPs concentration, there is no significant effect on the germination rate of radish seeds.

Figures 7 (b) and (c) show the changes in germination index and germination potential of radish seeds soaked in different concentrations of ZnO NPs with the advancement of time. The germination potential of radish seeds soaked in CK, 200mg·L⁻¹, 400mg·L⁻¹, 600mg·L⁻¹, 800mg·L⁻¹ ZnO NPs was 90.00%, 92.86%, 93.75%, 81.64% and 66.67%, respectively. Within the germination Dt=44.25-48h, the germination index of the seeds treated with each concentration was 44.53, 51.86, 48.33, 35.11 and 30.60, respectively. It can be seen that with the increase of ZnO NPs concentration, the germination potential and germination index showed an upward and then downward trend. Where, the germination potential and germination index of seeds treated with ZnO NPs of a concentration of 200mg·L⁻¹ and 400mg·L⁻¹ were higher than that of the control group; the germination potential and germination index of seeds treated with ZnO NPs of a concentration of 600mg·L⁻¹ and 800mg·L⁻¹ declined to different degrees compared to those of CK, and the higher the concentration, the more obvious the inhibitory effect. Therefore, the treatment with low-concentration ZnO NPs in breeding radish seeds in deionized water can improve the speed and potential of germination to a certain extent, while high-concentration ZnO NPs will inhibit the speed and potential of germination of seeds.

(2) The effects of different concentrations of ZnO NPs on the germination of radish seeds in 30mmol·L⁻¹ NaCl solution. The germination test of radish seeds treated with T1, AT1, BT1, CT1, and DT1 were carried out, as shown in Table 4, and the germination images within 48h were obtained, as shown in Figure 8; the YOLOV8-R model was to detect the germination images, thereby obtaining the germination rate, germination potential and germination index of radish seeds.
treated with different concentrations of ZnO NPs in 30mmol·L⁻¹NaCl solution, as shown in Figure 9.

Figure 9 (a) shows the change in germination rate of radish seeds with different concentrations of ZnO NPs soaked in 30mmol·L⁻¹NaCl solution with the advancement time (the same calculation method in (1) is adopted). As can be seen from Figure 9(a), with the advancement of germination Dt, the germination rate of radish seeds treated with different concentrations of ZnO NPs in 30mmol·L⁻¹NaCl solution showed an increasing trend. The initial germination time of radish seeds soaked in deionized water (CK) in the control group occurred in the first 12.25-16 hours, and the initial germination of radish seeds soaked in 400mg·L⁻¹ZnO NPs occurred in the first 8.25-12 hours. The initial germination time showed an earlier trend compared with that of the control group. Within the germination Dt=44.25-48h, the germination rates of radish seeds soaked in CK, 200mg·L⁻¹, 400mg·L⁻¹, 600mg·L⁻¹, and 800mg·L⁻¹ZnO NPs were 90.00%, 95.00%, 91.35%, 89.00% and 85.63%, respectively. It can be seen that with the increase of ZnO NPs concentration, the germination rate of radish seeds showed an upward and then downward trend, where the germination rate was the highest when the concentration was 200mg·L⁻¹ZnO NPs.

Figures 9 (b) and (c) show the changes in germination index and germination potential of radish seeds treated with different concentrations of ZnO NPs in 30mmol·L⁻¹NaCl solution with the advancement of time. The germination potential of seeds soaked in CK, 200mg·L⁻¹, 400mg·L⁻¹, 600mg·L⁻¹, 800mg·L⁻¹ZnO NPS was 78.33%, 81.83%, 74.25%, 67.85% and 61.17%, respectively. Within the germination Dt=44.25-48h, the germination index of the seeds treated with each concentration was 39.05, 41.10, 38.45, 36.04 and 35.07, respectively. It can be seen that with the increase of ZnO NPs concentration, both the germination potential and germination index show an upward and then downward trend. Where, the germination potential and germination index of the
seeds were the highest when they were soaked in 200mg·L⁻¹ ZnO NPs; the germination potential and
germination index of the seeds soaked in 400mg·L⁻¹, 600mg·L⁻¹, and 800mg·L⁻¹ ZnO NPs were
lower at varying degrees compared with those in CK, and the higher the concentration, the more
obvious the inhibition effect. Therefore, the treatment of radish seeds with low-concentration ZnO
NPs in 30mmol·L⁻¹ NaCl solution can improve the speed and potential of germination, while
high-concentration ZnO NPs will inhibit the speed and potential of germination.

(3) The effects of different concentrations of ZnO NPs on the germination of radish seeds
in 60mmol·L⁻¹ NaCl solution. The germination test of radish seeds treated with T2, AT2, BT2, CT2,
and DT2 were carried out, as shown in Table 4, and the germination images within 48h were
obtained, as shown in Figure 10; the YOLOV8-R model was used to detect the germination images,
thereby obtaining the germination rate, germination potential and germination index of radish seeds
treated with different concentrations of ZnO NPs in 60mmol·L⁻¹ NaCl solution, as shown in Figure
11.

Figure 11 (a) shows the change in germination rate of radish seeds with different
concentrations of ZnO NPs soaked in 60mmol·L⁻¹ NaCl solution with the advancement time (the
same calculation method in (1) is adopted). As can be seen from Figure 11(a), with the advancement
of germination Dt, the germination rate of radish seeds treated with different concentrations of ZnO
NPs in 60mmol·L⁻¹ NaCl solution showed an increasing trend. Within the germination
Dt=44.25-48h, the germination rates of radish seeds soaked in Ionized water (CK), 200mg·L⁻¹,
400mg·L⁻¹, 600mg·L⁻¹, and 800mg·L⁻¹ ZnO NPs were 78.33%, 89.12%, 82.50%, 77.50% and
78.13%, respectively. It can be seen that with the increase of ZnO NPs concentration, the
germination rate of radish seeds showed an upward and then downward trend, where the
germination rate was the highest when the concentration was 200mg·L⁻¹ ZnO NPs.
Figures 11 (b) and (c) show the changes in germination index and germination potential of radish seeds treated with different concentrations of ZnO NPs in 60mmol·L⁻¹NaCl solution with the advancement of time. The germination potential of seeds soaked in CK, 200mg·L⁻¹, 400mg·L⁻¹, 600mg·L⁻¹, 800mg·L⁻¹ZnO NPs was 48.63%, 54.17%, 62.33%, 56.17% and 50.00%, respectively. Within the germination Dt=44.25-48h, the germination index of the seeds treated with each concentration was 26.45, 33.00, 39.40, 26.93 and 25.52, respectively. It can be seen that with the increase of ZnO NPs concentration, both the germination potential and germination index show an upward and then downward trend. Where, the germination potential and germination index of the seeds were the highest when they were soaked in 400mg·L⁻¹ZnO NPs; the germination potential and germination index of the seeds soaked in 600mg·L⁻¹ZnO NPs started to decline; and the inhibition effect was more significant when they were soaked in 800mg·L⁻¹ZnO NPs. However, the germination potential of seeds treated with all concentrations of ZnO NPs was higher that that in CK. Except the seeds treated with 800mg·L⁻¹ZnO NPs, the germination index of all seeds treated with rest concentrations of ZnO NPs was higher than that of CK. Therefore, the treatment of radish seeds with low-concentration ZnO NPs in 60mmol·L⁻¹NaCl solution can improve the speed and potential of germination.

(4) The effects of different concentrations of ZnO NPs on the germination of radish seeds in 90mmol·L⁻¹NaCl solution. The germination test of radish seeds treated with T3, AT3, BT3, CT3 and DT3 were carried out, as shown in Table 4, and the germination images within 48h were obtained, as shown in Figure 12; the YOLOV8-R model was to detect the germination images, thereby obtaining the germination rate, germination potential and germination index of radish seeds treated with different concentrations of ZnO NPs in 90mmol·L⁻¹NaCl solution, as shown in Figure 13.
Figure 13 (a) shows the change in germination rate of radish seeds with different concentrations of ZnO NPs soaked in 90mmol·L\(^{-1}\)NaCl solution with the advancement time (the same calculation method in (1) is adopted). As can be seen from Figure 13(a), with the advancement of germination Dt, the germination rate of radish seeds treated with different concentrations of ZnO NPs in 90mmol·L\(^{-1}\)NaCl solution showed an increasing trend. Within the germination Dt=44.25-48h, the germination rates of radish seeds soaked in deionized water (CK), 200mg·L\(^{-1}\), 400mg·L\(^{-1}\), 600mg·L\(^{-1}\), and 800mg·L\(^{-1}\)ZnO NPs were 48.33%, 63.33%, 57.83%, 55.88% and 54.38%, respectively. It can be seen that with the increase of ZnO NPs concentration, the germination rate of radish seeds showed an upward and then downward trend. Where, the germination rate was the highest when the concentration was 200mg·L\(^{-1}\)ZnO NPs, and the germination rate of seeds soaked in each concentration of ZnO NPs was higher than that of the control group CK.

Figures 13 (b) and (c) show the changes in germination index and germination potential of radish seeds treated with different concentrations of ZnO NPs in 90mmol·L\(^{-1}\)NaCl solution with the advancement of time. The germination potential of seeds soaked in CK, 200mg·L\(^{-1}\), 400mg·L\(^{-1}\), 600mg·L\(^{-1}\), 800mg·L\(^{-1}\)ZnO NPS was 41.68%, 46.25%, 48.33%, 39.17% and 35.00%, respectively. Within the germination Dt=44.25-48h, the germination index of the seeds treated with each concentration was 17.14, 19.62, 18.44, 17.75 and 14.86, respectively. It can be seen that with the increase of ZnO NPs concentration, both the germination potential and germination index show an upward and then downward trend. Where, the germination potential and germination index of the seeds showed an increasing trend when they were soaked in 200mg·L\(^{-1}\) and 400mg·L\(^{-1}\)ZnO NPs, and reached the maximum value when they were soaked in 400mg·L\(^{-1}\)ZnO NPs. The germination potential and germination index of the seeds started to decline when they were soaked in
600mg·L⁻¹ZnO NPs, and the inhibition effect was more obvious when they were soaked in 800mg·L⁻¹ZnO NPs. The germination potential of seeds soaked in 600mg·L⁻¹ and 800mg·L⁻¹ZnO NPs was lower than that in CK, and the germination index of seeds soaked in 800mg·L⁻¹ZnO NPs was lower than that in CK. Therefore, the treatment of radish seeds with low-concentration ZnO NPs in 90mmol·L⁻¹NaCl solution can improve the speed and potential of germination, while high-concentration ZnO NPs will inhibit the speed and potential of germination.

(5) The effects of different concentrations of ZnO NPs on the germination of radish seeds in 120mmol·L⁻¹NaCl solution. The germination test of radish seeds treated with T4, AT4, BT4, CT4 and DT4 were carried out, as shown in Table 4, and the germination images within 48h were obtained, as shown in Figure 14; the YOLOV8-R model was used to detect the germination images, thereby obtaining the germination rate, germination potential and germination index of radish seeds treated with different concentrations of ZnO NPs in 120mmol·L⁻¹NaCl solution, as shown in Figure 15.

Figure 15 (a) shows the change in germination rate of radish seeds with different concentrations of ZnO NPs soaked in 120mmol·L⁻¹NaCl solution with the advancement time (the same calculation method in (1) is adopted). As can be seen from Figure 15(a), with the advancement of germination Dt, the germination rate of radish seeds treated with different concentrations of ZnO NPs in 120mmol·L⁻¹NaCl solution showed an increasing trend. Within the germination Dt=44.25-48h, the germination rates of radish seeds soaked in Ionized water (CK), 200mg·L⁻¹, 400mg·L⁻¹, 600mg·L⁻¹, and 800mg·L⁻¹ZnO NPs were 35.13%, 45.00%, 57.50%, 51.38% and 39.69%, respectively. It can be seen that with the increase of ZnO NPs concentration, the germination rate of radish seeds showed an upward and then downward trend, where the germination rate was the highest when the concentration was 400mg·L⁻¹ZnO NPs and the...
germination rate of seeds soaked with different concentrations of ZnO NPs was higher than that in CK.

Figures 15 (b) and (c) show the changes in germination index and germination potential of radish seeds treated with different concentrations of ZnO NPs in 120mmol·L⁻¹NaCl solution with the advancement of time. The germination potential of seeds soaked in CK, 200mg·L⁻¹, 400mg·L⁻¹, 600mg·L⁻¹, 800mg·L⁻¹ZnO NPs was 19.58%, 22.50%, 26.17%, 17.92% and 21.25%, respectively. Within the germination Dt=44.25-48h, the germination index of the seeds treated with each concentration was 10.12, 11.63, 14.73, 11.86 and 11.25, respectively. It can be seen that with the increase of ZnO NPs concentration, both the germination potential and germination index show an upward and then downward trend. Where, the germination potential and germination index of the seeds were the highest when they were soaked in 200mg·L⁻¹ZnO NPs; the germination potential and germination index of the seeds soaked in 600mg·L⁻¹ZnO NPs started to decline; and the inhibition effect was more significant when they were soaked in 800mg·L⁻¹ZnO NPs. The germination potential and germination index of seeds treated with all concentrations of ZnO NPs was higher than those in CK. Therefore, the treatment of radish seeds with low-concentration ZnO NPs in 120mmol·L⁻¹NaCl solution can improve the speed and potential of germination.

Finally, according to the longitudinal comparison of the above five sets of data, after the soaking in deionized water, the germination rate of radish seeds cultivated with 0, 30mmol·L⁻¹, 60mmol·L⁻¹, 90mmol·L⁻¹, and 120mmol·L⁻¹NaCl solution was 97.50%, 90.00%, 78.33%, 48.33% and 35.13%, respectively. It can be seen that with the increase of salt concentration, its inhibition effect on the germination of radish seeds is more obvious. After the soaking in other concentrations of ZnO NPs, as the concentration of NaCl solution increases, the inhibition effect on germination of radish seeds is more obvious.
4 Conclusions

In order to address low efficiency, large error, and proneness to damage to seed structure in the traditional manual testing of seed germination and cater to the needs of non-destructive monitoring of the whole-process germination of radish seeds, the following work has been carried out:

(1) A full time-series sequence seed germination phenotypic collection system consisting of seed cultivation module, environmental control module, image data acquisition module, human-computer interaction module, and phenotypic data analysis module was used. The images of the germination of radish seeds in 16 cells were collected at an interval of 15 minutes, thereby constructing a label data set of the images of the whole-process germination of radish seeds; the germination tests of radish seeds were conducted on the dual variables of ZnO NPs treatment and salt stress, and the whole-process germination images of radish seeds with 48h were collected;

(2) Based on the YOLOv8n model, tests were carried out to evaluate the detection precision of the germination images of radish seeds and the model complexity. With replacement of backbone network with PP-LCNet, the adoption of cross-scale feature fusion module (CCFM) in the neck part, the replacement of C2f of the neck part with OREPA, and the replacement of SPPF with FocalModulation, the YOLOv8n detection model was improved to P-YOLOv8, PC-YOLOv8, PCO-YOLOv8, and YOLOv8-R detection models, and ablation tests were carried out. Then, the detection precision and model complexity of the foregoing models were analyzed; Comparative tests were made among the YOLOv8-R, YOLOv3-tiny, YOLOv5s, YOLOv6-v3.0, YOLOv7-tiny, YOLOv8s and other widely used target detection models, which verified the effectiveness of the above improvement methods;

(3) The germination rate, germination index and germination potential were used as the
three indicators for evaluating the vitality. On the basis of the YOLOv8-R model, the germination of radish seeds cultivated in 0, 30mmol·L⁻¹, 60mmol·L⁻¹, 90mmol·L⁻¹, 120mmol·L⁻¹ NaCl after treatment with CK, 200mg·L⁻¹, 400mg·L⁻¹, 600mg·L⁻¹, and 800mg·L⁻¹ ZnO NPs was analyzed. The results show that: after the soaking in deionized water, with the increase of the concentration of NaCl solution, the number of germinated radish seeds gradually decreased, and the germination rate, germination potential and germination index all showed a declining trend; in the cultivation in deionized water, compared with the deionized water (CK) group, with the increase of the concentration of ZnO NPs, the germination rate does not change significantly, and the germination index and germination potential both show an upward and then downward trend; in the cultivation in 30mmol·L⁻¹, 60mmol·L⁻¹, 90mmol·L⁻¹, 120mmol·L⁻¹ NaCl solutions, compared with the deionized water (CK) group, with the increase of the concentration of ZnO NPs, the germination rate, germination potential and germination index of radish seeds all show an upward and then downward trend. Therefore, the treatment with low-concentration ZnO NPs can promote the germination rate and germination potential of radish seeds under salt stress, and while high-concentration ZnO NPs inhibits their germination rate and germination potential.

In summary, it is expected that the method for analyzing the whole-process germination of radish seeds based on the target lightweight YOLOv8-R test model will provide a valuable reference for a deeper understanding of the germination process of soaked crop seeds, the exploration of the influence of nanomaterials on crops’ germination characteristics and internal physiological characteristics, the application of nanomaterials in agriculture and biotechnology, and the breeding of salt-resistant crops, thereby achieving digital modern agriculture and high yield of high-quality crops.
List of abbreviations

ZnO NPs: Zinc Oxide Nanoparticles
YOLO: You Only Look Once
LED: Light Emitting Diode
PLC: Programmable Automation Controller
Adam: Adaptive Moment Estimation
P: Precision
R: Recall
AP: Average Precision
mAP: mean Average precision
FLOPs: Floating-point Operations Per second

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.
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**Authors’ contributions**

YZ and HZ: conceptualization; ZO, XF, ZZ and RB: methodology; ZO: writing original draft preparation; QC, GG and ML: writing—review and editing. All authors read and approved the final manuscript.

**References**


germination, emergence rate, electrical conductivity in common bean (Phaseolus vulgaris L.).


**Figure**

![Seed germination phenotypic collection system](image_url)
Fig. 2 (a) Germination test process. (b) Test parameters. (c) Collected images of radish seed germination. (d) Data set construction process.
**Fig. 3** (a) YOLOv8-R network structure. (b) DepthSepConv network structure. (c) OREPA network structure and block extrusion process. (d) FocalModulation network structure and aggregation process.
Fig. 4 (a) The detection results of each lightweight model at different stages of germination. (b)
Comparison of the performance indicators of each lightweight model

Fig. 5 The detection and experimental process of ZnO NPs treatment on the germination of radish seeds under salt stress
Fig. 6 Germination images of radish seeds treated with different concentrations of ZnO NPs
Fig. 7 Detection of germination of radish seeds treated with different concentrations of ZnO NPs.
Fig. 8 Germination images of radish seeds treated with different concentrations of ZnO NPs in 30mmol·L⁻¹ NaCl solution
Fig. 9 Detection of germination of radish seeds treated with different concentrations of ZnO NPs in 30mmol·L⁻¹NaCl solution
Fig. 10 Germination images of radish seeds treated with different concentrations of ZnO NPs in
60mmol·L⁻¹ NaCl solution
Detection of germination of radish seeds treated with different concentrations of ZnO NPs in 60 mmol·L⁻¹ NaCl solution
Fig. 12 Germination images of radish seeds treated with different concentrations of ZnO NPs in
90mmol·L$^{-1}$NaCl solution
Fig. 13 Detection of germination of radish seeds treated with different concentrations of ZnO NPs in 90mmol·L⁻¹NaCl solution
Fig. 14 Germination images of radish seeds treated with different concentrations of ZnO NPs in
120 mmol·L⁻¹ NaCl solution
Fig. 15 Detection of germination of radish seeds treated with different concentrations of ZnO NPs in 120mmol·L⁻¹NaCl solution