The effects of oregano essential oil on production performance and intestinal barrier function in growing Hyla rabbits

Chenyang Li*, Jinling Niu*, Yongxu Liu, Fuchang Li and Lei Liu

*Department of Animal Science, Shandong Agricultural University, Taian, China; Qingdao Kangda Food Co., Ltd., Huangdao, China

ABSTRACT
The purpose of this study was to investigate the effects of oregano essential oil on the production performance and intestinal barrier in rabbits. One hundred and ninety-two weaned Hyla rabbits (35 days old) with similar body weight (1268.5 ± 25 g) were randomly divided into four groups (24 replicates per group, two rabbits per replicate): fed a basal diet (Control group), fed a basal diet containing 0.02% oregano essential oil (LO group, the purity of oregano essential oil was 5%), fed a basal diet containing 0.04% oregano essential oil (MO group), or fed a basal diet containing 0.08% oregano essential oil (HO group). The trial included 7 days of adaptation and 23 days of testing. Although dietary addition of oregano essential oil did not affect significantly the average daily body weight and final body weight (*p > .05), dietary addition of 0.08% oregano essential oil decreased significantly feed intake and diarrhoea rate of the rabbits (*p < .05). When the addition of oregano essential oil in the feed reached 0.08%, the Villus high/Crypt depth value in the ileum of meat rabbits increased significantly (*p < .05). Dietary addition of 0.08% oregano essential oil increased significantly the gene expression of junctional adhesion molecule 2 (JAM2) and JAM3 in jejunum (*p < .05). The content of interleukin-2 (IL-2) and immunoglobulin A (SIgA) in jejunum and IL-10 and secretory immunoglobulin G (SIgG) in ileum were significantly increased after the addition of 0.08% oregano essential oil compared with the control (*p < .05). In conclusion, a dietary supplement of oregano essential oil modulates immune responses and enhances the intestinal barrier. Besides, our experiment offers positive evidence in improving rabbit health of oregano essential oil instead of antibiotics.

HIGHLIGHTS
- Oregano essential oil can improve the production performance of rabbits.
- Oregano essential oil improved intestinal barrier function in rabbits.
- Oregano essential oil can be used as a new additive in rabbit feed.

Introduction
In rabbit production, intestinal problems caused by early weaning are one of the main causes of diarrhoea and death of rabbits (Liu et al. 2019). To reduce diarrhoea and mortality in livestock production, farmers often add antibiotics to their feed. With the extensive use of antibiotics, bacterial pathogens have developed drug resistance. It is also an important problem for researchers to maintain the intestinal health of livestock and poultry without antibiotics (Cervantes 2015). So animal husbandry researchers want to use additives that can replace antibiotics.

Oregano (Origanum vulgare) is a phytobiotic and is known to contain antimicrobial compounds, such as carvacrol, thymol, and their precursors, p-cymene and γ-terpinene, generally equating to 80% of essential oil contents (Brenes and Roura 2010). Oregano essential oil has a more positive effect on animal growth and health than oregano powder (Puvača et al. 2013). Because of their antibacterial, anti-inflammatory, and antioxidant properties, plant essential oils have been widely used to improve health or treat human diseases (Kim et al. 2008; Faith et al. 2018). Schmidt et al. (2009) studied the chemical constituents of oregano essential oil by GC, FID, and GC-MS, which are mainly composed of geraniol, carvol, thymol, β-caryophyllene, and so on. And carvacrol and thymol are the most important active material, which has significant antibacterial and antioxidant effects. The antibacterial
activity of oregano essential oil has been reported in the previous literature (Figen et al. 2011). Oregano essential oil has been shown to have an inhibitory effect on *Escherichia coli*, *Staphylococcus aureus*, and *Salmonella typhimurium* (Friedman et al. 2002; Oussalah et al. 2007). Botsoglou et al. (2002) found that the addition of oregano essential oil in the diet reduced the malondialdehyde content in broiler meat. Li et al. (2012) found that the dietary addition of plant essential oils could reduce the diarrhoea rate in weaned piglets and the number of intestinal *Escherichia coli*. Hong et al. (2012) found that adding plant essential oils to the diet could increase the height of duodenal villi in broilers. Cheng et al. (2018) found that the addition of oregano essential oil to the diet could regulate the intestinal flora structure and improve the intestinal morphology of pigs. Cardinali et al. (2015) found that oregano improved production performance and feed conversion ratio in rabbits.

Currently, oregano essential oil is much studied in pigs and poultry, but less so in rabbits. In this experiment, we mainly studied the effects of oregano essential oil on the production performance and intestinal development of weaned meat rabbits. For the production performance, we tested the average daily feed intake (ADFI), average daily gain (ADG), feed-to-gain ratio (F/G), death rate, and diarrhoea rate of rabbits to determine the optimal amount of oregano oil to be added to rabbit farming and to conduct the next test. For the test of intestinal development, we selected the oregano essential oil adding group with better production performance and the control group to detect the intestinal morphology, intestinal barrier-related gene expression, and cytokine and immunoglobulin levels. The final results are useful to identify the efficacy and safety of oregano essential oil in the rabbit diet.

**Materials and methods**

**Animal diet, management, and experimental design**

In this experiment, 192 weaned healthy Hyla rabbits (male-female ratio of 1:1, and the rabbits were 35 days old) with similar body weight (1268.5 ± 25 g) were divided into four groups (24 replicates per group, two rabbits per replicate): fed a basal diet (control) or fed, respectively, an experimental diet with the supplement of 0.02% (LO group), 0.04% (MO), or 0.08% (HO) oregano essential oil (Dosto Farm, Germany). The main components of oregano essential oil are shown in Table 1. Oregano essential oil was sprayed on a carrier and added to the diet in the final purity of 5%. all rabbits were fed twice a day (8:00 and 16:00). The experiment lasted for 30 days which included 7 days adaptation period and 23 days experimental period. Temperature and lighting were maintained according to commercial conditions. The ingredients and composition of the diet are listed in Table 2. All rabbits had free access to feed and water during the rearing period. During the experiment, the feed intake and body weight of rabbits were recorded.

**Sample collection and preparation**

At the end of the experiment, nine rabbits with fasting for 12 h from each group (the weight of each rabbit was close to the average weight of the corresponding group) were euthanized. We collected four copies of jejumum and ileum from each rabbit, two of which were fixed with 4% paraformaldehyde-fixed solution for 24 h, replaced with fresh 4% paraformaldehyde 24 h later, and then replaced with fresh 4% paraformaldehyde every 7 days. The fixed tissue was used to create intestinal tissue sections to observe intestinal

---

**Table 1. The main components of oregano essential oil in this experiment.**

| Component       | Content, % |
|-----------------|------------|
| Carvacrol       | 60.00      |
| P-Cymen         | 5.00       |
| Gamma-Terminen  | 4.00       |
| Thymol          | 1.00       |
| Beta-caryophyllen| 2.00      |
| Linalool        | 5.00       |
| Alpha-Terpinen  | 1.50       |
| Terpinen-4-ol   | 1.50       |
| Trans-Sabinenhydrate | 0.30    |

**Table 2. Composition and nutrient levels of basal diets (air-dry basis).**

| Item             | Content, % | Nutrient levelb |
|------------------|------------|-----------------|
| Ingredients      |            | Nutrient levelb |
| Corn             | 13.3       | DM 84.49        |
| Soybean meal     | 13         | CP 16.24        |
| Wheat bran       | 19         | EE 3.11         |
| Corn Germ        | 19         | CF 15.44        |
| Alfalfa          | 12         | NDF 36.14       |
| Soya             | 19         | ADF 19.11       |
| Bean oil         | 0.7        | Ca 0.42         |
| Premixa          | 4          | P 0.42          |
| Total            | 100        |                 |

DM: dry matter; CP: crude protein; EE: ether extract; CF: crude fibre; NDF: neutral detergent fibre; ADF: acid detergent fibre; Ca: calcium; P: phosphorus.

*aThe premix provided the following per kg of diet: VA 12,000 IU, VD3 9000 IU, VE 50 mg, VK1 1.5 mg, VB1 1.5 mg, VB2 25 mg, VB3 40 mg, VB5 50 mg, VB6 0.5 mg, VB11 2.5 mg, VB12 0.02 mg, cholinechloride 600 mg, biotin 0.2 mg, K 7 mg, Mg 3 mg, Fe 60 mg, Zn 60 mg, Cu 40 mg, Mn 9 mg, I 1 mg, Se 0.2 mg, limestone 15,000 mg, NaCl 5000 mg, Lys 1000 mg, Met 2000 mg. The rest was miscellaneousmeal carrier complement.

*bNutrient levels were measured values.
morphological changes. The other two pieces were collected in tubes and placed in liquid nitrogen, and then stored at −80°C. Two samples of the caecal contents were collected from each rabbit into 5 mL cryopreservation tubes, placed in liquid nitrogen, and then preserved at −80°C until intestinal flora analysis.

**Analysis of production performance**

Average daily feed intake (ADFI) = Total feed intake per rabbit during normal feeding/Test days

Average daily gain (ADG) = (Final body weight (FBW) − Initial body weight (IBW))/Test days

Death rate = Number of death rabbits/Total number of rabbits in each group*100%

Diarrhoea rate = Number of diarrhoea rabbits/Total number of rabbits in each group*100%

F/G = ADFI/ADG

After the rabbits were slaughtered, the head, bleed, skin, removed the stomach, intestines, lungs, trachea, spleen, pancreas and reproductive organs were removed, and the left body with heart, liver, and kidneys was weighted (half-bore weight). Afterwards, the heart, liver, and kidneys were removed and weighed (full-bore weight). After that, we calculated the half-bore rate and the full-bore rate.

Half-bore rate = Half-bore weight/pre-slaughter weight

Full-bore rate = Full-bore weight/pre-slaughter weight

**Analysis of intestinal morphology**

After the rabbits were slaughtered, the tissues of the duodenum, jejunum, and ileum were collected from each rabbit. The samples were processed, embedded, and stained according to the procedures of Liu et al. (2019). Afterwards, the height of the villus and the depth of the crypt were observed under the microscope.

**Analysis of intestinal physical barrier**

The samples of jejunum and ileum were collected for the detection of the intestinal physical barrier and the expression of intestinal tight junction-related genes. We extracted the total RNA, from intestinal tissue by the Trizol method, then reverse transcribed it with the kit provided by Beijing TransGen Biology Co., Ltd. (Beijing, China), and finally got cDNA (Li et al. 2020). After that, we used the kit provided by the Hunan Accurate Biological Co., Ltd. (Hunan, China) for RT-PCR (Fu et al. 2017; Liu et al. 2017). Finally, we used 2−ΔΔCt method to calculate the expression of related genes. The mRNA levels of the target genes were normalised to that of β-actin (Wang et al. 2017; Zhu et al. 2017). The sequences of the primers used in the experiment are shown in Table 3. And the instrument of RT-PCR is Swiss Roche LightCycler 96.

**Analysis of intestinal immune barrier**

After the rabbits were slaughtered, the jejunum and ileum were placed in 1.5 mL cryopreservation tubes, and stored at −80°C. The contents of interleukin-2 (IL-2), interleukin-10 (IL-10), secretory immunoglobulin A (SlgA), secretory immunoglobulin G (SlgG), and tumour necrosis factor-α (TNF-α) in the jejunum and ileum were measured in samples from each group. The detection method is carried out according to the method of Li et al. (2020). The Elisa kits were provided by Shanghai Hengyuan Biological Co., Ltd. (Shanghai, China).

**Statistical analysis**

Data were analysed with the generalised linear model (GLM) one-way analysis of variance test using the SAS (Version 8e, SAS Institute, Cary, NC, USA) statistical software package (for production performance analysis, n = 24; for slaughter performance, intestinal morphology, gene expression, cytokine and immunoglobulin levels analysis, n = 9), followed by Duncan’s multiple range test to compare differences among the groups.
treatments when significant differences \((p < .05)\) were observed. And we used GraphPad Prism (GraphPad Software Inc., CA, USA) to graph the data.

### Result

#### Effect of oregano essential oil on production performance and slaughter performance

The effect of oregano essential oil on the growth performance of rabbits is shown in Table 4. When the addition of oregano essential oil reached 0.08%, the F/G of meat rabbits reached the lowest level, at 3.61 \((p < .05)\). The diarrhoea rate was significantly decreased \((p < .05)\). Based on the F/G and diarrhoea rate, we chose the control group and HO group for the next experiment.

The effect of oregano essential oil on the slaughter performance of rabbits is shown in Table 5. The addition of oregano essential oil to the feed had no significant effect on all slaughter performance indexes of rabbits \((p > .05)\).

#### Effect of oregano essential oil on intestinal morphology

The effect of oregano essential oil on the intestinal morphology of rabbits is shown in Table 6. After adding oregano essential oil to the diet, for the jejunum and the ileum, there was no significant difference in villi heights and crypt depth in duodenum, jejunum, and ileum \((p > .05)\). Although the dietary adding of oregano essential oil did not affect significantly the V/C value in the duodenum and jejunum, increased significantly the V/C value in the ileum (rising by 1.3, \(p < .05\)).

#### Effect of oregano essential oil on intestinal physical barrier

The effect of oregano essential oil on the intestinal physical barrier of rabbits is shown in Figure 1. We detected the gene expression of Occludin, Claudin-1, Zonula occludens 1 \((ZO-1)\), Zonula occludens 2 \((ZO-2)\), Junctional adhesion molecule 2 \((JAM2)\), Junctional adhesion molecule 3 \((JAM3)\), Mucoprotein 1 \((MUC1)\), and Mucoprotein 4 \((MUC4)\) in jejunum and ileum. In jejunum, the addition of 0.08% oregano essential oil increased significantly the gene expression of JAM2 and JAM3 \((P_{JAM2} = 0.0049, P_{JAM3} = 0.0494)\). But there

### Table 4. Effect of oregano essential oil on production performance of rabbits.

| Item                     | Control | LO | MO | HO | R-MSE | p-Value |
|--------------------------|---------|----|----|----|-------|---------|
| IBW, g                   | 1266.90 | 1264.55 | 1270.91 | 1274.46 | 187.93 | .9982   |
| FBW, g                   | 2432.86 | 2510.00 | 2400.93 | 2481.96 | 289.68 | .6004   |
| ADG\(^a\), g/d          | 31.51   | 33.66 | 30.54 | 32.64 | 6.14  | .3673   |
| ADFI\(^a\), g/d         | 126.67\(^ab\) | 128.97\(^ab\) | 118.50\(^ab\) | 115.37\(^b\) | 18.40  | .0474   |
| F/G\(^c\)                | 4.22\(^a\) | 3.85\(^ab\) | 4.00\(^ab\) | 3.61\(^b\) | 0.85  | .1213   |
| Diarrhoea rate, %        | 43.75   | 25.00 | 56.25 | 31.25 | 30.78  | .0035   |
| Death rate, %            | 29.17   | 22.92 | 25.00 | 20.83 | 31.11  | .8153   |

IBW: initial body weight; FBW: final body weight; ADFI: average daily feed intake; ADG: average daily gain.

Oregano essential oil was added at 0.00% in the Control group; 0.02% in the LO group; 0.04% in the MO group; and 0.08% in the HO group.

Means within lines with different superscript letters are significantly different \((p < .05)\).

\(^a\)ADG = (FBW − IBW)/Test days.

\(^b\)ADFI = Total feed intake per rabbit during normal feeding/Test days.

\(^c\)F/G = ADFI/ADG.

### Table 5. Effect of oregano essential oil on slaughter performance of rabbits.

| Item                     | Control | HO | R-MSE | p-Value |
|--------------------------|---------|----|-------|---------|
| Pre-slaughter weight, g  | 2384.00 | 2385.56 | 0.98 | .9883   |
| Full-bore weight, g      | 1100.89 | 1152.78 | 156.24 | .4913  |
| Half-bore weight, g      | 1195.56 | 1242.22 | 163.72 | .5539   |
| Full-bore rate, %        | 46.03   | 48.19 | 2.94 | .1385   |
| Half-bore rate, %        | 50.02   | 51.94 | 3.08 | .2045   |

Full-bore rate = Full-bore weight/Pre-slaughter weight.

Half-bore rate = Half-bore weight/Pre-slaughter weight.

### Table 6. Effect of oregano essential oil on intestinal morphology of rabbits.

| Item                     | Control | HO | R-MSE | p-Value |
|--------------------------|---------|----|-------|---------|
| Duodenum                 |         |    |       |         |
| Villus high, um          | 847.33  | 852.67 | 82.6542 | .9408  |
| Crypt depth, um          | 184.50  | 183.00 | 8.3964  | .8375  |
| V/C                      | 4.59    | 4.68 | 0.5252 | .8384  |
| Jejunum                  |         |    |       |         |
| Villus high, um          | 755.00  | 822.37 | 67.8903 | .5627  |
| Crypt depth, um          | 154.50  | 186.87 | 20.7553 | .0695  |
| V/C                      | 4.95    | 4.57 | 0.709  | .4772  |
| Ileum                    |         |    |       |         |
| Villus high, um          | 526.28  | 548.67 | 40.9694 | .5399  |
| Crypt depth, um          | 178.33  | 133.67 | 28.1753 | .1241  |
| V/C                      | 2.96\(^b\) | 4.25\(^a\) | 0.5539 | .0471  |

V/C: Villus high/Crypt depth.

Means within lines with different superscript letters are significantly different \((P < .05)\).
was no significant effect for the ileum. Dietary addition of 0.08% oregano essential oil had no significant effect on the gene expression of Occludin, Claudin-1, ZO-1, ZO-2, ZO-3, JAM2, JAM3, Muc1, Muc4 in jejunum and ileum ($p > .05$).

**Effect of oregano essential oil on intestinal immune barrier**

The detection results of intestinal immune barrier indicators were shown in Figure 2. The content of IL-2 and SlgA in the jejunum and IL-10 and SlgG in the ileum were significantly increased after the addition of 0.08% oregano essential oil compared with the control ($p < .05$). Dietary addition of 0.08% oregano essential oil had no significant effect on the content of IL-10, SlgG, TNF-α in the jejunum and IL-2, SlgA, and TNF-α in the ileum ($p > .05$).

**Discussion**

**Oregano essential oil improved the production performance**

Weaning can be a difficult process for rabbit breeding. Weaning could induce diarrhoea and low production performance in rabbits. Alleviating weaning stress is one of the important prerequisites for improving rabbit production performance (Campbell et al. 2013). There have been many reports about the effect of oregano essential oil on animal production performance. Hertrampf (2001) found that adding 399 mg/t oregano essential oil to drinking water could improve the performance of broilers. Figen et al. (2011) found that the dietary addition of oregano essential oil decreased the feed intake of broilers. In our experiment, dietary addition of oregano essential oil increased the feed conversion efficiency. Allan and Bilkei (2005) found that adding oregano essential oil to the diet of breeding sows could significantly increase the litter yield of sows and the survival number of piglets, and reduce mortality. In our experiment, the death rate and diarrhoea rate of meat rabbits were decreased significantly when dietary addition of oregano essential oil. However, when the addition of oregano essential oil reached 0.04%, the diarrhoea rate of meat rabbits reached 56.25%, which was higher than that of the other three groups. According to the index of production performance of meat rabbits, when the addition of oregano essential oil was 0.08%, the F/G ratio of meat rabbits decreased to the lowest level ($p < .05$), and the death rate and diarrhoea rate were also decreased compared with the control group. The better production performance may be caused by the enhancement of intestinal function by oregano essential oil, so we selected the control group and HO group for the next experiment.

Slaughter performance is an important indicator to judge the growth and development of animals, which has an important impact on the economic efficiency of the farming industry. The improvement of slaughter performance depends mainly on the increase of growth performance, the proportion of muscle, and the reduction of abdominal fat (Musa et al. 2006). In the previous study, the slaughter rate and full-bore rate of broiler chickens were increased after the dietary addition of oregano essential oil (Peng et al. 2016). According to the study by Khattak et al. (2014), the addition of a natural blend of essential oils to broiler diets increased carcass weight as well as breast weight of broilers. The addition of oregano essential oil to the diet increased carcass weight and improve
meat quality in goats (Lei et al. 2018). However, there were also opposite results. The addition of 300 mg/kg of oregano essential oil to broiler diets had no effect on broiler carcase weight (Alp et al. 2012), which is similar to our present result indicating that the dietary addition of 0.08% oregano essential oil had no significant effect on the half-bore weight and full-bore weight in weaned meat rabbits. The reason for this differential effect of oregano essential oil on slaughter performance maybe related to the level of oregano essential oil addition, feeding environment, type of diet, and hygiene (Amad et al. 2011).

**Oregano essential oil improved the intestinal morphology**

Villus height, crypt depth, and V/C value are important indicators of intestinal health (Qaisrani et al. 2014).
In livestock, early weaning leads to intestinal mucosal damage, characterised by reduced villus height and deepened crypt (Hu et al. 2013). The decrease of V/C value represents the decrease of intestinal absorption function and may lead to diarrhoea, while the increase of V/C value represents the increase of intestinal absorption area and absorption capacity (Li et al. 2012). In this experiment, dietary addition of oregano essential oil significantly increased the V/C value of ileum of meat rabbits but had no significant effect on the V/C value of the duodenum and jejunum. Similar results have been obtained in the experiments of Peng et al. (2016). These results suggest that oregano essential oil can increase the intestinal absorption area.

**Oregano essential oil improved the intestinal barrier**

The intestinal barrier mainly includes the physical barrier, chemical barrier, immune barrier, and biological barrier. In terms of the intestinal physical barrier, intestinal mucosal permeability is an important aspect of the intestinal physical barrier, which is closely related to tight junction proteins in the intestinal tract. It is reported that JAM belongs to the immunoglobulin superfamily, which not only participates in the tight junction structure of the intestinal tract but also acts as a ligand of lymphocyte function-associated antigen-1 (LFA-1). In this experiment, oregano essential oil could affect the physical barrier of rabbits jejunum via increasing the expression of JAM2 and JAM3 genes.

IL-2, known as the T cell growth factor, plays an important role in immunity. It can stimulate the proliferation and differentiation of T cells and B cells, and induce the secretion of interferon and other cytokines (Atkins et al. 2000). In this experiment, the content of IL-2 in rabbit jejunum increased significantly after the dietary addition of oregano essential oil to rabbit feed, indicating that oregano essential oil increases the immunity of jejunum to some extent.

It has been shown that IL-10 is associated with intestinal diseases. IL-10 can help the animal organism to effectively defend against intestinal inflammation (Kole and Maloy 2014). IL-10 is mainly derived from monocytes, T cells, and B cells (Maynard and Weaver 2008), and is an important immunomodulatory factor with a strong limiting effect on the inflammatory response (Ashwini et al. 2016). Increased IL-10 levels could inhibit the production of IFN-γ, IL-1, IL-12, and TNF (Ashwini et al. 2016). In the previous study, Carvacrol (the main component of oregano essential oil) has potential anti-inflammatory and anti-nociceptive effects (Damasceno et al. 2014). In this test, the content of IL-10 in rabbit ileum was significantly increased in the HO group, but oregano essential oil had no effect on the content of TNF-α. In the jejunum, there was a slight increase in IL-10 content and a decrease in TNF-α content in the HO group (non-significant difference). These results imply that oregano essential oil could regulate the IL-10 secretion to affect the immune response in rabbit gut.

In addition, SlgA and SlgG have important regulatory roles in gastrointestinal mucosal immunity (Iijima et al. 2001). SlgA constitutes a major mucosal immune effector and provides an important first line of defence against pathogens. SlgG could promote immune cells to swallow pathogens and neutralise bacterial toxins. The content of SlgA in jejunum and SlgG in ileum were increased by the addition of oregano essential oil to rabbit feed, which indicates oregano essential oil could increase the ability to swallow pathogens and toxins, improve the ability of anti-disease and anti-inflammatory, and then enhance the immune function and promote intestinal health.

**Conclusions**

In conclusion, a dietary supplement of oregano essential oil modulated immune responses via increasing the secretion of IL-2, IL-10, SlgA, and SlgG and improved intestinal barrier by regulating JAM2 and JAM3 genes expression. These may be the cause of the low death rate and diarrhoea rate of weaned rabbits, so our experiment offered positive evidence of oregano essential oil instead of antibiotics.

**Acknowledgements**

Thank you to all those who contributed to this experiment.

**Ethical approval**

All study procedures were approved by the Shandong Agriculture University Animal Care and Use Committee (SDAU-2015-011) and were conducted in accordance with the Guidelines for Experimental Animals established by the Ministry of Science and Technology (Beijing, China).

**Disclosure statement**

The authors declare that they have no competing interests.
Funding
This work was supported by the Natural Science Foundation of Shandong Province (ZR2021Z2200454), Modern Agro-industry Technology Research System (CARS-43-B-1), Modern Agro-industry Technology Research System of Shandong Province (SDAIT-21-16), National Natural Science Foundation of China (31972594), Taishan Industry Leadership Project (TSCY20190107), Industrial Upgrading Project of Agricultural Science and Technology Park of Shandong Province (2019YQ008), and Key Research and development project of Xinjiang (2020B01004-1-3).

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

References
Allan P, Bilkei G. 2005. Oregano improves reproductive performance of sows. Theriogenology. 63(3):716–721.
Alp M, Midilli M, Kocabaglı N, Yılmaz H, Turan N, Gargul A, Acar N. 2012. The effects of dietary oregano essential oil on live performance, carcass yield, serum immunoglobulin G level, and oocyst count in broilers. J Appl Poultry Res. 21(3):630–636.
Amad AA, Manner K, Wendler KR, Neumann K, Zentek J. 2011. Effects of a phytopgenic feed additive on growth performance and ileal nutrient digestibility in broiler chickens. Poult Sci. 90(12):2811–2816.
Ashwini R, Venkataram S, Sunil VK, Janardhanan CN, Manjula S, Deepti V, Anekal CA, Ganesan V, Monojit D. 2016. The impact of IL10 polymorphisms and shHLA-G levels on the risk of schizophrenia. Asian J Psychiatr. 23:39–43.
Atkins MB, Kunkel L, Sznol M, Rosenberg SA. 2000. High-dose recombinant interleukin-2 therapy in patients with metastatic melanoma: long-term survival update. Cancer J Sci Am. 6(Suppl 1):S11–S14.
Brener A, Roura E. 2010. Essential oils in poultry nutrition: main effects and modes of action. Anim Feed Sci Technol. 158(1–2):1–14.
Botoglu N, Florou-Paneri P, Christaki E, Fletouris DJ, Spais AB. 2002. Effect of dietary oregano essential oil on performance of chickens and on iron-induced lipid oxidation of breast, thigh and abdominal fat tissues. Br Poult Sci. 43(2):223–230.
Campbell JM, Crenshaw JD, Polo J. 2013. The biological stress of early weaned piglets. J Anim Sci Biotech. 4:124–127.
Cardinali R, Cullere M, Dal BA, Mugnai C, Ruggeri S, Mattioli S, Castellani C, Trabalza MM, Dalle ZA. 2015. Oregano, rosemary and vitamin E dietary supplementation in growing rabbits: effect on growth performance, carcass traits, bone development and meat chemical composition. Livest Sci. 175:83–89.
Cervantes HM. 2015. Antibiotic-free poultry production: is it sustainable? J Appl Poultry Res. 24(1):91–97.
Cheng CS, Xia M, Zhang XM, Wang C, Jiang SW, Peng J. 2018. Supplementing oregano essential oil in a reducec-
intestinal health. Asian Australas J Anim Sci. 25(11): 1617–1626.

Li SY, Ru YJ, Liu M, Xu B, Péron A, Shi XG. 2012. The effect of essential oils on performance, immunity and gut microbial population in weaner pigs. Livest Sci. 145(1-3): 119-123.

Liu L, Liu H, Fu C, Li C, Li F. 2017. Acetate induces anorexia via up-regulating the hypothalamic pro-opiomelanocortin (POMC) gene expression in rabbits. J Anim Feed Sci. 26(3): 266-273.

Liu L, Zhao X, Liu Y, Zhao H, Li F. 2019. Dietary addition of garlic straw improved the intestinal barrier in rabbits. J Anim Sci. 97(10):4248–4255.

Maynard CL, Weaver CT. 2008. Diversity in the contribution of interleukin-10 to T-cell-mediated immune regulation. Immunol Rev. 226(1):219–233.

Musa HH, Chen GH, Cheng JH, Li BC, Mekki DM. 2006. Study on carcass characteristics of chicken breeds raised under the intensive condition. Int J Poultry Sci. 5(6):530–533.

Oussalah M, Caillet S, Saucier L, Lacroix M. 2007. Inhibitory effects of selected plant essential oils on the growth of four pathogenic bacteria: E. coli O157:H7, Salmonella typhimurium, Staphylococcus aureus and Listeria monocytogenes. Food Control. 18(5):414–442.

Peng QY, Li JD, Li Z, Duan ZY, Wu YP. 2016. Effects of dietary supplementation with oregano essential oil on growth performance, carcass traits and jejunal morphology in broiler chickens. Anim Feed Sci Tech. 214:148–153.

Puvača N, Stanačev V, Glamocić D, Livić J, Perić L, Stanačev V, Milič D. 2013. Beneficial effects of phytoadditives in broiler nutrition. World Poult Sci J. 69(1):27–34.

Qaisrani SN, Moquet PC, Krimpen MV, Kwakkel RP, Verstegen MW, Hendriks WH. 2014. Protein source and dietary structure influence growth performance gut morphology, and hindgut fermentation characteristics in broilers. Poult Sci. 93(12):3053–3064.

Schmidt E, Bail S, Buchbauer G, Stoilova I, Atanasova T, Stoyanova K, Krastanov A, Jirovetz L. 2009. Chemical composition, olfactory evaluation and antioxidant effects of essential oil from Mentha x piperita. Nat Prod Commun. 4(8):1107–1112.

Wang C, Zhu Y, Li F, Huang L. 2017. The effect of Lactobacillus isolates on growth performance, immune response, intestinal bacterial community composition of growing Rex rabbits. J Anim Physiol Anim Nutr. 101(5): e1–e13.

Zhu Y, Sun Y, Wang C, Li F. 2017. Impact of dietary fibre: starch ratio in shaping caecal archaea revealed in rabbits. J Anim Physiol Anim Nutr. 101(4):635–640.