INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
18F–156/2019/21–2–463–471
DOI: 10.17957/IJAB/15.0916
http://www.fspublishers.org

Full Length Article

Mutual Allelopathic Effect between Invasive Plant *Aegilops tauschii* and Wheat

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Abstract

The *Aegilops tauschii* Coss. is a worldwide invasion weed. The competitions between *A. tauschii* and native species not only caused serious influence on ecosystem structure and succession, moreover, it poses a greater threat to the safety of food production. There was a significant interaction allelopathic between *A. tauschii* and wheat, and the allelopathic inhibition of *A. tauschii* on the seed germination of wheat is stronger than the effect of wheat on the *A. tauschii*. Both *A. tauschii* and wheat have allelopathic on each other seedling growth, and it is expressed as promotion at low concentrations but inhibitory at high concentrations on the growth of seedling height and root length. On the one hand, adaptation of wheat or *A. tauschii* seedlings to the allelopathic stress from the other depends on a constant increased in proline content and SOD activity. On the other hand, allelopathic stress can destroyed the cell membrane structures and disrupt the function of seedlings, aggravate membrane lipid peroxidation, and increased both the relative electrical conductivity and MDA content. The synthetic allelopathic effect showed that, at 10-100 mg mL^{-1} concentrations, the aqueous extracts of *A. tauschii* stem and leaves had higher allelopathic inhibitory effects on wheat seedlings than the aqueous extracts of roots. At 25–100 mg mL^{-1}, the aqueous extracts of wheat had similar allelopathic inhibitory effects on *A. tauschii* seedlings. In summary, the strong allelopathic inhibition of *A. tauschii* on the seed germination and seedling growth of wheat may be the important reason for its large-scale invasion in wheat field.

Keywords: Allelopathic; *Aegilops tauschii*; SOD activity; Wheat; Seed germination

Introduction

Biotic intrusion by invasive species has resulted in biodiversity loss and ecosystem degradation worldwide (Mack *et al.*, 2000). The study of the invasion mechanism of exotic plants is important for predicting their invasion speed and the development of effective preventive measures (Huangfu *et al.*, 2010). The allelopathic effect has been deemed one of the successful invasion mechanisms of exotic plants and its role has been affirmed by the novel weapon hypothesis (Wang *et al.*, 2004; Wu and Peng, 2005). The exploration of the allelopathic effects of an exotic plant using local plants as receptors is a common approach for studies, and it has been applied to studies of the allelopathic effects of *Eupatorium adenophorum* Spreng (Zheng and Feng, 2005), *Solidago canadensis* L. (Zhang *et al.*, 2014), and *Alternanthera philoxeroides* (Zhang *et al.*, 2013). Furthermore, given the allelopathic inhibitory effect of local plants, the biological control and prevention of a specific weed through replacement and control has become a new research focus of allelopathic effects (Zhang *et al.*, 2006; Farooq *et al.*, 2011; Liu *et al.*, 2014a; Shen *et al.*, 2017). Exotic and local plants affect and compete with each other when they live in the same environment. As an integral part of plant symbiotic relationships, allelopathy is the basis for rebuilding a vegetation community in an artificial ecosystem, and the key approach for the exploration of internal causes of symbiosis (Xu, 2006). However, there are few studies on the allelopathic interactions between plants. Such studies were conducted by Huangfu *et al.* (2010), who have explored *Flaveria bidentis* and four types of pastures, and by Yao *et al.* (2015), who have studied *Galinsoga parviflora* and white clover. Their studies on allelopathic effects were conducted merely from the angle of seed germination (Koodkaew and Rottasa, 2017).

Aegilops tauschii Coss. is an annual or winter annual aegilops plant of the grass family (Poaceae) that originated from Eastern Europe, Western Asia, and other regions and is now a noxious weed throughout the world (Fang *et al.*, 2015). The first sighting of *A. tauschii* in China was in Xinxiang City of Henan Province, China, in 1955 (Yang, 1992). Recently, it has become widely distributed in Henan, Shaanxi, and Hebei Provinces and it shows a rapid expansive tendency. *A. tauschii* has a close genetic relationship with wheat, and they share similar appearance, growth habits, and capabilities, such as tillering, propagation, and adaptability. Thus, among noxious weeds in wheat fields, *A. tauschii* is the most difficult to destroy

To cite this paper: Wang, N., Y. Tian and H. Chen, 2019. Mutual allelopathic effect between invasive plant *Aegilops tauschii* and wheat. *Intl. J. Agric. Biol.*, 21: 463–471

(Wang *et al.*, 2010; Fang *et al.*, 2014). *A. tauschii* has been incorporated into the Directory of Harmful Plants compiled by Plant Importing Quarantine of the People's Republic of China because of its serious threats to China's crop production and safety. Wheat is main accompanying plants in the agroecosystem invaded by *A. tauschii,* and allelopathic play an important role in the mutual competition of plants. So, the study on the mutual allelopathic between *A. tauschii* and wheat is very necessary. In this study, physiological indicators, particularly seed germination percentage, seedling height and root length were determined, and the mutual allelopathic effects between *A. tauschii* and wheat were investigated to illustrate the internal mechanisms of their mutual effects and to offer reference data for the effective prevention and control of *A. tauschii* in wheat fields.

Materials and Methods

Materials

The experiments were conducted from January 2016 to September 2016. *A. tauschii* seeds were sampled from the wheat field at the back of Zhoushan Forest Park of Luoyang City, which was located at 112°38′ E and 34°63′ N. Wheat seeds ('Luoyang Wheat 28') were obtained from Luoyang Academy of Agriculture and Forestry Sciences.

Preparation of Aqueous Extract

In September 2016, after accelerated germination, the seeds of *A. tauschii* and wheat were planted separately in a pot of 25 cm. After 60 days, the well-grown plants were selected, and the whole plants were harvested from the soil. The plants were returned to the laboratory and cleaned with deionized water. Stem and leaves, and roots were removed, dried in the shade, and cut into pieces. Approximately 100 g of stem and leaves, and roots were weighed separately and soaked in 1 L distilled water. The plant tissues were then leached and extracted at 25°C for 24 h before the solutions were passed through a double-layer filter paper to remove plant residues. Raw extract at 100 mg mL^{-1} was obtained and diluted with distilled water to yield 5, 10, 25, 50 and 100 mg mL^{-1} aqueous extracts. These extracts were stored in the refrigerator at 4°C until further use. When the extracts were taken out from the refrigerator they were allowed to warm to room temperature before use to prevent cold shock to the seeds of test species.

Tests of Seed Germination and Seedling Growth

In June 2016, we randomly selected seeds from each parent plant of *A. tauschii* and wheat from the populations grown in the wheat field of Luoyang suburb. For the test of seed germination, *A. tauschii* and wheat seeds with similar size and in good shape were selected and soaked in 1% chloric acid sodium solution for 10 min for sterilization, rinsed repeatedly with distilled water, and dried naturally at room temperature. Then, the seeds were placed into a culture dish (⌀12 cm, and 50 seeds per culture dish) and spread with double-layer filter paper. The aqueous extract of each concentration (10 mL) was placed into a dish, and the dishes were weighed and recorded. A treatment with the same amount of distilled water was assigned as the control group, and three replicates of each treatment were conducted. They were cultured in an incubator at 25°C daytime and 18°C nighttime temperatures, for 12 h each. The status of seed germination was recorded every 24 h (with the radicle breaking seed coat taken as the threshold of seed germination), and seed germination percentage of wheat was calculated on the 7^{th} day, but the seed germination percentage of *A. tauschii* was calculated on the 10^{th} day Then, 10 seedlings were sampled randomly to measure the seedling height and root length. During the test, culture dishes were replenished regularly with aqueous extract to ensure that the weight of each culture dish remained unchanged.

For the seedling growth test, *A. tauschii* and wheat seeds that were previously treated with pre-germination measures (the seed were cultured in an incubator at 25°C daytime and 18°C nighttime temperatures, and with the radicle breaking seed coat) were transferred to plastic cups (diameter: 10 cm; height: 15 cm) filled with a proper amount of silica sand, and 10 seeds were placed in each cup. Then, 10 mL aqueous plant tissue extracts of different concentrations were placed into each cup. A cup with the same volume of distilled water was used as the control group, and three replicates of each treatment were conducted. Culture conditions were similar to those for seed germination. Fifteen days after planting, seedlings that showed similar growth trends were sampled to measure the various physiological indicators.

Measurement of SOD Activity

Seeds (0.5 g) were ground in a mortar and pestle in 5 mL of 50 m*M* phosphate buffer (pH 7.8) at 4°C. The homogenate was centrifuged at 13,000×*g* for 15 min. The supernatant fluid was collected for the determination of SOD activities (Zou, 2000). To determine SOD activity, a 3 mL reaction solution containing 13 μM methionine, 63 μM ρ-nitro blue tetrazolium chloride (NBT), 1.3 μM riboflavin, 50 m*M* phosphate buffer (pH 7.8), and 50 μL of the supernatant fluid was incubated for 10 min under fluorescent light (80 μmol m^{-2} s^{-1}). Absorbance was determined at 560 nm using a spectrophotometer. One unit of SOD activity was defined as the amount of enzyme required for inhibition of photochemical reduction of NBT by 50%.

Measurement of MDA

All samples were prepared for MDA and enzyme analyses by homogenization of the fresh tissue with a mortar and

Table 1: Synthesis effects of aqueous extracts from *A. tauschii* on the seedlings of wheat

Parts	Concentration (mg mL^{-1})	$RI_{\text{root length}}$	$RI_{\text{seedling height}}$	RI_{REC}	RI_{SOD}	RI_{Pro}	RI_{MDA}	Inhibition synthesis effect (*SE*)
Stems and leaves	5.00	0.00	0.15	-0.22	0.11	0.08	-0.06	0.01
	10.00	-0.04	0.06	-0.34	0.18	0.12	-0.32	-0.06
	25.00	-0.08	-0.03	-0.56	0.25	0.19	-0.41	-0.11
	50.00	-0.10	-0.04	-0.67	0.35	0.21	-0.51	-0.13
	100.00	-0.34	-0.29	-0.70	0.32	0.32	-0.57	-0.21
Roots	5.00	0.01	0.01	-0.15	0.05	0.09	-0.03	0.00
	10.00	-0.10	-0.02	-0.22	0.15	0.17	-0.18	-0.03
	25.00	-0.13	-0.02	-0.48	0.22	0.21	-0.32	-0.09
	50.00	-0.11	-0.03	-0.59	0.31	0.29	-0.44	-0.10
	100.00	-0.14	-0.04	-0.67	0.36	0.35	-0.53	-0.11

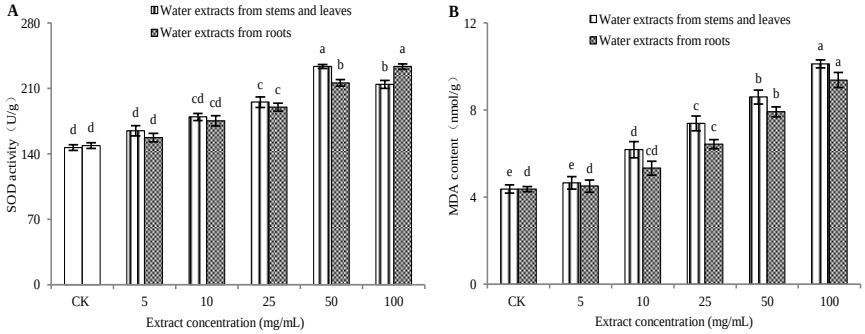

Fig. 4: Effect of the aqueous extracts from *A. tauschii* on SOD activity and MDA content of wheat

pestle and a small amount of sand in a solution (4 mL g^{-1} fresh weight) containing 50 m*M* KH_2PO_4/K_2HPO_4 (pH 7.8), 1% PVP, 0.2 m*M* EDTA and 1% Triton X-100. After the homogenate was centrifuged at 12,000×*g* for 20 min at 4°C, the supernatant fluid was used to determine enzymatic activities (Unhaing and Jungo, 2000). All spectrophotometric analyses were conducted on a UV-vis recording spectrophotometer (UV-160A, Shimadzu, Japan). MDA content was measured by the thiobarbituric acid reaction as described by Heath and Packer (1968). The concentration of MDA was calculated based on A_{532} - A_{600} (ε = 155 m*M* cm^{-1}).

Measurement of Proline Contents

The contents of proline were measured using the method of Li (2000).

Determination of Relative Electrical Conductivity

The sliced 5 g of seed was soaked in 40 mL deionized water for 1 min. The conductance (E_0) was measured (DDS-307; Shanghai Precision Scientific Instrument Co., Ltd., China) after 12 h, the first conductance (E_1) was measured. The second conductance (E_2) was measured after the sample was boiled in deionized water for 30 min and soaked in 40 mL of deionized water for 12 h. The relative electrical conductivity (REC) was calculated as follows (Zou, 2000);

$$\text{REC} = (E_1–E_0) / (E_2–E_0) \times 100\%.$$

Data Processing

The response index, *RI*, was calculated based on the Williamson and Richardson (1988) method:

$$RI = 1 - C/T \ (T \geq C) \text{ or } RI = T/C - 1 (T < C),$$

Where *C* is the control value, and *T* is the processing value. $RI > 0$ signifies the stimulation effect, whereas $RI < 0$ signifies the inhibition effect, and the absolute value indicates the strength of allelopathy (Williamson and Richardson, 1988). Given that relative electrical conductivity and MDA content measurements are positively correlated with the strength of allelopathic inhibition, *RI* should be multiplied by "−1" when calculated (Gao *et al.*, 2015).

The synthetic allelopathic effect is the arithmetic mean of *RI* of the receptor plant's indicators under the allelopathic effect of the donator (Liu *et al.*, 2014b). The synthetic allelopathic effect was used in this study to reveal the allelopathic effect strength of the aqueous extracts of the different parts of the seedlings and is calculated using the following formula: $SE = (RI_{\text{root length}} + RI_{\text{seedling height}} + RI_{\text{REC}} + RI_{\text{SOD}} + RI_{\text{Pro}} + RI_{\text{MDA}})/6$ (Liu *et al.*, 2014b). Values are presented as mean ± 1 standard deviation (SD) of three replicates. Statistical analyses were performed by analysis of variance using DPS software. Duncan's multiple range test was used to compare significant differences among treatments.

Results

Effect of *A. tauschii* Aqueous Extract on Wheat Seed Germination and Seedling Growth

Effect on wheat seed germination: The germination percentage of the wheat seeds showed a gradual decline with

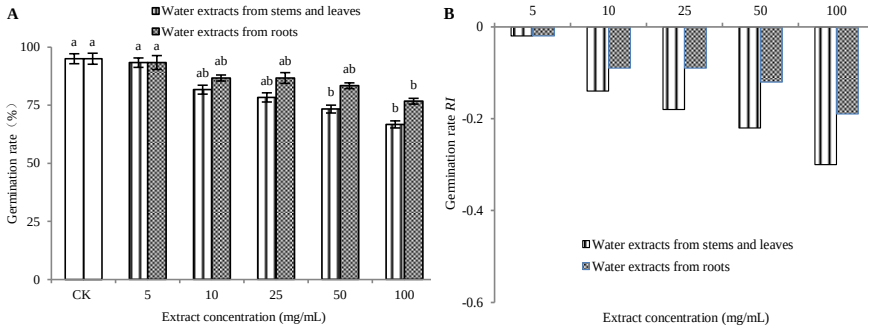

Fig. 1: Effect of the aqueous extracts from *A. tauschii* on the germination rate (**A**) and response index (**B**) of wheat
"CK" is the control treatment using distilled water. Note: The different lowercase letters mean significant differences at 0.05 levels

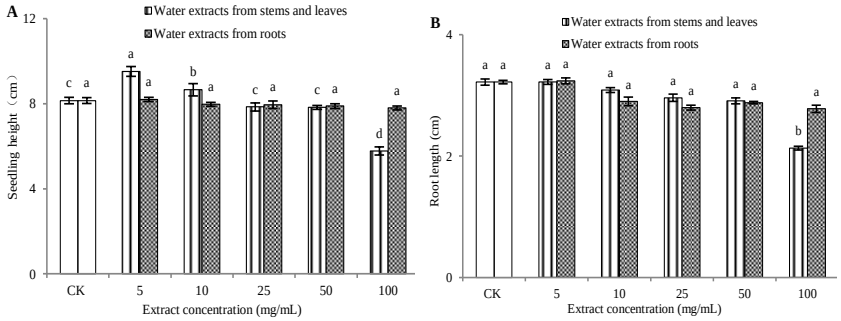

Fig. 2: Effect of the aqueous extracts from *A. tauschii* on seedling height and root length of wheat

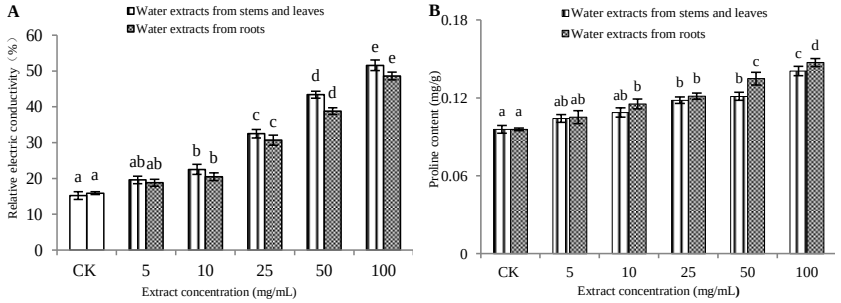

Fig. 3: Effect of the aqueous extracts from *A. tauschii* on relative electrical conductivity and proline content of wheat

the increase in aqueous extract concentration (Fig. 1A). In Fig. 1B, the *RI* showed that the aqueous extracts of different parts of *A. tauschii* had concentration-related allelopathic inhibitory effects on the wheat seed germination. At similar concentrations, *RI* of the seed germination percentage treated with stem leaf aqueous extract was lower than that treated with root aqueous extract; this result indicates that *A. tauschii* stem and leaf aqueous extract had a greater inhibition effect on wheat seed germination than *A. tauschii* root aqueous extract.

Effect on Wheat Seedling Growth

With increasing aqueous extract concentrations, the wheat seedling height and root length showed rising and then declining trends (Fig. 2). Fig. 2A shows that when treated with 5 to 10 mg mL^{-1} stem and leaf aqueous extract seedling height was greater than that of CK and the difference reached a significant level ($P < 0.05$). However, with increasing extract concentrations beyond 10 mg mL^{-1}, the seedling height declined, and its difference from that of CK reached a significant level ($P < 0.05$) of inhibition at 100 mg mL^{-1}. When treated with root aqueous extract, the seedling height had no significant difference from that of CK regardless of minor fluctuations. From Fig. 2B, the root length was shorter than that of CK and reached a significant level ($P < 0.05$) when treated with stem and leaf aqueous extract at the concentration of 100 mg mL^{-1}. When treated with root aqueous extract, the root length had no significant difference from that of CK regardless of minor length fluctuations.

With the increase in aqueous extract concentration of either stem and leaves or roots, the relative electrical

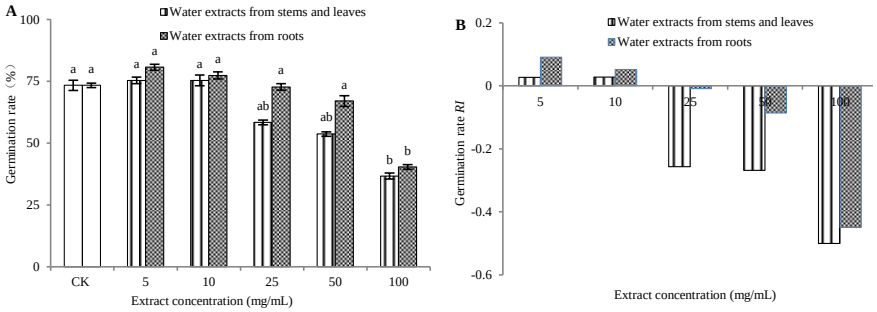

Fig. 5: Effect of the aqueous extracts of wheat on the germination rate (**A**) and response index (**B**) of *A. tauschii*

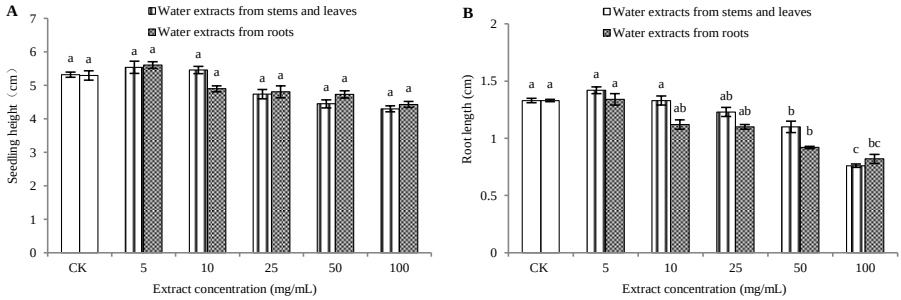

Fig. 6: Effect of the aqueous extracts from wheat on seedling height and root length of *A. tauschii*

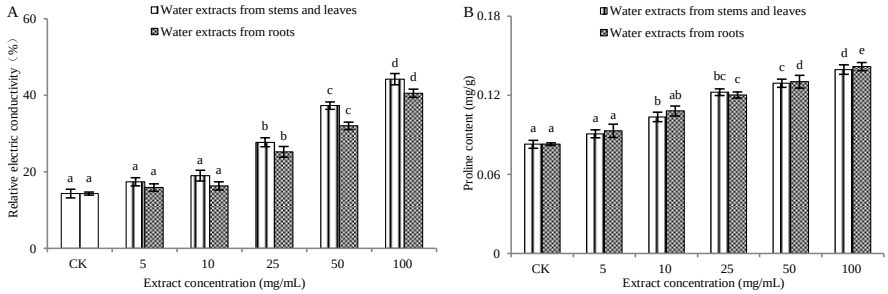

Fig. 7: Effect of the aqueous extracts from wheat on relative electrical conductivity and proline content of *A. tauschii*

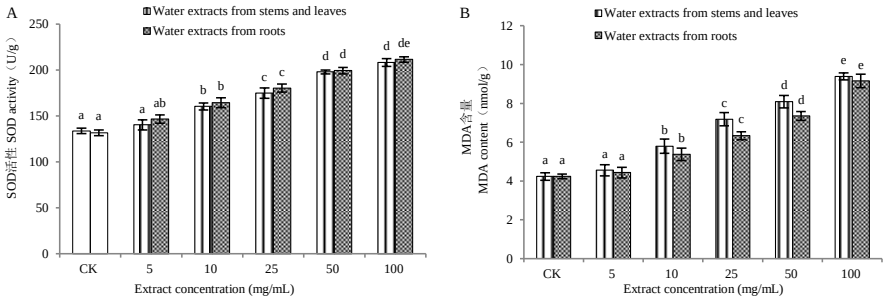

Fig. 8: Effect of the aqueous extracts from wheat on SOD activity and MDA content of *A. tauschii*

conductivity and proline content of wheat seedlings showed gradually rising trends (Fig. 3). From Fig. 3A, the relative electrical conductivity of wheat seedlings had no significant difference from that of CK when treated with 5 mg mL^{-1} aqueous extracts of stem and leaves or root. Also, the relative electrical conductivity showed no significant difference among the wheat seedlings treated with different concentrations of aqueous extract or from that of CK. Fig. 3B shows that the proline content of seedlings treated with 25 mg mL^{-1} stem and leaf aqueous extract was higher than CK, and their difference reached a significant level ($P < 0.05$); however, a significant difference occurred at the

Table 1: Synthesis effects of aqueous extracts from *A. tauschii* on the seedlings of wheat

Parts	Concentration (mg mL^{-1})	$RI_{\text{root length}}$	$RI_{\text{seedling height}}$	RI_{REC}	RI_{SOD}	RI_{Pro}	RI_{MDA}	Inhibition synthesis effect (*SE*)
Stems and leaves	5.00	0.00	0.15	-0.22	0.11	0.08	-0.06	0.01
	10.00	-0.04	0.06	-0.34	0.18	0.12	-0.32	-0.06
	25.00	-0.08	-0.03	-0.56	0.25	0.19	-0.41	-0.11
	50.00	-0.10	-0.04	-0.67	0.35	0.21	-0.51	-0.13
	100.00	-0.34	-0.29	-0.70	0.32	0.32	-0.57	-0.21
Roots	5.00	0.01	0.01	-0.15	0.05	0.09	-0.03	0.00
	10.00	-0.10	-0.02	-0.22	0.15	0.17	-0.18	-0.03
	25.00	-0.13	-0.02	-0.48	0.22	0.21	-0.32	-0.09
	50.00	-0.11	-0.03	-0.59	0.31	0.29	-0.44	-0.10
	100.00	-0.14	-0.04	-0.67	0.36	0.35	-0.53	-0.11

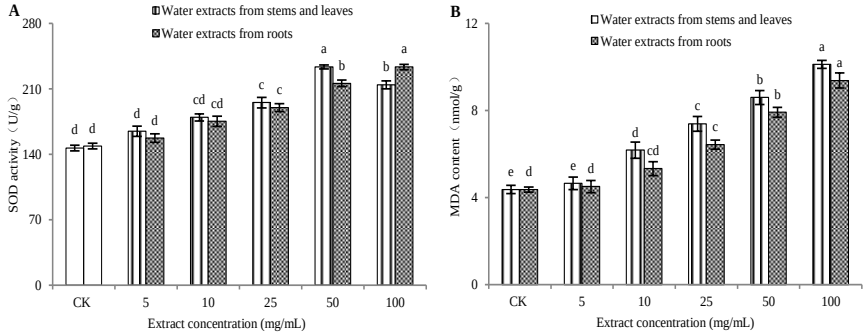

Fig. 4: Effect of the aqueous extracts from *A. tauschii* on SOD activity and MDA content of wheat

concentration of 10 mg mL^{-1} when they were treated with root aqueous extract.

From Fig. 4A, SOD activity of seedlings treated with aqueous extracts of stem and leaves and roots at 5 to 10 mg mL^{-1} concentrations had no significant difference from that of CK. When treated with 100 mg mL^{-1} aqueous extract of stem and leaves, the seedling SOD activity was lower than 50 mg mL^{-1} treatment result and reached a significant level ($P < 0.05$) of difference. In Fig. 4B, MDA content was greater than that of CK and reached a significant level ($P < 0.05$) when the aqueous extracts of stem and leaves and root reached a concentration of 10 and 25 mg mL^{-1}, respectively. Lastly, with the increase in aqueous extract concentration, MDA content was higher than that of CK but did not reach a significant level.

Synthetic Allelopathic Effect on Wheat Seedlings

From Table 1, a synthetic analysis was performed on the *RI* of root length, seedling height, relative electrical conductivity, SOD activity, proline content, and MDA content to uncover the effects of aqueous extract of *A. tauschii* on the growth of wheat seedlings. When the concentration of the aqueous extract was 5 mg mL^{-1} and $SE \geq 0$, this result indicates that the low concentration aqueous extract of stem and leaves or roots had a stimulating effect on the growth of wheat seedlings. However, when the concentration was higher than 10 mg mL^{-1}, $SE < 0$, and the *SE* value decreased with the increasing aqueous extract concentration, this result signifies that *A. tauschii* had a concentration-related allelopathic inhibiting effect on wheat seedlings. Within the concentration range of 10 to 100 mg mL^{-1}, the *SE* values of seedlings treated with the stem and leaf aqueous extracts was lower than the values of seedlings treated with root aqueous extracts at the same concentration. This result indicates that the aqueous extract of *A. tauschii* stem and leaves had a stronger allelopathic inhibiting effect on wheat seedlings than the aqueous extract of root when the concentrations fell within this range.

Effect of Wheat Aqueous Extract on *A. tauschii* Seed Germination and Seedling Growth

Effect on *A. tauschii* seed germination: With the increase in aqueous wheat extract concentration, *A. tauschii* seed germination percentage showed a rising and then declining trend (Fig. 5A). In Fig. 5B, *RI* indicated that the aqueous extract of different parts of wheat had low-concentration stimulatory and high-concentration inhibitory effects on seed germination of *A. tauschii*. When the concentrations ranged from 25 mg mL^{-1} to 100 mg mL^{-1}, *RI* of the germination percentage of *A. tauschii* seeds treated with aqueous extract of stem and leaves was lower than that treated with the root aqueous extract at the same concentration. This result indicates that the wheat stem and leaf aqueous extract had a stronger allelopathic inhibitory effect on *A. tauschii* seed germination than the wheat root aqueous extract within this concentration range.

Effect on *A. tauschii* Seedling Growth

In Fig. 6, *A. tauschii* seedling height and root length increased and then declined with an increase of the wheat aqueous extract concentration. As shown in Fig. 6B, after

Table 2: Synthesis effects of aqueous extracts from wheat on the seedling of *A. tauschii*

Parts	Concentration (mg mL^{-1})	$RI_{\text{root length}}$	$RI_{\text{seedling height}}$	RI_{REC}	RI_{SOD}	RI_{Pro}	RI_{MDA}	Inhibition synthesis effect (*SE*)
	5.00	0.12	0.04	-0.28	0.05	0.09	-0.07	-0.01
Stems	10.00	0.06	0.03	-0.25	0.17	0.19	-0.27	-0.01
and	25.00	-0.08	-0.11	-0.48	0.24	0.32	-0.41	-0.09
leaves	50.00	-0.17	-0.16	-0.62	0.32	0.35	-0.45	-0.12
	100.00	-0.43	-0.19	-0.68	0.36	0.41	-0.55	-0.18
	5.00	0.01	0.06	-0.10	0.09	0.11	-0.05	0.02
	10.00	-0.16	-0.08	-0.12	0.20	0.23	-0.21	-0.02
Roots	25.00	-0.17	-0.09	-0.43	0.26	0.31	-0.33	-0.08
	50.00	-0.31	-0.11	-0.55	0.33	0.36	-0.42	-0.12
	100.00	-0.38	-0.16	-0.65	0.37	0.42	-0.54	-0.16

treatment with different concentrations of stem and leaves or root aqueous extracts, the seedling height may be higher or lower than that of CK; however, their differences did not reach a significant level. In Fig. 6B, the root length was shorter than that of CK, and their difference reached a significant level ($P < 0.05$) when the aqueous extracts of stem and leaves or root were 50 mg mL^{-1}.

With the increase in aqueous wheat extract concentration, the relative electrical conductivity and proline content of *A. tauschii* seedlings showed a continually increasing trend (Fig. 7). In Fig. 7A, the relative electrical conductivity increased gradually when *A. tauschii* seedlings were treated with 5 to 10 mg mL^{-1} stem and leaves or root aqueous extracts, but showed no significant difference from that of CK. When treated with 100 mg mL^{-1} aqueous extracts of different parts, their difference reached a significant level than that of CK ($P < 0.05$). In Fig. 7B, the proline content was more than that of CK, and their difference reached a significant level ($P < 0.05$).

With the increase in aqueous extract concentration, the SOD activity and MDA content of *A. tauschii* seedlings showed a continually increasing trend (Fig. 8). From Fig. 8A, SOD activity was not significantly higher than that of CK when treated with 5 mg mL^{-1} stem and leaves or root aqueous extract. When treated with 100 mg mL^{-1} aqueous extract of different parts, SOD activity reached a significant level than that of CK ($P < 0.05$). From Fig. 8B, MDA content was not significantly higher than that of CK when treated with 5 mg mL^{-1} aqueous extract of stem and leaves or root. Then, MDA content increased rapidly. MDA content in treatments by different concentrations of aqueous extract had a significant difference from that of CK ($P < 0.05$).

Synthetic Allelopathic Effect on *A. tauschii*

In Table 2, $SE > 0$ occurs only when the concentration of aqueous extract of wheat root was 5 mg mL^{-1}. In all other treatments, *SE* was consistently lower than 0 and decreased with an increase in the aqueous extract concentration. These results indicate that *A. tauschii* seedlings were subjected to concentration-related inhibition effects of wheat. When the concentration ranged from 25 mg mL^{-1} to 100 mg mL^{-1}, stem and leaf aqueous extract-treated seedlings had an *SE* value lower than or equal to that for seedlings treated with the root aqueous extract at the same concentration. This trend indicates that stem and leaf aqueous extract had an equal or stronger allelopathic inhibitory effect on *A. tauschii* seedlings than the wheat root aqueous extract.

Discussion

As a mode of competition among plants, allelopathy exists widely in various ecosystems (Rice, 1984). Plants with allelopathic potential affect receptor plants by acting on their different growth stages, particularly the early stages of seed germination and seedling growth (Kong *et al*., 2006; Duke, 2007; Shen *et al*., 2017). As one of the major noxious weeds in wheat fields of Northern regions, allelopathic effects of *A. tauschii* on neighboring plants, particularly wheat, have rarely been studied. This study showed that the allelopathic activities of *A. tauschii* and wheat depended on the plant parts that were extracted and the concentration of the aqueous extracts, which are probably associated with the content and type of the allelochemicals in different organs of the plants (Hu and Kong, 1997).

Seed germination plays a crucial role for species regeneration, and the decline of seed germination percentage affects the abundance and competitive power of plants in a vegetation community (Huang *et al.*, 2009). In this study, the aqueous extract of *A. tauschii* consistently had an allelopathic inhibitory effect on seed germination of wheat. However, the aqueous extract of wheat had low-concentration stimulation and high-concentration inhibition effects on seed germination of *A. tauschii*. The allelopathic inhibitory effect consistently increased with the increase in aqueous extract concentration. *A. tauschii* would be able to occupy more surrounding space by inhibiting the seed germination of wheat, and these findings were similar to the studies that reported the allelopathic effects of other invasive plants (Zheng and Feng, 2005; Wan *et al.*, 2011; Zhang *et al.*, 2013). However, the low-concentration aqueous extract of wheat had an allelopathic stimulation effect on the seed germination of *A. tauschii*. This effect may be the reason for the rapid spread of *A. tauschii* observed in the wheat fields of China. Moreover, the stem and leaf aqueous extract stronger inhibitory effect on seed germination than the aqueous extract of root, and this may be related to the types and contents of allelochemical

substances in different plant organs. These findings were similar to the study of Huangfu *et al.* (2010) on *F. bidentis* and Yu *et al.* (2008) on *Astragalus adsurgens.*

The seedling stage is one of the key stages in the whole plant life and a period when the plant is sensitive to external adversity (Turk and Tawaha, 2002). This study showed that *A. tauschii* and wheat both had allelopathic low-concentration stimulation and high-concentration inhibition effects on seedling height and root length. The fact that the allelopathic effect on root length was stronger than on seedling height was probably because of the direct contact between the root and the aqueous extract. These findings were consistent with the conclusion of many previous studies (Ge *et al.*, 2015). Allelopathic stress may destroy the cell membrane and function in the receptor plant, and cause electrolyte leakage out of the cells that results in the consistent increase of the relative electrical conductivity (Zhu *et al.*, 2007; Tian *et al.*, 2015). In this study, the relative electrical conductivities of wheat and *A. tauschii* showed similar changes. Plants adapted to stress by reducing the osmotic potential of cells through the increased content of osmotic adjustment substances, such as proline and soluble sugars (Ye and Fan, 2013). As one of the key enzymes that scavenge active oxygen in cells, SOD plays a crucial role in maintaining the stability of the membrane system. In this study, seedlings of wheat and *A. tauschii* adapted to the allelopathic stress through the increase of proline content and SOD activity, and the result was consistent with the findings of previous research (Huang *et al.*, 2012; Liu *et al.*, 2014c). When treated with 50 to 100 mg mL^{-1} aqueous extract of *A. tauschii* stem leaves, SOD activity in the wheat seedlings declined most likely because the increased allelopathic effect led to the accumulation of much active oxygen, instead of it being scavenged completely by SOD. As one of the major products of membrane lipid peroxidation, MDA content directly indicated the lipid peroxidation degree of the cell membrane and how much the plant was stressed (Bao *et al.*, 2015). In the study of Zhang *et al*. (2013) on *A. philoxeroides* and of Ge *et al*. (2015) on sorghum, MDA content in receptor plant seedlings increased gradually with the increase in aqueous extract concentration. In the present study, the MDA content of the two types of seedlings showed similar changes.

Based on the *RI* of several indicators, the synthetic allelopathic effect can better reflect the allelopathic effect of plants; thus, it has been widely used in studies of plant allelopathic effects (Zhao *et al.*, 2010; Fu *et al.*, 2012; Wang *et al.*, 2013). From *SE* values, only the aqueous extract of wheat stem leaves had a consistent allelopathic inhibitory effect on *A. tauschii* seedling growth. However, the aqueous extracts of wheat root and of different parts of *A. tauschii* had allelopathic low-concentration stimulatory and high-concentration inhibitory effects on seedling growth. Within the concentration range of 10 to 100 mg mL^{-1}, the aqueous extract of *A. tauschii* stem leaves had a stronger allelopathic inhibitory effect on wheat seedlings than the root aqueous extract, whereas at 25 to 100 mg mL^{-1} wheat aqueous extract showed similar allelopathic effects on *A. tauschii* seedlings. These findings were consistent with the conclusions of the studies of Lu *et al.* (2012) and Wang *et al.* (2012) on *F. bidentis* and *Thymus mandschuricus*, respectively.

Based on the indoor test and through its combination with the changes in physiological indicators, including seed germination and seedling growth, we explored the mutual allelopathic effects between *A. tauschii* and wheat. Essentially, several possible means of releasing allelochemicals from plants, such as through the roots or the aerial parts (leaves and stems) were presented, and allelochemical production is known to be subjected to several environmental factors in natural conditions (Zhang *et al.*, 2004). Thus, a more in-depth study on the mutual allelopathic effects between *A. tauschii* and wheat in farmlands could provide reference data for the illustration of the invasive mechanism of *A. tauschii* and of weed prevention in wheat fields.

Conclusion

To summarize, mutual allelopathic effects exist between *A. tauschii* and wheat, but *A. tauschii* had a higher allelopathic inhibitory effect than wheat. Therefore, *A. tauschii* must be considered as an allelopathic species posing production risks in mixed cropping systems. With a goal of alleviating its adverse effects on intercropping or subsequent crops, farmers should remove *A. tauschii* and its residues from farmland. Specific allelochemical compounds in *A. tauschii* extracts and their plant-growth inhibitory mechanisms should be further investigated in future studies.

Acknowledgements

The first author acknowledges the financial grant from Henan natural science fund projects (182300410092, 182300410082).

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(Received 27 July 2018; Accepted 04 September 2018)