海藻生物有机肥对冬小麦的生长和产量的影响

徐文文[1]，刘恒洋[2]，谭秀山[3]，王建明[4]，李明潭[4]，毕建杰[1*]

（1. 山东农业大学农学院，山东泰安 271018；2. 山东农业大学经管学院，山东泰安 271018；3. 泰安市圣田农林科技开发有限公司，山东泰安 271000；4. 山东威海世代海洋生物科技有限公司，山东威海 264300）

摘 要 [目的] 探讨海藻生物有机肥对冬小麦的产量和品质造成的影响程度。[方法] 采取大田小区试验方法，在冬小麦返青期后拔节——成熟期，叶面喷施海藻生物有机肥 3 次，共 45 kg/hm^2，调查冬小麦的株高、干物质积累、旗叶光合特性和籽粒产量等。[结果] 喷施海藻生物有机肥对冬小麦的株高影响较小，促进茎杆粗壮、干物质积累量增加，旗叶光合速率增加了 3.16%，小麦产量增加 6.85%。[结论] 叶面喷施海藻生物有机肥可促进冬小麦智能化生长，增粗抗倒伏，显著提高了单株穗重的同时，增加了容重，提高小麦籽粒的物理品质；有利于叶片叶绿素的合成和缓解叶绿素的分解。在目前国家提出的化肥和农药双减战略形势下，该试验结果和数据可在全省和全国小麦种植区推广应用。

关键词 海藻生物有机肥；冬小麦；干物质积累；产量；光合速率

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作者简介 徐文文（1996.5--），女，山东文登人，大学本科在读，研究方向：作物栽培。*通讯作者，教授，硕士，主要从事作物栽培与农业气象研究，E-mail: jianjieb@126.com。

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*Corresponding author. E-mail: jianjieb@126.com

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Effects of Seaweed Bio-organic Fertilizer on Growth and Yield of Winter Wheat

Wenwen XU[1], Hengyang LIU[2], Xiushan TAN[3], Jianming WANG[4], Mingtan LI[4], Jianjie BI[1*]

1. College of Agronomy, Shandong Agricultural University, Tai'an 271018, China;
2. College of Economics & Management, Shandong Agricultural University, Tai'an 271018, China;
3. Tai'an Shengtian Agriculture and Forestry Science and Technology Development Co., Ltd., Tai'an 271000, China;
4. Shandong Shidai Marine Biological Technology (Weihai) Co., Ltd., Weihai 264300, China

Abstract [Objective] This study aimed to investigate the effects of seaweed bio-organic fertilizer on yield and quality of winter wheat. **[Method]** Seaweed bio-organic fertilizer was applied to leaves of winter wheat according to the dose of 45 kg/hm^2 from jointing stage to maturing stage, and plant height, dry matter accumulation, flag leaf photosynthetic characteristics and grain yield of winter wheat were investigated. **[Result]** Foliar spraying of seaweed bio-organic fertilizer showed little effect on plant height of winter wheat, thickened stems, promoted dry matter accumulation, increased flag leaf photosynthetic rate by 3.16%, and increased yield of winter wheat by 6.85%. **[Conclusion]** Foliar spraying of seaweed bio-organic fertilizer promoted the intelligent growth, thickened the stems, improved the lodging resistance, significantly increased the panicle weight per plant, and increased the bulk density of winter wheat, as well as improving the physical quality of wheat grain. In addition, foliar spraying of seaweed bio-organic fertilizer promoted the synthesis of chlorophyll and mitigated the decomposition of chlorophyll in winter wheat. Under the background of fertilizer-pesticide double reduction, the test results and data of this study can be promoted in the wheat-growing areas of Shandong Province and even whole China.

Key words Seaweed bio-organic fertilizer; Winter wheat; Dry matter accumulation; Yield; Photosynthetic rate

Wheat is one of the world's major food crops, and is the staple food of more than 1/3 of the world's population. Stabilizing production area and improving yield, quality and efficiency are the development trends of wheat production in the world[1]. The annual planting area of wheat in Shandong Province is 5.20×10^6 hm^2, and it is the most important food crop in Shandong Province. There are many problems in wheat production process. Excessive application of chemical fertilizers and pesticides leads to wheat farmland production, and restricts the sustainable development of wheat production. Currently, the average application amount of fertilizer in China's land exceeds 400 kg/hm^2, which is much higher than the standard of 225 kg/hm^2 adopted by United States and the European[2]. Fertilizer residue in the soil is quite serious. Acid rain, sulfur

and heavy metals produce pollution to the soil, crop and water, resulting in pesticide toxicity in biological products. In Shandong Province in 2012, the annual application amount of chemical fertilizer was 4.74×10^6 t, which was higher than the national average, and the effective irrigation area was 4.99×10^6 hm^2[3]. To address the negative effects of chemical fertilizers on agricultural products, the application amount of chemical fertilizers must be reduced, and the application amount of microbial fertilizers and bio-organic fertilizers should be increased to fundamentally solve the pollution of chemical fertilizers and to improve the quality of agricultural products. Bio-organic fertilizer can improve the yield, quality and economic efficiency, and this has become the fertilizer industry's public knowledge. China has a vast territory, and the natural conditions and agronomic management techniques differ greatly among different regions. The development level of wheat production is also every uneven among different cities of Shandong Province[4]. The selection of type, application method and application technique of bio-organic fertilizer also has a great blindness, and it is urgent to carry out tests to determine the optimum application amount and application time. Winter wheat encounters 230-250 d from sowing to mature, and grain-filling stage is the critical period. Domestic scholars and experts have conducted a lot of exploration on the fertilizer demand laws and fertilization tests of winter wheat[5-8]. In this study, Haishenfeng seaweed bio-organic fertilizer produced by Shandong Shidai Marine Biological Technology (Weihai) Co., Ltd. was sprayed on the foliage of winter wheat to study the effects of this kind of bio-organic fertilizer on the growth and yield of winter wheat and to explore the simple high-quality cultivation method of wheat under current production mode.

1. Materials and Methods

1.1. Experimental materials and design

The experiment was carried out in the field of Agronomy Experiment Station of College of Agronomy, Shandong Agricultural University between October 2014 and June 2016. Shannong 28 was selected as the tested variety winter wheat.

Shannong 28 was bred by the wheat breeding laboratory of Shandong Agricultural University (LNS 2014036). It is a semi-winter mid-maturity variety with semi-erect seedling, dark green narrow upward leaves, semi-compact plant type, large stem-leaf bulk density, long spikes, white husk, hard white grains, earbearing tiller percentage of 46.9%, plant height of 75 cm, grain number per panicle of 48.2, 1 000-grain weight of 46.9 g and protein content of 14.5%. Its flour has wet gluten content of 36.6%, sedimentation value of 33.5 ml and bulk density of 794.8 g/L, and is a kind of strong-gluten wheat. Shannong 28 is suitable to be promoted in the medium land of northern Huanghuai winter wheat area (across Shandong Province). The tested leaf fertilizer was Haishenfeng seaweed bio-organic fertilizer produced by Shandong Shidai Marine Biological

Technology (Weihai) Co., Ltd.

The tested soil was brown loam with organic matter content of 1.35%, total nitrogen content of 1.18%, available nitrogen content of 86.3 mg/kg, available phosphorus content of 53.2 mg/kg, available potassium content of 84.0 mg/kg, bulk density of 1.48 g/cm^3, field capacity of 32.8% and saturation moisture content of 41.8%.

1.2. Experimental methods

Total two treatments were designed, namely spraying seaweed bio-organic fertilizer and spraying water. The seaweed bio-organic fertilizer was diluted by 300 and 500 times, respectively. There were three replicates for each treatment. The seaweed bio-organic fertilizer was sprayed to the foliage of winter wheat according to the dose of 15 kg/hm^2, which was repeated three times from standing to gain-filling stage. Similarly, water was sprayed to winter wheat. The area of each plot was 10 m^2 (3.3 m × 3.3 m). Foliar spraying of seaweed bio-organic fertilizer was carried out at turning green-jointing stage, booting-heading stage and flowering-grain filling stage, respectively. At the same time, sampling was conducted.

1.3. Indicator measurement and methods

Dry matter accumulation amount was determined by conventional weighing method; and wheat stem thickness was measured with vernier caliper.

Wheat bulk density (g/L) was determined with bulk density tester (61-71).

Photosynthetic rate *Pn* [μmol/(m^2•s)], intracellular CO_2 concentration *Ci* [mmol/(m^2•s)] and transpiration rate *Tr* [mmol/(m^2•s)] of wheat flag leaf were determined respectively by the Li-Cor6400 portable photosynthesis apparatus (Lagos, United States) during 10:00 am-12:00 am of a sunny day. Total 3-5 pieces of flag leaf were prepared for each index, and the mean was calculated.

Chlorophyll content of flag leaf was measured by SPAD-502 (Minolta, Japan) chlorophyll meter at 10:00 am of a sunny day.

Agronomic efficiency of seaweed bio-organic fertilizer (kg/kg) = (Wheat yield in fertilization area - Wheat year in control area)/Fertilization amount × 100[9-10].

Agronomic efficiency of fertilizer refers to the increased economic yield per unit of fertilizer under specific fertilization conditions.

The final experimental data were expressed as the means of two-year test results.

2. Results and Analysis

2.1. Effect of foliar spraying of seaweed bio-organic fertilizer on dry matter accumulation in shoot of winter wheat

As shown in Fig.1, foliar spraying of seaweed bio-organic fertilizer significantly increased

the dry matter accumulation amount in winter wheat. The dry matter accumulation amounts on April 22, May 4 and June 8 were all significantly higher than that of the control. Particularly, at flowering stage, the dry matter accumulation amount in the treatment group was 20.27% higher than that of the control.

As shown in Table 1, the dry matter accumulation amounts in various organs (stem, leaf and panicle, except root) of winter wheat changed greatly after the foliar spraying of seaweed bio-organic fertilizer. The dry matter amounts in stem and leaf of winter wheat increased significantly in the early period, and that in panicle of winter wheat increased significantly in the late period.

Table 1 Effects of different treatments on dry matter accumulation in various parts of winter wheat g

	Spraying seaweed bio-organic fertilizer				Spraying water			
	April 12	April 22	May 4	June 8	April 12	April 22	May 4	June 8
Root	0.85	2.40	1.90	2.05	0.85	2.00	1.90	2.00
Stem	7.60	9.20	12.00	12.90	7.60	7.90	10.20	12.30
Leaf	4.20	4.38	4.50	4.95	4.20	4.25	4.48	4.75
Panicle	3.40	4.28	10.20	12.80	3.40	3.50	7.20	10.90
Total dry matter	16.05	20.26	28.60	32.70	16.05	17.65	23.78	29.95

2.2. Effects of foliar spraying of seaweed bio-organic fertilizer on stem height and thickness of winter wheat

2.2.1. Effect of foliar spraying of seaweed bio-organic fertilizer on stem height of winter wheat

As shown in Table 2, in the early growth period, foliar spraying of seaweed bio-organic fertilizer promoted the vegetative growth and increased the plant height of winter wheat. On April 22, the plant height of winter wheat in the treatment group was 68.5 cm, and that in the control group was 64.5 cm. Thus, foliar spraying of seaweed bio-organic fertilizer showed obvious growth-improving effect. It was just the opposite after the flowering period, *i.e*., the increase of plant height in the treatment group was smaller than that in the control group, indicating that foliar spraying of seaweed bio-organic fertilizer promoted the reproductive growth of winter wheat in the middle-late growth period. It suggests that the active substances in seaweed can promote the growth of wheat. Many wheat varieties suffer heavy rains and strong winds in the flowering period, and are prone to lodging. Strong winds and heavy rains occurred in Tai'an, Shandong on May 3, 2016, resulting in different degrees of lodging in winter wheat in the control group.

However, no lodging appeared in the treatment group.

As shown in Table 3, L1 standards for the bottom first node, L2 stands for the bottom second node, and so on, L6 standards for the bottom sixth node, namely internodes below ear. Among them, there were small differences in length of L2, L3 and L4, and there were great differences in length of L1, L5 and L6. The length of L1 sprayed with seaweed bio-organic fertilizer was 2.8 cm higher than that sprayed with water, the length of L5 sprayed with seaweed bio-organic fertilizer was 2.7 cm lower than that sprayed with water, and the length of L6 in the treatment group was 5.4 cm lower than that in the control group. It indicated that seaweed bio-organic fertilizer produced effect on both upper and lower part of wheat stem. Foliar spraying of seaweed bio-organic fertilizer contributed to increasing the length of L1 and decreasing the length of L5 and L6. In particular, the length of L6 was reduced by as high as 26.34%, thus avoiding the occurrence of lodging.

Table 2 Effects of different treatments on plant height of winter wheat cm

	April 12	April 22	May 4	June 8
Spraying seaweed bio-organic fertilizer	62.0	68.5	72.5	75.0
Spraying water	62.0	64.5	74.0	76.0

Table 3 Effects of different treatments on length of various nodes of wheat stem cm

	L1	L2	L3	L4	L5	L6
Spraying seaweed bio-organic fertilizer	6.2	5.6	8.0	10.5	13.0	15.1
Spraying water	3.0	5.7	7.7	10.5	15.7	20.5

2.2.2. Effect of foliar spraying of seaweed bio-organic fertilizer on stem thickness of winter wheat

As shown in Table 4, foliar spraying of seaweed bio-organic fertilizer significantly increased the thickness of L2 (by 0.5 mm), L3 (by 0.8 mm) and L4 (by 0.7 mm), but showed no effect on the thickness of L1 and L5. It indicated that the spraying of seaweed bio-organic fertilizer had very significant effect on the thickness of wheat stem.

Table 4 Effects of different treatments on thickness of various nodes of wheat stem mm

	L1	L2	L3	L4	L5	L6
Spraying seaweed bio-organic fertilizer	1.4	2.4	3.3	3.5	1.4	-
Spraying water	1.4	1.9	2.5	2.8	1.4	-

2.3. Effects of foliar spraying of seaweed bio-organic fertilizer on yield and yield composition of winter wheat

As shown in Table 5, foliar spraying of seaweed bio-organic fertilizer significantly increased the biomass and yield of winter wheat. Compared with those in the control group, the biomass, panicle weight per plant, grain number per panicle, 1 000-grain weight, bulk density and yield per plot of winter wheat in the treatment group were increased by 9.18%, 17.43%, 3.56%, 2.05%, 2.68% (20.5 g) and 6.85% (0.554 kg), respectively, indicating that the effects of foliar spraying of seaweed bio-organic fertilizer on the biomass, yield and panicle weight per plant of winter wheat were greatest, while on the 1 000-grain weight, bulk density and grain number per panicle were smaller.

Table 5 Effects of different treatments on yield and yield composition of winter wheat

	Biomass//kg/plot	Panicle weight per plant//g	Grain number per panicle	1 000-grain weight//g	Bulk density//g/L	Yield per plot//kg	Yield per hectare//kg	Grain weight per plant//g
Spraying seaweed bio-organic fertilizer	19.62	12.80	49.5	48.25	784.5	8.641 8	8 642.25	14.96
Spraying water	17.97	10.90	47.8	47.28	764.0	8.087 8	8 089.35	14.10

2.4. Effects of foliar spraying of seaweed bio-organic fertilizer on flag leaf photosynthetic properties of winter wheat

Photosynthates produced during the heading-mature stage account for 50%-70% of the grain yield of winter wheat[11]. The photosynthates of winter wheat after flowering depend on the ability of photosynthesis. Flag leaf photosynthetic properties are the main parameters to evaluate the ability of photosynthate production in wheat leaves.

As shown in Fig.2, the photosynthetic rate in winter wheat flag leaf of the treatment group was 3.16% higher than that of the control group, indicating that spraying seaweed bio-organic fertilizer could improve the photosynthetic capacity of mesophyll cells of winter wheat. The photosynthetic rate was determined on May 4 in the post flowering-grain filling period. It indicated that foliar spraying of seaweed bio-organic fertilizer improved the photosynthate production ability of wheat leaves.

As shown in Fig.3, foliar spraying of seaweed bio-organic fertilizer increased the chlorophyll content in winter wheat flag leaf by 2.5 compared with the control[12]. Leaf chlorophyll content is an important parameter to measure leaf senescence, and is also an important factor affecting

photosynthate production. The results showed that the foliar spraying of seaweed bio-organic fertilizer delayed the aging of winter wheat. It could be concluded that seaweed bio-organic fertilizer can maintain the green leaf area and delay the senescence of wheat.

As shown in Table 6, foliar spraying of seaweed bio-organic fertilizer showed effect on the photosynthetic rate (*Pn*), intracellular CO2 concentration (*Ci*) and transpiration rate (*Tr*) of wheat flag leaf. Compared with those in the control group, the *Pn* and *Tr* in the treatment group were increased by 0.29 μmol/(m^2•s) (3.16%) and 0.01 mmol H2O/(m^2•s), respectively, and the *Ci* was reduced by 23.7 mmol CO_2/(m^2•s). This suggested that seaweed bio-organic fertilizer could improve the leaf photosynthetic rate and decrease the intracellular CO_2 concentration of wheat, but had little effect on transpiration rate. In short, seaweed bio-organic fertilizer can improve the photosynthetic performance of wheat leaves.

Table 6 Effects of different treatments on flag leaf photosynthetic properties of winter wheat

	Spraying water			Mean	Spraying seaweed bio-organic fertilizer			Mean
Photosynthetic rate (*Pn*)	9.10	9.20	9.25	9.18	9.30	9.50	9.60	9.47
Intracellular CO2 concentration (*Ci*)	178	225	223	208.7	193	177	185	185
Transpiration rate (*Tr*)	2.70	2.69	2.70	2.70	2.70	2.72	2.70	2.71

2.5. Agronomic efficiency of seaweed bio-organic fertilizer

According to the calculation formula, the average agronomic efficiency of seaweed bio-organic fertilizer of the two-year test results was 0.122 9 [(576.15-539.29)/3 × 100)]. The agronomic efficiency of seaweed bio-organic fertilizer is a comprehensive performance of fertilization's yield-improving effect, and it directly reflected the yield-improving situation of seaweed bio-organic fertilizer.

3. Conclusions

Foliar spraying of seaweed bio-organic fertilizer could promote the growth and dry matter accumulation of wheat shoot. It increased the thickness of wheat stem, especially the thickness of L2, L3 and L4 nodes. Spraying seaweed bio-organic fertilizer increased the dry matter accumulation in wheat panicles, and the increase of dry matter accumulation in stem and panicle was the main source of dry matter increase of whole plant. In addition, foliar spraying of seaweed bio-organic fertilizer increased the dry matter accumulation in wheat leaves to a certain extent, but it showed little effect on the plant height and root system of wheat. It can be concluded that foliar spraying of seaweed bio-organic fertilizer can promote the intelligent growth, reduce the plant height, improve the lodging resistance and promote the reproductive growth of winter wheat. It

better coordinates the transition from vegetative growth to reproductive growth of wheat, avoiding unfavorable delayed senescence of wheat in the late period caused by excessively vigorous vegetative growth.

On the basis of increasing the total biomass, foliar spraying of seaweed bio-organic fertilizer increased the grain number per panicle, panicle weight per plant, 1 000-grain weight and bulk density of winter wheat. In addition to improving the yield, spraying seaweed bio-organic fertilizer improved the physical quality of winter wheat, so that the wheat grains were more uniform, fuller and more compact. A study[13] showed that there was a positive correlation between bulk density and processing yield of wheat. Spraying seaweed bio-organic fertilizer increased the yield of winter wheat by 6.85%, characterized by obvious yield-improving effect.

Foliar spraying of seaweed bio-organic fertilizer is conducive to improving the synthesis of chlorophyll, mitigating the decomposition of chlorophyll, increasing the transpiration (stomatal conductance should be also increased), and promoting the photosynthesis of flag leaves. It also increased the photosynthetic rate (*Pn*)[14], which caused the decrease of intracellular CO_2 concentration (*Ci*), accelerated the growth of wheat leaves, increased the length and thickness of wheat stem, and increased the dry matter accumulation in wheat panicles. Therefore, the dry matter accumulation amount and the yield of winter wheat in the treatment group were significantly higher compared with those in the control group.

4. Discussion

In this study, the conclusions were achieved based on the analysis on effects of foliar spraying of seaweed bio-organic fertilizer on the agronomic traits and photosynthetic properties of winter wheat. At the same time, the experimental data and results can provide theoretical and practical basis for rational fertilization and fertilizer-pesticide double reduction strategy implementation in winter wheat-growing areas of Huanghuai region and even the whole China. The agronomic efficiency of seaweed bio-organic fertilizer is 0.122 86 kg/kg, which is calculated referring to the calculation of chemical fertilizer's agronomic efficiency. However, the utilization rate of seaweed bio-organic fertilizer is related to fertilization amount, crop type and management measures, and their relationships still need further study. The effect of seaweed bio-organic fertilizer on soil microenvironment is also to be further studied.

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Fig.1 Effect of foliar spraying of seaweed bio-organic fertilizer on dry matter accumulation in wheat shoot

日期 Date

4 月 12 日 April 12

4 月 22 日 April 22

5 月 14 日 May 14

6 月 8 日 June 8

干物质积累//g Dry matter accumulation amount//g

喷施 Spraying

Fig.2 Effect of foliar spraying of seaweed bio-organic fertilizer on photosynthetic rate of winter wheat

喷施 Spraying

光合速率//μmol/(m^2•s) Photosynthetic rate//μmol/(m^2•s)

Fig.3 Effect of foliar spraying of seaweed bio-organic fertilizer on flag leaf chlorophyll content of winter wheat

喷施 Spraying