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The Influence of Partial Substitution of Potassium by Sodium on the Growth Effect of Sugarcane

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Abstract: The effects of different potassium and sodium levels on the growth of Taisugar No. 22 (ROC22) were studied by potted nutrient solution-sand culture experiment in this paper. The results showed that under low potassium stress (0 mmol/L) supply, the proper application of sodium could significantly promote photosynthesis of sugarcane and dry matter accumulation, reduce root shoot ratio and promote shoot growth. When low potassium (0.2 mmol/L) was applied, the proper application of sodium could reduce the root shoot ratio of sugarcane. When high potassium (2 mmol/L) was applied, the proper application of sodium could significantly promote the growth of sugarcane root and increase root shoot ratio. In the case of low potassium or high potassium, the rational application of sodium can promote photosynthesis of sugarcane, while excessive sodium can inhibit photosynthesis. Thereby, sodium can be used as a substitute for partial potassium to promote the growth of sugarcane in the soil with low available potassium and water-soluble sodium.

Keywords: Sugarcane, Partial Substitution of Potassium by Sodium, Growth Effect

Introduction

Potassium is one of the essential nutrient elements in plants. Potassium deficiency is one of the important reasons for limiting crop growth and development, yield formation and decrease in quality. It is generally believed that deficiency of potassium inhibits growth and development mainly because of its effect on plant photosynthesis (Sobbarao *et al*., 2003). To solve this problem, some researchers proposed that sodium replacing some potassium can meet the nutritional needs of plants (Abdul *et al*., 2011). Pi *et al*. (2014) thought that the substitution between K+ and Na+ is a physiological function of nutrient ions replacing another nutrient ion. As a monovalent cation closest to the K+ ion structure, sodium also can be used as the substitution of positive ion with the biggest advantage; in the case of potassium deficiency, sodium addition can make the total positive ions in plants remain stable in order to maintain the normal turgor of vacuoles and reduce the adverse effects caused by the osmotic potential of potassium deficiency. However, the degree of partial substitution for potassium by sodium varies and crop type does not exist in all crops. Many experiments prove that some crops, such as corn (*Zea mays*) and lettuce (*Lactuca serriola*) do not have sodium substitutive effect, while cotton (*Gossypium hirsutum*) and sugar beet (*Beta vulgaris*) and other crops have this substitution ability (Maser *et al*., 2002; Alice *et al*., 2014). Maser and Alice showed by experiment that under the conditions of potassium deficiency or low potassium, sodium had a significant effect on the growth and yield of cotton and sugar beet; sodium could replace part functions of potassium. The results of Gattward *et al*. (2012) also showed that potassium substitution by sodium could increase leaf area, chlorophyll content and net photosynthetic rate of sugar beet seedlings, and the net photosynthetic rate increased with the increase of replacement proportion of sodium to potassium.

Sugar cane (*Saccharum* L.) is the most important sugar crop in the world. Because of its long growth period and large biomass, the demand for potassium is also large. Related studies have shown that for every 1t of sugarcane, potassium oxide 2.2~3.0kg, pure nitrogen 1.5~2.0kg and P_2O_5 1.0 ~1.5kg should be removed from the soil (Chen *et al*., 2003). Sugarcane can absorb more potassium than nitrogen and phosphorus. However, the total area of potassium deficient soil in China's cultivated land is as high as 23 million hm^2. Generally, potassium deficiency and serious potassium deficiency account for 23% of the total cultivated land area (Zhang *et al*., 2007). The southern latosol and lateritic soils are the main planting areas of sugarcane in China. Due to the strong leaching and other factors, the available potassium content in these soils is generally low and most of potassium is ineffective that is difficult to use (Lei *et al*., 2015).

Therefore, the effect of partial substitution of potassium by sodium has been found in some plants, and few studies have been done on sugarcane. Furthermore, the problem of potassium deficiency caused by insufficient supply of potassium in soil has become the main factor that restricting the production of sugarcane and other crops. This study can enrich the theory of sodium and potassium nutrition and provide theoretical basis for the practice of sugarcane nutrition and production.

Materials and Methods

Experiment Designs

The experiment was conducted at the glass house of the Institute of biotechnology, Guangdong Ocean University on October 21, 2015. The plantlets of new Taisugar ROC 22 was used with river sand and nutrient solution as the test medium and cultivated in the form of bottled sand-nutrient solution. River sand was washed with clean water to remove soil and silt, and then washed with hydrochloric acid (to prevent the dissolved salts and non-adsorbing salts in the sand influencing the test results); finally, using tap water to clean it to neutral and then using deionized water to clean two times. According to the absorption characteristics of sugarcane to N, P and K, the formula of Hoagland nutrient solution was properly improved and the nutrient solution was obtained (Tocquin *et al*., 2003). K nutrient solution and NaCl solution were prepared separately.

Three potassium levels (0, 0.2, 2 mmol/L) and three sodium levels (0, 0.2, 2 mmol/L) were set as K_0, K_1, K_2, Na_0, Na_1 and Na_2, and a total of nine treatments (K_0N_0、K_0Na_1、K_0Na_2、K_1Na_0、K_1Na_1、K_1Na_2、K_2N a_0、K_2Na_1 K_2Na_2) with four times repeat and 36 buckets in all 3 kg sand in each bucket with small holes at the bottom of the sand barrel, which was immersed in the nutrient liquid barrel with 5 cm deep. The sugarcane seedlings with 20 cm high and uniform growth were selected for transplanting (transplanting should be carried out before 10 am or after 5 pm), four trains for each bucket. Deionized water was supplied daily till the nutrient solution to the plant level, and then pH of the nutrient solution was regulated to 6.0 and the nutrient solution was replaced 1-2 times a week. After 30-60 days of transplanting, the leaves on the above-ground were taken to determine the various photosynthetic indexes. The sugarcane was harvested and washed after 67 days; the fresh and dry weight of the above-ground and below-ground of the sugarcane were calculated, and the root shoot ratios were calculated.

Determination Items and Methods

Determination of plant biomass: Through drying and weighing method, above-ground and root were put in the oven at 105°C for 30s green removing, and then dried to constant weight at 75°C, finally the dry weight of above-ground and root were weighed respectively; the sum represented the biomass and root shoot ratio can be calculated.

Determination of photosynthetic characteristics: use portable LI-640 photosynthetic measuring system produced by LI-COR of United States in full light to measure the net photosynthesis rate of sugarcane leaf (Pn, CO_2 μmol/m^2s), transpiration rate (Tr, H_2Omol/m^2s), stomatal conductance (Gs, mol/m^2s) and CO_2 concentration of intercellular space (Ci, μmol/m^2s).

Data Reduction

The Microsoft Office Excel 2003 software was used to make statistics and drawing and the Duncan's method was used for significant comparison. The significant level was $\alpha = 0.05$.

Results

The Effect of Partial Substitution of Potassium by Sodium on the Biomass of Sugarcane

Table 1 show that there is a significant difference in the biomass of sugarcane under different treatment levels of potassium and sodium for Taisugar No. 22. Studies have shown that the concentration of K+ in the cytoplasm decreases and the typical symptom of K deficiency appear when the crop is seriously lack of K, which brings serious adverse effects on the growth and development (Pi *et al*., 2016). However, in this experiment, under the treatment of K_0, the root and above-ground of the sugarcane increased significantly and the root shoot ratio decreased significantly with the increase of sodium concentration, and the sugarcane grew well. This is most likely that Na^+ supplemented the content of positive ion in vacuoles, which made up for the negative effect of positive ion deficiency and stabilized the osmotic potential of vacuoles so that sugarcane can maintain normal growth rate. It is preliminarily indicated that the function of sodium can partially replace potassium in the physiological growth of sugarcane under low potassium stress. At the level of K_1 and K_2, the root and above-ground weight of sugarcane were reduced by Na_2 treatment. The results showed that at a certain level of potassium supply, sodium can inhibit the absorption of nutrients in the root system, hinder the normal growth of roots and stems and leaves and was not conducive to the accumulation of biomass. Especially at K_2 level, sodium treatment promoted the root growth and hindered the transport of root nutrients to the above-ground; meanwhile, the total biomass of sugarcane would be significantly reduced with the increase of sodium concentration. Even under the potassium treatment, sodium application could inhibit the growth of sugarcane, and the higher the concentration of sodium could lead to the stronger the inhibition and the less biomass accumulation. However, potassium application could significantly increase the biomass of sugarcane, especially in the case of no sodium supply.

The Effect of Partial Substitution of Potassium by Sodium on the Root Shoot Ratio of Sugarcane

The root shoot ratio (Root/shoot, R/S) is an important index to measure the coordination of growth and development of the above-ground and the below-ground part of the crops. When R/S is large, the growth of crops tends to allocate the resources to below-ground; and when R/S is small, it tends to allocate the resources to above-ground. Table 1 show that the change of root shoot ratio of No. 22 is not consistent with the different levels of potassium and sodium. At the K_0 level, the sodium treatment promoted the growth of the roots and above-ground, and Na_2 treatment reached the maximum. The root shoot ratio decreased by 0.03 and 0.07. The amplitude increased at the K_1 level and sodium treatment significantly inhibited the growth of the root and above-ground, especially the root shoot ratio decreased in the Na_2 treatment. The amplitude of the root shoot ratio increased by 0.11 and 0.24 successively at the K_2 level; the root shoot ratio of Na_2 treatment was even higher than that of all treatments. This indicated that in the direction and intensity of distribution, the proportion of photosynthate allocated to the above-ground began to decrease with the increase of sodium level, which promoted the root development and expanded the contact area with soil, thus made root obtain enough nutrient to promote the growth of above-ground.

Effects of Partial Substitution of Potassium by Sodium on the Photosynthesis of Sugarcane

Photosynthesis is an important metabolic process in plants. Its strength is very important for plant growth, yield and resistance. Therefore, photosynthesis can be used as an index to estimate the growth and stress tolerance of plants (Silveira and Carvalho, 2016).

The Effect of Partial Substitution of Potassium by Sodium on the Net Photosynthesis Rate (Pn) of Sugarcane

It can be known from Fig. 1A that when the potassium is K_0 and K_1, the net photosynthetic rate curve of sugarcane is increasing; when the potassium level is K_2, the net photosynthetic rate curve of sugarcane is decreasing linearly. Perhaps that on the one hand, proper increase of sodium ion concentration under low potassium stress can improve the chlorophyll synthesis of plants; on the other hand, it can promote the transformation of pyruvate to pyruvic acid so as to improve the efficiency of photosynthesis. Especially at K_1, the effect of each sodium level treatment has significant difference and sodium can increase the photosynthetic rate of sugarcane; while at K_2, the higher the sodium concentration is and the more obvious inhibiting effect on the photosynthesis rate of sugarcane.

Table 1: Effects of partial substitution of potassium by sodium on sugarcane biomass

	Dry weight (g)			
Treatments	Root/shoot rate	Root weight	Shoot weight	Total weight
K_0Na_0	1.56±0.31 de	4.86±0.56 d	6.42±0.85 f	0.32±0.03 b
K_0Na_1	2.04±0.06 d	7.32±0.09 c	9.35±0.15 d	0.29±0.01 bc
K_0Na_2	2.23±0.14 cd	9.98±0.48 b	12.21±0.34 bc	0.22±0.23 d
K_1Na_0	2.84±0.51 bc	9.77±0.83 b	12.60±1.32 bc	0.28±0.03 bc
K_1Na_1	2.12±0.15 d	7.08±0.43 cd	9.17±0.57 de	0.30±0.02 bc
K_1Na_2	1.22±0.07 e	5.42±1.26 cd	6.64±1.33 ef	0.24±0.04 d
K_2Na_0	2.98±0.01 b	13.90±1.41 a	16.88±1.41 a	0.22±0.03 d
K_2Na_1	3.32±0.15 ab	10.03±0.45 b	13.62±0.58 b	0.33±0.01 b
K_2Na_2	3.84±0.14 a	6.77±0.46 cd	10.61±0.44 cd	0.57±0.04 a

Note: Duncan's multiple range tests is used to deal with data and a b c d e f in the table indicates significant differences at 0.05 levels.

Thereby, it is hypothesized that under low potassium stress, sodium can partly replace the function of potassium and provides nutrients to sugarcane for photosynthesis to maintain normal net photosynthetic rate. At the K_1 level, the interaction of potassium and sodium had the greatest effect on the net photosynthetic rate of sugarcane, when the interaction of potassium and sodium reached the best effect. At the high K level, there is antagonism between sodium and potassium and the effect of it on photosynthesis is great with the increase of sodium concentration.

The Effect of Partial Substitution of Potassium by Sodium on the Stomatal Conductance (Gs) of Sugarcane

Stoma is the main channel of gas exchange between plant leaves and the outside world. Plant stomata is the gap between two guard cells and the stomatal conductance indicates the degree of stomatal opening, which affects photosynthesis, transpiration and more (Rogiers and Clarke, 2013). In many plants, K^+ is the main ion responsible for the changes of turgor pressure during the movement of induced stomata (Benito *et al*., 2014). The increase of K^+ content in guard cells can cause the increase of osmotic potential, resulting in water absorption from the nearby cells and increase of cell turgor pressure, leading to stomatal opening. Stomatal closure is related to K^+ outflow of guard cells: K^+ outflow causes the decrease of the osmotic potential of guard cells and thus the closure of the water loss stomata. Presently, the osmotic regulation theory of K^+ accumulation is relatively common in the mechanism of stomatal movement (Wakeel, 2010).

Figure 1B shows that in the deficiency of K supply, proper increase of sodium can make the stomatal opening degree of the sugarcane leaves increase so that stomatal conductance value increases; the stomatal conductance reaches the peak at the K_1 level, especially the stomatal conductance reaches the maximum at the Na_1 level treatment and there are significant difference among K_1Na_0, K_1Na_1 and K_1Na_2. However, at the K_2 level, sodium inhibited the stomatal expansion of sugarcane leaves; the higher the concentration could lead to the stronger inhibiting effect and the larger of the impact on stomatal conductance. Therefore, sodium can increase the expansion ability of the stoma of sugarcane under low potassium stress.

The Effect of Partial Substitution of Potassium by Sodium on CO_2 Concentration of Intercellular Space (Ci) of Sugarcane

The CO_2 concentration in intercellular space can reflect the intensity of photosynthesis to a certain extent. According to the law reflected by the data of CO_2 concentration and net photosynthetic rate, it is speculated that there is a negative correlation between intercellular CO_2 concentration and photosynthetic rate, which is a regular reaction between them. The CO_2 in intercellular space transferred to the chloroplast when photosynthesis is vigorous, which results in a decrease of intercellular CO_2 concentration. Figure 1C shows that Ci value increases first and then decreases with the increase of sodium concentration in K_0 treatment, which indicates that when the potassium supply is deficient, proper sodium increase can promote the photosynthesis. When it reaches the saturation point of CO_2, CO_2 concentration would increase and the photosynthetic intensity would not increase. The CO_2 in intercellular space transferred to the chloroplast, resulting in intercellular CO_2 concentration decreased, thereby its concentrations would increase first and then decrease. From K_0 to K_1 level, the value of Ci decreases with the increase of sodium level, and the decline trend is more obvious with K_1 treatment. It may be that potassium supply promotes the photosynthetic rate of sugarcane and leads to the decrease of intercellular CO_2 concentration. K_2 treatment, the Ci of sugarcane is $Na_2> Na_1> Na_0$, that is the CO_2 concentration of intercellular space at Na_2 level with increasing trend. The other two sodium levels make the CO_2 concentration of intercellular space in sugarcane leaves be decreasing trend. That shows that the photosynthesis is not strong under Na_2 and has strong inhibitory effect on the photosynthesis of sugarcane, which leads to the increase of intercellular CO2 concentration significantly.

The Effect of Partial Substitution of Potassium by Sodium on the Transpiration Rate (Tr) of Sugarcane

From the trend line in Fig. 1D, proper addition of sodium can promote transpiration and increase the transpiration rate of sugarcane under low potassium stress. At the K_1 level, the transpiration rate of sugarcane by Na_1 and Na_1 treatment has a maximum value. The transpiration rate decreases gradually with the increase of K concentration, and the Na_0 level does not decrease but increases gradually; meanwhile, Na_2 and Na_1 have significant difference. While at the treatment level of K_2, sodium inhibits the transpiration of sugarcane leaves. The higher the sodium concentration is and the more serious the inhibition is, and the greater the effect on the transpiration rate of sugarcane. Therefore, it can be speculated that sodium can promote the transpiration of sugarcane and accelerate the water exchange speed of sugarcane leaves, thus accelerating the transpiration rate of sugarcane. At the K_2 level, it has obvious inhibitory action on the transpiration rate and photosynthesis of sugarcane with the increase of sodium concentration, and the difference was significant. While at the K_1 level, sodium and potassium interaction can effectively promote sugarcane transpiration and improve the transpiration rate.

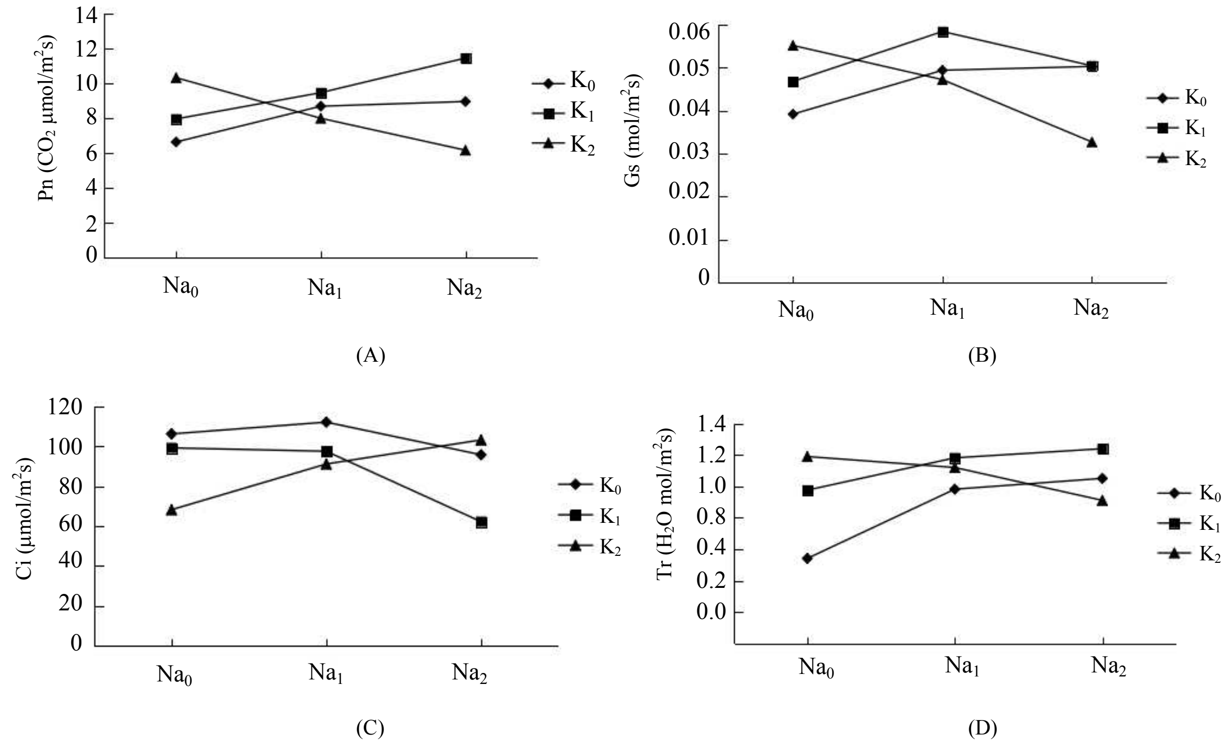

Fig. 1: Effects of different Na and K levels treatments on photosynthesis in sugarcane. (A) Net photosynthetic rate (Pn) (B) Stomatal conductance (Gs) (C) CO_2 concentration of intercellular space (Ci) (D) Transpiration rate (Tr)

Discussion

Some researchers thought that the essence of K^+ and Na^+ substitution effect is a physiological function that one nutrient ion replacing another. Na+ as the replacing positive ion of K+ with the biggest advantage, sodium addition can make the concentration of total positive ions in plants remain stable in the case of potassium deficiency, which can maintain the normal turgor of vacuoles and reduce the adverse effects of osmotic potential changes caused by potassium deficiency (Krishnasamy *et al*., 2014; Carneiro *et al*., 2017). The results show that:

The biomass of sugarcane: when the potassium concentration was 0 mmol/L, the biomass accumulation of sugarcane increased with the increase of Na concentration, which showed that the biomass of sugarcane increased continuously and the difference of increasing was significant. When the potassium concentration was 0.2 mmol/L, the increase of sodium concentration had slight inhibitory effect on the growth of sugarcane, which made the accumulation of sugarcane biomass decrease with a decreasing trend. When the potassium concentration was 2 mmol/L, the increase of sodium concentration had obvious inhibitory effect on the growth of sugarcane, which restricted the accumulation of sugarcane biomass seriously with a decreasing trend and obvious difference. Therefore, proper sodium addition in the case of potassium deficiency can significantly promote the biomass of sugarcane. When it was low potassium or high potassium, sodium application would inhibit the growth of sugarcane and the higher the concentration was, the greater the effect would be.

The root shoot ratio of sugarcane: When the potassium level was 0 mmol/L and 0.2 mmol/L, with the increase of sodium concentration, the root shoot ratio of sugarcane generally decreased gradually, the ratio of nutrient substance distribution to the above-ground increase at this time. That showed that the growth of stems and leaves accelerated and hindered the water absorption and root respiration of root system, decreased the growth of root system and influenced the accumulation of biomass in above-ground. When the potassium level was 2 mmol/L, the increase of sodium concentration has obvious inhibition on the growth of items and leaves of sugarcane at the above-ground, the ratio of nutrient substance distribution to the above-ground increased at this time, which accelerated the vegetative growth and elongation growth of root system. The root shoot ratio increased significantly with significant difference of increase.

When No.22 was sugar deficiency, sodium can partly replace the function of potassium and provide the sugarcane with nutrients needed by photosynthesis to maintain the normal net photosynthetic rate. At the high

K level, sodium had antagonistic effect on potassium, which had great impact on photosynthesis with the increase of sodium concentration. While at the low K level, the interaction of sodium and potassium had the greatest promoting effect on the net photosynthetic rate of sugarcane. The interaction of sodium and potassium had the best promoting effect on the photosynthesis of sugarcane.

The stomatal conductance of sugarcane: In the deficiency of K, sodium can increase the degree of sugarcane stoma, improve the photosynthetic capacity of leaves and enhance the stomatal conductance of leaves. At the high K level, with the increase of sodium concentration, it had an obvious inhibiting effect on the stomatal conductance and photosynthesis with significant difference. While at the low K level, the interaction of potassium and sodium had the greatest promoting effect on the stomatal conductance of sugarcane.

The intercellular CO_2 concentration of sugarcane: Studies found that the intercellular CO_2 concentration was negatively correlated with photosynthesis, which can significantly promote photosynthesis in potassium deficiency or low potassium treatment. The intercellular CO_2 transferred to the chloroplast, resulting in the decrease of intercellular CO_2 concentration. At the high K level, excess sodium supplementation had significant inhibitory effect on the photosynthesis of sugarcane and intercellular CO_2 concentration increased significantly. While, the inhibiting effect of photosynthesis was obvious when the sodium level was 0 mmol/L and 0.2 mmol/L. Therefore, appropriate sodium application can promote photosynthesis of leaves and decrease the concentration of CO_2 in intercellular space.

The transpiration rate of sugarcane: When K is lack; sodium can promote the transpiration of sugarcane, improved light energy capture ability of sugarcane leaves, thus accelerating the transpiration rate of sugarcane. At the high K level, it had obvious inhibition on the transpiration rate and photosynthesis of sugarcane with significant difference. At the low K level, the interaction of sodium and potassium can effectively promote sugarcane transpiration and improve the transpiration rate.

Conclusion

Therefore, under the levels of low potassium or potassium deficiency, proper application of sodium can promote sugarcane photosynthesis, increase sugarcane yield and stress resistance ability. At high potassium level, excessive sodium can significantly inhibit the growth of sugarcane, and yield decreases, leading to the waste of sodium and potassium. In addition, due to its physical and chemical properties of sodium, it often causes adverse effects on the soil structure. We must pay special attention to the dosage and frequency of application in the production practice. Thereby, we should make reasonable combined application of potassium and sodium according to local conditions in the production practice of sugarcane in order to obtain the maximum economic benefits.

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Author's Contributions

Chao Zheng: Performed the numerical experiments. Revised the manuscript.

Yong-Xiang Huang: Performed the numerical experiments, analyzed the data and wrote the paper.

Jin Li: Designed and developed the method.

Qi-wei Li, Zhen-rui Huang and Jun-hua Ao: Designed experiments.

Ke-xing Liu: Revised the manuscript.

Ethics

The authors declare their responsibility for any ethical issues that may arise after the publication of this manuscript.

Conflict of Interest

The authors declare that they have no competing interests. The corresponding author affirms that all of the authors have read and approved the manuscript.

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