

Review Article

Can Superabsorbent Polymers Improve Plants Production in Arid Regions?

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Superabsorbent polymers (SAPs) have shown to be quite effective and useful in acting as a reservoir for water and some nutrients in arid and semiarid regions. There are many studies in Iran that have been performed in relation to SAPs and their useful application in agriculture; however, there is still a lack of its applied definition in arid regions. Therefore, this study was conducted with the aim of doing a meta-analysis of the results of studies conducted in Iran and answering a general question about whether the application of SAPs has been effective in enhancing the production or not, and if so, how much of SAP is recommended. To conduct this research, articles published during 2006–2016 on the subject of the effects of different rates of SAP application on yield and yield components of crops (including cereals, legumes, and medicinal and grassland plants) were investigated. The results of the meta-analysis showed that the mean consumption rate of SAPs for cereals, legumes, and medicinal and grassland plants was 83, 322, 1031, and 210 kg ha⁻¹, respectively, and that, at these SAP application rates, the mean seed yield in cereals, medicinal plants, and legumes increased by 15.2, 12.6, and 38% (equivalent to 1059, 345, and 452 kg ha⁻¹), respectively, compared with the control. Dry matter response to superabsorbent application was slower compared with the seed yield response. The mean consumption of 83 kg ha⁻¹ of superabsorbent for cereals increased seed yield by 15.2% on average. According to the results, it seems that the application of 100 kg SAP ha⁻¹ is the most appropriate rate for increasing seed and dry matter yields and satisfying economic aspects. These study findings may shed light on the environment and socioeconomic concerns and improve efficacy and reduction of costs.

1. Introduction

One of the fundamental agricultural constraints, particularly in arid and semiarid regions, is water scarcity [1]. Iran, as one of the countries located in the dry belt of the Earth, is facing a serious water shortage problem. Increasing population growth and the increasing demand for agricultural products and water resources restrictions, which are the main obstacle for agricultural production, have hit the country with a water shortage problem very seriously. Optimal water consumption in agricultural production, as one of the most important environmental factors affecting plant growth and development, is of great importance especially in arid and semiarid regions like Iran [2–4]. Optimization of the factors which positively affect the production and management of water

application on the farm helps to save the limited water resources, improves soil conservation, and also boosts quality of the products [5]. There have been lots of efforts up to now to decrease water consumption by crop plants [6], or in other words, to produce more out of each drop of water. Reza et al. reported that redistribution of water from soil evaporation toward plant transpiration is the key element of increasing water consumption efficiency [7]. Infrastructure processes in most of the progress made in improving water consumption efficiency indicate that research should focus on water absorption capacity of the plant. Deng et al. named deficit irrigation, the use of complementary fertilizers, and modified new cultivars alongside the biological mechanisms of water supply and water-saving irrigation technologies, such as low pressure irrigation, drip irrigation under plastic

cover, rainwater collection, and terracing, as strategies for increasing water consumption efficiency [8].

In recent years, the highly hydrophilic superabsorbent polymers (SAPs) have been used as an additive to the soil and a potential reservoir for some nutrients and water in agriculture. These materials have shown an effective role in decreasing the effects of drought stress, and also in increasing the productivity for both crops and horticultural plants [3, 9]. This issue has been the focus of researchers' attention in Iran [10–12]. Increasing irrigation intervals as a result of application of superabsorbent hydrogels has been considered as a basic strategy in order to save and use water efficiently [13]. The properties of these materials depend on many factors, including their composition and chemical properties, method and quantity of application, soil texture, plant species, and also environmental conditions [14, 15]. In SAPs, large amounts of water from rain or irrigation are saved (at a rate of 200–250 ml of water for 1 g of dry matter of polymer) [16], and deep soil penetration and water losses are prevented, and, if needed, water is available to the plant under dry conditions [17–19]. It has been reported that SAPs decrease the irrigation water needs by 15–50% [15]. Water absorption rate in these polymers varies up to 400 times according to their formulation, water impurities, and salt content [20]. It has been said that these polymers can maintain soil moisture and some of the nutrients for up to five years after their application at the farms [21, 22]. There are reports that indicate that SAPs can improve the qualitative and quantitative characteristics of different agricultural products by making improvements in soil physical properties and soil structure [13]. Some of the reported effects are increasing water penetration into the soil and reducing soil erosion, reducing soil bulk density [23], increasing nutritional intake efficiency [24], increasing seed germination and growth [24], decreasing water needs of plants [25], decreasing evaporation rate from soil surface [17, 26] and decreasing losses caused by fertilizer application [27], increasing water use efficiency [28], increasing germination vigor, increasing crop yields, and decreasing crop water requirements. There are other positive characteristics of SAP application, including increasing water and nutrient retention capacity for the long term, reducing irrigation frequencies, uniform water consumption by plants, normal and rapid growth of roots, reducing the leaching of soil nutrients, reducing irrigation costs, optimum use of chemical fertilizers, improved soil weathering, possibility of planting in desert areas and steep lands, increasing the activity and proliferation of mycorrhizal fungi and other soil microorganisms, and increasing soil porosity and soil structure stability, which some researchers have attributed to SAPs [29, 30].

The process of statistical combination of the results of independent and separate studies, in order to achieve a general conclusion on treatments or variances, is called meta-analysis. In other words, this technique is a summary of previous researches that applies quantitative methods for comparing the results in an extensive range of studies. Meta-analysis is the same as quantitative combination of experimental reports; that is, research studies are compiled, coded, and interpreted using statistical methods like the ones being used in primary data interpretation [31]. Quantitative methods of meta-analysis help to assess some challenges

caused by the existence of various responses to one research question. Combination of numerical results from different studies, and a precise appraisal of characteristics and explanation of inconsistencies and also discovery of moderators and mediators in the collected research findings are made possible by meta-analysis [32, 33]. By applying meta-analysis, researchers are able to justify the contradictions and differences in studies and reach more tangible, precise, and valid results rather than what is seen in one or some introductory studies, or even in nonquantitative, general, and narrative reviews. When the effect of a treatment is concordant from one study to another, meta-analysis can determine this concordant effect, and when this effect changes from one assessment to another, meta-analysis may help to determine the reasons for the change [34]. The meta-analysis approach is useful and effective in highlighting and moderating the gaps and challenges in the research background of the subject of the study as a result of safer and more tangible conclusions and provides the necessary insight toward the new approaches to the researcher [33]. Based on meta-analysis results, it can be said decisively if there is a need for further research on a particular subject or not [35].

Van Groenigen et al. conducted a meta-analysis of the effect of earthworms on plant production increase and reported that the existence of earthworms in agro-ecosystems caused a 25% increase in crop yield and a 23% increase in the aboveground biomass on average [36]. They stated that the positive effect of earthworms increased when a greater part of plant residues returned to the soil and that this effect decreased when soil nitrogen availability increased. They concluded that earthworms had a vital effect on decreasing the yield gap for the farmers who did not use nitrogen fertilizers. Soltani and Soltani conducted a meta-analysis of the effect of seed priming on germination and reported that priming caused a 4% and 7% increase in germination percentage and germination rate, respectively. Also, application of organic acids and hormones caused the greatest increase in germination, with hydropriming having the next most positive effect. Osmopriming had a negative effect on both the percentage and rate of germination, and also seed priming had a more positive effect on dicotyledonous rather than monocotyledonous plants [37].

There are many studies in Iran that have been performed in relation to SAPs and their useful application in agriculture; however, there is still a lack of its applied definition on arid regions. Therefore, this study was conducted with the aim of doing a meta-analysis of the results of studies conducted in Iran and answering a general question about whether the application of SAPs has been successful or not, and if so, how much of SAP is recommended. The existence of variations regarding the consumption rate, experimental conditions, and treatments makes it impossible or very difficult for decision makers to conclude an applied use of SAPs. Therefore, the current study was conducted to review, assess, and investigate a meta-analysis of studies conducted in Iran to answer a question as whether the application of SAPs has been effective in enhancing the production or not, and if so, which application rate of these materials can be recommended for various crops.

2. Materials and Methods

2.1. Data Source. In order to perform this study, the conducted experiments on the effect of different application rates of water superabsorbents on yield and yield components of some crop plants (including cereals, medicinal plants, and industrial plants) were put under investigation. The study included 32 scientific research articles published between 2009 and 2017. The articles were chosen in such a way that the necessary data for doing meta-analysis would be available. The necessary data included the mean of the control and fertilizer treatments, mean standard deviation, variance of the experimental error, and the number of replications [38]. The necessary data were extracted from the relevant and suitable articles, which included research specifications (research title, location and duration of research implementations, plant species, type of experimental design, number and kind of experimental treatments, rates of applied superabsorbent, research results, and the effect rate of different superabsorbents on each of the considered factors) that were used in order to conduct a meta-analysis. All of the primary experiments had been performed in arid and semiarid regions of the Iranian Plateau under deficit irrigation conditions using the drip irrigation method.

Out of the 32 articles reviewed, 13 of them were used in the meta-analysis of the effect of superabsorbents on seed yield, dry matter yield, and harvest index. The specifications of the articles are provided in Table 1. Sixteen out of the 32 articles did not have the necessary data in order to conduct the meta-analysis of the effect of superabsorbents on seed yield, dry matter yield, and harvest index. Nonetheless, some of the information contained in them, for example, determination of the levels of the applied superabsorbent, was used (Table 2). There were also three articles on the effect of superabsorbent polymers on soil characteristics, but there were no crop plants assessed.

2.2. Statistical Analysis. Full description of the method of meta-analysis statistical calculations has been provided by Hedges and Olkin and Gurevitch and Hedges, and the steps involved in conducting it are described in the following [32, 39]. The first step towards conducting a meta-analysis is the calculation of the standard difference between the control treatment and experimental treatments (superabsorbent treatment), which is called the effect size (d). Therefore, the d value was calculated for each of the 11 independent experiments which were assessed during this meta-analysis (1). It should be noted that the effect size was calculated for both of the means, superabsorbent rates, and control to compare the control treatment with different rates of superabsorbent application separately:

$$d = \frac{\bar{X}_t - \bar{X}_c}{S_p} \times J, \quad (1)$$

where \bar{X}_c and \bar{X}_t are the means of the control and superabsorbent treatments, respectively, S_p is the integrated

standard deviation of the means, and J is the correction factor for standard deviation skewness of the means. Values of J and S_p are calculated from (2) and (3), respectively:

$$J = 1 - \left[\frac{3}{4(df_c + df_t) - 1} \right], \quad (2)$$

$$S_p = \sqrt{\frac{df_c(S_c^2) + df_t(S_t^2)}{df_c + df_t}}, \quad (3)$$

where S_c and S_t are standard deviations of the mean of the control and superabsorbent treatments, respectively. If the values of standard deviations of the means are not given in an article, it is possible to calculate the S_p value (4) according to the variance of the experimental error (mean square error, MSE), which is provided in the tables of the analysis of variance in the articles:

$$S_p = \sqrt{\left(\frac{n_c + n_t - 2}{n_c + n_t} \right) \text{MSE}}, \quad (4)$$

where n_c and n_t are the number of control and treatment replications, respectively.

Undoubtedly, all of the experiments under assessment do not have the same precision. So, it is necessary that a weight determined by the precision of each of the experiments is calculated and then the value of the effect size of each experiment is weighted according to it. Therefore, the variance of the effect size for each experiment (V_d) is calculated as follows:

$$V_d = \left[\frac{n_c + n_t}{n_c \times n_t} \right] + \left[\frac{d^2}{2n(n_c + n_t)} \right]. \quad (5)$$

The reciprocal of this variance is the weight corresponding to a given experiment, so the lower the variance value in an experiment is, the more the weight attached to it is [36]:

$$w_i = \frac{1}{V_d}. \quad (6)$$

Finally, the total, or cumulative, effect size is calculated (7), which is the standardized difference between the control and SAP treatments for all of the experiments under consideration:

$$d^* = \frac{\sum w_i d_i}{\sum w_i}. \quad (7)$$

And its standard deviation (S_{d^*}) is calculated using

$$S_{d^*} = \sqrt{\frac{1}{\sum w_i}}. \quad (8)$$

The last step in a meta-analysis is the significance test of d^* , in which, if the S_{d^*} is revealed, the confidence interval is calculable. If this confidence interval overlaps zero, the weighted cumulative effect size (d^*) is insignificant and there is no difference between control and treatment; otherwise,

TABLE 1: Some information on the articles used in the meta-analysis of the effect of water superabsorbents.

Authors	Number of articles	Crop species
Jahan et al. (2013), Koohestani et al. (2009), Khadem et al. (2010) and Yousefi Fard et al. (2010)	4	Maize
Gholami et al. (2012)	1	Wheat
Allahyari et al. (2013), Rajabi et al. (2011)	2	Pea
Jahan et al. (2012) and Jahan et al. (2017)	2	Bean
Roostayi et al. (2011)	1	Soybean
Rahmani et al. (2009)	1	Mustard
Jahan et al. (2014)	1	Basil
Jahan et al. (2019)	1	Sesame

TABLE 2: Some information on the articles which did not contain the required data and were only partly used in the meta-analysis.

Authors	Number of articles	Crop species
Zanguyinasab et al. (2012)	1	Atriplex
Pour Esmael et al. (2009)	1	Bean
Mohammadi et al. (2011) and Mohammadi et al. (2010)	2	Medicago
Sheykhmoradi et al. (2011)	1	Lolium
Karimi and Naderi (2006)	1	Corn (forage)
Roshdi 2012 and Karimi (2000)	2	Sunflower
Fazeli Rostampour et al. (2000) and Fazeli Rostampour and Mohebbian (2010)	2	Corn (grain)
Abedi Koopay and Mesforush (2009)	1	Cucumber (greenhouse)
Souri and Motamedi (2015)	1	Festuca
Pirzad et al. (2012)	1	Chamomile
Banch Shafiee et al. (2009)	1	Panicum
Dehbashi et al. (2013)	1	Tagetes
Jahan et al. (2013)	1	Sugar beet

the difference between treatment and control is significantly greater than zero. All of the calculations and graph drawings were done with MS-EXCEL Ver. 14.

3. Results and Discussion

3.1. Summary of the Results of the Analyzed Experiments.

The frequency of the ranges of SAP application rates used in the 29 articles studied (experiments conducted on plants) was investigated. Figure 1 shows the frequency distribution of the applied rates of superabsorbent per unit land area in the investigated experiments. In 83% of the experiments, the application rate range of a superabsorbent was between 26 and 240 kg ha⁻¹. The highest frequency was that of the application range of 41 to 80, followed by that of 81 to 140 kg ha⁻¹, which included 63% of all the experiments. The range of superabsorbent application rates in cereals (maize and wheat) in the investigated experiments was between 22.5 and 300 kg ha⁻¹. This rate was between 30 and 360 kg ha⁻¹ for three medicinal species (tagetes, chamomile, and basil), and from 2250 to 3150 kg ha⁻¹ for one medicinal species (mustard).

The range of superabsorbent application rates was between 1500 and 3150 kg ha⁻¹ for two legume species (red bean and pea) and between 9 and 200 kg ha⁻¹ for three legume species (rain-fed pea, soybean, and bean). The range for three grassland species was between 45 and 450 kg ha⁻¹ of a superabsorbent.

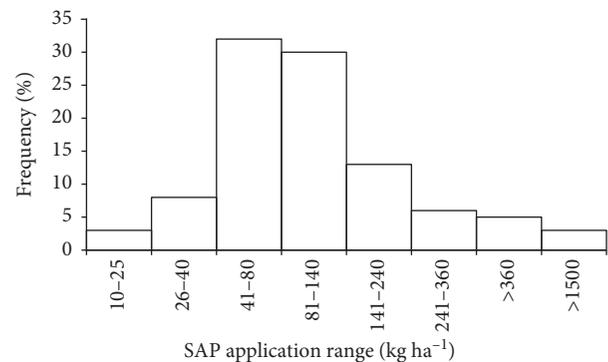


FIGURE 1: Frequency distribution of superabsorbent application levels in the studied experiments.

The means of superabsorbent consumption were 83, 322, 1031, and 210 kg ha⁻¹ for cereals, medicinal plants, beans, and grassland plants, respectively, and application of superabsorbents at these rates caused increases in seed yield in cereals, medicinal plants, and beans by 15.2%, 12.6%, and 38% (1059, 345, and 452 kg ha⁻¹), respectively, compared with control treatments (Table 3).

3.2. Response of Seed Yield, Dry Matter Yield, and Harvest Index to Superabsorbent Application. Integration of the data from 14 experiments showed that the response of seed yield, dry matter yield, and harvest index to superabsorbent application

TABLE 3: Means of the studied traits for three crop families as a result of different levels of superabsorbent application.

	Mean of SAP treatments (kg ha ⁻¹)	Mean of control treatment (kg ha ⁻¹)	Coefficient of variations (%)	Min level of SAP (kg ha ⁻¹)	Max level of SAP (kg ha ⁻¹)
<i>Cereals (six experiments)</i>					
Seed yield (kg ha ⁻¹)	8013.7	6954.8	59.49	7398.8	8194.4
Dry matter yield (kg ha ⁻¹)	31319.2	25248	78.28	29464	32976.2
Harvest index (%)	36.96	37.22	35.35	35.17	36.11
<i>Medicinal plants (three experiments)</i>					
Seed yield (kg ha ⁻¹)	3079.62	2734.61	38.49	3040.30	3119.45
Dry matter yield (kg ha ⁻¹)	21323.5	17056	13.83	20823	21829.5
Harvest index (%)	15.45	14.64	31.44	15.18	14.1
<i>Pulses (five experiments)</i>					
Seed yield (kg ha ⁻¹)	1642.47	1190.32	56.83	1526.22	1749.59
Dry matter yield (kg ha ⁻¹)	3684.63	3301.30	63.84	3555.83	3796.12
Harvest index (%)	49.49	42.37	20.29	48.29	50.40

rates, followed by the exponential function, the second-order function, and the second-order function, respectively (Figure 2).

Seed yield increased linearly with superabsorbent increment to 60 kg ha⁻¹ and then its slope decreased exponentially. The response of dry matter yield to superabsorbent application followed a second-order* function. The response was slower compared with that of seed yield. In other words, the curve slope in the 0 to about 60 kg ha⁻¹ range was not as steep as the corresponding slope in the figure showing the seed yield response. Meanwhile, the curve's slope in the application rate range of 100 to 120 kg ha⁻¹ became constant and then gradually decreased in the rate range of up to 200 kg ha⁻¹.

Harvest index response to superabsorbent application, like that of dry matter yield, followed a second-order* function (Figure 2), but unlike the constant slope in the range of 100 to 120 kg ha⁻¹ in the dry matter yield response, it showed a descending slope. It has been reported that the existence of a second-order function in wheat and maize response to an increase in nitrogen fertilizer rate is indicative of a decreasing yield at higher levels of fertilizer application, which has been proven by significant experimental evidence [40]. However, Cerrato and Blackmer fitted different kinds of curves reflecting the response to fertilizer rates in different crop plants, analyzed the equations statistically, and showed that the best statistical form for expressing plant response to nitrogen fertilization was a second-order function that becomes constant at higher application rates [41]. In the current study, however, response curves with final stability and without a descending trend for dry matter yield and harvest index had a more acceptable explanation, but because of their lower practicality and some statistical considerations, the second order function was used. This trend complies with the results of most of the independently investigated studies, although the descending points of the curve in those articles are very different.

3.3. Statistical Comparison between Superabsorbent Rates.

In Figure 3, the control treatment has been compared with different rates of superabsorbent application separately. Meta-analysis results show that the highest superabsorbent effect on seed yield was obtained in the range of 0–100 kg ha⁻¹ of superabsorbent. The effect size of a superabsorbent on dry matter yield was more apparent and its numerical values were greater than those for the effect on seed yield. For a superabsorbent application rate of more than 200 kg ha⁻¹, the difference between seed yield and dry matter yield was significant. The rates from 0 to 80 kg ha⁻¹ of superabsorbent did not produce a significant difference compared with the rates of 0 to 100 kg ha⁻¹ in terms of seed yield and also produced no significant difference regarding the effect on dry matter yield.

The harvest index was affected by the application of 0 to 80 kg ha⁻¹ of superabsorbent; however, the effect size was insignificant for this range too. The relative similarity of variation in slope of seed yield and dry matter yield responses to superabsorbent applications was the reason that the harvest index, which is a variable dependent on them, did not show a marked response to superabsorbent application rates (Figure 3). Generally, the results showed that the effect of superabsorbent on seed yield and dry matter yield was significant but was not significant on the harvest index. The effect size of the application of different rates of superabsorbent was greater at all levels on dry matter yield compared to seed yield. In this regard, the levels of 80 and 100 kg ha⁻¹ and also of more than 200 kg ha⁻¹ of superabsorbent had the greatest effect; however, the differences between them were not significant, but the difference between these three levels and the level of 40 kg ha⁻¹ was significant (Figure 3). The levels of 100, 200, and 80 kg ha⁻¹ of superabsorbent had, in that order, the greatest effect on seed yield. At the same time,

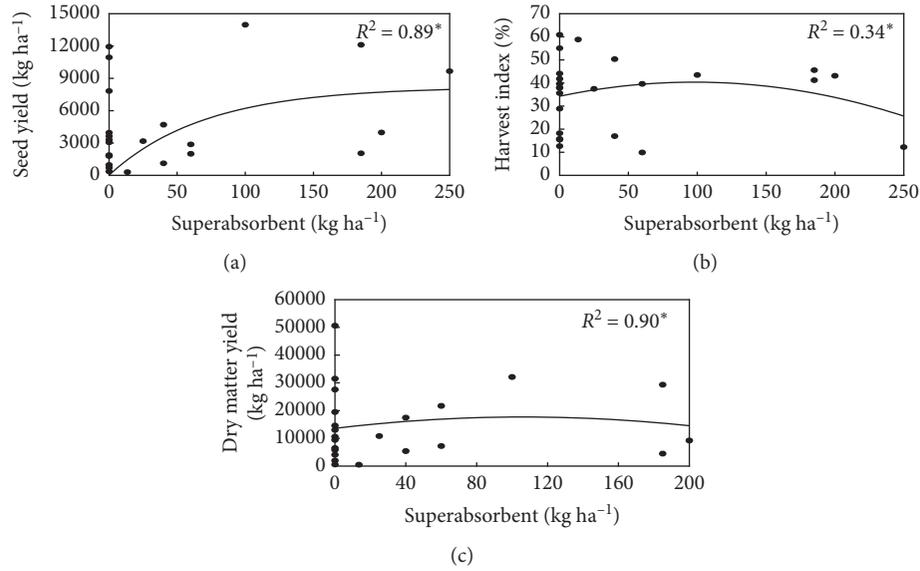


FIGURE 2: Response of seed yield, dry matter yield, and harvest index of crops to superabsorbent application levels.

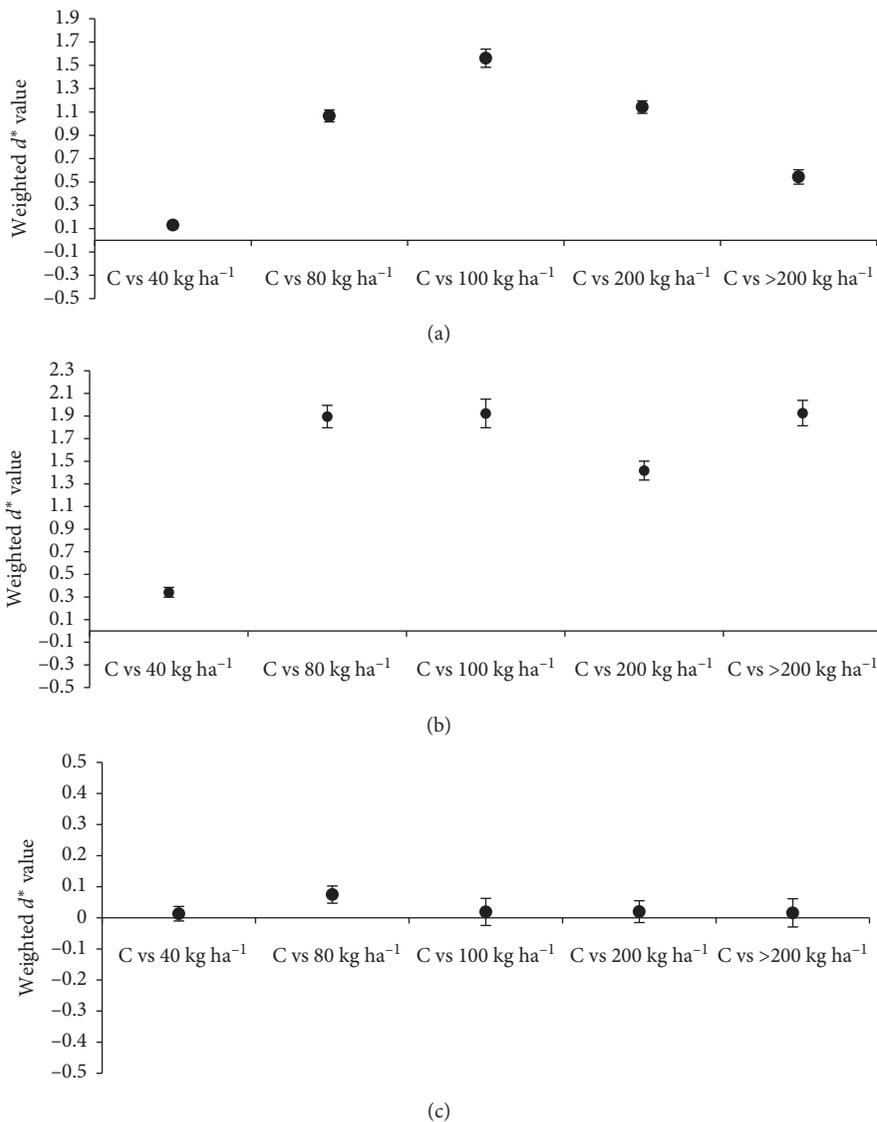


FIGURE 3: Comparison of the effect of different levels of superabsorbent application on (a) seed yield, (b) dry matter yield, and (c) harvest index of studied crops. Bars indicate the confidence intervals of the weighted cumulative effect size among the investigated experiments (C denotes the control).

the difference between the levels of 80 and 200 kg ha⁻¹ was not significant. The greatest effect size on seed yield was that of the level of 100 kg ha⁻¹, while the rates of more than 200 kg ha⁻¹, in contrast to dry matter yield, did not have a significant effect (Figure 3). Regarding the mentioned results and points, it seems that the application rate of 100 kg ha⁻¹ of superabsorbent is the most suitable rate considering the effect size on seed yield and dry matter yield. Higher material and energy spending on the application of greater levels of superabsorbent does not have any justification according to the law of diminishing returns. On the other hand, resource utilization decreases when the resource application rates are at a great level.

The effect size of the different levels of superabsorbent on the harvest index was not significant, which matches the results of a meta-analysis of the research results relevant to the consumption of nitrogen chemical fertilizers in cereal production [42]. There are many reports that indicate that the harvest index is a hereditary trait and is not affected by management practices. Genetic control of the harvest index in rice [43], wheat [44], and maize [45] has been confirmed. Some of the existing variations in experimental results refer to the statistical aspects such as the coefficient of variation, and the rest depends on climatic conditions, soil characteristics, and other factors. Dabhi et al. reviewed some experiments on the effect of superabsorbent application and concluded that the determination of the application rate of a superabsorbent polymer should be based on the analysis of soil decomposition results and its quality, irrigation water quality, and the crop species [15]. They suggested that more experiments were needed in order to answer the question whether the application of a superabsorbent polymer can optimize cash-crop yields and improve the economic and social conditions of small and marginal farmers. Meanwhile, governmental programs, nongovernmental organizations, and institutes of agricultural research should become involved in presenting practical training programs to farmers so that they can use this technology.

4. Conclusions

The findings of this research showed that in spite of the different studies conducted on the effect of superabsorbent polymers on crop plant yield in Iran, the obtained results are highly varied and show great dispersion. This issue is the reason that although there is strong inclination and enthusiasm for the utilization of this new input in the agricultural sector, its optimized application has not been determined yet. In 83% of the examined experiments, the application rate range of a superabsorbent polymer was between 26 and 240 kg ha⁻¹. The highest frequency was that of the application rate range of 41 to 80 kg ha⁻¹, followed by the range of 81 to 140 kg ha⁻¹, which together included 63% of all the experiments. Dry matter response to superabsorbent application was slower compared with the seed yield response. The mean consumption of 83 kg ha⁻¹ of superabsorbent for cereals increased seed yield by 15.2% on average. The results of this research showed that the application rate of 100 kg ha⁻¹ of a superabsorbent polymer

is the most suitable rate considering the effect size on seed yield and dry matter yield.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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