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Organic and Hydrogel Soil Amendments for Winter Wheat Adaption to Drought Stress

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Abstract: The recent dry years in Europe have illustrated the urgent need to secure agricultural yields. In order to achieve good plant growth without overusing resources such as water or fertilizer, the approach to the improvement of the soil could be a good alternative. Winter wheat is the most common cultivated crop in northern Germany. For this reason, a new organic soil amendment based on tree compartments and one with polymers for water retention were tested for their effectiveness in reducing effects of drought stress during three vegetation periods (2016-2018). It was examined whether their use can reduce or substitute irrigation and leads to better yields. The experiments were carried out in controlled nursery conditions with 8 replicates and under two irrigation regimes, well-watered with 64 l/m² in 4 month and controlled water restriction (9,6 l/m² in 4 month) during vegetative growth. Biometric plant parameters such as the SPAD (single-photon avalanche diode) value, plant height, over- and underground biomass and grain yield were used to compare the variants. Initially, both components were tested separately to be used in combination in the second and third year. When both amendments were used, results showed same plant heights, 10% more biomass and 25% more yield by water deficit compared to treatments without additives. The organic component promoted the chlorophyll value from 35 to 45. The experiments showed that this both soil amendments can lead to a grain yield of 70% compared to irrigated variants and to good wheat growth during drought.

Keywords: Soil Amelioration, Pot Experiment, Irrigation, Soil Additives, Food Security

1. Introduction

By 2050, the global population is expected to increase up to 9.8 billion or even 11 billion people [1, 2]. Such population numbers imply a growing need for food, i.e. the yield of all crops have to be improved by 2.5% every year until 2050 to supply a world population of 11 billion [2]. However, heat and drought periods threaten grain production [3]. Drought is a predominant cause of low yields worldwide [4].

In addition to corn, soybeans, millet and rice, wheat is one of the five most important types of grain. Winter wheat (Triticum aestivum L.) is the most common crop in Germany. Hence, drought management is becoming increasingly important for this region, which is projected to experience more dry periods in important phases of crop growth [5]. However, many cultivated areas are necessary to feed the population. It is therefore also necessary to cultivate regions for commercial purposes in which less precipitation falls.

In fact, water availability is often a key factor limiting plant growth, productivity and survival [6]. Too little water can lead to drought stress symptoms in plants. Plants' ability to withstand this varies from species to species [7]. The negative impacts of drought on yield mainly depend upon the severity of the stress and the stage of plant growth. Drought stress significantly reduces growth, the SPAD (single-photon avalanche diode) index and grain yield compared to irrigation [8]. For example, winter wheat shows a high tolerance to its environmental conditions, but reacts with reduced photosynthesis to water deficit [9].

There are numerous studies on the effects and characteristics of water deficiency in different plants. Results of Ozturk & Aydin suggest that soil moisture conditions increase grain yield and kernel weight of winter wheat but decrease its quality [10]. Fahad et al [7] found out that drought-induced reduction in the yield might be due to various factors, such as decreased rates of photosynthesis, mentioned by Flexas et al. [11], disturbed assimilate partitioning, mentioned by Farooq et al. [8], or poor flag leaf development, to read by Blum & Johnson [12].

Yield is basically the complex result of different physiological processes. The effect of water deficit on wheat plants in the vegetative development phase has already been the subject of several studies. Blum & Johnson collected data on root dry matter distribution, soil moisture status, midday leaf water potential, leaf relative water content and parameters of plant growth and yield [13]. Their results indicated that drought stress significantly decreased the leaf water potential and relative water content of wheat, which had pronounced effects on the photosynthetic rate. Leaf and canopy temperatures increased which might have occurred due to increased respiration and decreased transpiration resulting from stomatal closure. Finally, Balla et al. also showed yield losses caused by drought stress in wheat [14].

Cui et al. conducted trials in China to investigate the effects of water deficit on the vegetative growing season of winter wheat [15]. In the vascular experiments with two winter wheat varieties, they found that a lack of water had a significant impact on the yield of wheat plants, measured by the reduced number of ears. Baher et al. [16] and Colom & Vazzana [17] found that the above-ground biomass weighed negatively in relation to water stress in plants. Weigel & Manderscheid showed that a lack of water reduced the CO_2 supply and thus the photosynthesis rate of the plants [18]. The results of Rashtbari et al. suggested that soil moisture conditions increase grain yield and kernel weight of winter wheat but decrease its quality [19]. However, all studies only analyzed the impact of drought on the plants and offer few options to counteract the adverse impacts.

Nevertheless, several options exist to secure agricultural yields amid water deficit. Management activities concentrate on irrigation methods, processing techniques, genetic changes or the use of fertilizer. The aim of various measures is to provide plants with nutrients and at the same time use water resources sparingly. However, there is an urgent need for more water-efficient cropping systems facing large water consumption of irrigated agriculture and high unproductive losses via runoff and evaporation [4]. Strategies for precise and sustainable management of water supply in dry areas must be developed.

At present, and even more so in the future, the supply of irrigation is not sufficient for all crops. Irrigation management will shift from accentuating the importance of production per unit area towards maximizing the amount of mass produced per unit of consumed water, i.e. water productivity [20]. Irrigation, however, lowers the groundwater level. It is also associated with enormous financial expenditures [21]. In addition, there are long-term negative soil changes, such as salinization or silting up.

New processing techniques, like microsegregation or the use of drones for precision farming can also reduce the negative effects of drought [22–24]. Furthermore, research is also being carried out on genetically modified cultivars, which are adapted to changed soil conditions [25]. By cultivating drought-tolerant and water-saving cultivars, an increase in wheat productivity can be achieved [26]. According to Bodner et al., the interactions between plants and soil, particularly in the rhizosphere, are one way to improve crop water supply [4]. Soil amelioration products are another means of improving the conditions for plant growth. These have generally been designed to make infertile soils arable [27]. An essential criterion for the approval of soil additives is the content of the nutrient elements nitrogen, phosphorus, potassium, sulphur, copper and zinc, as well as basic active ingredients, which must not exceed certain limits. In addition, maximum amounts for certain foreign substances and pollutants have been specified [28]. Examples of soil amelioration products are biochar [29], charcoal [30], rock powder [31], expanded shale [32] or plastics such as Styromull [33]. Green manure, mulching or other organic fertilizers are used to reduce unfavorable physical soil properties, such as low infiltration or water storage.

Several studies concentrate on the usage of soil amendments. Saletnik et al. assessed the possibility of using biochar and ash, resulting in a significant increase in plant yield and an improvement in soil chemical properties [34]. Vermicompost is also described as an excellent soil amendment and biocontrol agent, which make it the best organic fertilizer and more eco-friendly compared to chemical fertilizers, e.g. [19]. The results of Spaccini et al. confirmed that ligno-cellulose residues may be effectively recycled as composting additives in order to enrich mature compost in aromatic and lignin compounds. Organic additives (sewage sludge) and inorganic fertilizers were also used to compare the effectiveness [35]. However, these substrates have a very one-sided effect, are produced artificially or are very complex or expensive to produce.

Only a few products concentrate their effects on drought stress reduction. Akhzari & Pessarakli used a biofertilizer and urea (as a chemical fertilizer) as water retention additives in pot experiments with seedlings of vetiver grass [36]. Results showed that the root dry weight increased significantly as the soil moisture content, percentage of vermicompost, or urea addition decreased.

The use of polymeric soil improvers has also been tested in recent years. These include e.g. Perlite, Igeta, Hydroplus and other superabsorbents or polymers. In addition to water absorption, which can lead to better plant and root development, reduced nutrient leaching from the soil by polymers is expected [37]. Cross-linked copolymers of acrylamide and acrylic acid can reversibly absorb up to 250 times their weight in water by increasing the water storage capacity of the soil [38]. Hydrophilic polymers have successfully increased the yields of various crops [39]. Improved water storage is considered to be the cause of prolonged survival of maize and beans, when water is scarce [40]. Li et al. used a superabsorbent polymer and biofertilizer on winter wheat plants under drought stress [41]. The results suggest that a combination of these is a good strategy for enhancing the efficiency of biofertilizers, which are beneficial for plants responding to drought stress. Azizi figured out that the addition of absorbent hydrophilic polymers by Panicum antidotale Retz would increase the height in addition to dry matter production [42]. It can be concluded that the application of polymers not only influences soil moisture but also affects soil stabilization. Farrell et al. noticed that water retention additives have the potential to increase substrate water availability, leading to greater plant growth and survival of winter wheat [43]. The effect of the addition of polymers is most pronounced when the irrigation frequency is low or medium [40]. Geesing & Schmidhalter evaluated the effectiveness of sodium polyacrylate to increase soil water retention and enhance growth of wheat under water deficit [44]. The biomass and grain yield of plants without water deficit were increased by the polymer amendment, but decreased under severe water deficit stress. They concluded that sodium polyacrylate changes the hydraulic properties of soils only at high rates of application, but does not alleviate water deficit stress in wheat plants.

One problem with polymers is the possibility of bioaccumulation with continuous use in agriculture. The degradation rates in the environment are low; a mineralization of 2.2% of the polymers was observed after 22 weeks by [38]. Barvenik mentioned that acrylamide degrades in the soil within a few days at temperatures above 20°C [45]. Stabilization is therefore necessary. The high cost of many polymers has usually restricted their use to high-value crops.

The use of water-storing soil amendments is particularly interesting for regions with longer periods of drought, such as northern Germany. Especially regions with sandy soils, like Brandenburg, will have to take more measures in the future to maintain the yield. Brandenburg is characterized by its sandy soil texture and low nutrient content. For this reason, it usually has a low water storage capacity. This region has an average annual temperature of 8.7°C and an average annual precipitation of 557 mm [46]. In the summer months of 2018, the temperatures exceeded 30°C on more than 25 days [47] and only 390 mm precipitation fell. In this year, Brandenburg was also the nationwide leader, with over 2,180 hours of sunshine (long-term average: 1,634 hours) [48].

To improve the soil properties, soil supplements that increase the storage capacity for nutrients and water should be used. So far, mainly fertilizers are in use in Brandenburg. Experiments with compost, sewage sludge and biochar were carried out by Yu et al. [49]. Investigated plants included spring barley [50], quinoa [51] and maize [52]. However, only effects of individual soil amendments were tested with regard to drought stress reduction. However, a combination of several soil amendments is missing. Therefore, this research concentrates on the combined use of two selected soil amendments to improve the nutrient content of the sandy soil as well as the water holding capacity.

The research question is: Can the combined use of an organic soil supplement and a water-storing polymer improve Brandenburg's sandy substrate in such a way that the yield and vitality of plants is guaranteed even in dry periods, or is irrigation alone sufficient? Winter wheat is chosen as a test plant, which is the most cultivated cereal in Brandenburg with 33% of the agricultural area (166,600 hectares) [53].

In order to determine the effect of the soil amelioration products on the plant growth and grain yield, water deficit studies with controlled irrigation were carried out. Biometric qualitative and quantitative characteristics of plants were expected to be improved by water deficit in the critical growing phase. Growth improvements were expected to affect not only the yield, but also the amount of plants and biomass. The above-ground biomass can be used as straw for bedding and as raw feed for horses. Plants should not be too high, because wind throw can then be a problem.

2. Materials and Methods

2.1. Design and Material

Experimental site

The investigations were conducted as outdoor pot trials under a rain shelter in the field at the experimental station in Marquardt, 10 km north of Potsdam in Brandenburg (federal state in the Northeast of Germany). Covers were set up 2.0 m above the soil surface and extended horizontally beyond the sides of the plot to protect the pots from rainfall. In order to initiate conditions of drought stress due to longer dry periods, water supply was controlled. The investigations were carried out from the beginning of April (potting the plants from the field) until mid-July (harvest) during three consecutive years (2016 to 2018). The effect of reduced water amounts on wheat plant growth and yield was tested. The water deficit was initiated in the vegetative phase, which is the most important phase with the highest impact on crop yield [54].

Design

Two different soil amelioration products (organic (O) and hydrogel (Pi)) and two irrigation amounts were studied. The organic amendment (O) had already been successfully used for re-greening extreme mining dump sites in South Africa, Greece and Germany [55]. The second soil amendment was a hydrogel (P) that was a further developed and improved polymer for increasing the water storage capacity.

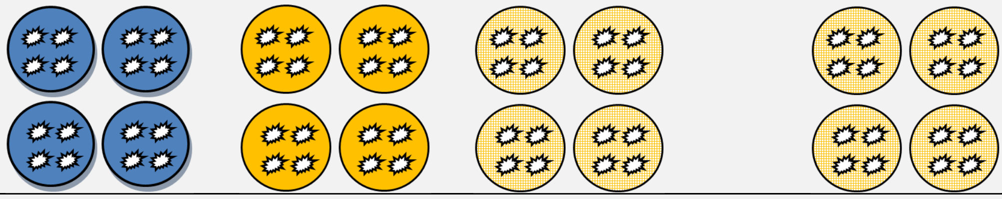
Differences in the irrigation scheme were introduced to study drought stress in detail. A comparable irrigation scheme to that of Kariuki et al. was used [56]. Four different rows were conducted. A watered row (W) was irrigated twice a week. This one was used as a reference for watering the plants (Table 1). The other rows received very low amounts of water. The row DS (drought stress) was the reference for long-term dry periods in Brandenburg. The other pots contained a mixture of soil and concentrations of O and Pi. To obtain information about their effects, these two soil amendments were tested separately during the first year (2016). In 2017, O was tested together with a customary polymer (P) to obtain information about a combined effect. In the third year, the organic soil amendment was used with the improved polymer from 2016 (Pi) to obtain findings regarding the differences between the polymers.

The structure of the experiments permitted statements about the effect of irrigation on the winter wheat plants (comparing

W vs DS), about the effect of the use of two separate soil amelioration products on reducing drought stress symptoms (comparing DS vs DS-Pi vs DS-O, 2016) and their combined effect (DS vs DS-OP(i), 2017 and 2018).

For information on the different effects of the two polymers, a comparison of DS-OP 2017 and DS-OPi 2018 was necessary. Results of the comparison between irrigated plants (W) and those receiving soil amendments (DS-OP(i)) provide information about the better method to adapt to dry periods.

Table 1. *The different test series (rows) of the experiment.*

row	W	DS	DS-O	DS-Pi	Winter wheat cultivar
					
Input (irrigation and soil)	pots that were watered the whole time / basic soil substrate	pots with a water deficit phase / basic soil substrate	pots with a water deficit phase and 5.0% vol. organic soil amendment	pots with a water deficit phase and 0.33% vol. of the improved polymeric soil amendment	
2016	Watered	Drought stress	Drought stress + soil amendment O	Drought stress + soil amendment Pi	Opal
2017	Watered	Drought stress	Drought stress + soil amendment O and a commercial polymer P (DS-OP)		Edgar
2018	Watered	Drought stress	Drought stress + soil amendment O and the improved polymer Pi (DS-OPi)		Edgar

Material

The basic substrate soil was taken from the A horizon (0 to 20 cm depth) of a ground moraine in Marquardt on the site of the Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB). The characteristics of the soil are listed in Table 2.

Two different soil amendment products (O and Pi) were used to promote soil fertility and water storage and thus reduce the drought stress. Soil amelioration product (O) is an organic supplement. The natural raw material is mainly wood. It was attributed with increasing the organic matter content as well as changing the textural characteristics of the substrate. That was expected to increase its capacity to deliver water to the plants. O served as an additional nutrient source (P, K, Mg, N, Ca). In contrast to vermicompost, it has higher contents of N, P and K. Furthermore, the manufacturer promises a loosening of the soil by soil organisms contained within the product, and an increase in water retention capacity from its fibrous structure [57]. The organic soil amendment was used at 5% vol., which shows the best results in preliminary tests [55]. An increase of above-ground biomass of the grass was already shown with application quantities of 3% vol.

Table 2. *Chemical and physical characterization of the substrate/soil (pH- pH-value, EC: electrical conductivity, OC: organic content; O: organic amendment, Pi: polymeric amendment.*

Substrate	pH	EC	OC	Texture		
	[-]	[µS *cm^{-1}]	[%]	Sand [%]	Silt [%]	Clay [%]
Basic soil substrate	6.3	120	1.3	76	12	12
Soil after the experiment (2016)	6.3	120	1.6	-	-	-
Soil with 5.0% vol. O after the experiment (2016)	7.0	130	2.6	-	-	-
Soil with 0.3% vol. Pi after the experiment (2016)	6.6	120	2.2	-	-	-
Soil with O and P after the experiment (2017)	6.5	140	1.8	-	-	-
Soil with O and Pi after the experiment (2018)	5.8	90	1.8	-	-	-

The second amelioration product used (Pi) is a hydrogel. Due to its chemical composition, it is able to store water and nutrients. By adding the cross-linked copolymers to the soil structure, the water storage capacity of the soil can be increased and thus the water availability for the plants can be improved [38]. It releases nutrients only slowly. The polymer Pi is improved in comparison to commercially available water-storing polymers (P), which was used for comparison in 2017. The improved one is expanded through chemical processes in terms of its constituents in order to better release the absorbed water. Therefore, it is stabilized against chemical and physical degradation. Its optimized grain size is between 0.2 and 0.5 mm. This means that it cannot be easily blown away and it is not so large that it forms sticky webs. The pH value of the product is between 4.5 and 5, its density 0.83g*cm-3. Preliminary tests have shown the best effect with an additional amount of 0.3% vol. This corresponds to the results of other studies [42].

Winter wheat varieties Opal (2016) and Edgar (2017 and 2018) were selected. Opal is characterized by medium-yield characteristics, with the number of grains being above average. It is assigned to quality group A, as well as showing particular drought resistance [58]. The seeds for Opal were not available on the market in 2017. Therefore, in the following two years, the winter wheat variety Edgar was used, which has similar properties to Opal. As a B wheat variety, it has a crude protein value at the A wheat level.

Investigation handling

For the pot experiments, individual plants from the field were selected. The wheat plants were taken from an agriculturally used field in Marquardt at maturity stage 30 in April. Each plant had 3 stalks at the time of potting. Every row had 4 pots with 4 plants each, so in total there were 16 plants per row. These were put in plastic pots 25 cm in height and 25 cm in diameter. Each pot contained 11 L of soil. The ones with soil amendments contained 5.0% vol. of O and/or 0.3% vol. of Pi.

The substrate in the pots was saturated with water to full field capacity (FC). The pots were arranged in a randomized complete block design. The drought stress treatment started at the three-leaf stage of seedling growth after 18 to 32 days (Table 3). Depending on the outside temperatures (> 28°C), the pots of the trials (DS-x) were watered while maintaining drought stress of 0 or 100 mL. Without the addition, the plants would have dried out completely, because the vessels did not allow for capillary rise from deeper layers. Irrigation started again 21 to 28 days later at the end in the late terminal spikelet or until the maximum growth level was reached. The watered plants regularly received water twice a week. In Table 4, the water amounts during the experiments are listed. They were calculated into precipitation values by using the pot surface area. The average precipitation in Potsdam is 41 mm in April, 54 mm in May, 67 mm in June and 56 mm in July [59]. So, the irrigation corresponded to these quantities.

Table 3. *Timetable of the pot experiments.*

	2016	**2017**	**2018**
1. Repotting the plants	15/04 (32 days)	11/04 (29 days)	19/04 (18 days)
2. Start of water deficit	17/05 (27 days)	10/05 (38 days)	07/05 (21 days)
3. Irrigation restarted	13/06 (35 days)	17/06 (32 days)	28/05 (23 days)
4. Harvest	18/07	19/07	20/06

Plants from each trial were harvested at defined time intervals 62 to 99 days after potting (Table 3). After the experiment, the soil substrates were analyzed. They showed a change in soil properties based on the application of soil amelioration products (Table 2), especially an increase in organic matter.

Table 4. *Irrigation amounts of the pots from 1 April to 31 July.*

Water amount added during water deficit phase [ml]			
	2016	2017	2018
Watered (W)	4,000 (64.0 mm)	4,000 (64.0 mm)	3,400 (54.4 mm)
Drought stress (DS)	600 (9.6 mm)	600 (9.6 mm)	600 (9.6 mm)
Drought stress and soil amendments (DS-O, DS-P)	600 (9.6 mm)	600 (9.6 mm)	600 (9.6 mm)
Water amount added after water deficit phase [ml]			
	2016	2017	2018
Watered (W)	4,500 (72.0 mm)	6,000 (96.0 mm)	4,500 (72.0 mm)
Drought stress (DS)	4,500 (72.0 mm)	6,000 (96.0 mm)	4,500 (72.0 mm)
Drought stress and soil amendments (DS-O, DS-P(i))	4,500 (72.0 mm)	6,000 (96.0 mm)	4,500 (72.0 mm)

Weather conditions

The temperature under the shelter at 2 m height was recorded hourly by Hobo-Logger. The maximum, minimum and average night and day temperatures are listed in Table 5: Maximal and minimal average temperatures under the shelter during the experiments. The time between 8 am and 7 pm is the most important for photosynthesis. 2018 was the hottest year, especially in the important growing phase in May (Figure 1).

Table 5. *Ratio between shoot and root mass of the pots (n = 16) and their water content.*

2016	Watered (W)	Water deficit (DS)	Water deficit with O (DS-O)	Water deficit with Pi (DS-Pi)
shoot / root biomass	4.0	2.3	3.7	4.2
shoot / root dry mass	6.0	3.2	4.8	4.3
water content shoot mass	58.7%	55.9%	54.3%	65.1%
water content root mass	72.4%	69.1%	64.9%	65.6%
2017	Watered (W)	Water deficit (DS)	Water deficit with O and P (DS-OP)	
shoot / root biomass	1.8	1.4	1.8	
shoot / root dry mass	4.3	3.2	3.5	
water content shoot mass	52.8%	57.8%	60.8%	
water content root mass	80.0%	81.6%	80.0%	
2018	Watered (W)	Water deficit (DS)	Water deficit with O and Pi (DS-OPi)	
shoot / root biomass	1.5	1.3	1.3	
shoot / root dry mass	3.0	1.7	2.0	
water content shoot mass	46.4%	52.3%	50.3%	
water content root mass	73.5%	64.9%	68.6%	

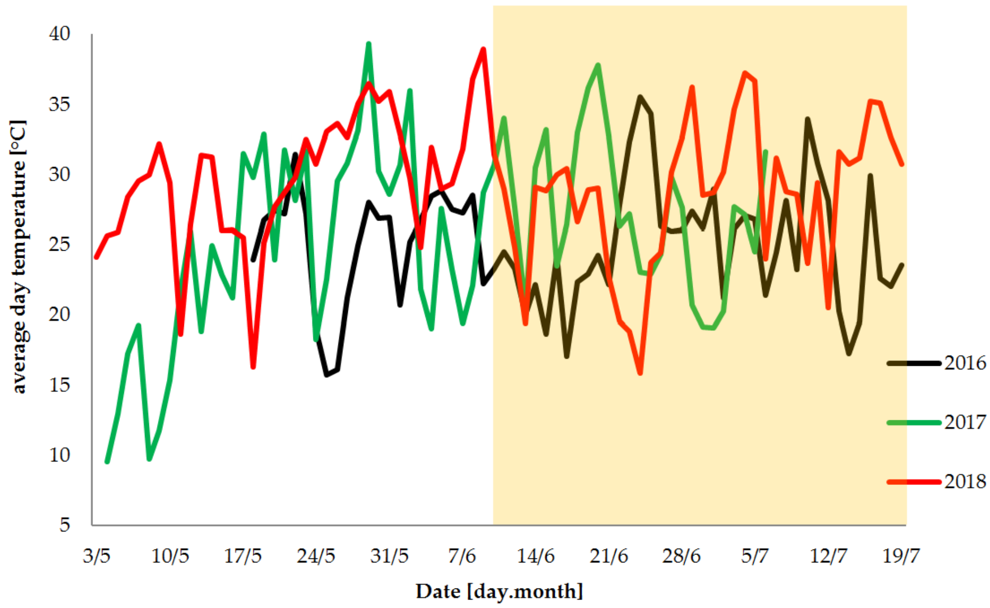


Figure 1. *Average temperature for the trial periods in Marquardt, Brandenburg (Germany). Orange shaded area: water deficit phase.*

2.2. Methods

After potting the plants, data that would not destroy the plants were collected weekly, i.e. growth height, chlorophyll content and soil moisture. After harvesting the plants per pot (with four plants each), further parameters were determined: above-ground (shoot) and underground (root) biomass and the dry mass, as well as the number of grains and their masses.

The data were collected using the following methods.

Soil moisture

The soil moisture was measured weekly (3-4 days after irrigation) with the ThetaProbe Type ML2x and the logger Moisture Meter Type HH2. Five measurements per pot were recorded; the mean values were used for the analyses.

Growth height

The growth height was measured from the soil surface to the blade tip of the plant. After the ears of the wheat plant were visible, the height was measured to the end of these. In each case, the longest stalk per plant was measured.

Chlorophyll value

The SPAD (single-photon avalanche diode) index of the leaves was recorded by a chlorophyll meter (SPAD-502 Plus, [60]. The SPAD-502 measures the transmittance of red (650nm) and infrared (940nm) radiation through the leaf, and calculates a relative SPAD meter value that corresponds to the amount of chlorophyll present in the leaf [60]. Relationships between the chlorophyll concentration and the SPAD values were non-linear with an increasing slope by increasing SPAD (r2~0.9) [61]. The measurements were conducted on ten leaves of all four plants per pot with various degrees of greenness. The values were averaged per pot.

Shoot und root fresh weight, shoot and root dry weight

The above- (shoot) and below-ground (root) biomass was measured at harvest. The plants in each pot were cut at the base and weighed per plant. The roots were separated from the soil by watering the pot. They were weighed per pot. After the plants were oven-dried at 105°C for 24 hrs, their dry weight was measured. The grains were separated and weighed per plant. The water content was calculated as follows: water content [%] = biomass [g] - dry mass [g]/ biomass [g]* 100%.

Number and mass of grains

The number of grains per plant and their weights were determined after harvesting at maturity stage 85. The grains were counted and weighed after oven-drying at 105°C for 24 hours with a digital scale (Thermotex EMB 1200-1). The 1000-kernel weight was calculated as follows: 1000-KW = mass (dry) [g]/ number [-]* 1000.

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

The results of the individual parameters are shown separately according to the test setup. The results of 2016 with separate use of O and Pi will be presented first, followed by the two consecutive years in which the soil amendments were used together: 2017 with the commercial polymer, 2018 with the improved polymer. Some initial interpretations of the results are shown.

Soil moisture

2016:

With weekly irrigation, the soil moisture varied between 5 and 8% vol. (W - watered row). The soil moisture of the pots under water deficit was lower at all times (Table 6). There was no notable difference between the moisture content in pots with and without soil amelioration products. When irrigating these pots in small amounts, due to the hot outside temperatures (Figure 1) the increase in soil moisture was much higher when there were additives in the soil, especially in soil with O.

Table 6. *Yield data of the winter wheat plants.*

2016	Watered (W)	Water deficit (DS)	Water deficit with O (DS-O)	Water deficit Pi (DS-Pi)
grain number [-]	514 (100.0%)	200 (38.9%)	344 (66.9%)	36 (7.0%)
grain mass sum [g]	20.4 (100.0%)	7.4 (36.1%)	14.9 (72.9%)	1.6 (7.7%)
1000 KW [g]	39.8	35.7	42.7	38.6
2017	Watered (W)	Water deficit (DS)	Water deficit with O and P (DS-OP)	
grain number [-]	692 (100.0%)	163 (23.6%)	209 (30.2%)	
grain mass sum [g]	20.98 (100.0%)	5.84 (27.8%)	7.34 (35.0%)	
1000 KW [g]	28.5	24.7	24.2	
2018	Watered (W)	Water deficit (DS)	Water deficit with O and Pi (DS-OPi)	
grain number [-]	437 (100.0%)	169 (38.7%)	248 (56.8%)	
grain mass sum [g]	12.28 (100.0%)	6.07 (49.4%)	9.04 (73.6%)	
1000 KW [g]	28.0	36.0	35.5.	

2017 and 2018:

In 2017 and 2018, the soil moisture in pots with weekly irrigation was around 8% vol. In all other pots, it fell during the water deficit phase sharply to 4% vol. In 2017, the pots with additives had 1 to 5% vol. higher soil moisture values than pots without additives. However, in 2018 with the improved polymer (Pi) it was the other way around. After the water deficit phase with weekly irrigation, the soil moisture was much higher in these pots than without additives.

There are two possibilities to interpret the lower water content in pots with soil amelioration products. The water binding of the polymer component is too strong, so that it is not possible to measure it with ThetaProbe; the plant's available water cannot be determined. Another opportunity involves the more intensive water uptake by plants during their growing process. This could be seen in the higher biomass (Figure 4). In the years 2017 and 2018, the high air temperatures during the experimental phase (Figure 1) along with no rain led to high evaporation in the pots. The measurement of soil moisture was carried out in the upper 5 cm of the pots. This was the area with the highest evaporation. Due to gravity, the water was more likely to be in the root area.

Plant height

2016:

The plants grew around 50 days in the pots until the beginning of June. With weekly irrigation, the plants reached an average height of 71 cm (n=16). Under water deficit stress, the height was reduced to 55 cm. Component O promoted effects related to the plants' height (67 cm). This was only 4 cm lower than that of the plants in the irrigated pots. With use of component Pi, there was a reduced effect with an average height of 39 cm visible (Figure 2).

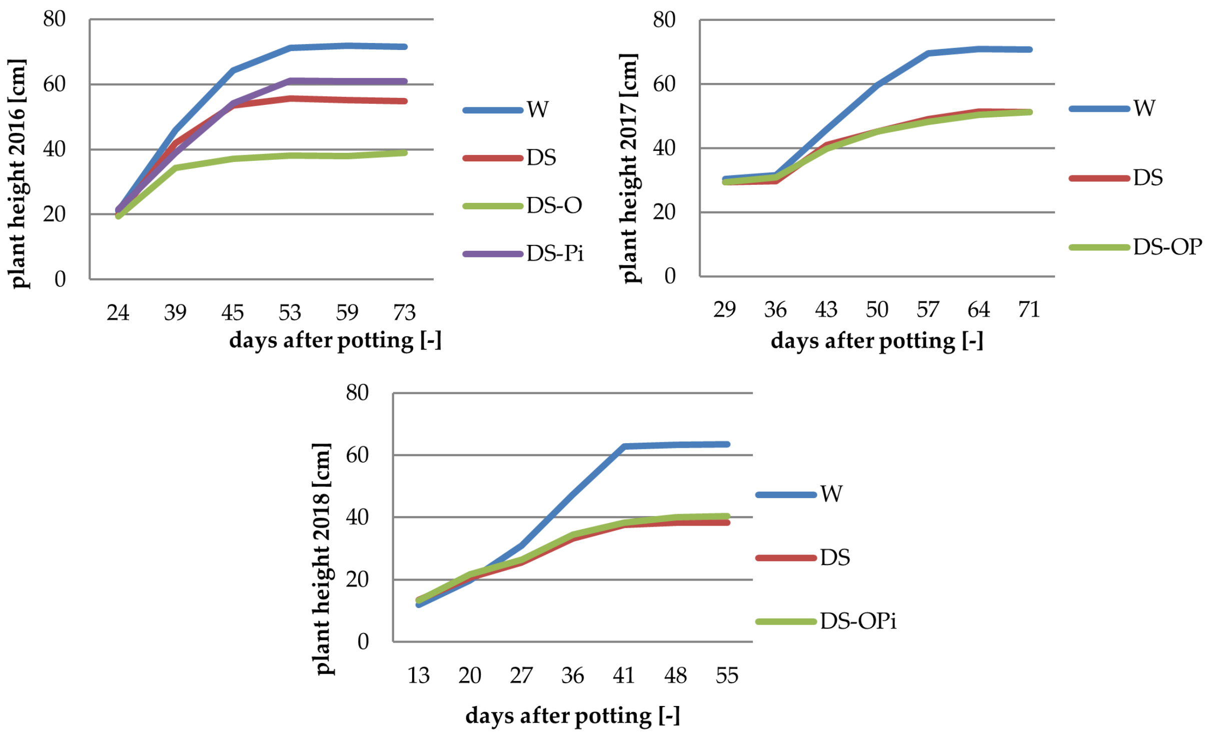


Figure 2. *a-c: Average plant height of the trials (days after potting).*

2017 and 2018:

The maximum plant height was reached at the beginning of June, 57 days (2017) or 41 days (2018) after potting. The irrigated plants had an average height of 70 cm in 2017 and 63 cm in 2018. Plants with water deficit only reached heights around 20 cm lower, i.e. 51 cm in 2017 and 40 cm in 2018. When using both soil amendments, there was no difference in plant height compared to water deficit without them, but it was recognized that after renewed irrigation the plants with soil amendments grew again up to 55 cm in 2017 (Figure 2).

The nutrients contained in additive O could lead to better growth of the winter wheat plants, despite the water retention of P. The water retention of the organic component seemed not to be very strong. There was enough plant available water. However, the water retention of the polymer (Pi) minimized the plant height. The combined use of both decreased the positive effect of the organic component. Additionally, the application of both promoted shoot and leaf growth in well-watered plants and increased the shoot-root ratio, which could be a disadvantage under water stress [62]. Another possibility is the need for water caused by the higher biomass (Figure 4) and number of stalks (Table 7).

Chlorophyll values measured by SPAD

2016:

There were identifiable differences in the chlorophyll values between the different trials. Plants in the substrate of irrigated pots (W) and in pots with water deficit (DS) showed more or less the same value, around 50 units (Figure 3). Using soil amendment products, the chlorophyll values in the wheat plants were 8 units higher than without them. After maturity and watering again (10th June), this chlorophyll value was stable two weeks longer in plants with O or Pi compared to the basic substrate soil. This effect continued when using Pi until the harvest. The stalks were still vital and productive. This means that isolated stalks of the plants had resumed growth and thus the ripening process was delayed.

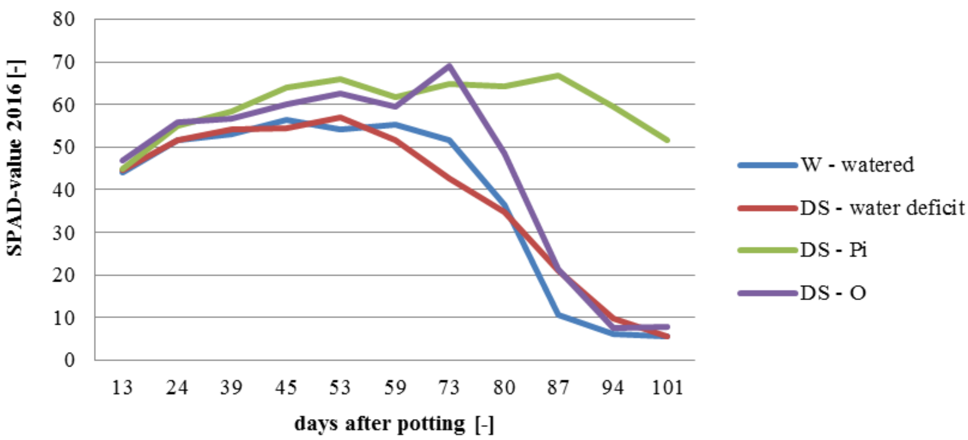
As a result, component Pi as well as component O added to the soil led to higher chlorophyll values in the winter wheat plants. This can be caused by the better and continuous supply of N, as well as the supply of water.

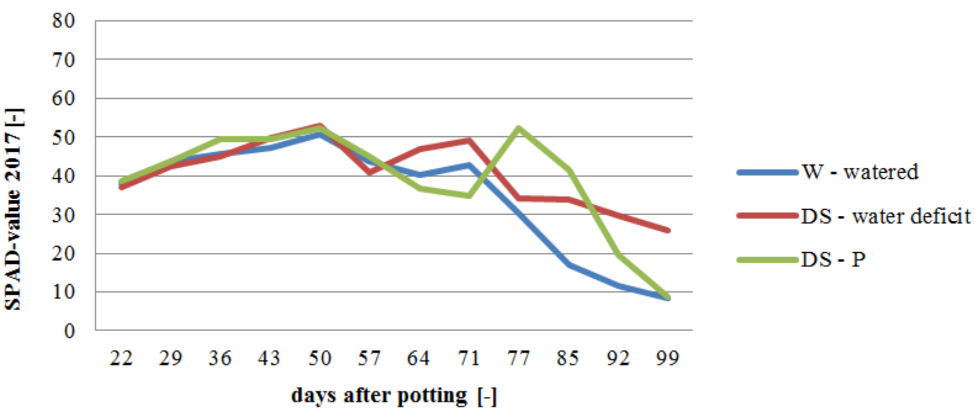
2017 and 2018:

In the following years, no differences in the chlorophyll values between plants in watered and dry pots with the basic soil substrate could be identified. Using both amelioration products, these values were 5 units higher the whole time (around 50 instead of 45). After irrigation in the maturity phase, the values increased from 15 to 52 units (Figure 3).

In 2018, when using Pi the chlorophyll value was more than 10 units higher (up to 70) compared to the basic substrate soil during the whole observation period. Watered plants showed the most rapid decrease in chlorophyll values. They reached the maturity phase with chlorophyll values below 10 units.

Both of the soil amelioration products kept the chlorophyll level high for a longer time. As a result, the light energy of sunlight could be better absorbed and stored for the metabolism of usable chemical energy (ATP - adenosintriphosphate) and as reduction equivalents (NADPH - Nicotinamide adenine dinucleotide phosphate). Photosynthesis processes were possible for a longer period of time.





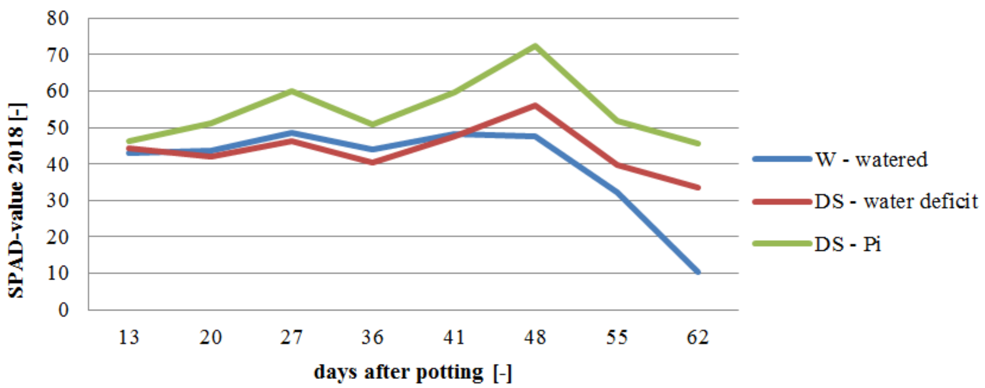


Figure 3. *a-c: Chlorophyll values (SPAD) of winter wheat 2016 to 2018, days after potting.*

Number of stalks:

2016:

All wheat plants that were planted in the pots had three stalks at the beginning, i.e. 12 stalks per pot or 48 per row. The four watered plants (W) had at the end a total of 22 stalks (Table 7). Water deficit reduced the stalks to 18. Both soil amendments increased the number of stalks. Wheat plants that grew in soil with the organic supplement or in soil with the improved polymer Pi had around 50% more stalks than the watered plants (Table 7).

2017 and 2018:

These results showed up again in 2017. The 16 well-watered plants (W) had together 42 stalks. Water deficit reduced the number by 60%. The usage of both soil amendments together increased the number of plant stalks by 130% compared to watered plants (Table 7). In the hot year of 2018, however, no big differences between the rows could be seen. Drought stress reduced the stalk number by 85%. The soil amendments O and Pi had no effect. Most of the plants only had one stalk.

Table 7. *Number of stalks per pot (p, sum of 4 wheat plants).*

	W					***DS***					***DS-O***					***DS-P***				
	p1	**p2**	**p3**	**p4**	**sum**	**p1**	**p2**	**p3**	**p4**	**sum**	**p1**	**p2**	**p3**	**p4**	**sum**	**p1**	**p2**	**p3**	**p4**	**sum**
2016	6	7	4	5	22	4	6	4	4	18	6	7	8	8	29	5	10	8	7	30
	DS-OP and DS-OPi																			
2017	11	8	14	9	42	6	8	6	6	26	16	15	11	13	55					
2018	6	5	6	4	21	4	4	6	4	18	4	4	5	5	18					

Biomass

2016:

The shoot biomass of plants in the irrigated pots (W) was the highest (181 g, n = 16 plants, Figure 4). A lack of water led to a reduction in the above-ground biomass and dry matter down to 46 - 50%. By using the soil amelioration products, the negative impact of water deficit on biomass production was reduced. With component Pi, 65 to 77% of the harvested mass was achieved, with O even 72 to 80% of the irrigated variant.

Irrigation of the plants led to better results in terms of biomass, but soil amendments also had good results during water deficit. Through their use, the amount of water saved was between 45 and 54 mm per month (Table 4).

The distribution of the biomass of all 16 plants indicated the positive impact of O. The average corresponded with the irrigation method, but the maximum was higher. Pi supported the above-ground biomass.

Furthermore, a lack of water changed the ratio of above-ground (shoot) to underground (root) biomass. For irrigated plants, this ratio was 4.0 (Table 8). However, conditions under water deficiency triggered the development of the underground biomass. In this case, the ratio was 2.3. The addition of the organic component O led to a slight reduction of the ratio (3.7), which means relatively more underground biomass. On the other hand, the artificial component Pi led to an increase of the above-ground biomass (ratio = 4.2). An influence of the soil amelioration products on the absolute underground biomass, i.e. root mass, could not be detected. Component Pi slightly increased the water content of the above-ground biomass, while component O left it unchanged.

Table 8. *Ratio between shoot and root mass of the pots (n = 16) and their water content.*

2016	Watered (W)	Water deficit (DS)	Water deficit with O (DS-O)	Water deficit with Pi (DS-Pi)
shoot / root biomass	4.0	2.3	3.7	4.2
shoot / root dry mass	6.0	3.2	4.8	4.3
water content shoot mass	58.7%	55.9%	54.3%	65.1%
water content root mass	72.4%	69.1%	64.9%	65.6%
2017	Watered (W)	Water deficit (DS)	Water deficit with O and P (DS-OP)	
shoot / root biomass	1.8	1.4	1.8	
shoot / root dry mass	4.3	3.2	3.5	
water content shoot mass	52.8%	57.8%	60.8%	

water content root mass	80.0%	81.6%	80.0%
2018	Watered (W)	Water deficit (DS)	Water deficit with O and Pi (DS-OPi)
shoot / root biomass	1.5	1.3	1.3
shoot / root dry mass	3.0	1.7	2.0
water content shoot mass	46.4%	52.3%	50.3%
water content root mass	73.5%	64.9%	68.6%

2017 and 2018:

The harvested biomass in 2017 and 2018 confirmed the results of 2016: Wheat plants with water deficit produced only 56% of the biomass compared to the watered plants. By using soil amelioration products, above-ground and underground biomass production was almost completely compensated (75% to 95%) despite the water deficit (Figure 4). In 2018, even 105% of the biomass was achieved compared to irrigated plants. This means that the improved polymer (Pi) had better results than the commercial polymer P.

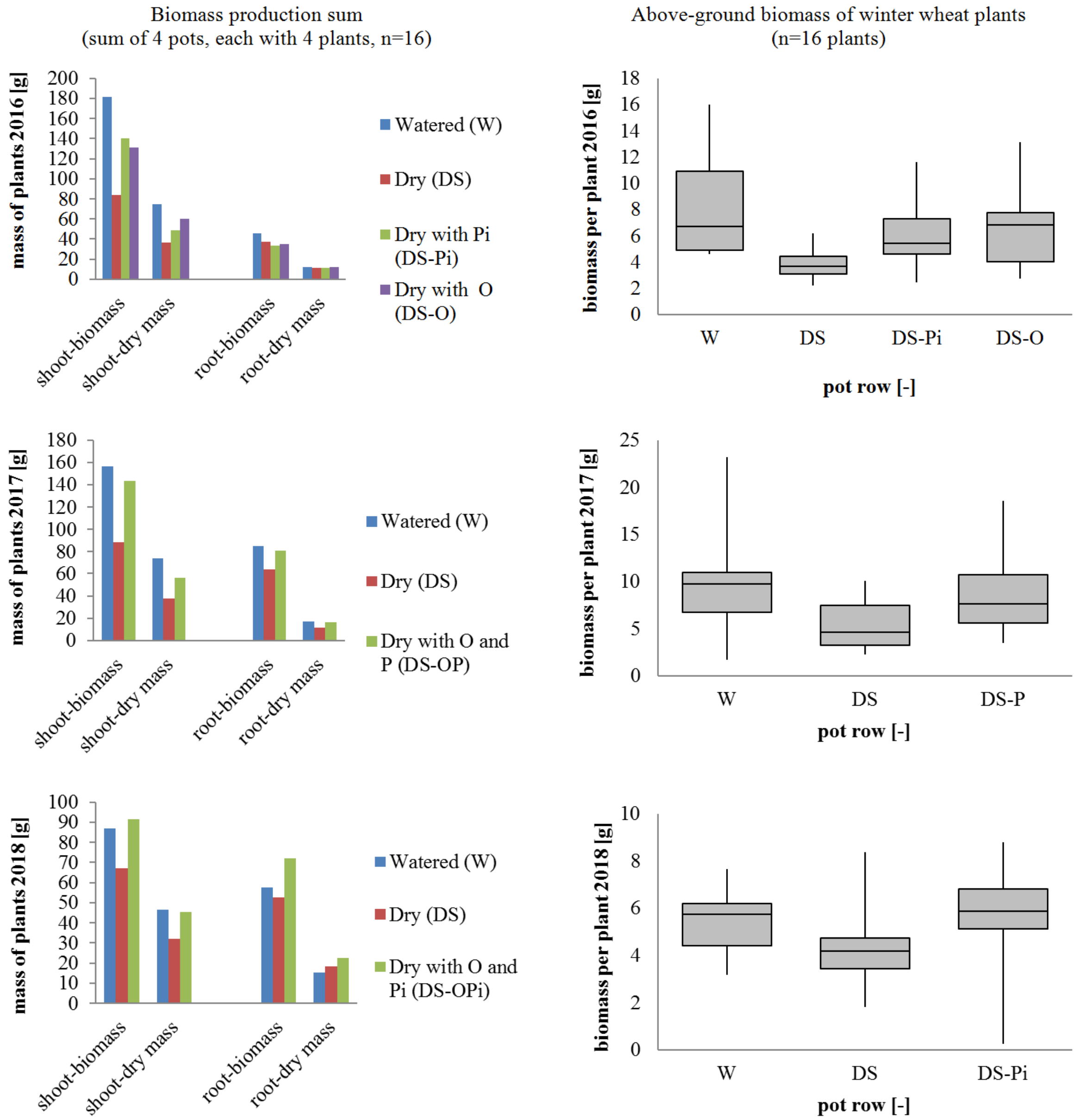


Figure 4. *a-f: Biomass of winter wheat plants.*

The analysis of the individual values (Figure 4) confirmed the increase in biomass production of the wheat plants caused by the combination of soil amendments. The median of the results of the improved polymer in 2018 led to more biomass than the watered row (W).

There was no indication of an influence of soil water shortage or soil amelioration products on the water content of the roots. In all experimental years, the ratio between above-ground and underground dry matter was increased by the soil amendments (Table 8). Due to the lack of water, the ratio of above-ground (shoot mass) to underground biomass (root mass) was reduced compared to the irrigated row (Table 8). When combining the two soil amelioration products, no change in this ratio was observed during drought stress in 2018. The water content of above-ground biomass was highest in plants of the irrigated series. The water content in the plants with the commercial polymer was higher than in the following year with the improved polymer.

Effects of the soil amelioration products were also shown in the water content of the total above-ground biomass, especially with Pi. When using O alone or in combination with polymer P, no increase in the water content of the shoot mass was observed. Differences in the water content of the roots could not be detected with any of these soil products (see Table 8).

With regard to the biomass production, it can be concluded that the use of soil amelioration products could compensate drought stress in biomass production. In the extremely warm year 2018, Pi also supported root growth. This resulted in 25% (root biomass) and 48% (root dry mass) more weight compared to the irrigated plants.

Grain mass

2016:

The 16 watered plants produced grains with a weight of 20.4 g (Table 9). Drought stress in the vegetative phase reduced this yield about 37%. Plants in pots with the addition of Pi delivered only 7% of the yield compared to the irrigated row and 20% of the row under drought stress. Using the organic component O, 70% of the yield of irrigated plants was achieved, with drought stress up to double the amount (Table 9).

The 1000-KW as a meaningful variable for the expectable yield was reduced from 40g (W) to 36g (DS) by water shortage. The soil amendments increased this 1000-kernel weight to 39g (polymer) and 43g (organic).

2017 and 2018:

The combined use of the soil amelioration products increased the yield in terms of the number and mass of grains compared to drought stress without them. In 2017, the lack of water caused a loss of more than 72% of the yield. With soil amendments, 1/3 of the yields of the fully irrigated series could be achieved. In 2018, the water shortage led to only 39% (number) or 50% (mass) of the yield using the irrigation method. Using the improved polymer Pi, over 50% more grains (56% of the number and 74% of the mass of the irrigation row) were counted. Nevertheless, the yields were not as positive as the single use of 5% vol. O in 2016.

The 1000-KW changed in 2017 only slightly with the use of both soil amelioration products. In 2018, the 1000-KW of the plants with soil amendments increased compared to the fully irrigated ones (Table 9). The less developed grains showed a higher weight. The number of grains was lower, but these were significantly larger and heavier due to the use of Pi (Figure 5).

Table 9. *Yield data of the winter wheat plants.*

2016	Watered (W)	Water deficit (DS)	Water deficit with O (DS-O)	Water deficit Pi (DS-Pi)
grain number [-]	514 (100.0%)	200 (38.9%)	344 (66.9%)	36 (7.0%)
grain mass sum [g]	20.4 (100.0%)	7.4 (36.1%)	14.9 (72.9%)	1.6 (7.7%)
1000 KW [g]	39.8	35.7	42.7	38.6
2017	Watered (W)	Water deficit (DS)	Water deficit with O and P (DS-OP)	
grain number [-]	692 (100.0%)	163 (23.6%)	209 (30.2%)	
grain mass sum [g]	20.98 (100.0%)	5.84 (27.8%)	7.34 (35.0%)	
1000 KW [g]	28.5	24.7	24.2	
2018	Watered (W)	Water deficit (DS)	Water deficit with O and Pi (DS-OPi)	
grain number [-]	437 (100.0%)	169 (38.7%)	248 (56.8%)	
grain mass sum [g]	12.28 (100.0%)	6.07 (49.4%)	9.04 (73.6%)	
1000 KW [g]	28.0	36.0	35.5.	

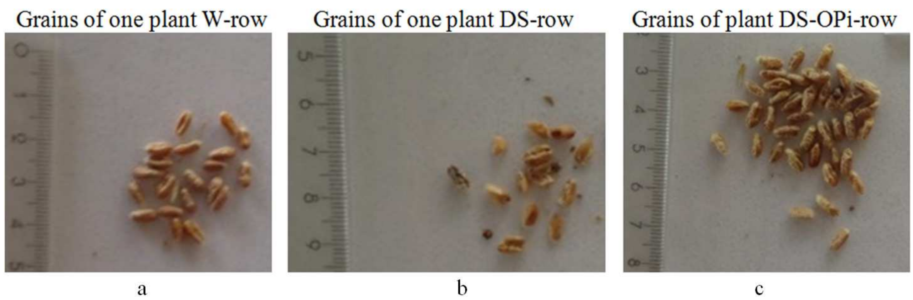


Figure 5. *a-c: Grains of the plants.*

4. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

The discussion is divided into three parts examining the impact of drought stress, soil amendments and irrigation on wheat plant growth. First of all, the consequences of water deficit on the wheat plants are discussed (W vs DS). This is followed by statements on the effects of the separate use of each of the two soil supplements during times of water deficit in 2016 (DS vs DS-O and DS-Pi), in order to then explain their joint effect (DS vs DS-OP 2017 and DS-OPi 2018). Differences in the effects of the commercial polymer and the improved polymer are subsequently discussed by comparing DS-OP and DS-OPi. For conclusions regarding the superiority of irrigation or the use of both soil amendments, the results are summarized in 4.2.

4.1. Impact of Drought Stress and Soil Amendments on Wheat Plant Vitality

Impact of drought stress

A lot of other research papers have already analyzed the impact of drought on plant growth rate and nutrient uptake. The negative impacts of drought on the yield mainly depend upon the severity of the stress and the plant growth stage. In this experiment, the water deficit was in the vegetative stage, in which the grains are trained. Here, water deficit was initiated in winter wheat plants in the vegetative growing phase between May and June (Figure 1). The plants with water deficit received around 54 mm (3.4 L per pot) of water less than irrigated controls. The temperature under the shelter reached values up to 40°C. This simulated a dry period in Brandenburg.

Crop growth and yields are negatively affected by sub-optimal water supply and abnormal temperatures due to physical damage, physiological disruptions and biochemical changes [7].

Also, in this experiment winter wheat plants grew 20 cm smaller in height and attained half of the biomass compared to irrigated plants. Drought stress caused reductions in the growth rate along with a cascade of metabolic changes [63]. The shoot-root ratio decreased by half during water deficit. These results were similar to those of [64]. They showed that with water deficit the shoot to root partitioning shifted towards root growth. However, the existence of compensatory growth occurring in deeper layers could not be proven. An impact on the chlorophyll values could not be determined. According to Cui et al., water deficit during vegetative periods can improve the photosynthetic capacity of flag leaves during the reproductive period with the enhanced absorbed light use efficiency and better adaption to high light intensity, as indicated by the measured changes [15]. Drought causing reduction in the yield might be due to various factors, including decreased rate of photosynthesis, mentioned by Flexas et al. [65] or disturbed assimilate partitioning [8].

Significant yield losses have been reported in major field crops [8]. Winter wheat plants in this study showed losses of 66%. If such dry phases occur more frequently in the future, a change in management is essential.

Impact of soil amendments by separate usage

An impact of either O or Pi on the soil moisture measured in the uppermost 5 cm was not visible. The positive effect of the investigated amelioration products on winter wheat plants in case of water shortage was mainly demonstrated by the enhanced growth height, chlorophyll values and biomass.

The sole use of the organic soil amendment (5% vol.) increased the height of the winter wheat plants. There was also a rise in the number of stalks, and connected with that the above-ground biomass. These can be caused by the nutrient supply from O, especially nitrogen and phosphorus [66]. The nutrients are mainly used in the production of photosynthetic active biomass and the reproductive organs. This is particularly evident in the results of the chlorophyll value, which in all experiments was higher in substrates with the soil amelioration product O than without (see Figure 3).

As Rashtbari et al. has already shown, that effects of vermicompost could be attributed to a variety of other factors (soil microbial structure and activity, mineralization, soil enzymatic factors) [19]. Other research results report that fresh and dry weights were also severely reduced under water limiting conditions [67]. The dry weights of shoots and roots increased significantly, like Paul & Metzger found out [68], or were not significantly influenced by vermicompost additives [69]. Experiments by Rashtbari et al. clearly indicated that vermicompost may be an efficient plant growth media for sustainable plant production [19]. Berova & Karanatsidis mentioned that leaf chlorophyll contents significantly increased with vermicompost application [70]. In contrast, a decrease in chlorophyll content using pure vermicompost was reported by Ali et al. [71]. Results of Weigel & Manderscheid could not confirm that a lack of water reduced the CO_2 supply and thus the photosynthesis rate of the plants [18].

The supply of the organic additive (O) led to an increase in grain yields. Despite the water shortage, 70% of the number and mass of the grains could be achieved by using soil organic matter, also caused by the higher number of stalks. This is consistent with research results from Cui et al. [15], who found that severe water deficit significantly reduced grain yield due to a strong reduction in the number of stalks as compared to a control run.

The water-storing capacity of the organic substrate is not strong, so it is plant available and there is no decreased effect on the yield results. No effect of O could be detected in the root biomass or the water content of the plants. The addition of 5% of the component O is considered sufficient. As already shown in earlier studies by Münzel & Blumenstein [55], higher quantities did not lead to improved growth and must therefore be rejected with regard to economic aspects. Other research studies have shown controversial results. The survival capacity of plants may be altered negatively, showed by Lazcano & Dominguez [72], or significantly enhanced by the addition of organic supplements [73]. Joshi also noted that the growth, yield and quality parameters in vermicompost treatments varied significantly from controls, though differences between various vermicompost treatments were not found to be significant [74].

It has been observed that there is no significant difference in applying higher doses of vermicompost. The lowest dose (5 t/ha) is as effective as higher doses [74]. According to Joshi et al., vermicompost is an ideal organic manure for better growth and yield in many plants [75]. Moreover, it may take more than two years' time for an organic farm to improve its soil health enough to make the growth and yield equivalent to that of chemical fertilizers. Therefore, O can be used for this and will lead to better results.

The improved hydrogel soil amendment (0.33% vol.) did not have such an effect on the plants under water deficit. The plants were much shorter compared to those under water deficit and without additives. Therefore, it can be concluded that there is not enough plant available water for the growth of productive organs. Due to the hygroscopic effect, the use of water-storing component P perhaps reduces nutrient absorption and thus reduces growth. In the vegetative phase, there may be too little water for the formation of the grains. Pi led to a reduction in the number of grains and also in grain mass. A subsequent water supply could not compensate for this deficit.

In contrast to the reduced height, an increased number of stalks was measured, and connected with that a higher absolute above-ground biomass. The higher stalk number did not lead to a higher number of grains. The plants did not fully train the reproductive organs. Only 20% of the yield was reached.

There was also no change in the absolute root biomass. However, during the determination of the root mass, an accumulation of roots around the soil amelioration products could be detected, which ensured the additional supply of water for the above-ground biomass.

Positive effects of the polymer could be demonstrated in the plants' water content, as well as chlorophyll values. When adding water after a longer dry period, the plants remained green longer. This illustrates the effect of P as a water-storing component and thus reversible water release [64]. His results showed that the water uptake rates increased quickly after rewatering and exceeded the uptake rate of the non-stressed treatment about 2 - 3 weeks after the deficit release. Studies of Geesing & Schmidhalter argued in the same direction, in which a significant increase in dry matter in wheat was only achieved if water shortage was avoided by the polymers [44].

The results are not in line with the findings of [42]. In his experiments, the addition of a polymer increased the height in addition to increasing dry matter production. Farrell et al. mentioned that polymers have the potential to increase substrate water availability and lead to higher plant growth and survival [43]. They determined that the water-retentive hydrogel additive increased substrate water-holding capacity, plant available water and growth of winter wheat. However, there was no increase in time until wilting in either substrate. According to Banedjschafie & Herzog, effects of the polymeric soil improver occurred indirectly through reduced nutrient leaching in the event of excess rain [40]. Nutrients are necessary for plant cell growth, and are mainly supplied in this research by O.

Therefore, the combined use of both the nutrient soil amendment and the polymer led to better effects.

Impact of the combined use of organic and hydrogel amendments

In 2017, the organic amendment O (5.0% vol.) was combined with a commercial polymer (0.3% vol.). The combined use of both amendments, however, had no effect on the height of the wheat plants experiencing a lack of water. An increased effect of polymers (individually and in combination) on the growth height of wheat plants was also not evident.

As in the experiment investigating the two components separately, the number of stalks also increased. The effect of O, whose sole use reached 80% of the biomass production, was limited by the water-storing polymer. On the other hand, there was an increase in underground biomass. The combination of both components along with reduced irrigation quantities led to an increase in biomass of about 30% compared to substrates with no amelioration. Associated with this, the above-ground biomass also increased in comparison to plants that grew in untreated soil.

The combined use of both soil amendments also showed an increase in underground biomass in wheat plants. Sufficient water supply was available to guarantee the reproduction of the plants. However, the water content in the biomass did not change.

After a longer period of water deficit, the substrate combined with Pi and O had lower soil moisture contents when fully irrigated, because the growth of the plants was not yet complete; this is also confirmed by the higher chlorophyll values. To enable growth despite water shortages, a high proportion of the development and energy metabolism was used for chlorophyll production. The chlorophyll levels in plants with water shortage and the addition of soil amendments were higher than in continuously irrigated wheat plants. Senescence occurred with a delay in the first experimental group mentioned (Figure 3).

The combined use of the organic matter and the water-storing polymers improved the yield in the case of drought stress on the plants (see Table 9). In the case of water shortage in the vegetative phase, O and P produced 50% more grain mass than without their addition. The number of grains increased, but their size was significantly smaller. In the experiments the 1000-KW was increased by the combined use of both soil amendments. Hence, a moderate water deficit during vegetative periods is beneficial for yield stability and can provide a water-saving strategy in winter wheat [15]. However, the positive effect of the organic component is slightly limited by its combination with the water-storing component. Lower water availability for the plants could be one explanation for this.

In summary, the soil amendment O is a very important source of nutrients. In combination with the polymer, wheat plants showed improvements in their growth parameters. Also, O alone achieved growth enhancement and increased chlorophyll values.

Impact of polymer improvements P and Pi

Comparing the effects on the plant growth using commercial (2017) and improved polymers (2018) together with O allow statements to be made about the effectiveness of the two different polymers.

Both polymers had no effect on height with a lack of water. There were also no differences in the water content of the above-ground biomass. In contrast, results showed an increase in the number of stalks due to the commercial polymer. The improved polymer, however, did not increase the number of stalks. It could not be clarified whether this was due to the dry year 2018 or to the kind of plant itself. However, the polymer Pi in its improved form had better effects on plant growth. Although the number of stalks was the same with and without this polymer, the improved polymer showed significantly higher biomass sums in shoot and root biomass.

The improved Pi in combination with O increased the grain yield in terms of their number and mass more than the commercially available product. In addition, plants with the addition of Pi showed higher chlorophyll values than the drought stress variant (DS) throughout the trial period. However, when using the commercially available polymer, these values fluctuated continuously.

4.2. Comparison of Growth Success Using Soil Amendments vs. Irrigation

To make statements about the recommended method to use during long dry periods, it is useful to compare the well-watered plants with plants that lacked water but were grown in amended soil.

The expected differences in the soil moisture caused by the different water applications were presented in the previous section. Comparing the growth success, the plants grew much higher receiving irrigation rather than soil amendments. This was not desirable, because the likelihood of bending over was much higher. Lower plants are better for harvesting. Therefore, the use of growth inhibitors can also be spared in agriculture. The number of stalks in all plants receiving O and/ or P was much higher than those that were irrigated. If there are more stalks, there can be more spikes and finally more grain yield. This is independent of the plants' height.

The most important factor for farmers and food security is the yield. Compared to the fully irrigated plants, the best option, when using soil amendments, is the sole use of organic amendment O or in combination with Pi. Two-thirds of the yield can be achieved by using around 55 L/m² less water per month. Further studies could analyze whether a slight increase in the amount of irrigation also increases the yield. Using polymers alone showed no success and is therefore not recommended. Moreover, the normal polymer P in combination with the organic O did not yield greater success than the improved polymer (Table 9).

A by-product of the wheat biomass is the straw, which can be used as bedding for the animals. Therefore, the biomass production is also important. The combination of both soil amendments analyzed here led to higher biomass production than the single use of either one of them alone. When using the organic O in combination with Pi, the biomass is higher than in the irrigation row. The dry masses of wheat plants in pots with both soil amelioration products corresponded to 75% of well-irrigated plants, the biomass to 65% (see Figure 5).

The water content of the plants at harvest time was slightly increased by the combined use of both soil amelioration products. This, however, was not intended. A dry state is better for processing after harvest. However, premature senescence is not beneficial. If the plants dry out too early, the grains can drop out of the ears.

The chlorophyll values of the plants can give information about the production status. Well-irrigated plants reached a low chlorophyll value earlier than the plants that grew in soil with additives. This can be an advantage or a disadvantage. If the chlorophyll value is low, the growing processes are low, too. However, there was no senescence reached using only polymers. In contrast, the organic amendment only shifted the reduction of the chlorophyll values by a few days.

The combination of both soil amendments seems to be the best option. Higher and longer-lasting chlorophyll values were observed during the growing period. The values decreased at the normal harvest time in July (Figure 3). Especially in 2018, the irrigated plants reached senescence already in June due to the high temperatures, which was too early. Plants with drought stress stayed vital longer. Therefore, harvesting was necessary.

In summary, by using the analyzed soil amendments, shorter plants with more stems were achieved, producing more biomass and postponing senescence. From a practical point of view, these findings seem to be advantageous compared to irrigation. Only the number of grains was lower, but the grains themselves were larger. This is desirable for the production of cereals and is also a quality parameter indicating higher protein and starch content. As roughage, grain straw has nutritional properties and, in addition to hay, is an alternative to young or especially renewable grass [76].

The analyzed soil amelioration products have a high potential for reducing drought stress impact in the plants. Due to varying soil properties, treatments might result in very different outcomes. Therefore, the application of soil supplements has to be adapted to the properties of the treated soil and the crop. However, their substrate-specific mixture is important. All the statements here are valid for loamy sand. Their effect in clayey soil should be analyzed if there is a lack of organic material.

In the context of the experiment, it should be noted that this was a pot experiment. As a result of the experimental conditions, these are subject to a varied influence of the control parameters of radiation, temperature, wind and humidity. Due to their growth in pots, the plants are subject to greater dehydration than in the field. The plants cannot use all of their capillary water. Winter wheat, however, normally roots up to 1.80 m deep and can therefore use even deeper water resources in the field [77].

5. Conclusion

The aim of this study was to test whether the combination of an organic soil amendment and polymers can provide a reasonable strategy for water-saving management of winter wheat. The following conclusions can be drawn from the experiments during the three vegetation periods:

The two soil amelioration products together led to better growing results for the plants compared to their separate use.

They delayed the onset of senescence.

The wheat plants consistently showed higher chlorophyll content if soil amendments were used, independent of the soil amendment.

The polymeric component Pi had no considerable influence on increasing biomass. The improved hydrogel (Pi) compared to the commercial P together with the organic amendment yielded higher biomass.

The combined application of O and Pi increased the grain yield in terms of mass and number during drought stress despite the lower growth height of the wheat plants. It was possible to achieve 55 to 70% of the yield compared to irrigation. This was mostly caused by the organic soil amendment.

The use of the analyzed products in the pot experiment showed advantages in terms of lower height, more stalks and biomass compared to irrigation.

From these results, conclusions can be drawn regarding the use of the analyzed soil amendments O and Pi. O improved the physical, chemical and biological properties of the sandy soil substrate. The sole use of hydrogelic components P or Pi in agricultural sandy soil is not recommended. There was no benefit in terms of yield or growth height. However, it could be used as an alternative to growth inhibitors. Its effects over the years should still be investigated.

The combined use of both soil amendments is recommended if the aim is to increase the biomass with less irrigation. Irrigation seems an easier method. The resulting costs have to be taken into account, as well as the use of groundwater reserves. These are particularly important in the future, when dry years will occur more frequently.

The study plants in the pot experiments were two types of winter wheat. Nevertheless, the results can be transferred to cereals with the same course of vegetation stages, such as barley, oats, triticale or rye. The statements from the results only apply to the use of soil amelioration products if germination has already occurred. Possibilities for further research might involve experiments with spring wheat and thus the use of soil amelioration products before germination of the plants. This is important, because the soil amendments should be in the soil for several years. Both supplements led to an increase in biomass. For this reason, their use is also conceivable in crops in which the above-ground biomass is harvested, such as lettuce or cucumber.

In the future, investigations into the protein content of the grains or the baking properties of the flour could also be carried out. This will be an important requirement for wheat in the future. The introduction of the examined soil amendments is expected to last for at least 5 years. After that, it might be necessary to add them again. Soil amelioration products save only water, but also fertilizer, ploughing work and thus fuel, personnel and equipment rental costs. To evaluate the pay-off of the soil amendments, an economic calculation of the costs and benefits over a period of several years should be undertaken. Furthermore, farmers should be sensitized to the use of these additives. Especially in the course of climate change, a combination or replacement of chemical fertilizers will be necessary. An area-specific use of these components in locations with reduced yields makes sense.

This would make it possible in the future to achieve higher yields by saving on irrigation volume, even in unfavorable weather conditions with long dry phases and to further secure the food supply for the population. This approach can help secure long-term stable agricultural yields, especially given changing amounts and intensities of precipitation as well as temperature conditions in the future.

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