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Article

Fertilizing Potential of Rye Stillage in A Maize Agroecosystem

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Abstract: The distillery stillage is a major byproduct generated during ethanol production from plant raw materials (e.g., cereals) and molasses. It contains a high percentage of organic matter susceptible to biodegradation and nutrients necessary for plant growth, and therefore, can be used for fertilization purposes. This study evaluated the fertilizing value of rye stillage applied in a grain maize agroecosystem. The field study was carried out in 2017–2018 (two growing seasons) on Luvisol (loamy sand) in Poland. The experiment scheme included four treatments: W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, and W45—45 m^3 of stillage per hectare. It was found that application of rye stillage was significant for maize yields. However, it demands supplementary potassium fertilization and regulation of the soil reaction and/or stabilization of the pH of stillage before its application. Moreover, due to its contribution to the build-up of residual available phosphorus in the soil, rye stillage may pose an environmental risk.

Keywords: byproduct; soil properties; maize grain; fertilizer; nutrient content

1. Introduction

The distillery stillage is a major byproduct generated during ethanol production from plant raw materials (e.g., cereals, potatoes, and sugar beets) and molasses that contain simple and complex carbohydrates. In Europe, the USA, and Canada, cereals are among the main crops used in the production of ethanol. Depending on the type of technology and equipment used, during the distillery production of one cubic decimeter of spirit, 8–20 dm^3 of stillage is produced [1–4]. This byproduct is characterized by a high content of organic matter susceptible to biodegradation, accompanied by mineral nutrients necessary for plant nourishment, and therefore, stillage can be used for fertilization purposes. In general, all stillage types obtained from ethyl alcohol production indicate relatively high contents of organic carbon, very low concentrations of phosphorus (P) and, at times, those of potassium (K), in relation to nitrogen (N) contents [5–9]. Among them, cereal stillage is characterized by the highest content of P and the lowest content of K [7,10]. A wide range of organic byproducts and wastes applied to agricultural soils have already been extensively assessed, with results showing that their beneficial effects on soil properties that far outweighed the negative impacts [2]. It has been proven that soil treatments with stillage enhance microbial biodiversity and are particularly beneficial for the species involved in the N cycle [11]. Improvements in the microbial activity are crucial for the transformations of organic matter and nutrients in the soils, making them available to crops. Throughout the world, stillage land disposal has been credited for improving nutrient availability, soil biochemical properties, and eventually crop growth and development [1]. Szulc et al. [10] have found that applying rye and molasses stillage to a maize system cultivated on a sandy soil increased crop yield significantly, on average, by 112.5% and 209.2%, respectively, in comparison to the control treatment.

The fertilizing use of stillage may to some extent be limited due to its low pH because of the presence of organic and inorganic acids [1,6,7,9]. The acidifying effect of stillage applied to the soil is also associated with a resultant increase in the amount of base cations, which leach from the soil along with their transformation products (bicarbonates and organic acid anions), and is also associated with an increase of acid-forming N compounds in the soil environment (ions NH_4^+). Acidification influences the transformation, biogeochemical cycling, and consequently the mobility of nutrients in soils, and so indirectly affects crop plant growth. Depletion of soil pH results predominately in: (i) a reduction of cation exchange capacity decreasing the ability of the soil to retain nutrients in cation forms, that are then prone to leaching, (ii) an inhibition of soil biological processes which have significant cascading effects on transformations of nutrients, especially N, (iii) an induction of nutrient precipitation (e.g., P), (iv) a reduction of nutrient uptake by plant roots [12,13]. These effects, however, might be mitigated, since the decomposition of stillage organic matter, including transformations of organic anions, the reactions of ligand exchange, as well as ammonification and denitrification of nitrogen compounds, potentially increase soil pH [7,14].

It should be emphasized that available literature data on the use of stillage for fertilizer purposes refers mainly to molasses stillage [3,7,14], and the studies carried out under field conditions have had a rather limited scope [2,7].

Soil treatments with stillage allow for the recycling of nutrients, which on the one hand contributes to the protection of natural resources, and on the other minimizes the costs associated with the use of mineral fertilizers on a local scale [2,3,7,11]. This is particularly important in the case of cultivation of maize, which is the crop with high nutritional requirements and a negative impact on soil organic matter contents [15,16].

The aim of this study was to evaluate the fertilizing value of rye stillage applied in a grain maize agroecosystem.

2. Materials and Methods

A field study was carried out in 2017–2018 (two growing seasons) at the same experimental plots, in a randomized complete block design with three replicates, at a farm situated in Konstantynów (52°12′21″ N, 23°05′02″ E), on Luvisol (loamy sand) with a slightly acidic reaction (pH −5.14), medium availability of P (52.80 mg kg^{-1}), high—of K (152.76 mg kg^{-1}) and low—of magnesium (Mg) (24.73 mg kg^{-1}). Each treatment plot had dimensions of 4.5 m wide × 15 m long. The test plant was grain maize, variety Mas 16R. Maize planting distance was 16.6 cm by 75 cm (six lines per plot) corresponding to a plant population of 80,321 per hectare.

Average temperature and precipitation are reported for each year in Figure 1.

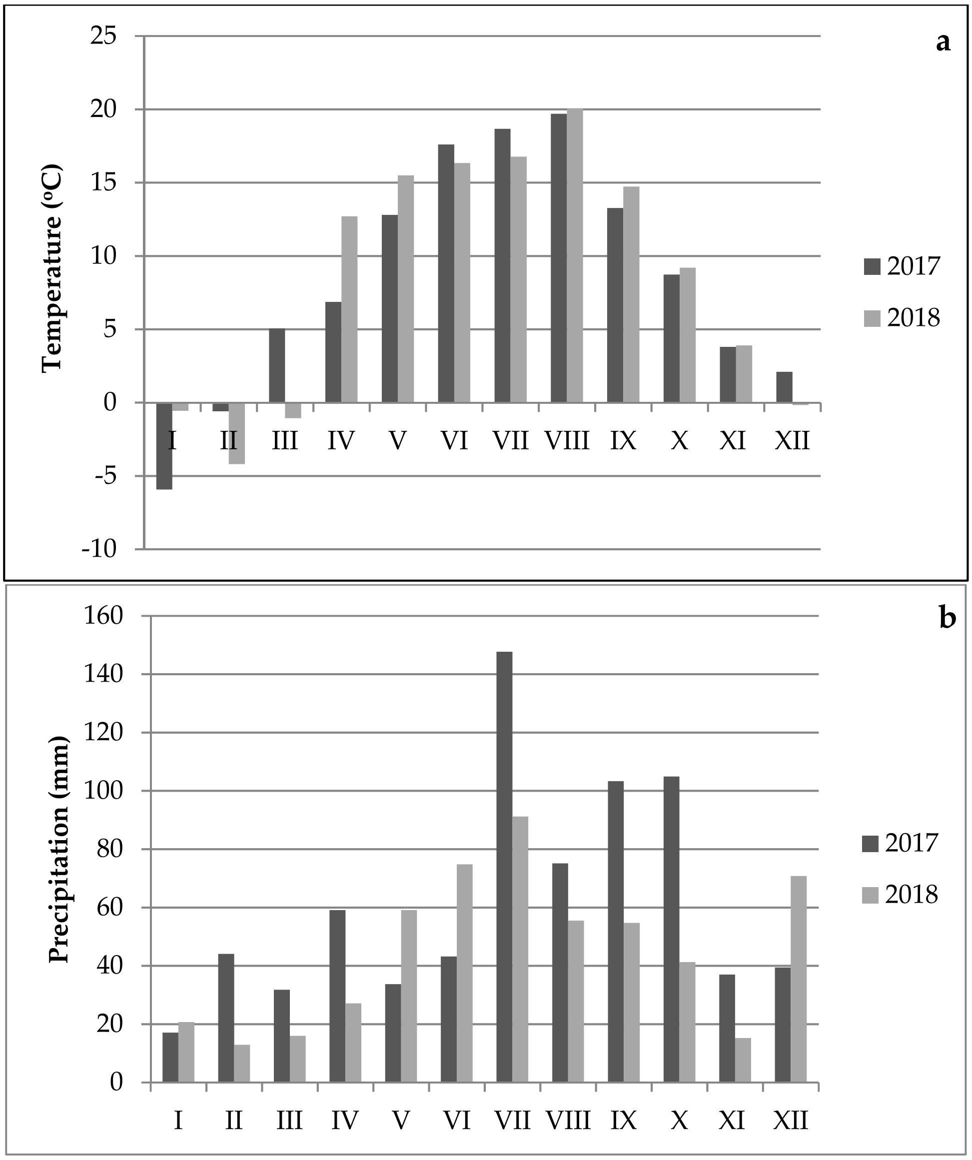

Figure 1. Weather data in the experimental field (**a**) Temperature; (**b**) Precipitation.

Before establishing the experiment, N fertilizer in the form of urea (92 kg N ha^{-1}) and K salt (60 kg K ha^{-1}) were applied over the entire experimental area. The experiment scheme included three blocks in which four treatments were randomly distributed: W0—the control with mineral fertilizers and no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, and W45—45 m^3 of stillage per hectare. Plots received the same treatments in both 2017 and 2018. Prior to sowing grain maize (7 days before), the soil was treated with rye stillage (59 g DM kg^{-1}, 40.0 g N, 11.1 g P, 14.9 g K, 3.0 g Mg, 4.0 g Ca per 1 kg of dry matter). At the time of sowing, ammonium phosphate as a starter fertilizer was applied (18 kg N ha^{-1}, 46 kg P ha^{-1}). Plant samples were collected at harvest, at full maturity (BBCH 89) following the methodology used in experiments on maize [17]. Grain yield was measured by harvesting two central rows from each plot and adjusted to 14% moisture. Nitrogen content in grain was determined by the Kjeldahl method [18]. The contents of P, K, Mg and Ca were analyzed by the vanadate-molybdate method and atomic absorption spectrometry (ASA), after digestion of plant material (grain) in concentrated sulfuric acid (H_2SO_4) with perhydrol (H_2O_2) [18].

Soil samples (15 per plot) were collected before the beginning of the experiment and at the end of each growing season in 2017 and 2018. In each sample the following parameters were determined:

pH in 1 mol KCl dm^{-3} (the potentiometric method) [19], available P and K contents (the Egner-Riehm method) [20,21], as well as available Mg contents (the Schachtschabel method) [22].

Statistica PL 13.3 (TIBCO Software Inc., Tulsa, OK, USA) was used to conduct ANOVA analysis and Tukey's mean separation was used to determine statistical significance at $p < 0.05$.

3. Results and Discussion

In the first and second year of study, in maize grains, the highest contents of N, P, Mg, and Ca were observed in the experimental plots treated with the highest stillage rates (W45) (Figures 2–5). The results on the content of N, P, Mg and Ca in plants fertilized with stillage correspond with those reported by Szulc et al. [10], who tested the stillage fertilizing effect under the conditions of pot and micro-field experiments.

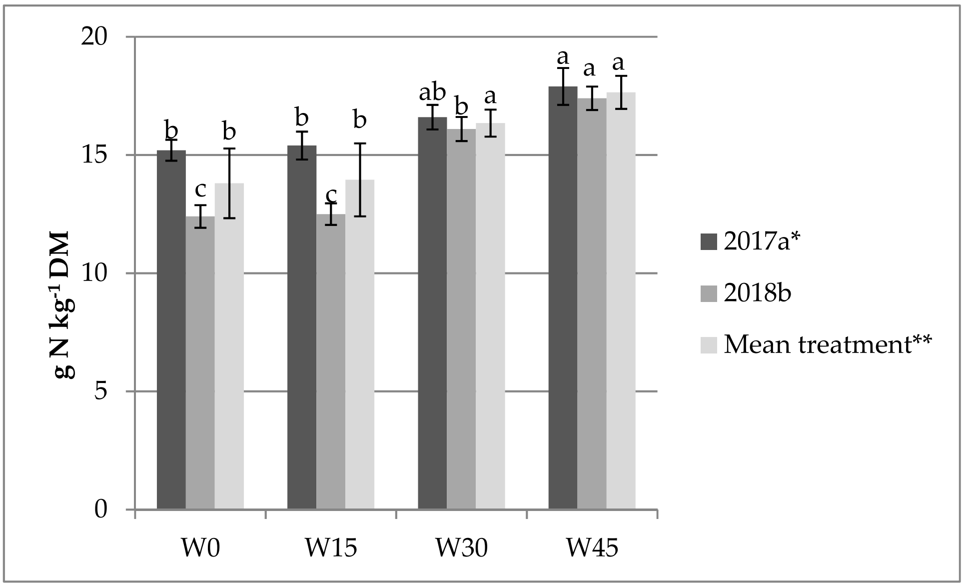

Figure 2. Nitrogen content in maize grain. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

In contrast to N, P Mg, and Ca, regardless of rye stillage treatment, the content of K in maize grains was lower compared to the W0 (Figure 6). This was undoubtedly influenced by, on the one hand, high K requirements of maize (at some growth stages the accumulation rate of K exceeds 8 kg/day/ha) and low content of this macroelement in stillage and, on the other, elevating biomass production with increasing doses of byproduct applied, i.e., the dilution effect. The negative correlation between grain yield and the K content in it (r = −0.683) seems to confirm this thesis. This result indicates the need for corrective mineral fertilization with K. Chemical analyzes conducted with a view to evaluating the possibility of stillage agricultural management [1,10] showed that stillage, especially that of molasses and cereal origin, is characterized by an unbalanced composition and so-called nutrition calibration is required, i.e., supplementary fertilization with nutrients.

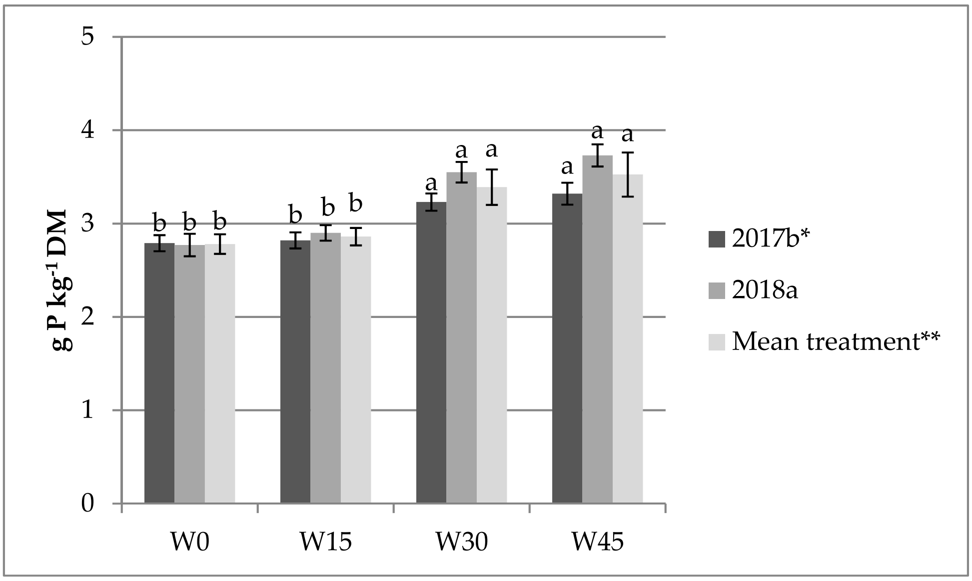

Figure 3. Phosphorus content in maize grain. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

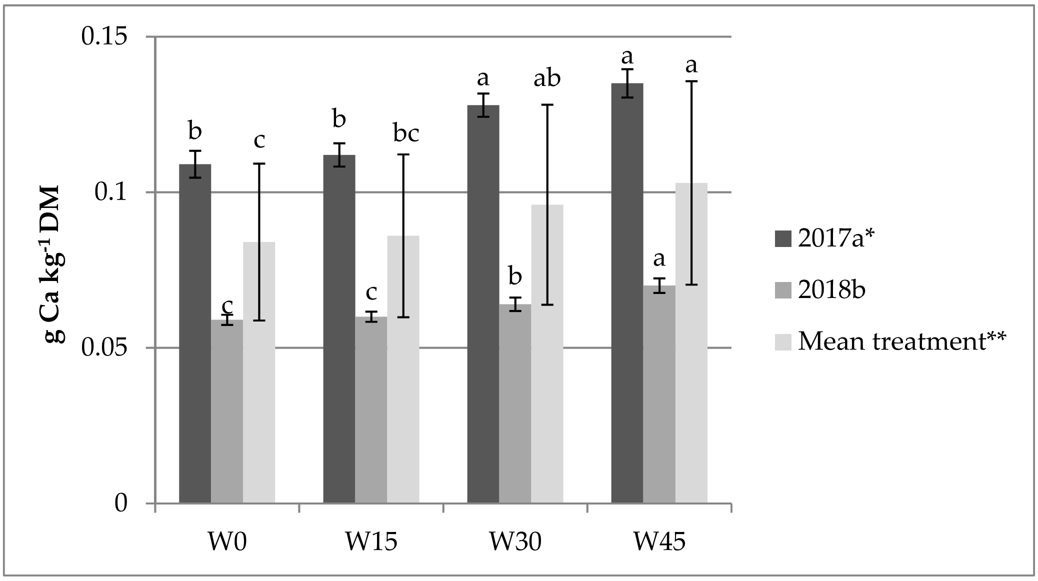

Figure 4. Calcium content in maize grain. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

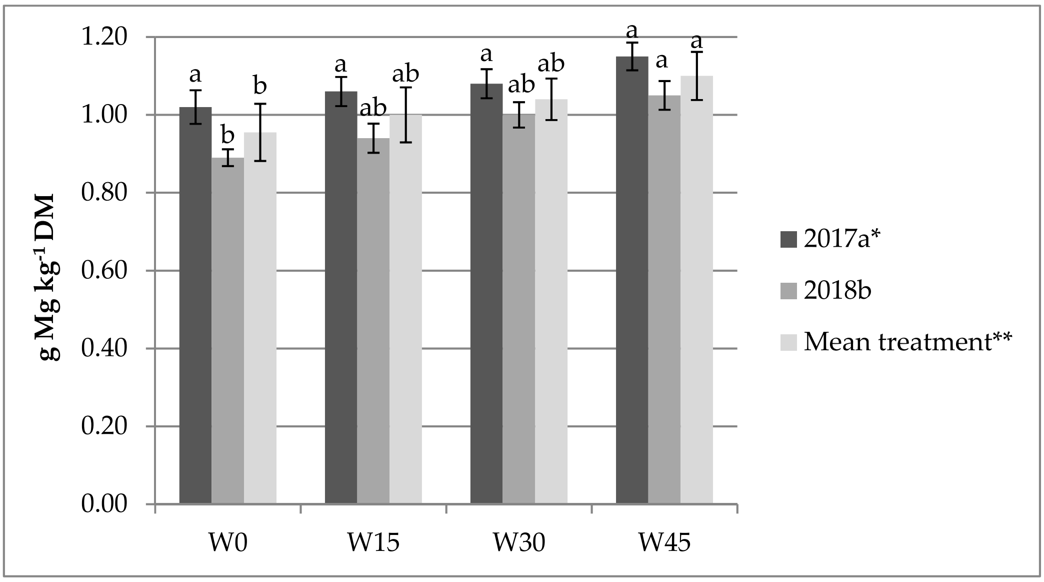

Figure 5. Magnesium content in maize grain. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

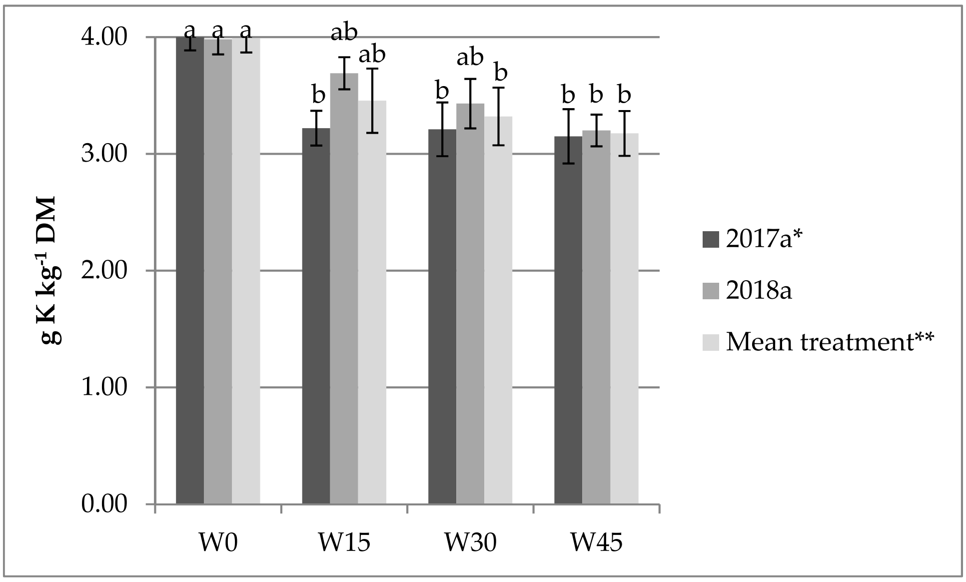

Figure 6. Potassium content in maize grain. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

In the present study, soil treatments with increasing rye stillage doses resulted in K content decrease in maize grain on the one hand, and on the other—an increase in Mg and Ca. This resulted in a narrowing down of the K: (Ca + Mg) ratio, below the optimal values recommended for fodder and/or plant growth and development (Figure 7). No significant correlation was found between the K: (Ca + Mg) ratio and maize grain yield ($r = -0.153$).

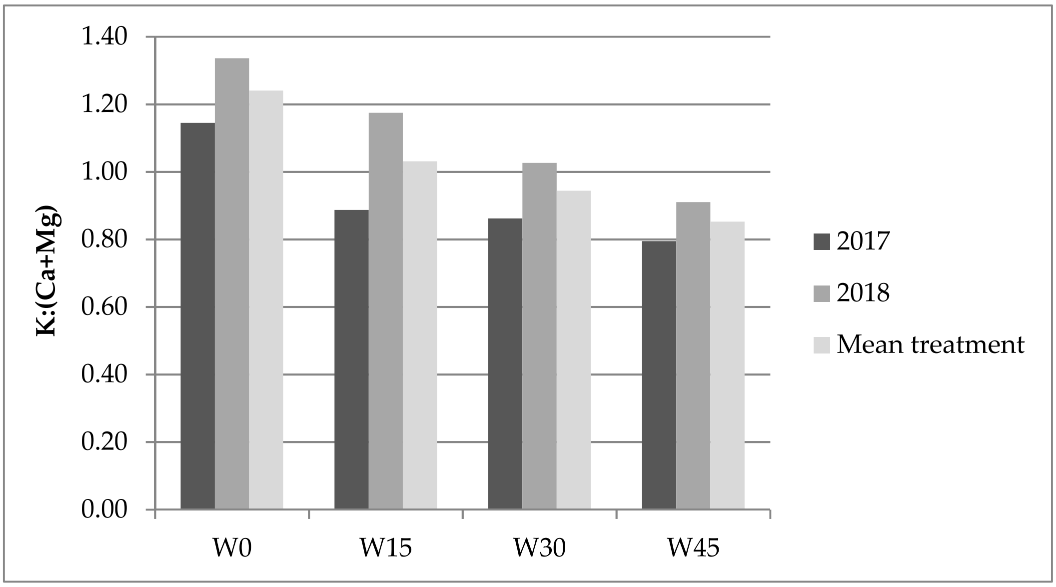

Figure 7. The K: (Ca + Mg) ratios in maize grain. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. The same letter means not significantly different.

When compared to the values obtained in the W0 treatment, soil fertilized with the lowest and highest stillage doses tested resulted in a grain yield increase of 5.9%–6.9% and 12.8%–16.1%, respectively (Figure 8).

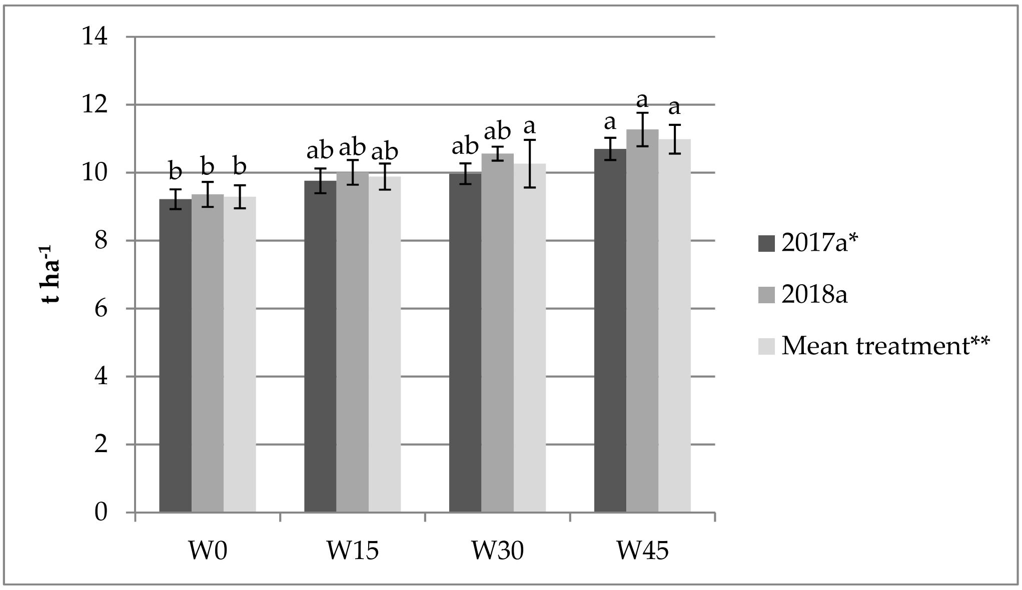

Figure 8. Maize grain yield. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

Other authors [10,23] also report that regardless of the stillage type used, maize yield increases with increasing doses applied. A study conducted in Spain showed that simultaneous treatment with stillage 2 m^3 ha^{-1} and mineral fertilizers (NP) resulted in a maize yield increase of 13.8% [1]. Several authors have emphasized that even at high NPK doses, concurrent organic and mineral fertilization enhances plant growth during the vegetation period and stimulates nutrient uptake. The yielding effect of stillage soil application is attributable both to its direct effects, i.e., soil enrichment with nutrients, and indirect effects, i.e., improvement of soil physicochemical, chemical and microbiological properties [2,7,24].

In this study, stillage application contributed to a significant increase in soil P and Mg contents when compared to the values obtained in the W0 treatment (Figures 9 and 10).

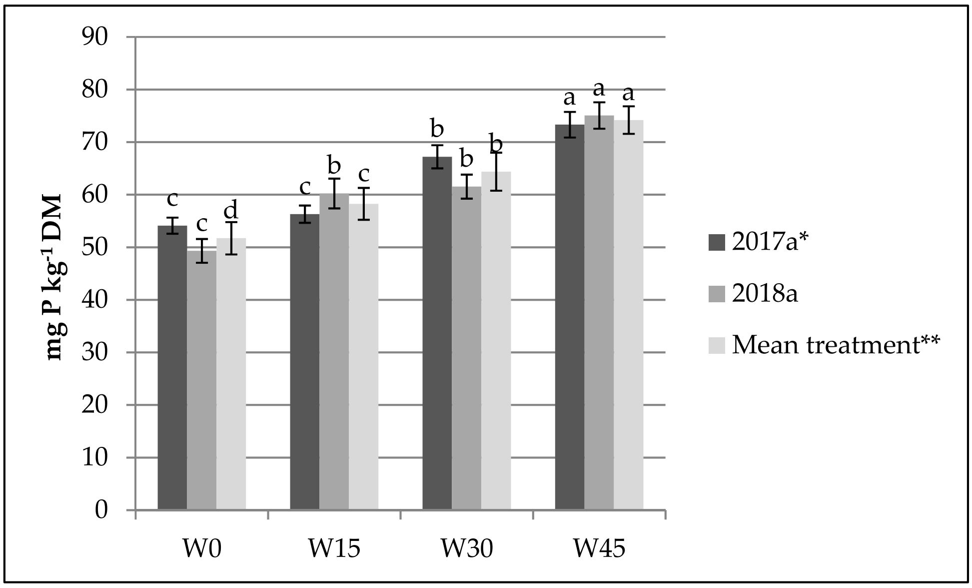

Figure 9. Available P content in soil. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

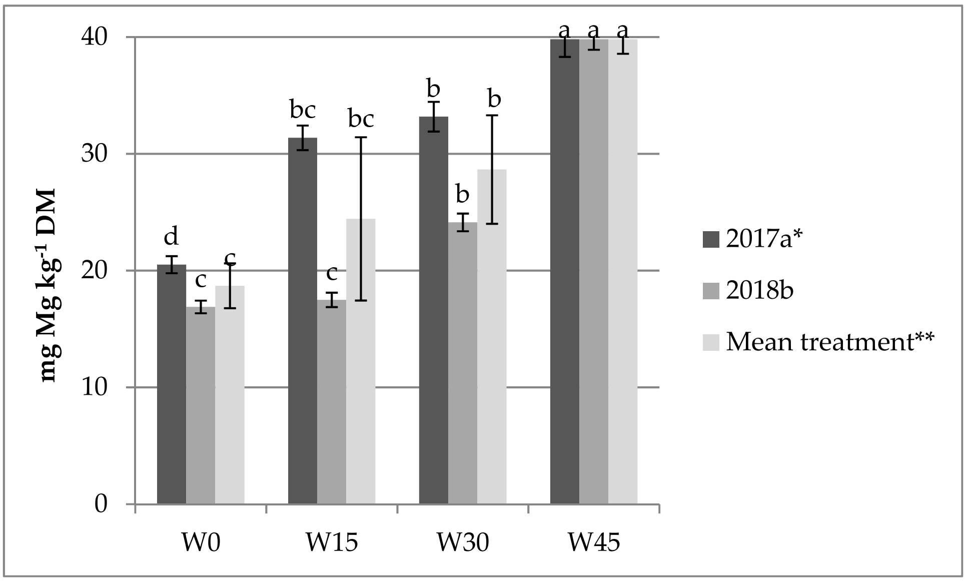

Figure 10. Available Mg content in soil. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

The highest content of P and Mg was observed in the soil fertilized with stillage at 45 m^3 ha^{-1} (73.32–75.06 mg P kg^{-1} and 39.81 mg Mg kg^{-1}, respectively). Undoubtedly, this result was due to the P and Mg pool applied with rye stillage, as well as its organic matter, which participates in the chelation of cations limiting P absorption, increases solubility of P compounds, and shows good buffering properties [1,7,25]. Attention should be paid to the possibility of risk related to the occurrence of available P in quantities exceeding plant fertilization requirements and its excessive accumulation in the case of the annual use of stillage with a narrow N:P ratio, especially when the doses applied are determined based on fertilizer needs relative to N [2].

After two years of tests, a significant decrease in soil K content was observed (Figure 11), down to the level of medium K availability and also—a decrease in soil pH (Figure 12) below the optimal value for light soils (pH < 5.6–6.0). Apparently, the application of increasing doses of stillage raised the uptake of K by maize plants exceeding its inputs in mineral fertilizers and stillage, which eventually resulted in a decrease of K content in the soil.

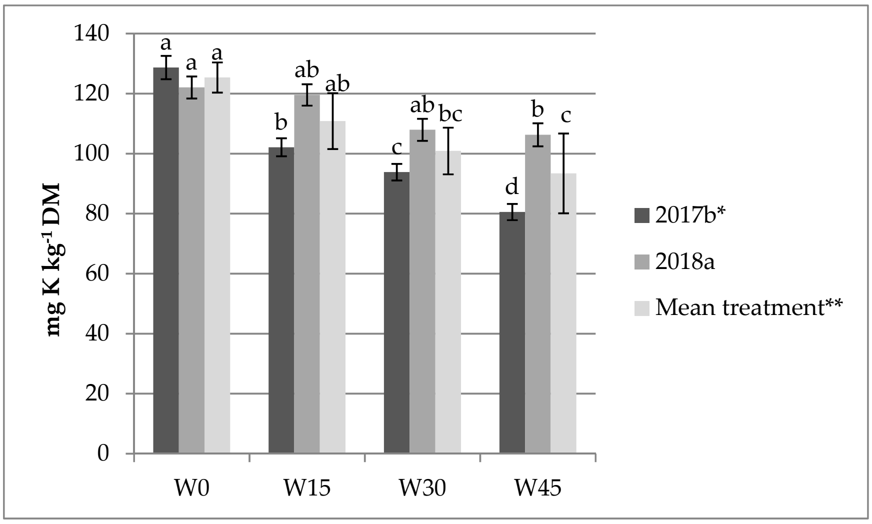

Figure 11. Available K content in soil. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

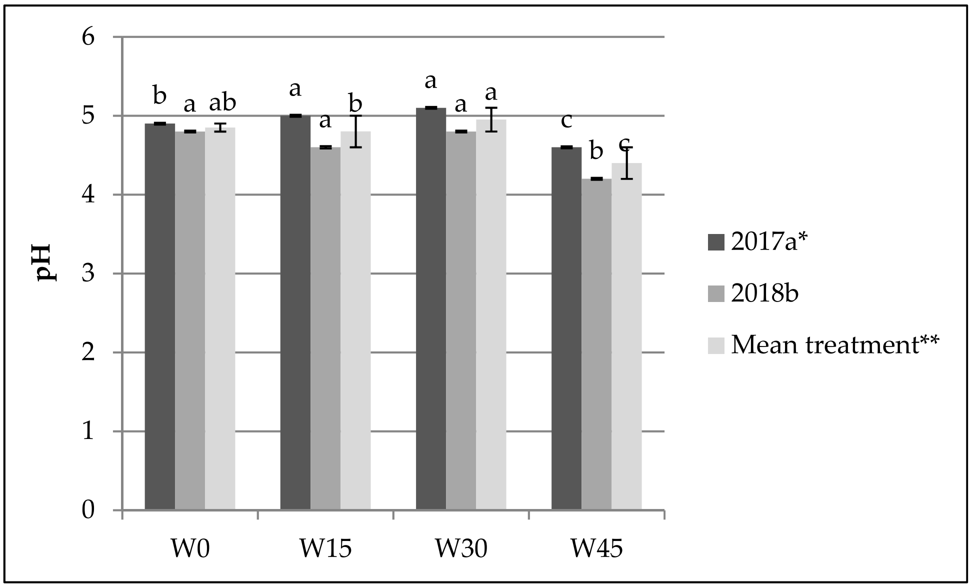

Figure 12. Soil pH. W0—the control with no stillage treatment, W15—15 m^3 of stillage per hectare, W30—30 m^3 of stillage per hectare, W45—45 m^3 of stillage per hectare. * means of years regardless of treatments; ** means of treatments regardless of years. The same letter means not significantly different.

Risks related to such effects of stillage land disposal have also been raised in studies carried out by other authors [7]. Hence, additional mineral fertilization with K should be applied along with stillage treatments, and the acidifying effects of the latter should be taken into account when regulating the pH of the soil to be treated, and/or the pH of stillage should be adjusted before soil treatment.

4. Conclusions

The results of the current study indicate that fertilization of a grain maize agroecosystem with rye stillage can significantly increase crop yields. However, the byproduct effect toward reducing soil available potassium and narrowing the K: (Ca + Mg) ratio in maize grain below the optimal values indicated the need for corrective mineral fertilization with K. Moreover, a plan to monitor and adjust soil pH is needed when rye stillage is applied as a soil amendment, especially in a long-term application. Particular care is also required in the case of soils with high P content to minimize the environmental risk that may arise from excessive accumulation of stillage P origin in the profile.

Author Contributions: H.R. and P.K. conceptualized the research; H.R., M.S. and P.K. designed the research; H.R., S.C. and P.K. performed the experiments; H.R., M.S., S.C., P.K., S.A. and A.M.-P. analyzed data; H.R., M.S. and P.K. wrote the paper. All authors have read and approved the manuscript.

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