agronomy

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The Effect of Phosphogypsum and Turkey Litter Application on the Properties of Eroded Agrochernozem in the South Ural Region (Russia)

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Abstract: The possibility of using industrial and poultry wastes as an ameliorant/fertilizer for erosion-prone soils was investigated. We studied the impact of phosphogypsum (PG) and turkey litter (TL) application on the physicochemical properties of weakly eroded agrochernozem in conditions of a 5-year field experiment in the South Ural region, Russia. In particular, we examined the effect of treatments on the soil moisture reserves, soil structure, microaggregate composition and particle size distribution, aggregate stability (water resistance), organic carbon content (C_{org}), ammonium, nitrate and alkaline hydrolysable nitrogen, available phosphorus (P_{av}), exchange potassium (K_{ex}), and potato productivity/ecological quality. Treatments included the application of the PG at 5, 10, and 20 t ha^{-1}, the TL at 40 and 60 t ha^{-1}; and in mixes of PG and TL at ratios of 1:10, 1:5, and 1:2. The obtained results indicated that the introduction of PG and TL increased (compared to control) the moisture reserves (by 10–17%), resistance of soil aggregates to water (8–15%), the content of C_{org} (6–10%), available nitrogen (two orders of magnitude), P_{av} (3–6 times) and K_{ex} (2–3 times), and improved, as well, soil structure. In general, years factor had a significant effect on soil water-physical properties; its influence was 44–67%, while the effect of treatments was 21–30%. The agrochemical properties (C_{org} and P_{av}) were dependent on treatments factor (77 and 95%, respectively), while the content of all forms of nitrogen depended on the year factor (34–57%). The obtained results suggest the application of PG and TL to improve agrochernozem fertility status and minimize its erodibility without soil and plant contamination.

Keywords: eroded agrochernozem; phosphogypsum; turkey litter; physical and chemical soil properties; erosion resistance; potato yield/ecological quality

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Citation: Komissarov, M.; Gabbasova, I.; Garipov, T.; Suleymanov, R.; Sidorova, L. The Effect of Phosphogypsum and Turkey Litter Application on the Properties of Eroded Agrochernozem in the South Ural Region (Russia). *Agronomy* **2022**, *12*, 2594. https://doi.org/10.3390/agronomy12112594

Academic Editor: Elena Baldi

Received: 31 August 2022
Accepted: 20 October 2022
Published: 22 October 2022

1. Introduction

Water erosion is one of the principal factors of soil loss and reducing fertility of agricultural lands, worldwide [1–3] and especially, in the South Ural region of Russia [4,5]. The introduction of soil ameliorants and fertilizers, in particular, of substances having a complex effect on physicochemical and biological soil properties is important for restoring and improving the fertility of eroded soils.

One of the soil amendments/conditioners is phosphogypsum (PG), that consists mainly of $CaSO_4 \cdot 2H_2O$, and is an industrial byproduct of phosphoric acid and other chemicals derived from apatite and sulfuric pyrites. The production of one ton of phosphoric acid generates up to 5 tons of PG, which is frequently stocked near the production units [6]. The global production of PG, according to various authors [7,8], ranges from 100 to 280 million tons per year. For example, in a country as small as Tunisia, more than 10 million tons of PG are produced annually [9]; near the city of Huelva (Spain) about 100 million tons of PG are stored in stacks on salt marshes near the mouth of the Tinto River, covering an area of about 1000 hectares [10]. Almost over 40 million tons of PG is produced in China [11], and in Russia about 15 million tons of PG is formed annually at the enterprises producing mineral fertilizers. It is noteworthy that the storage duration of PG in dumps and accumulators exceeds 50 years [12]. In this regard, there arises the problem of its utilization and rational use, in agriculture as well, especially on saline and alkaline/sodic soil [13–18] and solonized soils [19–22].

In addition, it is advisable to use the PG for the reclamation of technologically salinized and solonized soils [23–27]. Besides, as PG is able to dissolve better in soil solution, it does not require reprocessing, thus, it is cheaper and more effective than gypsum.

Many research works showed that PG can be used as an ameliorant to improve a number of soil properties, especially in conditions of moisture deficiency. The PG introduction resulted a significant improvement of soil chemical [18] and water-physical properties in the arid southern regions of the African continent, in the countries such as South Africa, Botswana, Namibia, Swaziland, Zimbabwe, and Ethiopia [28]. A decrease of the bulk density and the structuring of soil horizons was also noted in response to PG application [29,30].

The practice of using PG together with carbon-containing wastes of the agro-industrial complex such as manure, litter, various plant residues, is widespread in many countries [31–34], including the production of nutrients-enriched biochar [35]. In the South Ural region, where poultry farming is rapidly developing, thousands of tons of litter are formed annually and there exists a problem of its utilization [36,37]. To date, the volume of PG in the dumps of South Ural region is more than 10 million tons, and its related using is small. Such a situation enforces to research the impact of industrial and agricultural wastes, required for their disposal, on possible ecological recycling and improving of degraded soils properties. Moreover, no similar research was conducted earlier in the South Ural region. Thus, the purpose of this study is to consider using PG and turkey litter (TL) as an ameliorant and organomineral fertilizer for improving soil fertility and increasing erosion resistance of agrochernozem. Specifically, the work will investigate the following: i) the effect of various ratios (1:10, 1:5, 1:2) and application doses of PG (3.6–20 t ha^{-1}) and TL (33–60 t ha^{-1}) on water-physical properties and erosion resistance of the soil; and ii) the effect of the same ratios and doses of PG and TL application on the dynamics of soil nutrients content and potato yields.

2. Materials and Methods

2.1. Study Site Description

The research was carried out at the experimental farm "Water-Balance Station" (54° 50′ 23′′ N, 55° 44′ 55′′ E; 170 m a.s.l.), located in the Ufimsky district, Republic of Bashkortostan, Russia (Figure 1). According to the natural zonal climatic characteristics, the study area belongs to the South Ural region. The climate of the study area is characterized as moderate continental with average humidity or as warm-summer humid continental (Dfb) according to the Köppen climate classification [38]. According to the long-term meteorological data obtained by employers of the Water-Balance Station [39] and from automatic weather station WXT530 (Vaisala, Vantaa, Finland) installed in 2000 at the study site, the average annual air temperature is +3.8 °C; and the mean annual precipitation is 590 mm, about 1/3 of which falls in the form of snow. The total annual precipitation during the 5-year (2015–2019) field experiment was determined at 461−606 mm, and the average monthly air temperature was 3.4–5.1 °C. The vegetation period (May–August) of 2016 was extremely arid with only 120 mm of precipitation. That was almost two times lower than the average annual values (227 mm). The average temperature during the same time was 19.1 °C, while in other years of research it was 16.1–17.2 °C (Table 1).

Figure 1. Location of the study site (red point) on the Eurasian continent.

Table 1. Meteorological data in study area during research period.

Years	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Avg. (Jan.–Dec.)
Average monthly air temperature, °C													
2015	−12.1	−7.7	−4.6	4.9	14.7	21.2	17.5	15.5	13.8	2.4	−2.5	−5.0	4.8
2016	−12.0	−4.5	−1.2	9.1	14.3	17.8	21.0	23.2	12.3	2.9	−6.1	−15.2	5.1
2017	−12.4	−11.6	−3.8	4.1	11.5	15.4	19.1	18.7	11.8	3.7	−0.2	−6.9	4.1
2018	−12.5	−11.6	−10	4.2	12.7	15.9	21.4	17.7	12.5	5.7	−4.6	−10.1	3.4
2019	−12.1	−9.8	−0.5	5.9	14.6	17.5	19.2	15.9	9.4	7.2	−3.9	−6.6	4.7
Average annual	−12.3	−11.8	−5.1	5.2	13.2	18.1	19.7	17.2	11.3	4.6	−4.2	−10.7	3.8
Average monthly precipitation, mm													
2015	29	24	20	48	107	21	49	44	36	97	74	57	606
2016	50	41	30	45	25	58	18	19	62	37	74	49	507
2017	78	60	22	33	54	166	104	12	62	78	45	26	740
2018	22	25	46	48	62	43	16	51	47	46	40	15	461
2019	50	42	50	6	75	40	39	76	67	53	14	43	553
Average annual	48	39	32	33	47	67	55	58	51	58	52	51	590

The soil at the study area and experimental plots are represented by weakly eroded leached agrochernozem (*Luvic Chernozem* (*Clayic*, *Aric*, *Pachic*) [40]). The water-physical and agrochemical properties of the soil are given in detail at "Sections 3 and 4".

2.2. The Description of Field Experiment and Laboratory Analyzes

The field experiment was established to test the effect of PG, TL, or in combination at different ratios on soil characteristics. The PG was taken from the dumps of a mineral fertilizer factory (Meleuzovsky District, Republic of Bashkortostan, Russia). The compositions of PG in terms of oxides were the following: CaO – 30.9%; SO_3 – 48.12%; P_2O_5 – 2.05%; Al_2O_3 – 0.05%; K_2O – 0.04%; Fe_2O_3 – 0.09%; TiO_2 – 0.08%; MgO – 0.01%; and traces of other elements. The TL before its application into the soil was treated with a microbial substance according to the technology patented by Chetverikov et al. [41]. Details of the application rate of each treatment are provided in Table 2.

Table 2. The different treatments with PG, TL, and their combined application ratio.

№	Treatment	Description
1	C	Control—without PG or TL
2	PG_5	5 t PG ha^{-1}
3	PG_{10}	10 t PG ha^{-1}
4	PG_{20}	20 t PG ha^{-1}
5	$PG_{3.6}TL_{36.4}$	PG+TL, 1:10, 40 t ha^{-1}
6	$PG_{5.5}TL_{54.5}$	PG+TL, 1:10, 60 t ha^{-1}
7	$PG_{6.7}TL_{33.3}$	PG+TL, 1:5, 40 t ha^{-1}
8	$PG_{10}TL_{50}$	PG+TL, 1:5, 60 t ha^{-1}
9	$PG_{13.3}TL_{26.7}$	PG+TL, 1:2, 40 t ha^{-1}
10	$PG_{20}TL_{40}$	PG+TL, 1:2, 60 t ha^{-1}
11	TL_{40}	TL, 40 t ha^{-1}
12	TL_{60}	TL, 60 t ha^{-1}

At the spring 2015, the PG and TL were applied on soil surface of experimental plots and to ensure uniform mixing, the soil was plowed to a depth of 20 cm with a 2-wheel tractor. Then, the potato seeds ("Snegir" sort) were planted by a traditional method (20 tubers about 5–8 cm deep and 40–50 cm apart) on each experimental plot. The area of each plot was 6 m^2 (2×3 m), with three field replicates for each treatment. The potato was cultivated for the first three years (2015–2017); before each planting potatoes, the soil was plowed to a depth of 20 cm. In 2018, the mixture of perennial grasses (27 kg h^{-1}) alfalfa (*Medicago sativa*) – 25%, fescue (*Festuca arundinacea*) – 40%, and timothy grass (*Phleum pretense*) – 35% was sown.

Soil samples were taken from each plot using a JMC hand-driven core sampler (Clements Associates Inc., Newton, MA, USA; inner diameter: 4.5 cm) a month after the beginning of the experiment—in the spring of and autumn 2015, as well in 2016 from topsoil layer (0–20 cm), then sampling was carried out annually in the autumn. The soil samples were dried (at 90 °C) in oven to constant weight, then grounded in a mortar, and passed through a 2 mm sieve for further laboratory analyses. The water-physical properties in soil samples were determined according to the methods described in Vadyunina and Korchagina [42]. In particular, the soil moisture was determined by the gravimetric method; the particle size distribution and microaggregate composition (for fractions <0.25 mm) were measured by standard sedimentation (pipette) method; the aggregate composition (dry sieving) and soil aggregate stability (SAS) (wet sieving) were determined using a 0.25-, 0.5-, 1-, 3-, 5-, 7-, and 10-mm sieves. The microaggregate analysis was used for an agronomic assessment of soil microstructure, the indicator of which is the Kachinsky dispersion coefficient (Equation (1)):

$$K_d = (P_m \;/\; P_t) \times 100\%, \tag{1}$$

where, K_d – Kachinsky dispersion coefficient, P_m and P_t – clay content under microaggregate and soil texture analysis proceeding. Remark: decreasing of K_d value means the improving of soil microstructure.

The SAS coefficient was calculated from the Equation (2):

$$K_{sas} = \Sigma_w \;/\; \Sigma_d, \tag{2}$$

where Σ_w – sum of aggregates > 0.25 mm under wet sieving (water-stable aggregates), Σ_d – sum of aggregates > 0.25 mm under dry sieving.

The content of agronomically valuable aggregates (AVA) Σ (0.25–10 mm) and the structural coefficient (Ks) as the main indicators in assessment/quality of soil aggregate composition was estimated according to the Equation (3):

$$K_s = \Sigma\,(0.25\text{-}10\text{ mm}) \;/\; \Sigma\,(>10, <0.25\text{ mm}) \tag{3}$$

The agrochemical properties in soil samples were determined according to methods described in Sokolov [43]. The soil pH was determined in 1 mol L^{-1} KCl suspension (1:2.5 soil/solution); the organic carbon content (C_{org}), with wet combustion by the Orlov and Grindel method, available phosphorus (P_{av}) and exchangeable potassium (K_{ex}) were extracted in 0.5 mol L^{-1} CH_3COOH at a 1:2.5 soil/solution ratio by Chirikov method; the degree of phosphorus mobility was measured in 0.015 mol L^{-1} K_2SO_4 suspension (1:5 soil/solution) by Karpinsky and Zamyatina method; and the ammonium nitrogen content (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were extracted 1 mol L^{-1} KCl (1:2.5 soil/solution) and alkaline hydrolysable nitrogen (AH-N) according to Cornfield method. The content of nitrates in potato tubers was measured with ionometric method using Anion 4100 (Infraspack-Analit, Novosibirsk, Russia), cadmium and plumbum (strontium in soil), with atomic absorption method using the analyzer Spectrum-5-4 (Soyuztsvetmetavtomatika, Moscow, Russia).

Soil penetration was measured from the soil surface to a depth of 20 cm with 2.5 cm intervals by using soil compaction meter FieldScout SC 900 (Spectrum technologies, Aurora, CO, USA), equipped with a metal rod with a cone (size 1/2 inch).

The PG composition was determined using an Elan-6100 inductively coupled plasma mass spectrometer, an Optima-4300 DV atomic emission plasma coupled spectrometer (Perkin Elmer, Waltham, MA, USA). The strontium concentration in the soil was determined on a S1 Titan portable X-ray fluorescence analyzer (Bruker, Billerica, MA, USA).

2.3. Statistical Analysis

The results discussed here, and the values provided in the tables and figures, represent the mean values obtained from three replicates. The significance of differences between treatments (Student's *t*-test) and correlation coefficients was determined using Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA), two-way analysis of variance (ANOVA) and Tukey's honestly significant difference (HSD)—Statistica 8.0 (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

3.1. Physical Properties

The soil penetration resistance on all variants increased with depth, and was in the optimum range for plants (average value for 0–20 cm layer not exceeding 2000 kPa) (Table 3). In 2015, only PG_{10} was not significantly lower than the control variant, while in 2016 only PG_5 had a significant difference.

At the beginning of the plant growing season, the soil moisture reserves varied in the range of 120–180 mm in the 50-cm soil layer (Table 4). The moisture reserves in the dry 2016 were significantly lower than in all other years (t_{stat} ranged from 7.8 to 40.3, $p < 0.01$). In 2017 and 2019, the moisture reserves were higher than in the first year of the experiment (t_{stat} 4.2 and 2.9, $p < 0.05$).

Table 3. Effect of treatments and years on the soil penetration resistance, kPa.

Treatment	Year	Depth, cm										*t*-test	
		0	2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	Average	2015	2016
C	2015	204	377	803	926	926	1238	1448	1605	2500	1114	–	–
	2016	175	295	288	498	667	912	1347	1376	2435	888	–	–
PG_{5}	2015	55	201	491	541	577	717	807	792	1098	586	4.05 **[1]	–
	2016	105	225	260	772	1312	1326	1453	1776	2669	1099	–	2.55 *
PG_{10}	2015	30	195	652	878	898	1139	1309	1524	1634	918	2.29 *ns*	–
	2016	168	238	470	547	638	653	1029	1319	1951	779	–	1.58 *ns*
PG_{20}	2015	120	211	1007	431	637	717	662	1068	1233	767	3.07 *	–
	2016	105	147	197	351	547	884	1179	1403	2898	856	–	0.48 *ns*
$PG_{3.6}TL_{36.4}$	2015	100	190	411	606	486	506	451	581	742	452	3.76 **	–
	2016	147	190	281	463	927	975	1081	1333	1565	773	–	1.09 *ns*
$PG_{5.5}TL_{54.5}$	2015	145	291	386	481	436	426	541	787	942	492	4.01 **	–
	2016	301	365	386	941	933	933	1207	1270	1769	900	–	0.12 *ns*
$PG_{6.7}TL_{33.3}$	2015	25	176	371	431	421	331	336	526	586	355	4.09 **	–
	2016	175	267	295	470	779	1102	1524	2955	3011	1175	–	1.66 *ns*
$PG_{10}TL_{50}$	2015	20	115	321	321	326	421	481	687	803	388	4.80 **	–
	2016	88	105	123	322	789	782	829	1557	1299	654	–	1.78 *ns*
$PG_{13.3}TL_{26.7}$	2015	15	91	161	252	371	442	467	678	883	373	5.27 **	–
	2016	70	133	337	576	1229	1453	1748	2070	2435	1116	–	2.13 *ns*
$PG_{20}TL_{40}$	2015	5	90	151	321	356	511	561	692	732	379	4.83 **	–
	2016	63	64	198	361	637	980	975	1421	2381	787	–	2.23 *ns*
TL_{40}	2015	5	45	436	792	897	917	927	1674	2075	863	3.91 **	–
	2016	99	134	194	713	1450	1736	2107	2157	2368	1217	–	2.21 *ns*
TL_{60}	2015	5	75	479	769	992	1137	1388	1415	1542	866	2.53 *	–
	2016	71	105	205	310	643	1029	1480	1784	2579	911	–	0.36 *ns*

[1] * – significant ($p < 0.05$), ** – significant ($p < 0.01$), *ns* – not significant.

Table 4. Effect of treatments and years on the soil moisture reserves (mm) in 0–50 cm layer.

Treatment/Year	2015	2016	2017	2018	2019
C	145 e [1] [I]	129 e	155 e [III]	148 d	153 bc
PG_{5}	146 de	124 f	149 e [IV]	150 cd [V]	154 bc
PG_{10}	145 e [I]	118 ef	142 f	150 cd [V]	152 c
PG_{20}	143 e	127 e	152 de	149 d	159 b [VI]
$PG_{3.6}TL_{36.4}$	156 bc	133 cd	158 d [II]	153 cd	157 bc
$PG_{5.5}TL_{54.5}$	160 ab	135 cd [I]	162 cd	160 a	168 a
$PG_{6.7}TL_{33.3}$	164 a	150 a	180 a	156 bc [I]	159 b [VI]
$PG_{10}TL_{50}$	159 ab [I]	152 a	182 a	156 bc [I]	158 bc
$PG_{13.3}TL_{26.7}$	160 ab	148 a [II]	178 a	157 b	155 bc
$PG_{20}TL_{40}$	157 bc	137 c	164 bc	162 a	166 a
TL_{40}	152 cd	142 b	170 b	163 a	167 a
TL_{60}	155 bc	141 bc	165 bc	165 a	169 a
Significance	** [2]	**	**	**	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] **: effect significant at $p < 0.01$ and of pairs: [I] – TL_{40}; [II] – TL_{60}; [III] – $PG_{5.5}TL_{54.5}$; [IV] – PG_{10}; [V] – $PG_{13.3}TL_{26.7}$; [VI] – $PG_{20}TL_{40}$ at $p < 0.05$.

The soil texture was characterized as clay loam for all treatments at the beginning and end of the experiment (Figure 2A).

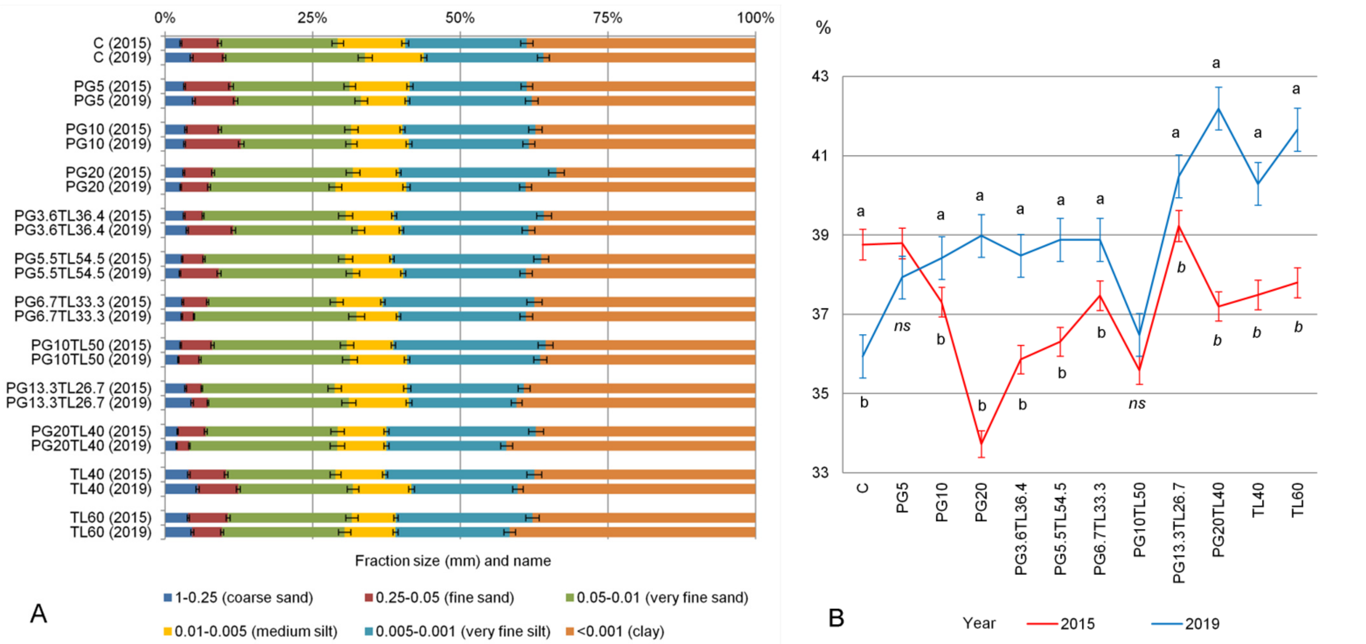

Figure 2. Effect of treatments and years on the particle size distribution (**A**) and the content (%) of clay fraction (<0.001 mm) (**B**) at the 0–20 cm soil layer. Various letters denote significant differences at $p < 0.01$, *ns* – not significant.

According to K_d, the soil of all variants belonged to the best category ($K_d < 15$), i.e., had a "high microstructure" (Figure 3). Here and hereafter the gradation of water-physical and agrochemical properties of soil on the following categories: "low", "medium", "elevated", "high", "very high", and "excessively high" are made according to the Russian classification [44].

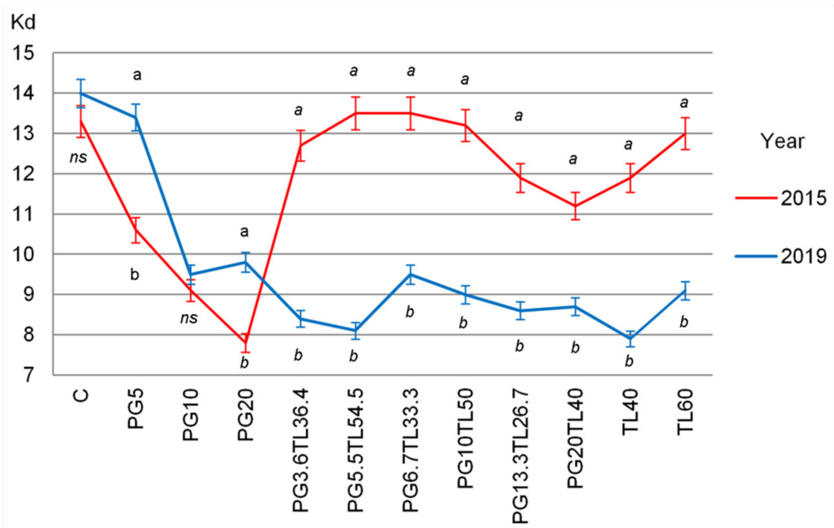

Figure 3. Effect of treatments and years on the Kachinsky dispersion coefficient (K_d) at the beginning and end of the experiment (0–20 cm soil layer). Various letters denote significant differences at $p < 0.01$, *ns* – not significant.

SAS in the experimental area was categorized as "excellent", the K_{sas} range was 0.6–0.8 (Table 5).

Table 5. Effect of treatments and years on the soil aggregate stability coefficients (K_{sas}, 0–20 cm).

Treatment/Year	2015	2016	2017	2019
C	0.79 b [1]	0.78 c	0.78 b	0.83 b
PG_5	0.85 a	0.79 c	0.79 b	0.86 b
PG_{10}	0.85 a	0.82 bc	0.78 b	0.87 ab
PG_{20}	0.84 a	0.83 bc	0.83 ab	0.85 b
$PG_{3.6}TL_{36.4}$	0.82 ab	0.84 b	0.81 ab	0.88 ab
$PG_{5.5}TL_{54.5}$	0.82 ab	0.86 a	0.82 a	0.87 ab
$PG_{6.7}TL_{33.3}$	0.83 ab	0.84 b	0.78 b	0.91 a
$PG_{10}TL_{50}$	0.84 a	0.89 a	0.84 a	0.87 ab
$PG_{13.3}TL_{26.7}$	0.81 ab	0.89 a	0.78 b	0.86 b
$PG_{20}TL_{40}$	0.83 ab	0.85 a	0.81 ab	0.85 b
TL_{40}	0.81 ab	0.87 a	0.81 ab	0.87 ab
TL_{60}	0.85 a	0.9 a	0.83 ab	0.88 ab
Significance	* [2]	*	*	*

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] *: effect significant at $p < 0.05$.

During the entire experiment, the soil at all variants had the "excellent aggregation", i.e., $K_s > 1.5$ (Table 6).

Table 6. Effect of treatments and years on the soil structural coefficients (K_s, 0–20 cm).

Treatment/Year	2015	2016	2017	2019
C	2.5 b [1]	3.1 d	2.6 c	1.7 c
PG_5	2.6 b	3.2 d	3.1 b	1.9 c
PG_{10}	2.8 b	4.5 b	2.9 bc	2.0 bc
PG_{20}	2.5 b	5.7 a	2.7 bc	2.2 bc
$PG_{3.6}TL_{36.4}$	2.9 b	3.7 c	2.7 bc	1.8 c
$PG_{5.5}TL_{54.5}$	2.8 b	4.2 bc	3.2 b	2.3 bc
$PG_{6.7}TL_{33.3}$	3.2 ab	4.6 b	3.8 a	1.8 c
$PG_{10}TL_{50}$	3.6 a	5.5 a	4.0 a	2.8 ab
$PG_{13.3}TL_{26.7}$	3.4 a	5.3 a	3.8 a	3.2 a
$PG_{20}TL_{40}$	3.2 ab	4.4 b	3.3 b	2.7 ab
TL_{40}	3.1 ab	4.3 b	2.8 bc	2.6 b
TL_{60}	3.3 ab	4.6 b	2.9 b	2.7 ab
Significance	* [2]	*	*	*

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] *: effect significant at $p < 0.05$.

The statistical summarizing of soil water-physical properties data are presented in Table 7.

3.2. Agrochemical Properties

The soils of the experimental plots were characterized by a moderately acidic pH (Table 8).

The C_{org} content was categorized as "low" for chernozems and equaled ~ 3.8% in the control plot (Table 9).

Table 7. Effect of treatments and years on soil water-physical properties/characteristics.

Treatment/Characteristic (Average in all Years)	Soil Moisture Reserves	Soil Aggregate Stability Coefficients	Soil Structural Coefficients
C	146.0 c [1]	0.80 b	2.5 c
PG_5	144.6 c	0.82 b	2.7 c
PG_{10}	141.4 c	0.83 ab	3.1 bc
PG_{20}	146.0 c	0.84 ab	3.3 b
$PG_{3.6}TL_{36.4}$	151.4 bc	0.84 ab	2.8 bc
$PG_{5.5}TL_{54.5}$	157.0 ab	0.84 ab	3.1 bc
$PG_{6.7}TL_{33.3}$	161.8 a	0.84 ab	3.4 ab
$PG_{10}TL_{50}$	161.4 a	0.86 a	4.0 a
$PG_{13.3}TL_{26.7}$	159.6 a	0.84 ab	3.9 a
$PG_{20}TL_{40}$	157.2 ab	0.84 ab	3.4 ab
TL_{40}	158.8 a	0.84 ab	3.2 b
TL_{60}	159.0 a	0.87 a	3.4 ab
Significance	* [2]	*	*
Years (Average of all Treatments)			
2015	153.5 b	0.83 ab	3.0 b
2016	136.3 c	0.85 ab	4.4 a
2017	163.1 a	0.81 b	3.2 b
2018	155.8 ab	*ND* [3]	*ND*
2019	159.8 a	0.87 a	2.3 c
Significance	**	*	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] *, **: effect significant at $p < 0.05$, and $p < 0.01$, respectively. [3] *ND* – not defined.

Table 8. Effect of treatments and years on the soil pH_{KCl} at 0–20 cm layer.

Treatment/Year and Season	2015		2016		2017	2018	2019
	Spring	Autumn	Spring	Autumn		Autumn	
C	4.8 b [1]	5.1 b	4.9 b	5.0 b	5.1 ab	5.1 b	5.1 b
PG_5	4.9 b	5.1 b	4.9 b	5.0 b	5.0 b	5.2 b	5.1 b
PG_{10}	5.0 b	5.0 b	4.8 b	5.0 b	4.9 b	5.2 b	5.1 b
PG_{20}	4.9 b	5.0 b	4.8 b	4.9 b	4.8 b	5.2 b	5.1 b
$PG_{3.6}TL_{36.4}$	5.4 ab	5.4 ab	5.1 ab	5.2 ab	5.2 ab	5.2 b	5.2 b
$PG_{5.5}TL_{54.5}$	5.5 ab	5.2 b	5.1 ab	5.2 ab	5.2 ab	5.2 b	5.4 ab
$PG_{6.7}TL_{33.3}$	5.8 a	5.2 b	5.2 ab	5.0 b	5.0 b	5.2 b	5.0 b
$PG_{10}TL_{50}$	6.2 a	5.9 a	5.5 a	5.0 b	5.1 ab	5.7 ab	5.7 a
$PG_{13.3}TL_{26.7}$	5.9 a	5.7 ab	5.4 a	5.1 ab	5.2 ab	5.9 a	5.8 a
$PG_{20}TL_{40}$	6.1 a	5.8 a	5.6 a	5.6 a	5.7 a	5.4 ab	5.2 b
TL_{40}	6.1 a	5.5 ab	5.4 a	5.0 b	5.1 ab	5.3 ab	5.1 b
TL_{60}	6.2 a	5.5 ab	5.3 a	5.1 ab	5.1 ab	5.2 ab	5.2 b
Significance	* [2]	*	*	*	*	*	*

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] *: effect significant at $p < 0.05$.

In the experiment, the content of NH_4^+-N (Table 10) changed by 1–2 orders of magnitude during the first year.

The dynamics of NO_3^--N was similar with NH_4^+-N (Table 11).

Table 9. Effect of treatments and years on the content of organic carbon (C_{org}, %) at 0–20 cm soil layer.

Treatment/Year	2015	2016	2017	2018	2019
C	3.83 c [1] [I]	3.81 b	3.84 b [I, VI]	3.79 b	3.82 b
PG_5	3.79 c [II]	3.81 b	3.85 b [I, VI]	3.83 b	3.85 b [V, VII]
PG_{10}	3.90 bc	3.90 b [V]	3.85 b [I, VI]	3.85 b	3.86 b [V, VII]
PG_{20}	3.92 bc	3.88 b	3.87 b [I, VI]	3.85 b	3.85 b [V, VII]
$PG_{3.6}TL_{36.4}$	3.99 ab	4.02 ab	3.97 ab	3.95 b [IV]	3.92 ab
$PG_{5.5}TL_{54.5}$	4.12 a [III]	4.15 a	4.09 a	4.07 ab	4.00 a
$PG_{6.7}TL_{33.3}$	3.97 bc [IV]	3.99 ab	4.01 ab	4.02 ab	4.00 a
$PG_{10}TL_{50}$	4.03 ab	4.03 ab	4.07 a	4.05 ab	4.01 a
$PG_{13.3}TL_{26.7}$	3.92 bc	3.96 b [IV]	3.98 ab	4.01 ab	3.98 ab
$PG_{20}TL_{40}$	4.01ab	4.04 ab	4.05 ab	4.07 ab	4.06 a
TL_{40}	4.09 ab	4.11 ab	4.07 a	4.08 ab	4.01 a
TL_{60}	4.18 a	4.18 a	4.12 a	4.15 a	4.05 a
Significance	** [2]	**	**	**	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters– statistically different. [2] **: effect significant at $p < 0.01$ and of pairs: [I] – $PG_{10}TL_{50}$; [II] – $PG_{3.6}TL_{36.4}$; [III] – $PG_{13.3}TL_{26.7}$; [IV] – TL_{60}; [V] – $PG_{5.5}TL_{54.5}$; [VI] –TL_{40}; [VII] – $PG_{6.7}TL_{33.3}$ at $p < 0.05$.

Table 10. Effect of treatments and years on the content of ammonium nitrogen (NH_4^+-N, mg kg^{-1}) at 0–20 cm soil layer.

Treatment/Year and Season	2015		2016		2017	2018	2019
	Spring	Autumn	Spring	Autumn	Autumn		
C	4.20 i [1]	1.50 c [I, II]	2.00 c	1.50 c	2.20 b	1.20 bc	3.70 a
PG_5	4.50 i	1.60 c [I, II]	4.20 b	1.00 c [III]	1.70 b	0.40 c	4.00 a
PG_{10}	5.20 i	1.50 c [I, II]	3.00 bc	0.30 d	1.10 b	0.90 bc	3.10 a
PG_{20}	5.10 i	1.60 c [I, II]	3.50 bc	0.60 cd	1.60 ab	1.80 b	2.90 a
$PG_{3.6}TL_{36.4}$	145.50 g	13.00 b	4.50 b	2.30 bc	2.50 ab	1.90 b	2.50 a
$PG_{5.5}TL_{54.5}$	361.90 e	56.50 a	8.30 a	2.40 bc	4.70 a	1.80 b	3.50 a
$PG_{6.7}TL_{33.3}$	159.80 f	13.70 b	5.80 b	2.40 bc	2.50 ab	2.00 ab	2.90 a
$PG_{10}TL_{50}$	418.80 c	53.90 a	5.00 b	3.50 b	4.30 a	2.60 ab	3.20 a
$PG_{13.3}TL_{26.7}$	117.60 h	11.40 b	4.10 b	3.10 b	2.80 ab	1.90 b	2.70 a
$PG_{20}TL_{40}$	379.90 d	56.80 a	7.20 ab	5.20 ab	4.90 a	4.00 a	3.50 a
TL_{40}	468.10 b	13.30 b	9.10 a	7.70 a	4.10 a	4.20 a	4.00 a
TL_{60}	565.90 a	18.10 b	9.30 a	8.30 a	5.10 a	4.00 a	4.10 a
Significance	** [2]	**	**	**	**	**	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] **: effect significant at $p < 0.01$ and of pairs: [I] – $PG_{3.6}TL_{36.4}$; [II] – TL_{40}; [III] – PG_{10} at $p < 0.05$.

At the same time, the soil enrichment with AH-N, the nearest reserve of nitrogen supply to agricultural plants, remained at a high level (Table 12).

The studied soil was characterized by low phosphate reserves, which increased with any applied treatment (Table 13).

The content of K_{ex} was ranged from 135–500 mg kg^{-1} and categorized as "high" for all years of the experiment (Table 14).

Table 11. Effect of treatments and years on the content of nitrate nitrogen (NO_3^--N, mg kg^{-1}) at 0–20 cm soil layer.

Treatment/Year and Season	2015		2016		2017	2018	2019
	Spring	Autumn	Spring	Autumn	Autumn		
C	10.5 i [1]	4.2 f	8.6 e	10.1 d	7.8 ab	5.5 b [VI]	4.1 c
PG_5	14.8 h	4.8 f	10.5 e	11.1 d	7.5 ab	3.9 b	2.4 c
PG_{10}	21.2 g	7.6 f [II]	9.4 e	13.1 d	6.9 ab	4.1 b	3.1 c
PG_{20}	23.4 g	12.4 e	8.1 e	8.9 d	4.9 b	3.7 b	5.6 c
$PG_{3.6}TL_{36.4}$	109.8 c	54.1 d	20 d	19.8 c	4.8 b	4.9 ab	7.0 bc
$PG_{5.5}TL_{54.5}$	123.5 a	111.8 a	43.1 ab	27.0 bc	10.0 a [I, II]	6.4 ab	11.3 a [I]
$PG_{6.7}TL_{33.3}$	77.8 f	64.1 c	22.5 d	23.5 c	9.1 a	5.0 ab	6.7 bc
$PG_{10}TL_{50}$	117.2 b	108.8 a	40.1 b [III]	36.3 a	9.8 a [I, II]	9.1 ab	9.3 ab
$PG_{13.3}TL_{26.7}$	88.3 e	62.6 c	18.8 d	14.8 d [I]	10.5 a	9.2 ab	11.9 a
$PG_{20}TL_{40}$	117.1 b	98.7 b	45.1 a	30.2 b [IV, V]	7.2 ab	3.9 b	5.1 c
TL_{40}	96.4 d [I]	61.2 c	33 c	30.3 b [IV, V]	10.6 a	9.6 a	5.3 c
TL_{60}	104.6 c	63.9 c	38.8 b	36.4 a	11.6 a	8.8 ab	10.1 ab
Significance	** [2]	**	**	**	**	**	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] **: effect significant at $p < 0.01$ and of pairs: [I] – $PG_{3.6}TL_{36.4}$; [II] – PG_{20}; [III] – $PG_{20}TL_{40}$; [IV] – $PG_{10}TL_{50}$; [V] – TL_{60}; [VI] – TL_{40} at $p < 0.05$.

Table 12. Effect of treatments and years on the content of alkaline hydrolysable nitrogen (AH-N, mg kg^{-1}) at 0–20 cm soil layer.

Treatment/Year and Season	2015		2016		2017	2018	2019
	Spring	Autumn	Spring	Autumn	Autumn		
C	168 g [1]	168 b	168 b	119 b	120 b	168 ab	154 ab
PG_5	168 g	168 b	154 b	154 a	154 ab	154 ab	147 b
PG_{10}	154 g	196 ab	140 b	168 a	154 ab	140 b	147 b
PG_{20}	154 g	196 ab	147 b	154 a	152 ab	168 ab	154 ab
$PG_{3.6}TL_{36.4}$	448 f	196 ab	224 a	147 ab	150 ab	175 a	161 ab
$PG_{5.5}TL_{54.5}$	560 d	224 a	224 a	154 a	152 ab	168 ab	168 ab
$PG_{6.7}TL_{33.3}$	504 e	196 ab	196 a	161 a	154 ab	182 a	175 ab
$PG_{10}TL_{50}$	1064 b	224 a	196 a	154 a	152 ab	182 a	182 a
$PG_{13.3}TL_{26.7}$	420 f	196 ab	196 a	154 a	151 ab	168 ab	168 ab
$PG_{20}TL_{40}$	896 c	192 ab	196 a	154 a	154 ab	168 ab	168 ab
TL_{40}	1092 b	210 a	196 a	161 a	160 a	168 ab	168 ab
TL_{60}	1148 a	224 a	224 a	175 a	172 a	168 ab	175 ab
Significance	* [2]	*	*	*	*	*	*

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] *: effect significant at $p < 0.05$.

Table 13. Effect of treatments and years on the content of available phosphorus (P_{av}, mg kg^{-1}) at 0–20 cm soil layer.

Treatment/Year and Season	2015		2016		2017	2018	2019
	Spring	Autumn	Spring	Autumn	Autumn		
C	50 f [1 I]	44 d	39 e [I]	49 e [I]	50 d	53 f [III]	50 e
PG_5	74 e	52 d	53 de	60 de	60 d	74 e	72 d
PG_{10}	70 e	57 d	62 d	70 d	65 d	80 e	75 d
PG_{20}	96 d	94 c	89 c	100 c	99 c	106 d	103 c
$PG_{3.6}TL_{36.4}$	217 c	179 b	181 a	159 a [II]	154 ab	154 c [IV]	159 b
$PG_{5.5}TL_{54.5}$	267 b	195 ab	190 a	164 a	162 a	168 bc	165 b
$PG_{6.7}TL_{33.3}$	204 c	176 b	172 a	159 a [II]	160 a [I]	174 b [V]	180 ab
$PG_{10}TL_{50}$	281 ab	193 ab	177 a	172 a	172 a	179 ab	175 b [VI]
$PG_{13.3}TL_{26.7}$	280 ab	177 b	193 a	169 a	170 a	173 b	168 b
$PG_{20}TL_{40}$	291 a [II]	206 a	181 a	169 a	171 a	182 ab	195 a
TL_{40}	270 b	179 b	148 b	139 b	140 b	164 bc	158 b
TL_{60}	282 ab	212 a	174 b	175 a	172 a	195 a	184 ab
Significance	** [2]	**	**	**	**	**	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] **: effect significant at $p < 0.01$ and of pairs: [I] – PG_{10}; [II] – TL_{40}; [III] – PG_5; [IV] – $PG_{6.7}TL_{33.3}$; [V] – TL_{60}; [VI] – $PG_{20}TL_{40}$ at $p < 0.05$.

Table 14. Effect of treatments and years on the content of exchangeable potassium (K_{ex}, mg kg^{-1}) at 0–20 cm soil layer.

Treatment/Year	2016	2017	2019
C	150 f [1]	155 d	165 d
PG_5	170 f	175 cd	170 d
PG_{10}	135 f	160 d	160 d
PG_{20}	150 f	160 d	155 d
$PG_{3.6}TL_{36.4}$	255 e	210 b	165 d
$PG_{5.5}TL_{54.5}$	310 d	200 b [I]	210 bc
$PG_{6.7}TL_{33.3}$	225 e	200 b [I]	160 d
$PG_{10}TL_{50}$	440 b	235 ab	275 a
$PG_{13.3}TL_{26.7}$	360 c	270 a	280 a
$PG_{20}TL_{40}$	500 a	250 a	190 cd
TL_{40}	225 e	200 b [I]	185 cd
TL_{60}	300 d	275 a	235 b
Significance	** [2]	**	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] **: effect significant at $p < 0.01$ and of pair: [I] – PG_5 at $p < 0.05$

The statistical summarizing of soil agrochemical properties data are presented in Table 15.

Table 15. Effect of treatments and years on soil agrochemical properties/characteristics.

Treatment/Characteristic (Average in all Years (Seasons))	pH_{KCl}	C_{org}	NH_4^+-N	NO_3^--N	AH-N	P_{av}	K_{ex}
C	5.0 b [1]	3.82 c	2.3 e	7.3 c	152 f	48 e	157 f
PG_5	5.0 b	3.83 c	2.5 e	7.9 c	157 f	64 d	172 e
PG_{10}	5.0 b	3.87 bc	2.2 e	9.3 c	157 f	68 d	152 f
PG_{20}	5.0 b	3.87 bc	2.4 e	9.6 c	161 f	98 c	155 f
$PG_{3.6}TL_{36.4}$	5.2 ab	3.97 b	24.6 d	31.5 b	214 e	172 b	210 d
$PG_{5.5}TL_{54.5}$	5.3 ab	4.09 ab	62.7 c	47.6 a	236 d	187 a	240 c
$PG_{6.7}TL_{33.3}$	5.2 ab	4.00 ab	27.0 d	29.8 b	224 de	175 b	195 d
$PG_{10}TL_{50}$	5.6 a	4.04 ab	70.2 b	47.2 a	308 b	193 a	317 a
$PG_{13.3}TL_{26.7}$	5.6 a	3.97 b	20.5 d	30.9 b	208 e	190 a	303 a
$PG_{20}TL_{40}$	5.6 a	4.05 ab	65.9 c	43.9 a	275 c	199 a	313 a
TL_{40}	5.4 a	4.07 ab	72.9 b	35.2 b	308 b	171 b	203 d
TL_{60}	5.4 a	4.14 a	87.8 a	39.2 ab	327 a	199 a	270 b
Significance	**	*	**	**	*	*	*
Year (Season) (Average of all Treatments)							
2015 (spring)	5.6 a	*ND* [3]	219.7 a	75.4 a	565 a	199 a	*ND*
2015 (autumn)	5.4 ab	3.98	20.2 b	54.5 b	199 b	147 b	*ND*
2016 (spring)	5.2 b	*ND*	5.5 c	24.8 c	188 b	138 b	*ND*
2016 (autumn)	5.1 b	3.99	3.2 c	21.8 c	155 c	132 b	268
2017	5.1 b	3.98	3.1 c	8.4 d	152 c	131 b	208
2018	5.3 ab	3.98	2.2 c	6.2 d	167 bc	142 b	*ND*
2019	5.3 ab	3.95	3.3 c	6.8 d	164 bc	140 b	196
Significance	* [2]	*ns*	**	**	*	*	**

[1] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [2] *ns*, *, **: effect not significant or significant at $p < 0.05$ and $p < 0.01$, respectively. [3] *ND* – not defined.

3.3. Potato Yield and Quality

Potato was cultivated in the experimental plots for the first three years (2015–2017), and over the years, the harvest declined (Table 16). Chemical analysis of potato tubers showed that the content of Pb and Cd was significantly lower than the maximum permissible concentration (MPC) defined by the Russian government (Table 16).

Table 16. Effect of treatments and years on potato yield (t ha^{-1}); content of nitrates, lead and cadmium in potato tubers ($mg \cdot kg^{-1}$ dry weight).

Treatment/Parameter and Year	Potato Yield			Nitrates (NO_3^-)		Lead (Pb)	Cadmium (Cd)
	2015	2016	2017	2015	2016	2015	2015
C	13.3 f [2]	11.9 c	8.4 c	29.2 g	30.0 e	0.06	0.018
PG_5	15.5 f	13.3 bc	9.8 c	29.2 g	30.0 e	0.04	0.018
PG_{10}	16.0 f	12.1 c	9.8 c	42.0 f	32.8 de	0.06	0.020
PG_{20}	23.0 e	11.7 c	8.2 c	68.5 e	40.5 d	0.06	0.017
$PG_{3.6}TL_{36.4}$	27.0 d	15.2 bc	15.8 a	119.0 d	91.2 c	0.04	0.016
$PG_{5.5}TL_{54.5}$	38.0 b	18.3 a	16.5 a	182.0 c	140.0 b	0.07	0.014
$PG_{6.7}TL_{33.3}$	32.7 c	17.5 ab	16.4 a	222.0 b	160.9 b	0.07	0.015
$PG_{10}TL_{50}$	36.8 b	20.4 a	16.0 a	368.0 a	220.3 a	0.07	0.020
$PG_{13.3}TL_{26.7}$	29.0 d	14.2 bc	14.1 ab	372.5 a	220.3 a	0.06	0.020
$PG_{20}TL_{40}$	34.8 bc	18.8 a	13.0 b	377.0 a	220.3 a	0.07	0.026
TL_{40}	43.2 a	17.7 ab	15.8 a	191.0 bc	142.2 b	0.07	0.024
TL_{60}	39.5 b	18.3 a	16.3 a	367.0 a	218.4 a	0.07	0.018
MPC [1]				250		0.5	0.03
Significance	* [3]	*	*	**	**	*ns*	*ns*

[1] MPC: maximum permissible concentration. [2] Means followed by the same letters within same column are not statistically different ($p < 0.05$), by the various letters – statistically different. [3] *ns*, *, **: effect not significant or significant at $p < 0.05$ and $p < 0.01$, respectively.

4. Discussion

4.1. Physical Properties

In the first year, 2015, the significant reduction in soil penetration resistance was observed for most experimental plots with amendments (Table 3). The maximum reduction occurred in the treatments with the joint application of PG and TL, where it amounted for 759–622 kPa, while it was 1114 kPa in the control variant. In 2016, the difference between the variants of the experiment with control became not significant. A decrease in soil penetration with the introduction of both PG and poultry litter was also noted in the works [45,46]. The similar tendency, that the penetration resistance is lower in the top layer and increases in the deep layer, gradually was found in a laboratory test by Tang et al. [47].

At the beginning of the experiment, the introduction of only PG in doses from 5 to 20 t ha^{-1} did not affect soil moisture reserves significantly (Tables 4 and 7), although some researchers [48,49] have noted that PG treatments increased the moisture storage in the plant root zone. However, a significant increase of soil moisture reserves (by 10–17%) was observed with the introduction of TL and PG+TL. In all these variants, the soil moisture reserves were significantly higher than only PG treatment. The effectiveness of TL was especially notable in the arid 2016, with the aftereffect also observed in 2017. The differences between the treatments in soil moisture reserves decreased in the 4^{th} and 5^{th} years of the experiment. In these years, the variants with high doses of TL ($PG_{5.5}TL_{54.5}$, $PG_{20}TL_{40}$, TL_{40}, TL_{60}) were significantly higher than the variants with PG only. In general, weather conditions had a greater influence on the soil moisture reserves than treatments. The two-way ANOVA showed that the influence of years factor was 54, the treatments factor – 30, and the interaction effect (years-treatments) – 15%.

The particle size distribution of the agrochernozem changed in the first year after the addition of the PG. A tendency towards the decreasing of clay (<0.001 mm) fraction content was observed, with a significant ($p < 0.05$) decrease only after the largest dose – PG_{20} (Figure 2B). However, there were not-so-noticeable changes in clay fraction content after the joint application of PG+TL. After 5 years, clay fraction content in the soil of the control variant fell from 39 to 36% ($t_{stat} = 3.84$, $p < 0.05$), and the sand (0.01–1 mm) content increased from 29 to 34% ($t_{stat} = 5.58$, $p < 0.01$). It is well known that clay and silt particles are preferentially transported by overland flow [50,51]. On the site of the experiment, a washout of fine particles from topsoil and an increase of silt+clay fraction in the sediments were found during snowmelt, rainfalls, or sprinkling irrigation [52,53]. The introduction of amendments resulted in the significant increase of clay (< 0.001 mm) fraction content in 2019 when compared to 2015 ($t_{stat} = 4.23$, $p < 0.01$). This fact indicates the increase of soil resistance to water erosion.

The introduction of PG_5 and PG_{10} in the first three years did not lead to a significant change in SAS, and only at the highest dose (PG_{20}) was there a significant increase of SAS in comparison with the control. The water resistance of the soil aggregates increased significantly (by 8–15%) with the addition of high doses of TL ($\geq$ 36.4 t ha^{-1}) with PG as well as TL_{60} (t_{stat} from 3.70 to 5.67, $p < 0.05$). In general, the introduction of amendments led to the change of SAS from "excellent" (2015) to "excessively high" gradation by 2019, i.e., K_{sas} became more than 0.8 (t_{stat} = 6.01, $p < 0.01$) (Tables 5 and 7). The increasing of SAS and soil resistance to water erosion under the introduction of PG [54,55] and manure [56,57] or broiler litter [46] has also been noted for other soil types.

K_{sas} depended not only on treatments but also on meteorological conditions. The influence of years and treatments factors on SAS were 45 and 24%, respectively, and the interaction effect was – 29%. The increase in SAS for all the treatments of the experiment in the last two years (t_{stat} = 7.24, $p < 0.01$) was apparently associated with the cessation of plowing practice [58] and cultivation of perennial herbs [59,60].

The use of amendments has a considerable impact on the microaggregate composition of the soil. K_d decreased after the introduction of PG, in accordance with the increase of its dose. This fact indicated an improvement in soil microstructure. Similar results were reported in the investigations by Semendyaeva and Elizarov [61] and Efremova et al. [49]. The addition of TL did not lead to significant changes in K_d in 2015, but it significantly decreased by 2019 (t_{stat} = 13.46 $p < 0.01$). On the contrary, the efficiency of PG worsened by the end of the experiment, but compared to the control it was significantly better even in 2019 at PG_{10} and PG_{20} doses. This is due to the washouting (by surface erosional runoff and/or lessivage process) of the clay fraction and the concomitant deterioration of the soil microstructure. The aftereffect of PG without introduction of organic additives was not prolonged.

The effect of PG on soil structure is controversial. A positive effect of PG appears for alkaline soils [62,63]. According to Vyshpolsky et al. [48] the effect of PG in irrigated areas was negative. The separate application of PG and TL during the entire experiment did not have a significant effect on the content of AVA. At the same time, their joint application led to a significant improvement of soil structure in comparison with the control (t_{stat} from 4.49 to 9.92, $p < 0.05$). An increase in the content of the 1–2 mm fraction with the introduction of PG and poultry manure is also shown in the work by Xue et al. [64]. It is interesting to note that this fact was most clearly manifested in the second year of the experiment after the severely arid growing season. In general, meteorological conditions had a higher influence on the AVA content than treatments and their interaction effect (51%, 22% and 23%, respectively).

On average throughout the five years, the content of AVA correlated closely (r = 0.84) with the K_s. Wherein, the higher effect on K_s was revealed with the introduction of the increased dose of TL (Tables 6 and 7). The effect of the years factor was 67, while treatments –19 and their interaction – 11%.

Thus, the introduction of TL, both separately and together with PG, improves the water-physical properties and anti-erosion resistance of eroded agrochernozem, especially in arid year. The two-way ANOVA showed that years had a significant effect on the water-physical properties of the soil; the influence of this factor was 44–67, while the effect of treatments was 21–30%.

4.2. Agrochemical Properties

In the first year after the introduction of the PG+TL, alkalization from "moderately acidic" to a "slightly acidic" and "neutral" categories was observed (Tables 8 and 15). This increase in pH_{KCl} was due to high $NH_4{}^+$-N content in TL; since PG, when applied separately, did not have a significant effect on soil acidity at any doses. The impact of PG on pH depends on the initial soil acidity. The addition of PG to alkaline soils contributed to their acidification, for example, pH was reduced from 7.9 in the control to 5.1 in the treatment with 20% PG [65]. In our earlier studies [23,24], the neutralization of the alkalinity of technogenic solonized soils was shown. At the same time, the addition of PG to the strongly acidic Rhodic Ferralsol (pH_{CaCl_2} in the 0–15 cm layer was 4.0–4.7) at a dose of 2100 kg ha^{-1} contributed to the neutralization of acidity to 4.2–5.1 [66]. In the subsequent years of the experiment, some acidification occurred, but the pH_{KCl} values remained in the "slightly acidic" category. The percentage of treatments effect was 43, years – 20, interaction effect – 31%. Similar results were obtained when high doses (40–120 t ha^{-1}) of chicken manure were applied into the same soil [36].

The introduction of PG did not contribute to an increase of C_{org} [67,68], although it could affect the carbon of microbial biomass [69], the content of various carbon fractions [70], and organic carbon concentrations in soil aggregates [71]. In contrast to PG, the TL application produced significant increasing trends in C_{org} [72]. In the present study, the application of sole PG did not significantly impact the C_{org} content, however, its significant increase was observed in all the treatments that included TL (Tables 9 and 15). C_{org} content in the variants with the highest TL doses (54-60 t ha^{-1}) was significantly higher than in PG treatments. The maximum C_{org} content was noted in the 2nd year after the application of TL at 60 t ha^{-1}, where the content of C_{org} was higher by 0.37%, when compared with the control. In PG+TL treatments, the greatest increases in C_{org} were at the dose of 60 t ha^{-1} in all the ratios. In the fifth year of the experiment, the maximum C_{org} content was also preserved in these treatments. This indicates the deposition of TL carbon in the composition of soil organic matter, and not mineralization with the release of CO_2 into the atmosphere. The t-test showed a significant increase in the C_{org} content compared to the control when TL was applied (t_{stat} from 8.16 to 18.45, $p < 0.01$). The influence of treatments factor was 77%, and the factor of years and interaction effect did not have a significant impact (1% and 6%).

Significant changes occurred in the soil nitrogen content, primarily in all the treatments that included TL (spring 2015). The NH_4^+-N increased by two orders of magnitude depending on the dose of TL (Tables 10 and 15). However, by the autumn of 2015, NH_4^+-N significantly declined, as follows: i) 6–8 times with the application of PG+TL at a dose of 60 t ha^{-1}, ii) 10–12 times with a dose of 40 t ha^{-1} PG+TL, and iii) 31–35 times with TL only. This change in NH_4^+-N indicates the ability of PG to fix NH_4^+-N and reduce its loss. PG ability to reduce significantly total nitrogen loss was shown by Lim et al. [73] and Li et al. [74]. In 2016, there was a further reduction in NH_4^+-N, but only after the 3rd year the leveling and stabilization of NH_4^+-N took place. The influence of years factor on the NH_4^+-N dynamics was 34, treatments – 17, interaction effect – 49% (only the autumn season was taken into account, as well in calculations for NO_3^--N, AH-N, and P_{av}).

The content of NO_3^--N also significantly increased up to ten times with the introduction of TL, either separately or together with the PG (Tables 11 and 15). The NO_3^--N dynamics generally corresponded to NH_4^+-N, as the NO_3^--N amount decreased with time but to a lesser extent. The two-way ANOVA showed that years had a significant effect; the influence of this factor was 52, while effect of treatments −16, interaction effect −32%.

The dynamics of the content of AH-N (Tables 12 and 15) correlated ($p < 0.001$) with the dynamics of NH_4^+-N (r = 0.98) and NO_3^--N (r = 0.71). The content of AH-N greatly increased immediately after the TL addition into the soil (from 168 to 1148 mg kg^{-1}). Later, the AH-N decreased to the control level possibly as a result of the plant nutrition and intensive development of denitrification. The years effect was 57, while treatments −20, and their interaction −16%.

The introduction of PG contributed to the increase in the P_{av} content (Tables 13 and 15), however, even with the highest dose (20 t ha^{-1}) the P_{av} enrichment did not exceed the "medium" category. Obviously, this is due both to the low content of phosphorus in PG and its difficult solubility. One of the effective ways to release the phosphorus from PG is using of phosphate-solubilizing fungi [75]. A slight increase in the content of mobile phosphorus was observed in the chernozems of Northern Kazakhstan [76]. In other soil types, the authors [77–80] noted a more noticeable increase in the content of P_{av}. The addition of TL, either alone or together with PG, in all the ratios, led to an increase in the P_{av} content to a "very high" category. However, in the 2nd and 3rd years, the P_{av} amount in the soil of these treatments gradually lessened, but the enrichment of soil with P_{av} remained high until the end of experiment in 2019. With the introduction of TL, the content of P_{av} was higher in all variants than of PG alone. It should be noted that the degree of phosphorus mobility with the addition of PG_5 and PG_{10} increased but remained in the "low" category, and only with the addition of PG_{20} it became "medium". On the other hand, the addition of PG+TL and TL contributed to a significant increase in the degree of phosphorus mobility ("elevated" and "high" categories), which persisted throughout the experiment. The t-test showed a significant increase in P_{av} content compared to the control in all variants of the experiment (t_{stat} from 6.17 to 50.87, $p < 0.01$). The percentage of treatment effect was 95, while years −1, their interaction −2%.

The content of K_{ex} did not change significantly with the addition of all doses of PG (Tables 14 and 15). The similar results were obtained by Nayak et al. [65]. The addition of PG+TL contributed to an increase of the enrichment of K_{ex} by one level (to a "very high" category – 450–500 mg kg^{-1}). By the autumn of the 3rd year, the content of K_{ex} slightly changed, especially in PG+TL and TL treatments. The maximum concentrations remained at the level of 250–275 mg kg^{-1}. In the subsequent years, the enrichment of K_{ex} remained "high" and "very high", although the degree of potassium mobility did not exceed the "medium" category (20 mg L^{-1}). The percentage of treatments effect was 56, while years −16, their interaction −26%.

4.3. Potato Yield and Ecological Quality

The first year of the experiment (2015) was an average in terms of meteorological conditions of this natural-climatic zone, with a sufficient level of heat and moisture supply. Potato yields increased with the application of amendments up to 3.2 times, as the maximum increase, after the application of TL_{40} (Table 16). The application of PG increased the potato yield, growing gradually with increasing the dose. Joint application of PG and TL at any ratio also had a significant ($p < 0.01$) effect on potato productivity, especially at a dose of 60 t ha^{-1} where the yield was higher. In all variants with TL introduction, the potato yield was significantly higher than with PG. The 2nd year of the study turned out to be arid, which had a strong negative impact on potato yield, but the main patterns were the same as in 2015. However, it should be noted that with a high dose of PG, potato yield was almost same with control variant in 2016–2017. In all other variants, the increase in yield was significant ($p < 0.01$). The meteorological conditions had a higher influence on the potato yield than treatments and their interaction effect (55%, 30%, and 14%, respectively). The applying of PG into other soils contributed to an increase in the yield of potato [6] and various other crops [66,76,81] and depended both on dose and weather conditions during plant development.

Being able to cause negative environmental consequences, the addition of PG into soil in order to improve its properties must be done with caution. Many heavy metals (HMs) are present as impurities in the PG composition, thus, the content of HMs total and soluble forms in the soil can increase due to PG application. In some cases, the addition of PG was reported to result in a dangerous increase in the activity of the Pb^{2+} in the soil solution [82]. Nevertheless, mobile and water-soluble forms of Ca, Ba, Sr, S, and Na increases soil toxicity [83]. One of the most important indicators of soil pollution when using PG is Sr content, since its ions are capable of replacing Ca^{2+} in the tissues of living organisms. According to the Russian guidelines, the concentration of more than 600 mg kg^{-1} of Sr in the soil is considered dangerous [84]. Taking this element into account, the permissible PG application should not exceed 6.8% for agricultural land [85]. When soil bulk density is 1.1 g cm^{-3} and at a layer of 20 cm, the PG dose should be not more than 150 t ha^{-1}. In the composition of PG used in the experiment, Sr concentration was 14691 mg kg^{-1}; while Sr in the untreated control soil was 130 mg kg^{-1}. Thus, in the highest dose ($PG_{20}TL_{40}$), the Sr concentration was 260 mg kg^{-1}, indicating that the applied doses of PG are environmentally safe. Moreover, organic additives could reduce the risk of Sr contamination [86]. Despite a slight increase in the content of water-soluble salts immediately after the addition of PG, the soil remained in the category "non-saline". Al-Hwaiti and Al-Khashman [87] found that concentrations of Cd, Cr, Pb, and Zn were below what are considered as acceptable limits for food production in soil and vegetables (tomatoes and green peppers) under PG applying in Jordan.

An important indicator of the ecological quality of agricultural crops is the assessment of content of HMs and nitrates in their composition. Chemical analysis of potato tubers showed that the content of Pb and Cd was significantly lower than the MPC defined by the Russian government (Table 16). However, the addition of high doses of TL, either alone or jointly with PG, in the first year, caused an increase in the content of nitrates in potato tubers to 1.5—the MPC guidelines adopted in Russia [88]—however, in the 2nd year, nitrate content in tubers gradually decreased and did not exceed the MPC. The correlation between potato yield and nitrates content was strong both for two years (r = 0.72) and separately (r = 0.75 at 2015, r = 0.82 at 2016). Obviously, in the first year it is more advisable to cultivate industrial crops.

In the 4th year, the experimental plots were seeded with perennial herbs, a mixture of alfalfa, fescue, and timothy grass; their hay productivity in the 5th year ranged 2.5–3.9 t ha^{-1}. The maximum increases were observed in the treatments with the joint addition of PG+TL at a ratio of 1:5.

5. Conclusions

A 5-year long field experiment (in South Ural, Russia) demonstrates that the joint application of phosphogypsum (PG) and turkey litter (TL) to weakly eroded agrochernozem improves water-physical properties, as follows: significantly increases soil moisture reserves, especially in the dry years, and the content of clay fraction and agronomically valuable aggregates; and improves aggregate stability and soil microstructure. These factors contribute to the increasing of soil resistance to water erosion. The statistical analyses show that weather conditions of different years have a significant effect on soil water-physical properties; the influence of this factor was 44–67%, while the effect of treatments was 21–30%.

The application of amendments also leads to the improvement of the soil agrochemical properties. The content of soil organic carbon (C_{org}) increases with the introduction of TL and remains stable until the end of the experiment. The ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) content increases sharply at the beginning of the experiment according to the dose of the TL, but then in the autumn, it noticeably decreases. The use of PG helps to fix NH_4^+-N, and reduces its loss by leaching from soil. The dynamics and the content of NO_3^--N and alkaline hydrolysable nitrogen in general corresponds to NH_4^+-N, with time their amount decreases but to a lesser extent. The introduction of PG helps to increase the content of available phosphorus (P_{av}) from a "low" to a "medium" level, and the addition of TL to a "very high" P_{av} level, which gradually decreases but remains in this category until the end of the experiment. The soil of the control plot is characterized by a "high" content of exchangeable potassium, which increases less noticeably than other nutrients and does not change significantly in subsequent years. The content of C_{org} and P_{av} is more dependent on treatments factor (77 and 95%, respectively), and the content of all nitrogen forms depend on the year factor (34–57%).

The amendments, especially TL increase potato yields in two to three times compared to control. The high doses of PG only at years with a lack of soil moisture do not lead to an increase in potato yield. Only in the first year an excess in the maximum permissible concentration of nitrate was observed in some cases, but with no presence of Pb and Cd.

Thus, the wastes from the phosphorus fertilizers production (PG) and poultry farming (TL) are advisable to use not only to increase fertility, but also for soil anti-erosion resistance. The wider use of these amendments will lead to an improvement of the ecological situation and will give an economic benefit for the agriculture in the region. The proposed techniques can also be useful on other soil types and climatic conditions.

Author Contributions: Conceptualization, I.G.; methodology, I.G.; software, M.K.; validation, M.K. and T.G.; formal analysis, M.K., T.G. and L.S.; investigation, M.K., I.G., T.G., R.S. and L.S.; resources, I.G.; data curation, M.K., T.G., R.S. and L.S.; writing—original draft preparation, M.K., I.G. and T.G.; writing—review and editing, M.K.; visualization, M.K.; supervision, I.G.; project administration, I.G.; funding acquisition, M.K. and I.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out within the framework of the Russian Federation Government task № 075-00326-19-00, research project № AAAA-A18-118022190102-3. The study was partly and financially supported by a grant from the President of the Republic of Bashkortostan "Assessment of the state of degraded lands of the Republic of Bashkortostan by the radiocesium method and the development of organomineral fertilizers to increase soil fertility". A part of the results was obtained using equipment of the "Agidel" Collective Use Center.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to Irik Saifullin for his fieldwork help, and Fliza Nazyrova and Guldar Gimaletdinova for their support in the laboratory analyses.

Conflicts of Interest: The authors declare no conflict of interest.

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