

The Effect of Renewable Phosphorus Biofertilizers on Selected Wheat Grain Quality Parameters

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Supplementary Information

Table S1. Elemental composition of P-fertilizers used in the field experiments.

Element	Unit	Biofertilizers ¹							Referential nutrient carriers					
		<i>AsBm</i>	<i>BsBm</i>	<i>AgAf</i>	<i>ABgAf</i>	<i>ABgBm</i>	<i>AHgBm</i> (2016)	<i>AHgBm</i> (2017)	SP ²	PR ³	A+H ₂ O ¹	<i>ABg</i> ¹	<i>AHg</i> ¹ (2016)	<i>AHg</i> ¹ (2017)
P	% mass.	0.176	0.259	9.24	7.50	5.87	9.55	4.95	17.6	12.9	0.176	6.10	8.68	5.40
N		0.255	0.350	0.530	3.190	3.14	2.87	3.15			0.255	3.82	2.89	3.44
K		0.487	0.217	0.963	0.727	0.772	1.16	0.67			0.487	0.846	1.09	0.62
Ca		0.694	0.373	12.5	12.0	10.7	14.6	12.3	7.14	35.3	0.694	11.4	13.4	14.2
Mg		0.119	0.009	2.442	1.176	1.188	1.70	0.78		0.295	0.119	1.296	1.54	0.79
S		0.055	0.046	1.38	1.50	1.91	0.56	0.40	2.0		0.055	2.28	0.56	0.47
Na		0.049	0.037	0.338	0.569	0.366	0.595	0.595			0.049	0.382	0.368	0.368
C		0.590	1.650	6.71	23.6	16.1	13.9	18.1			0.590	17.6	12.5	16.5
Fe	g kg ⁻¹	1.679	0.022	33.0	15.1	14.4	29.0	11.3	+	1.61	1.68	15.4	26.9	11.4
Al		1.774	0.008	24.4	13.9	11.3	25.5	12.1		1.69	1.77	12.8	23.7	11.3
Zn		0.117	0.007	2.00	1.18	1.56	3.29	0.99	+		0.12	1.75	3.14	1.09
As	mg kg ⁻¹	< 0.5	< 0.5	4.35	2.55	< 0.5	20.0	20.5		0.750	< 0.5	26.5	31.4	15.5
Cd		0.274	0.01	0.43	0.24	0.84	0.345	0.742		7.80	0.27	0.38	<0.01	0.66
Cr		5.94	0.218	135	60.0	94.7	62.9	59.1			5.94	114	54.7	63.9
Cu		55.0	0.433	880	398	444	850	334	+		55.0	470	778	334
Ni		2.45	0.212	57.7	25.1	44.3	62.6	21.2			2.45	52.3	54.8	28.5
Pb		10.4	1.04	21.6	11.2	14.5	21.8	4.53		6.21	10.4	34.0	19.9	0.92
B		nd	nd	nd	nd	35,2	74.1	57.6	+		nd	40,5	71.3	41.1
Ba		nd	nd	nd	nd	234	382	168			nd	245	349	162
Co		nd	nd	nd	nd	5,46	16.2	4.24	+		nd	5.97	14.0	5.24
Mn		nd	nd	nd	nd	346	609	437	+		nd	370	562	299
Mo		nd	nd	nd	nd	10,4	23.7	13.9	+		nd	13.3	35.3	2.25

¹ according to the Department of Advanced Material Technologies of the Wrocław University of Science and Technology, Wrocław, Poland;

² according to label information; ³ according to the New Chemical Syntheses Institute in Puławy, Poland; nd - no data; + - trace presence

Table S2. Field experiments conducted – experiment details and basic agricultural data.

Item	Experiment						
	I	II	III	IV	V	VI	VII
Growing season	2014	2015	2015	2016	2016	2017	2017
Test crop (cultivar)	spring wheat (Trappe)	spring wheat (Monsun)	winter wheat (Julius)	winter wheat (Julius)	spring wheat (Monsun)	winter wheat (Julius)	spring wheat (Monsun)
Biofertilizers tested	<i>A_sB_m</i>	<i>A_sB_m</i>	<i>A_gA_f</i>	<i>AB_gB_m</i>	<i>AH_gB_m</i>	<i>AH_gB_m</i>	<i>AH_gB_m</i>
	<i>B_sB_m</i>		<i>AB_gA_f</i>				
Reference treatments	no P	no P	no P	no P	no P	no P	no P
	SP	SP	SP	SP	SP	SP	SP
	PR	PR		AB _g	AH _g	AH _g	AH _g
	A + H ₂ O						
P ¹ doses, kg ha ⁻¹	21	17.6	17.6	17.6	17.6	17.6	17.6
		26.4	26.4	26.4	26.4	26.4	26.4
		35.2	35.2	35.2	35.2	35.2	35.2
K ¹ , kg ha ⁻¹	99.6	83	83	83	83	83	83
N, kg ha ⁻¹	100 (50 ¹ + 50 ³)	110 (60 ¹ + 50 ³)	130 (80 ² + 50 ³)	120 (70 ² + 50 ³)	130 (60 ¹ + 50 ³ + 20 ⁴)	150 (80 ² + 50 ³ + 20 ⁴)	110 (60 ¹ + 50 ³)
Plant protection (PP)	PP–	PP– PP+	PP+	PP+	PP+	PP+	PP+
– herbicides	–	–/+	+	+	+	+	+
– fungicides	–	–/+	+	+	+	+	+
– insecticides	–	–/+	+	+	+	+	+
– growth regulators	–	–	+	+	–	+	–
Previous crop	spring barley	cereal-legume mixture	winter rape	winter rape	winter rape	winter wheat	spring wheat
Soil tillage system	plough tillage	plough tillage	plough tillage	plough tillage	plough tillage	plough tillage	plough tillage
Sowing date	25 April 2014	9 April 2015	2 October 2014	15 October 2015	21 April 2016	4 October 2016	20 April 2017
Harvest date	11 August 2014	11 August 2015	5 August 2015	9 August 2016	12 August 2016	4 August 2017	18 August 2017
Number of treatment combinations	6	20 ⁵	10	10	10	10	10
Experimental design	randomized block	parallel strip	randomized block	randomized block	randomized block	randomized block	randomized block
Number of replications	4	4	4	4	4	4	4
Number of plots	24	80	40	40	40	40	40
Plot area, m ²	20	20	20	20	20	20	20

¹ pre-sowing, ² at post-winter vegetation start, ³ at wheat stem elongation, ⁴ at wheat heading; PP– - no plant protection treatments; PP+ - full plant protection; ⁵ in Experiment II, the level of plant protection was an additional experimental factor; + - applied, – - not applied.

Table S3. Soil characteristics before the start of the experiments.

Experiment	Soil Type	Soil Texture	pH _{KCl}	Total, g kg ⁻¹					
				C	N	P	K	Mg	P
I	Luvisols	sandy clay loam	6.23	8.31	1.30	0.57	2.98	2.07	0.57
II	Luvisols	sandy loam	5.32	8.90	1.35	0.57	2.90	2.01	0.57
III	Luvisols	sandy loam	5.51	8.87	1.36	0.43	3.21	2.25	0.43
IV	Luvisols	sandy loam	5.23	7.15	1.09	0.55	3.30	2.20	0.55
V	Luvisols	sandy clay loam	6.28	8.53	1.42	0.61	2.98	2.02	0.61
VI	Luvisols	sandy loam	4.98	6.48	1.01	0.49	2.95	1.88	0.49
VII	Luvisols	sandy clay loam	6.23	8.48	1.34	0.60	3.14	1.94	0.60

Table S4. Precipitation and air temperature during the study period according to the Meteorological Station in Bałcyny, Poland.

Year	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Precipitation, mm												
2014				26.1	34.9	72.2	20.4	59.2	30.8	21.3	21.2	56.6
2015	28.5	8.8	46.0	23.4	25.4	43.0	71.0	13.0	51.2	20.8	80.8	80.4
2016	28.7	50.5	20.5	33.1	70.8	66.3	138.6	71.9	17.1	96.3	78.2	77.8
2017	15.8	40.5	53.0	52.1	34.0	109.9	106.1	54.8				
1981–2010	30.1	23.1	30.7	29.8	62.3	72.9	81.2	70.6	56.2	51.2	46.1	42.6
Air temperature, °C												
2014				9.5	13.3	14.8	21.0	17.9	14.5	9.5	4.4	−0.6
2015	0.6	0.3	4.6	7.2	12.1	15.7	18.0	21.3	14.2	6.6	5.1	3.8
2016	−3.8	2.7	3.6	8.8	14.9	18.0	18.5	17.6	14.7	6.9	2.5	1.0
2017	−3.2	−1.2	5.1	6.7	13.1	16.7	17.3	18.7				
1981–2010	−2.4	−1.6	1.8	7.7	13.2	15.8	18.3	17.7	13.0	8.1	2.8	−1.0

Table S5. Wheat yields (t ha⁻¹) under the influence of P treatments in the experiments.

Experiment I ¹		Experiment II ²		Experiment III ²		Experiment IV ²		Experiment ²			
Treatments	Yield	Treatments	Yield	Treatments	Yield	Treatments	Yield	Treatments	V	VI	VII
No P	4.18 ^b	No P	4.85 ^d	No P	7.07 ^c	No P	8.27 ^b	No P	6.02 ^c	6.51 ^c	4.36 ^c
SP	5.40 ^a	SP-1	5.42 ^{bc}	SP-1	7.94 ^b	SP-1	9.23 ^a	SP-1	6.40 ^{ab}	7.42 ^b	5.45 ^{ab}
PR	4.77 ^{ab}	SP-2	5.60 ^{ab}	SP-2	8.19 ^{ab}	SP-2	9.53 ^a	SP-2	6.53 ^{ab}	8.08 ^a	5.71 ^a
A+H ₂ O	5.00 ^a	SP-3	5.83 ^a	SP-3	8.60 ^a	SP-3	9.45 ^a	SP-3	6.70 ^a	7.72 ^{ab}	5.38 ^{ab}
<i>AsBm</i>	5.26 ^a	PR-1	5.43 ^{bc}	<i>AgAf</i> -1	7.93 ^b	<i>AB_g</i> -1	9.32 ^a	<i>AH_g</i> -1	6.32 ^b	7.36 ^b	5.10 ^b
<i>BsBm</i>	4.89 ^{ab}	PR-2	5.49 ^{bc}	<i>AgAf</i> -2	8.41 ^a	<i>AB_g</i> -2	9.52 ^a	<i>AH_g</i> -2	6.40 ^{ab}	7.47 ^b	5.13 ^b
		PR-3	5.52 ^{bc}	<i>AgAf</i> -3	8.29 ^{ab}	<i>AB_g</i> -3	9.29 ^a	<i>AH_g</i> -3	6.39 ^{ab}	7.66 ^{ab}	5.23 ^{ab}
		<i>AsBm</i> -1	5.25 ^c	<i>AB_gAg</i> -1	7.96 ^b	<i>AB_gBm</i> -1	9.47 ^a	<i>AH_gBm</i> -1	6.38 ^{ab}	7.75 ^{ab}	5.28 ^{ab}
		<i>AsBm</i> -2	5.50 ^{bc}	<i>AB_gAg</i> -2	8.50 ^a	<i>AB_gBm</i> -2	9.78 ^a	<i>AH_gBm</i> -2	6.48 ^{ab}	8.00 ^a	5.45 ^{ab}
		<i>AsBm</i> -3	5.29 ^c	<i>AB_gAg</i> -3	8.46 ^a	<i>AB_gBm</i> -3	9.56 ^a	<i>AH_gBm</i> -3	6.59 ^{ab}	8.03 ^a	5.63 ^{ab}

¹ fertilizers applied at P dose of 21 kg ha⁻¹; ² fertilizers applied at P doses of 17.6 (1), 26.4 (2) and 35.2 (3) kg ha⁻¹; a-d - different letters within columns indicate significant differences at $p \leq 0.05$.

Table S6. Reference values for potentially toxic elements (mg kg⁻¹) in plants, according to various sources.

Content	As	Al	Cd	Cr	Cu	Fe	Ni	Pb	Zn
Sufficient or normal [1]	1-1.7	X0-X00	0.05-0.2	0.1-0.5	5-30	10-1000	0.1-5	5-10	27-150
Excessive or toxic [1]	5-20	NPD	5-30	5-30	20-100	NPD	10-100	30-300	100-400
Average in cereal grain [2]	0.03-0.6	10-140	0.03-0.5	0.003-0.4	2.6-6	31-98	0.1-0.5	0.2-0.5	15-60
Permissible in Poland									
– in cereal grain [3] ¹	0.20	n.s.	0.10 (0.20 ⁴)	n.s.	n.s.	n.s.	n.s.	0.20	n.s.
– in feed materials of plant origin [4,5]	2	n.s.	1	n.s.	n.s.	n.s.	n.s.	10	n.s.
Other standards for food grain									
– FAO/WHO [6]	0.35 (0.2 ²)	n.s.	0.1 (0.2 ⁴ ; 0.4 ⁵)	n.s.	n.s.	n.s.	n.s.	0.2	n.s.
– EU [7]	0.1-0.25 ³	n.s.	0.1 (0.05 ⁶ ; 0.15 ⁷ ; 0.18 ⁸)	n.s.	n.s.	n.s.	n.s.	0.2	n.s.
– PR of China [8]	0.5 (0.2-0.35 ³)	n.s.	0.1 (0.2 ⁵)	1.0	n.s.	n.s.	n.s.	0.2	n.s.
Suggested maximum values in plant material [9]									
– for food purposes	n.i.	n.i.	0.15	n.i.	20	n.i.	10	1	50
– for feed purposes	n.i.	n.i.	0.5	n.i.	25-50	n.i.	50	10	100

¹ regulation repealed, no new; ² for inorganic As in rice husked or polished (value in brackets); ³ for inorganic As in rice depending on its preparation and intended use; ⁴ for wheat; ⁵ for rice; ⁶ for barley and rye; ⁷ for rice and quinoa; ⁸ for durum wheat; n.s. – not standardized; n.i. – no information, NPD - not precisely defined.

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