

Supplementary Materials

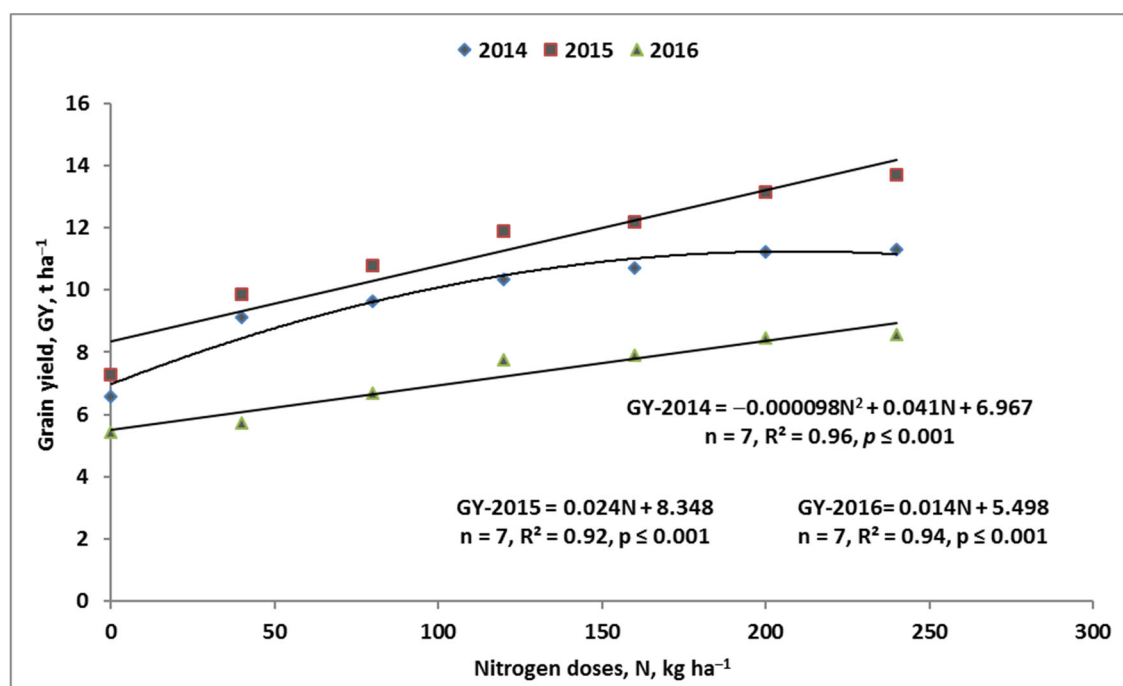


Figure S1. Regression models of grain yield of winter wheat response to doses of applied nitrogen.

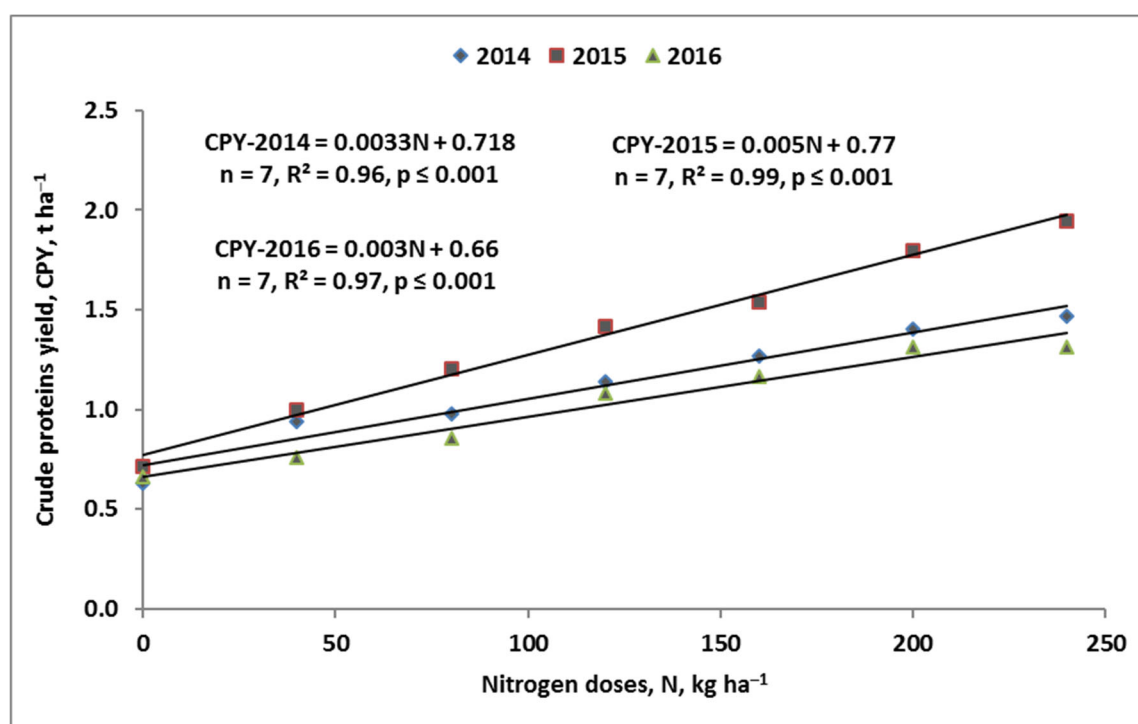


Figure S2. Regression models of crude protein yield of winter wheat response to doses of applied nitrogen.

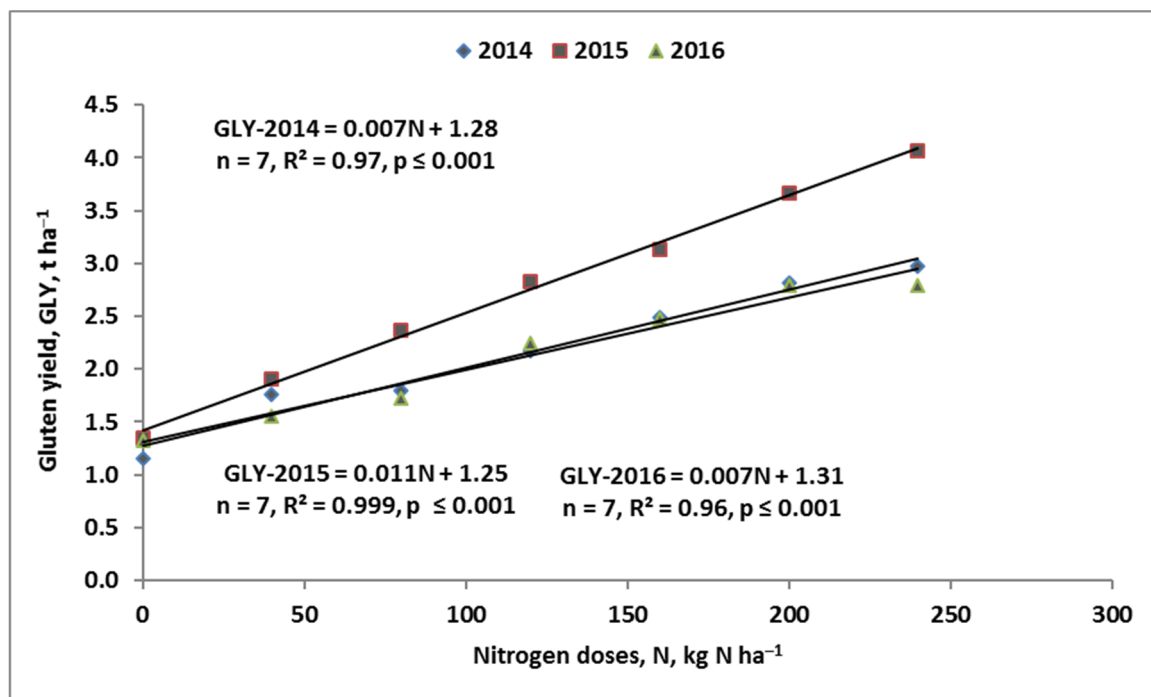


Figure S3. Regression models of wet gluten yield of winter wheat response to doses of applied nitrogen.

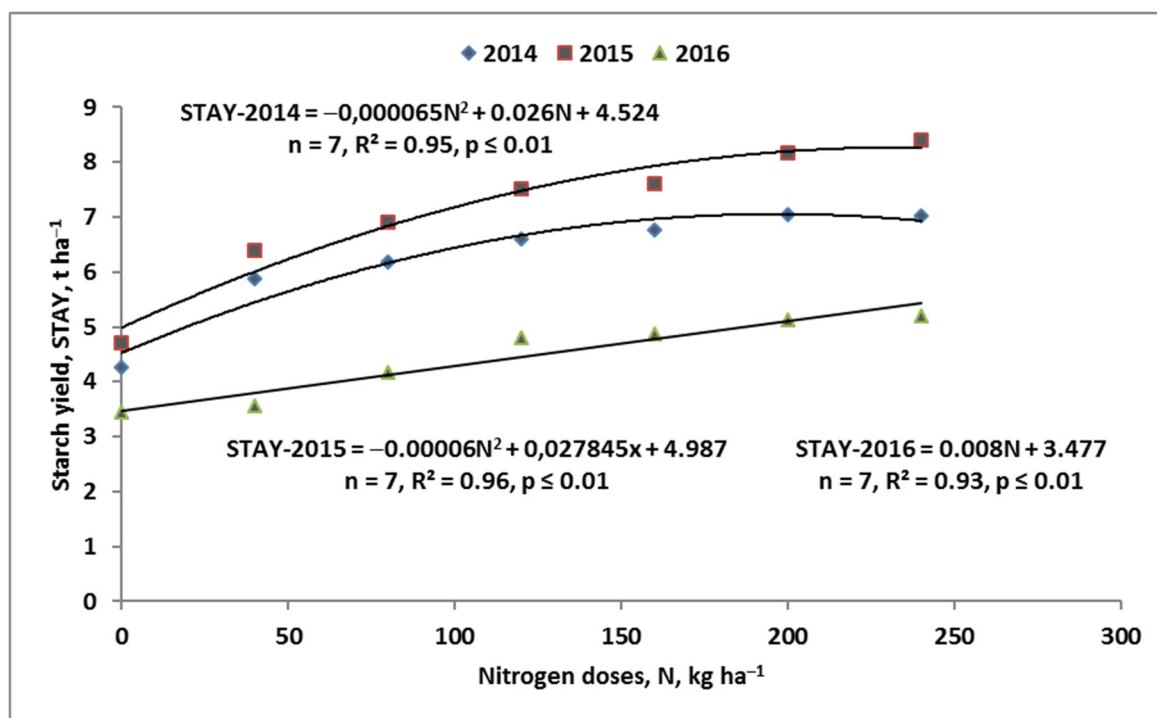


Figure S4. Regression models of starch yield of winter wheat response to doses of applied nitrogen.

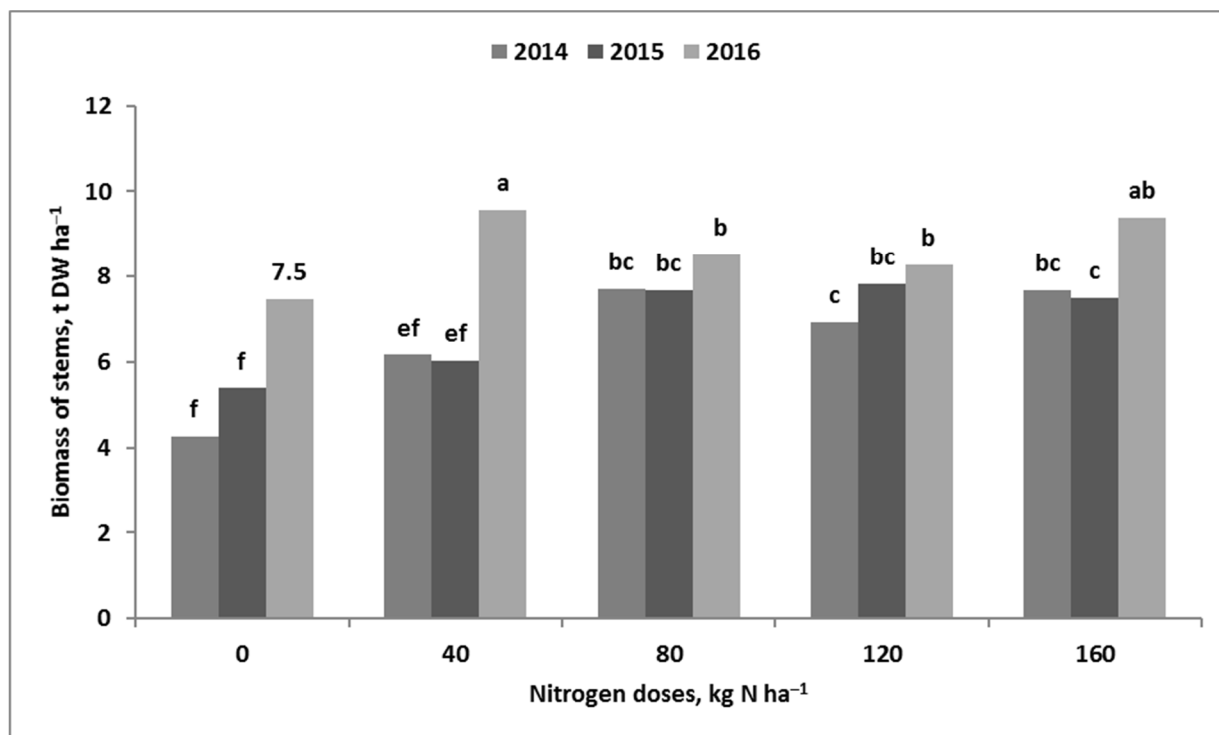


Figure S5. Effect of increasing nitrogen doses in subsequent years of studies on biomass of winter wheat at full flowering.

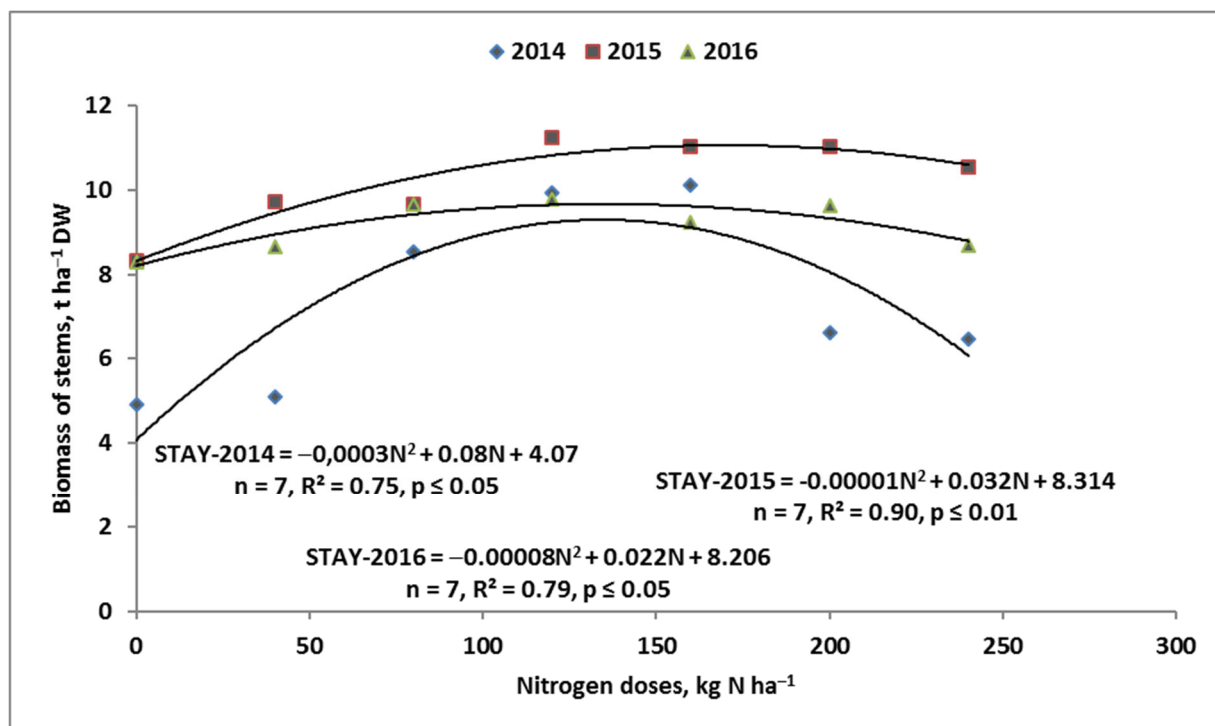


Figure S6. Regression models of winter wheat biomass at full flowering response to doses of applied nitrogen.

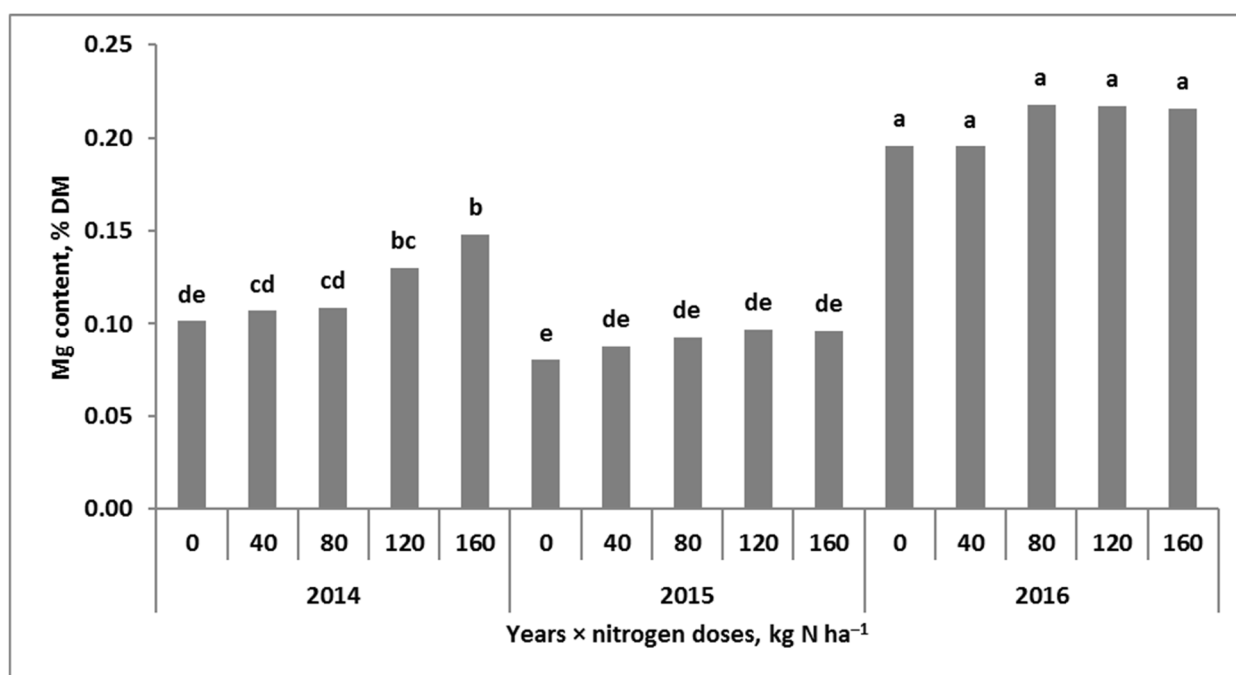


Figure S7. Effect of increasing nitrogen doses in subsequent years of studies on magnesium content in leaves of winter wheat at full flowering.

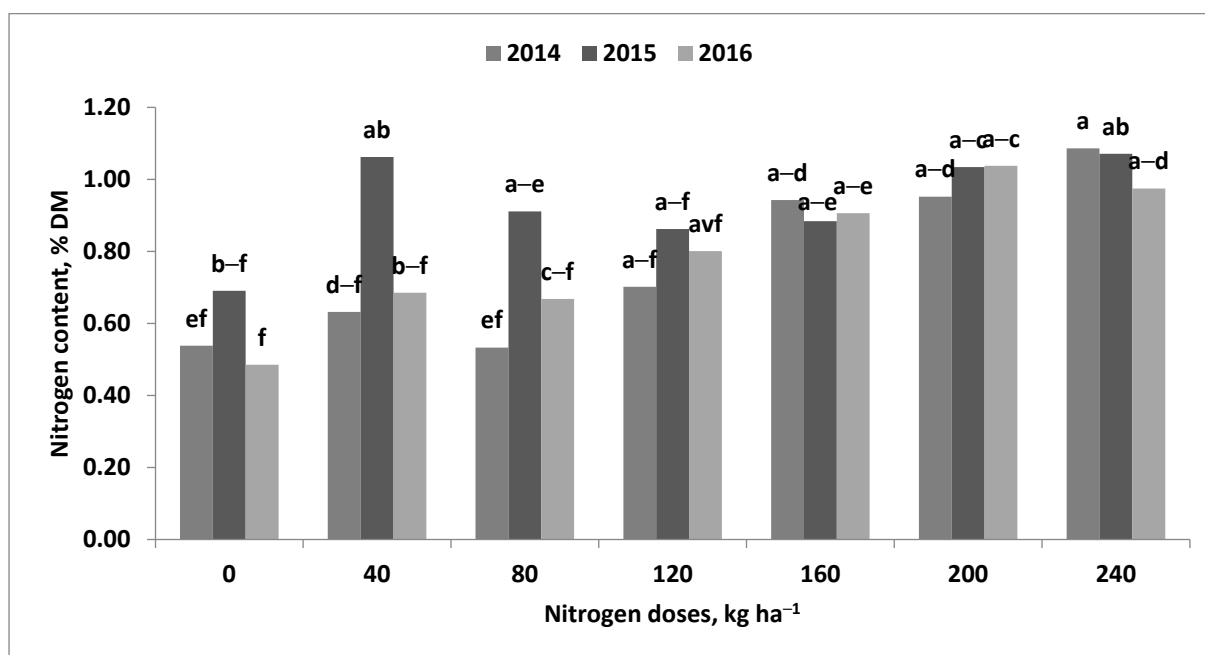


Figure S8. Effect of increasing nitrogen doses in subsequent years of studies on nitrogen content in stems of winter wheat at full flowering.

Table S1. Correlation matrix between winter wheat traits at the beginning of the full flowering (BBCH 65) and grain yield, n = 14.

Traits	ST65	EA65	TB65	CP	GL	STA	CPY	GLY	STAY	GY
LE65	0.81***	0.58**	0.92***	0.80***	0.81***	-0.81***	0.65**	0.71***	0.30	0.35
ST65	1.00	0.30	0.88***	0.37	0.37	-0.37	0.48*	0.49*	0.38	0.40
EA65		1.00	0.72***	0.76***	0.75***	-0.75***	-0.02	0.06	-0.44*	-0.38
TB65			1.00	0.70***	0.70***	-0.70***	0.40	0.45*	0.09	0.14
CP				1.00	1.00***	-0.99***	0.52*	0.60**	0.01	0.08
GL					1.00	-0.99***	0.51*	0.60**	0.01	0.08
STA						1.00	-0.56**	-0.64***	-0.06	-0.14
CPY							1.00	0.99***	0.85***	0.89***
GLY								1.00	0.79***	0.84***
STAY									1.00***	

***, **, * indicate significant differences between wheat traits at $p < 0.001$, $p < 0.010$, and $p < 0.05$, respectively. Legend: CP, GL, STA – content of total proteins, gluten starch; CPY, GLY, STAY – yield of total proteins, gluten, starch; GY – grain yield up to the N dose of 160 kg N ha⁻¹.

Table S2. Correlation matrix between winter wheat traits at the beginning of the booting stage (BBCH 40) and grain yield, n = 10.

Traits	ST	TB	CP	GL	STA	CPY	GLY	STAY	GY
LE	0.83***	0.91***	0.69***	0.69***	-0.68***	0.38**	0.45***	0.04	0.08
ST	1.00	0.99**	0.70***	0.69***	-0.70***	0.26*	0.32*	-0.08	-0.04
TB		1.00	0.73***	0.71***	-0.72***	0.31*	0.37	-0.05	-0.01
CP			1.00	0.99***	-0.99***	0.36**	0.47***	-0.18	-0.11
GL				1.00	-0.98***	0.36**	0.48***	-0.17	-0.11
STA					1.00	-0.41**	-0.52***	0.12	0.05
CPY						1.00	0.99***	0.85***	0.88***
GLY							1.00	0.77***	0.81***
STAY								1.00	1.00***

***, **, * indicate significant differences between wheat traits at $p < 0.001$, $p < 0.010$, and $p < 0.05$, respectively. Legend: CP, GL, STA – content of total proteins, gluten starch; CPY, GLY, STAY – yield of total proteins, gluten, starch; GY – grain yield up to the N dose of 160 kg N ha⁻¹.

Table S3. Correlation matrix between nutrient contents in leaves and quantitative and qualitative traits of winter wheat at the beginning of booting (BBCH 40), n = 10.

Traits	P	K	Mg	Ca	Fe	Mn	Zn	Cu	LE	ST	TB	CP	GL	STA	CPY	GLY	STAY	GY
N	0.10	0.36	0.23	0.57*	0.31	0.02	0.89***	0.89***	0.83***	0.75**	0.79***	0.84***	0.85***	-0.86***	0.70**	0.79***	0.26	0.32
P	1.00	0.90***	0.70**	0.49	0.59*	0.91***	0.41	-0.12	0.22	0.28	0.30	0.17	0.12	-0.26	0.30	0.26	0.23	0.25
K		1.00	0.75**	0.64*	0.56*	0.85***	0.60*	0.11	0.37	0.42	0.41	0.43	0.38	-0.52*	0.42	0.42	0.18	0.22
Mg			1.000	0.89**	-0.03	0.47	0.38	-0.08	0.45	0.58*	0.56*	0.59*	0.55*	-0.63*	-0.11	-0.05	-0.41	-0.38
Ca				1.00	-0.05	0.27	0.61*	0.27	0.74**	0.78**	0.78**	0.85***	0.82***	-0.87***	0.09	0.19	-0.35	-0.30
Fe					1.00	0.70**	0.50	0.32	0.15	0.06	0.08	-0.05	-0.06	-0.04	0.80	0.74**	0.84***	0.85***
Mn						1.00	0.37	-0.13	0.09	0.05	0.06	0.01	-0.03	-0.11	0.41	0.36	0.41	0.43
Zn							1.00	0.80***	0.79***	0.70**	0.74**	0.80***	0.80***	-0.84***	0.76**	0.83***	0.34	0.40
Cu								1.0	0.67**	0.59*	0.62*	0.65**	0.68**	-0.65**	0.72**	0.79***	0.38	0.43

***, **, * indicate significant differences between wheat traits at $p < 0.001$, $p < 0.010$, and $p < 0.05$, respectively.

Table S4. Components of path analysis of the grain yield response to the content of nutrients in leaves of winter wheat at the onset of booting (BBCH 40), n = 10.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.32	0.43		0.05	-0.10	-0.21	+0.12	+0.07	+0.01	-0.24	+0.18
P	0.27	0.62	+0.37		-0.24	-0.66	+0.10	+0.14	+0.41	-0.11	-0.03
K	0.22	-0.27	+0.15	+0.55		-0.71	+0.13	+0.14	+0.37	-0.16	+0.02
Mg	-0.41	-0.97	+0.09	+0.41	-0.20		+0.19	-0.01	+0.20	-0.10	-0.02
Ca	-0.29	0.21	+0.25	+0.29	-0.17	-0.86		-0.01	+0.12	-0.16	+0.05
Fe	0.85	0.22	+0.14	+0.37	-0.15	+0.04	-0.01		+0.31	-0.13	+0.06
Mn	0.43	0.44	+0.01	+0.57	-0.23	-0.45	+0.06	+0.16		-0.10	-0.03
Zn	0.39	-0.27	+0.38	+0.25	-0.16	-0.37	+0.12	+0.11	+0.17		+0.16
Cu	0.43	0.20	+0.38	-0.08	-0.03	+0.10	+0.06	+0.07	-0.06	-0.21	

R² = 0.94

Table S5. Components of path analysis of the gluten content response to the content of nutrients in leaves of winter wheat at the onset of booting (BBCH 40), n = 10.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.85	−0.11		−0.02	+0.07	+0.03	+0.16	−0.04	−0.01	+0.74	−0.17
P	0.10	−0.27	+0.01		+0.17	+0.10	+0.12	−0.08	−0.30	+0.33	+0.02
K	0.38	0.18	+0.04	−0.25		+0.11	+0.17	−0.08	−0.28	+0.50	−0.02
Mg	0.55	0.15	+0.02	−0.18	+0.13		+0.23	+0.01	−0.15	+0.32	+0.02
Ca	0.82	0.26	+0.06	−0.13	+0.12	+0.13		+0.01	−0.09	+0.51	−0.05
Fe	−0.06	−0.14	+0.03	−0.16	+0.10	+0.01	−0.02		−0.23	+0.41	−0.06
Mn	−0.04	−0.33	+0.01	−0.25	+0.16	+0.07	+0.07	−0.09		+0.31	+0.03
Zn	0.81	0.83	+0.09	−0.11	+0.11	+0.06	+0.16	−0.07	−0.12		
Cu	0.68	−0.19	+0.09	+0.03	+0.02	+0.02	+0.07	−0.04	+0.05	+0.66	

R² = 0.995

Table S6. Components of path analysis of the gluten yield response to the content of nutrients in leaves of winter wheat at the onset of booting (BBCH 40), n = 10.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.79	0.36		+0.02	+0.04	−0.20	+0.23	+0.06	+0.01	+0.34	−0.06
P	0.27	0.18	+0.03		+0.10	−0.61	+0.18	+0.11	+0.11	+0.15	+0.01
K	0.42	0.11	+0.13	+0.16		−0.68	+0.25	+0.10	+0.10	+0.23	−0.01
Mg	−0.08	−0.91	+0.08	+0.12	+0.08		+0.35	−0.01	+0.06	+0.15	+0.01
Ca	0.19	0.40	+0.21	+0.08	+0.07	−0.81		−0.01	+0.03	+0.23	−0.02
Fe	0.73	0.18	+0.11	+0.11	+0.06	+0.4	−0.03		+0.09	+0.20	−0.02
Mn	0.36	0.12	+0.01	+0.17	+0.10	+0.40	+0.11	+0.13		+0.14	+0.01
Zn	0.83	0.39	+0.32	+0.08	+0.07	−0.35	+0.24	+0.09	+0.05		−0.05
Cu	0.79	−0.07	+0.32	−0.02	+0.01	+0.09	+0.11	+0.06	−0.02	+0.31	

R² = 0.969

Table S7. Correlation matrix between nutrient contents in stems and quantitative and qualitative traits of winter wheat at the beginnig of booting (BBCH 40), n = 10.

Traits	P	K	Mg	Ca	Fe	Mn	Zn	Cu	LE	ST	TB	CP	GL	STA	CPY	GLY	STAY	GY
N	0.56*	0.61*	0.26	0.31	0.54*	-0.10	0.90***	0.84***	0.79***	0.58*	0.65**	0.66**	0.67**	-0.68**	0.79***	0.84***	0.45	0.50
P	1.00	0.67**	0.89***	0.50	0.08	0.14	0.76**	0.33	0.74**	0.75**	0.76**	0.83***	0.80***	-0.84***	0.15	0.24	-0.27	-0.22
K		1.00	0.37	0.87***	0.59*	0.67**	0.66**	0.19	0.52*	0.45	0.47	0.44	0.40	-0.52*	0.52*	0.52*	0.30	0.33
Mg			1.00	0.23	-0.32	0.01	0.52*	0.11	0.61*	0.70**	0.69**	0.81***	0.79***	-0.80***	-0.20	-0.09	-0.63*	-0.59*
Ca				1.00	0.55*	0.75**	0.33	-0.12	0.27	0.24	0.25	0.11	0.06	-0.19	0.26	0.22	0.22	0.23
Fe					1.00	0.42	0.44	0.40	0.15	0.01	0.05	-0.07	-0.07	-0.01	0.69**	0.63*	0.73**	0.74**
Mn						1.00	0.01	-0.45	-0.13	-0.09	-0.11	-0.18	-0.22	0.09	0.06	-0.01	0.16	0.15
Zn							1.00	0.76**	0.87***	0.75**	0.80***	0.84***	0.84***	-0.86***	0.67**	0.75**	0.24	0.29
Cu								1.00	0.68**	0.56*	0.60*	0.57*	0.59*	-0.57*	0.73**	0.78**	0.45	0.47

***0. **0. * indicate significant differences between wheat traits at $p < 0.0010$, $p < 0.010$, and $p < 0.050$, respectively.

Table S8. Components of path analysis of the grain yield response to the content of nutrients in stems of winter wheat at the onset of booting (BBCH 40), n = 10.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.50	−0.45		−0.02	+0.51	−0.31	+0.10	−0.26	+0.01	+0.21	+0.72
P	−0.23	−0.04	−0.25		+0.56	−1.03	+0.12	−0.03	−0.01	+0.18	+0.27
K	0.34	0.85	−0.28	−0.03		−0.43	+0.22	−0.29	−0.03	+0.15	+0.16
Mg	−0.58	−1.16	−0.12	−0.03	+0.31		+0.05	+0.16	+0.01	+0.12	+0.10
Ca	0.34	0.27	−0.17	−0.02	+0.69	−0.19		−0.29	−0.03	+0.09	−0.02
Fe	0.74	−0.49	−0.24	−0.01	+0.50	+0.38	+0.16		−0.02	+0.10	+0.34
Mn	0.16	−0.05	+0.05	−0.01	+0.56	+0.01	+0.18	−0.20		+0.04	−0.39
Zn	0.29	0.23	−0.41	−0.03	+0.56	−0.61	+0.11	−0.21	−0.01		+0.65
Cu	0.49	0.85	−0.38	−0.12	+0.16	−0.13	−0.01	−0.20	+0.02	+0.18	

R² = 0.969

Table S9. Components of path analysis of the gluten content response to the content of nutrients in stems of winter wheat at the onset of booting (BBCH 40), n = 10.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.67	-0.36		-0.47	+0.39	+0.22	-0.01	-0.10	+0.05	+0.97	-0.02
P	0.79	-0.85	-0.20		+0.43	+0.71	-0.01	-0.01	-0.07	+0.81	-0.01
K	0.40	0.64	-0.22	-0.57		+0.30	-0.01	-0.10	-0.34	+0.71	-0.01
Mg	0.80	0.80	-0.10	-0.76	+0.24		-0.01	+0.06	+0.01	+0.56	-0.01
Ca	0.09	-0.01	-0.13	-0.39	+0.52	+0.13		-0.11	-0.35	+0.43	+0.01
Fe	-0.08	-0.18	-0.19	-0.06	+0.38	-0.26	-0.01		-0.22	+0.47	-0.01
Mn	-0.23	-0.51	+0.04	-0.12	+0.42	-0.01	-0.01	-0.07		+0.02	+0.01
Zn	0.84	1.07	-0.33	-0.64	+0.42	+0.42	-0.01	-0.08	-0.01		-0.02
Cu	0.59	-0.03	-0.30	-0.27	0.12	+0.09	-0.01	-0.07	+0.23	+0.82	

R² = 0.997**Table S10.** Components of path analysis of the gluten yield response to the content of nutrients in stems of winter wheat at the onset of booting (BBCH 40), n = 10.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.85	-0.53		-0.37	+0.69	-0.13	+0.06	-0.23	+0.04	+0.84	+0.47
P	0.23	-0.67	-0.29		+0.76	-0.43	+0.07	-0.03	-0.06	+0.70	+0.18
K	0.52	1.14	-0.32	-0.45		-0.18	+0.12	-0.25	-0.27	+0.62	+0.11
Mg	-0.08	-0.48	-0.14	-0.60	+0.42		+0.02	+0.14	+0.01	+0.49	+0.06
Ca	0.32	0.15	-0.19	-0.31	+0.93	-0.08		-0.26	-0.27	+0.37	-0.01
Fe	0.63	-0.43	-0.28	-0.04	+0.67	+0.16	+0.09		-0.17	+0.41	+0.23
Mn	-0.01	-0.40	+0.05	-0.10	+0.76	+0.01	+0.10	-0.18		+0.01	-0.25
Zn	0.75	0.93	-0.47	-0.50	+0.75	-0.25	+0.06	-0.19	-0.01		+0.43
Cu	0.79	0.56	-0.44	-0.21	+0.22	-0.05	-0.01	-0.18	+0.18	+0.71	

R² = 0.948

Table S11. Correlation matrix between nutrient contents in the flag leaf and quantitative and qualitative traits of winter wheat at full blum (BBCH 65), n = 14.

Trait	P	K	Mg	Ca	Fe	Mn	Zn	Cu	SPAD	GY	CP	GL	STA	CPY	GLY	STAY
N	0.37	0.52*	-0.25	0.10	0.38	-0.27	0.45*	0.69***	0.61**	0.05	0.92***	0.92***	-0.91***	0.47*	0.55**	-0.02
P	1.00	0.23	0.62**	-0.33	0.8***	0.62**	-0.16	-0.07	0.57**	0.06	0.40	0.38	-0.45*	0.21	0.23	0.02
K		1.00	-0.37	0.74**	0.25	0.03	0.81***	0.76***	0.75	0.76***	0.50	0.50	-0.53	0.87	0.87	0.72
Mg			1.00	-0.59**	0.62**	0.79***	-0.58**	-0.59**	0.11	-0.15	-0.08	-0.12	0.04	-0.17	-0.19	-0.15
Ca				1.00	-0.26	-0.12	0.86***	0.64**	0.32	0.80***	0.03	0.04	-0.05	0.72***	0.68**	0.80***
Fe					1.00	0.65**	-0.11	-0.01	0.71***	0.21	0.52**	0.49*	-0.59**	0.39	0.41	0.17
Mn							-0.24	-0.42	0.32	0.36	-0.19	-0.22	0.12	0.22	0.17	0.37
Zn							1.00	0.80***	0.45*	0.62**	0.39	0.40	-0.40	0.73***	0.74***	0.59**
Cu								1.00	0.59**	0.44	0.70***	0.71***	-0.69***	0.69***	0.74***	0.39

***, **, * indicate significant differences between wheat traits at $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively.

Table S12. Components of path analysis of the grain yield response to the content of nutrients in the flag leaf of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.05	-0.10		-0.07	+0.16	+0.02	+0.08	+0.13	-0.10	-0.13	+0.07
P	0.03	-0.19	-0.04		+0.07	-0.04	-0.28	+0.27	+0.21	+0.05	-0.01
K	0.76	0.31	-0.05	-0.04		+0.03	+0.59	+0.08	+0.01	-0.24	+0.07
Mg	-0.16	-0.07	+0.22	-0.12	-0.12		-0.48	+0.21	+0.27	+0.17	-0.05
Ca	0.80	0.80	-0.01	+0.07	+0.23	+0.04		-0.09	-0.04	-0.26	+0.06
Fe	0.21	0.33	-0.04	-0.16	+0.08	-0.05	-0.22		+0.23	+0.03	-0.01
Mn	0.36	0.35	+0.03	-0.11	+0.01	-0.06	-0.10	+0.21		+0.07	-0.04
Zn	0.63	-0.30	-0.05	+0.03	+0.25	+0.04	+0.69	-0.04	-0.08		+0.08
Cu	0.44	0.10	-0.07	+0.02	+0.24	+0.04	+0.52	-0.01	-0.15	-0.25	

R² = 0.931

Table S13. Components of path analysis of the gluten content response to the content of nutrients in the flag leaf of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.93	0.42		−0.06	+0.06	−0.05	−0.04	+0.13	+0.06	+0.07	+0.33
P	0.39	−0.15	+0.16		+0.03	+0.15	+0.14	+0.27	−0.14	−0.03	−0.04
K	0.50	0.12	+0.22	−0.03		−0.09	−0.29	+0.09	−0.01	+0.13	+0.36
Mg	−0.07	0.24	−0.09	−0.09	−0.05		+0.23	+0.21	−0.18	−0.09	−0.27
Ca	0.04	−0.39	+0.04	+0.05	+0.09	−0.14		−0.09	+0.03	+0.14	+0.31
Fe	0.49	0.33	+0.16	−0.12	+0.03	+0.15	+0.10		−0.15	−0.02	−0.01
Mn	−0.22	−0.23	−0.11	−0.09	+0.01	+0.19	+0.05	+0.21		−0.04	−0.20
Zn	0.40	0.16	+0.19	+0.03	+0.10	−0.14	−0.33	−0.04	+0.05		+0.38
Cu	0.71	0.48	+0.29	+0.01	+0.09	−0.13	−0.25	−0.01	+0.10	+0.13	

R² = 0.974**Table S14.** Components of path analysis of the gluten content response to the content of nutrients in the flag leaf of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.55	0.31		−0.09	+0.12	−0.03	+0.06	+0.13	−0.05	−0.07	+0.18
P	0.22	−0.23	+0.12		+0.05	+0.09	−0.20	+0.28	+0.11	+0.03	−0.20
K	0.87	0.23	+0.16	−0.05		−0.05	+0.42	+0.09	+0.01	−0.13	+0.20
Mg	−0.18	0.15	−0.07	−0.14	−0.08		−0.34	+0.22	+0.15	+0.09	−0.15
Ca	0.68	0.57	+0.03	+0.08	+0.17	−0.09		−0.09	−0.02	−0.14	+0.17
Fe	0.41	0.35	+0.12	−0.19	+0.06	+0.09	−0.15		+0.12	+0.02	−0.01
Mn	0.17	0.19	−0.08	−0.14	+0.01	+0.11	−0.07	+0.22		+0.04	−0.11
Zn	0.74	−0.16	+0.14	+0.04	+0.19	−0.08	+0.49	−0.04	−0.05		+0.21
Cu	0.74	0.26	+0.21	+0.02	+0.17	−0.08	+0.37	−0.01	−0.08	−0.13	

R² = 0.930

Table S15. Correlation matrix between nutrient contents in leaves and quantitative and qualitative traits of winter wheat at full blum (BBCH 65), n = 14.

Trait	P	K	Mg	Ca	Fe	Mn	Zn	Cu	GY	CP	GL	STA	CPY	GLY	STAY
N	0.78***	0.78***	-0.48*	-0.42	0.89***	0.01	0.35	0.15	-0.11	0.90***	0.89***	-0.90***	0.28	0.37	-0.18
P	1.00	0.39	-0.41	-0.73***	0.81***	0.29	-0.14	-0.36	-0.31	0.59**	0.57**	-0.60**	-0.02	0.03	-0.35
K		1.00	-0.15	0.13	0.71***	-0.02	0.74***	0.60**	0.36	0.90***	0.90***	-0.91***	0.70***	0.76***	0.30
Mg			1.00	0.67**	-0.36	0.63**	0.18	0.10	0.79**	-0.38	-0.39	0.33	0.53*	0.44*	0.82***
Ca				1.00	-0.37	0.02	0.58**	0.67**	0.82***	-0.18	-0.17	0.16	0.63**	0.58**	0.84***
Fe					1.00	0.11	0.34	0.13	-0.03	0.84***	0.83***	-0.84***	0.33	0.40	-0.09
Mn						1.00	-0.14	-0.40	0.46*	-0.12	-0.13	0.05	0.33	0.27	0.47*
Zn							1.00	0.93***	0.61**	0.63**	0.64**	-0.64**	0.83***	0.86**	0.56**
Cu								1.00	0.53*	0.48*	0.50*	-0.46*	0.69*	0.72***	0.50*

***0. **0. * indicate significant differences between wheat traits at $p < 0.0010$, $p < 0.010$, and $p < 0.050$, respectively.

Table S16. Components of path analysis of the grain yield response to the content of nutrients in leaves of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	-0.11	0.05		+0.09	+0.19	-0.14	-0.23	-0.05	+0.01	-0.09	+0.06
P	-0.35	0.12	+0.04		+0.09	-0.13	-0.42	-0.04	+0.10	+0.04	-0.15
K	0.36	0.25	+0.04	+0.05		-0.04	+0.07	-0.04	-0.01	-0.19	+0.23
Mg	0.80	0.30	-0.02	-0.05	-0.03		+0.38	+0.02	+0.22	-0.05	+0.05
Ca	0.82	0.56	-0.02	-0.09	+0.03	+0.20		+0.02	+0.01	-0.15	+0.26
Fe	-0.03	-0.05	+0.05	+0.10	+0.18	-0.10	-0.21		+0.04	-0.09	-0.05
Mn	0.46	0.35	+0.01	+0.03	-0.01	+0.19	+0.01	-0.01		+0.03	-0.15
Zn	0.61	-0.25	-0.02	-0.02	+0.18	+0.06	+0.33	-0.02	-0.05		+0.36
Cu	0.53	0.38	-0.05	-0.05	+0.15	+0.04	+0.38	-0.01	-0.14	-0.23	

R² = 0.954

Table S17. Components of path analysis of the gluten content response to the content of nutrients in leaves of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.90	0.25		0.14	+0.25	−0.04	+0.19	−0.02	−0.01	+0.04	+0.08
P	0.56	0.19	+0.19		+0.12	−0.04	+0.35	−0.02	−0.01	−0.02	−0.20
K	0.90	0.32	+0.20	+0.07		−0.01	−0.06	−0.02	+0.01	+0.01	+0.32
Mg	−0.37	0.09	−0.12	−0.08	−0.04		−0.31	+0.01	−0.01	+0.02	+0.06
Ca	−0.17	−0.46	−0.10	−0.14	+0.04	+0.06		+0.01	−0.01	+0.07	+0.35
Fe	0.83	−0.02	+0.22	+0.15	+0.23	−0.03	+0.17		−0.01	+0.04	+0.07
Mn	−0.15	−0.01	+0.01	+0.05	−0.01	+0.06	−0.01	−0.01		−0.02	−0.21
Zn	0.64	0.12	+0.09	−0.03	+0.24	+0.02	−0.27	−0.01	+0.01		+0.48
Cu	0.50	0.52	+0.04	−0.07	+0.19	+0.01	−0.31	−0.01	+0.01	+0.11	

R² = 0.978**Table S18.** Components of path analysis of the gluten yield response to the content of nutrients in leaves of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.37	0.12		+0.16	+0.24	−0.17	−0.01	−0.06	+0.01	+0.01	+0.10
P	−0.01	0.21	+0.09		+0.11	−0.16	−0.03	−0.06	+0.07	−0.01	−0.24
K	0.76	0.31	+0.09	+0.08		−0.05	+0.01	−0.05	−0.01	+0.01	+0.37
Mg	0.46	0.37	−0.05	−0.09	−0.04		+0.02	+0.02	+0.15	+0.01	+0.07
Ca	0.58	0.03	−0.05	−0.16	−0.04	+0.24		+0.03	+0.01	+0.01	+0.42
Fe	0.40	−0.07	+0.10	+0.17	+0.22	−0.13	−0.01		+0.03	+0.01	+0.09
Mn	0.27	0.24	+0.01	+0.06	−0.01	+0.23	+0.01	−0.01		−0.01	−0.25
Zn	0.86	0.02	+0.04	−0.04	+0.23	+0.07	+0.02	−0.02	−0.03		+0.58
Cu	0.72	0.62	+0.02	−0.08	+0.18	+0.04	+0.02	−0.01	−0.10	+0.02	

R² = 0.959

Table S19. Correlation matrix between nutrient contents in the stem and quantitative and qualitative traits of winter wheat at full blum (BBCH 65), n = 14.

Trait	P	K	Mg	Ca	Fe	Mn	Zn	Cu	GY	CP	GL	STA	CPY	GLY	STAY
N	0.42	0.47*	-0.07	0.41	0.62**	-0.26	0.24	0.73***	0.66***	0.53*	0.54*	-0.53*	0.79***	0.81***	0.62**
P	1.00	0.90***	0.46*	-0.24	0.14	0.52*	0.79***	0.62**	0.25	0.46*	0.43*	-0.50*	0.42	0.43*	0.21
K		1.00	0.29	0.01	0.23	0.56**	0.84**	0.72***	0.46*	0.38	0.36	-0.44*	0.56**	0.56**	0.43
Mg			1.00	-0.51*	-0.42	0.10	0.04	-0.16	-0.53*	0.67**	0.66**	-0.67**	-0.17	-0.09	-0.59**
Ca				1.00	0.71***	-0.50*	-0.17	0.44*	0.65**	0.15	0.16	-0.17	0.65**	0.64**	0.64**
Fe					1.00	-0.29	0.17	0.68**	0.75***	0.25	0.27	-0.28	0.77***	0.76***	0.74***
Mn						1.00	0.81***	0.13	0.01	-0.34	-0.37	0.30	-0.14	-0.19	0.04
Zn							1.00	0.67**	0.46*	0.01	-0.02	-0.06	0.40	0.36	0.48*
Cu								1.00	0.82***	0.35	0.34	-0.40	0.87***	0.85***	0.79***

***0. **0. * indicate significant differences between wheat traits at $p < 0.0010$, $p < 0.010$, and $p < 0.050$, respectively.

Table S20. Components of path analysis of the grain yield response to the content of nutrients in the stem of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.65	0.19		−0.17	+0.15	+0.02	+0.07	+0.09	−0.11	+0.20	+0.01
P	0.24	−0.41	+0.08		+0.27	−0.13	−0.04	+0.03	−0.21	+0.64	+0.01
K	0.46	0.32	+0.09	−0.35		−0.09	−0.01	+0.03	−0.24	+0.69	+0.01
Mg	−0.53	−0.29	−0.01	−0.18	+0.09		−0.07	−0.06	−0.05	+0.04	−0.01
Ca	0.61	0.15	+0.09	+0.11	−0.01	+0.13		+0.10	+0.24	−0.19	+0.01
Fe	0.75	0.14	+0.12	−0.73	+0.08	+0.12	+0.10		+0.13	+0.14	+0.01
Mn	0.02	−0.43	−0.05	−0.19	+0.18	−0.3	−0.08	−0.04		+0.67	+0.01
Zn	0.47	0.82	+0.05	−0.31	+0.27	−0.01	−0.04	+0.02	−0.35		+0.01
Cu	0.82	0.01	0.14	−0.25	+0.23	+0.05	+0.05	+0.10	−0.06	+0.55	

R² = 0.903

Table S21. Components of path analysis of the gluten content response to the content of nutrients in the stem of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.55	0.17		+0.03	−0.10	−0.05	+0.16	+0.07	+0.12	+0.09	+0.06
P	0.44	0.08	+0.07		−0.19	+0.42	−0.10	+0.02	−0.22	+0.31	+0.05
K	0.36	−0.22	+0.08	+0.07		+0.28	−0.02	+0.02	−0.25	+0.33	+0.06
Mg	0.67	0.95	−0.01	+0.04	−0.06		−0.16	−0.04	−0.05	+0.02	−0.01
Ca	0.23	0.36	+0.08	−0.02	+0.01	−0.44		+0.07	+0.25	−0.09	+0.03
Fe	0.27	0.10	+0.11	+0.01	−0.05	−0.40	+0.24		+0.13	+0.07	+0.05
Mn	−0.38	−0.45	−0.05	+0.04	−0.12	+0.10	−0.20	−0.03		+0.32	+0.01
Zn	−0.02	0.40	+0.04	+0.06	−0.18	+0.04	−0.08	+0.02	−0.36		+0.05
Cu	0.35	0.08	+0.13	+0.05	−0.16	−0.15	+0.07	+0.07	−0.06	+0.26	

R² = 0.985**Table S22.** Components of path analysis of the gluten yield response to the content of nutrients in the stem of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effect								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.80	0.10		−0.09	+0.02	−0.01	+0.16	+0.09	+0.15	+0.20	+0.10
P	0.43	−0.20	+0.08		+0.04	+0.12	−0.10	+0.03	−0.28	+0.66	+0.09
K	0.55	0.04	+0.09	−0.18		+0.08	−0.02	+0.03	−0.32	+0.74	+0.10
Mg	−0.08	0.28	−0.01	−0.09	+0.01		−0.017	−0.06	−0.06	+0.04	−0.02
Ca	0.63	0.36	+0.08	+0.06	−0.01	−0.13		+0.08	+0.31	−0.20	+0.05
Fe	0.76	0.14	+0.11	−0.04	+0.01	−0.12	+0.24		+0.17	+0.14	+0.10
Mn	−0.20	−0.57	−0.05	−0.10	+0.02	+0.03	−0.20	−0.04		+0.69	+0.02
Zn	0.36	0.86	+0.04	−0.16	+0.04	+0.01	−0.08	+0.02	−0.46		+0.10
Cu	0.85	0.14	+0.13	−0.13	+0.03	−0.05	−0.13	+0.10	−0.08	+0.57	

R² = 0.934

Table S23. Correlation matrix between nutrient contents in the ear and quantitative and qualitative traits of winter wheat at full blum (BBCH 65), n = 14.

Trait	P	K	Mg	Ca	Fe	Mn	Zn	Cu	GY	CP	GL	STA	CPY	GLY
N	-0.23	0.23	-0.70***	0.94***	-0.02	-0.76***	-0.22	0.38	0.65**	0.15	0.17	-0.14	0.63**	0.62**
P	1.00	-0.63**	0.79***	-0.20	0.64**	0.11	-0.21	0.07	-0.41	0.69***	0.70***	-0.66**	-0.06	0.02
K		1.00	-0.67**	0.11	-0.10	0.28	0.78**	-0.12	0.76**	-0.41	-0.42	0.34	0.48*	0.39
Mg			1.00	-0.67**	0.45*	0.45*	-0.11	-0.12	-0.67**	0.52*	0.51*	-0.50*	-0.35	-0.27
Ca				1.00	-0.03	-0.82***	-0.38	0.47*	0.52*	0.10	0.12	-0.07	0.50*	0.50*
Fe					1.00	0.20	0.18	0.23	0.08	0.71***	0.71***	-0.71***	0.39	0.45*
Mn						1.00	0.75***	-0.43**	-0.07	-0.03	-0.06	-0.01	-0.08	-0.10
Zn							1.00	-0.32	0.49*	-0.13	-0.16	0.07	0.35	0.30
Cu								1.00	0.17	0.22	0.25	-0.18	0.22	0.24

***0. **0. * indicate significant differences between wheat traits at $p < 0.0010$, $p < 0.010$, and $p < 0.050$, respectively.

Table S24. Components of path analysis of the grain yield response to the content of nutrients in the ear of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.65	1.11		+0.05	+0.22	-0.63	+0.11	+0.01	-0.26	+0.03	+0.02
P	-0.40	-0.27	-0.22		-0.59	+0.69	-0.03	-0.05	+0.03	+0.03	+0.01
K	0.77	0.97	+0.25	+0.16		-0.62	+0.01	+0.01	+0.10	-0.10	-0.01
Mg	-0.68	0.91	-0.78	-0.20	-0.66		-0.08	-0.03	+0.15	+0.02	-0.01
Ca	0.42	0.13	+0.93	+0.05	+0.01	-0.53		+0.01	-0.25	+0.05	+0.03
Fe	0.08	-0.07	-0.02	-0.17	-0.10	+0.39	-0.01		+0.07	-0.02	+0.01
Mn	-0.08	0.35	-0.84	-0.02	+0.28	+0.39	-0.09	-0.02		-0.10	-0.02
Zn	0.49	-0.13	-0.25	+0.06	+0.76	-0.12	-0.05	-0.01	+0.26		-0.02
Cu	0.18	0.05	+0.42	-0.02	-0.12	-0.10	+0.06	-0.02	-0.15	+0.04	

R² = 0.921

Table S25. Components of path analysis of the gluten content response to the content of nutrients in the ear of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.17	1.71		+0.08	+0.02	-1.02	-0.16	-0.01	-0.56	+0.10	-0.01
P	0.69	-0.38	-0.35		-0.06	+1.11	+0.04	+0.19	+0.06	+0.09	-0.01
K	-0.42	0.10	+0.39	+0.23		-0.99	-0.01	-0.03	+0.21	-0.34	+0.01
Mg	0.50	1.45	-1.20	-0.29	-0.07		+0.11	+0.13	+0.32	+0.06	+0.01
Ca	0.09	-0.19	+1.45	+0.08	+0.01	-0.85		-0.02	-0.53	+0.18	-0.01
Fe	0.71	0.29	-0.04	-0.25	-0.01	+0.63	+0.01		+0.15	-0.08	-0.01
Mn	-0.06	0.73	-1.30	-0.03	+0.03	+0.62	+0.14	+0.06		-0.32	+0.01
Zn	-0.16	-0.43	-0.38	+0.08	+0.08	-0.20	+0.08	+0.05	+0.55		+0.01
Cu	0.25	-0.01	+0.66	-0.03	-0.01	-0.16	-0.09	+0.07	-0.32	+0.14	

R² = 0.920

Table S26. Components of path analysis of the gluten yield response to the content of nutrients in the ear of winter wheat at full blum (BBCH 65), n = 14.

Nutrient	Correlation coefficient	Path coefficient	Indirect effects								
			N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
N	0.62	1.84		+0.10	+0.18	-1.02	-0.02	-0.01	-0.56	+0.10	-0.01
P	0.02	-0.48	-0.37		-0.49	+1.10	+0.01	+0.11	+0.06	+0.09	-0.01
K	0.40	0.81	+0.42	+0.29		-0.99	-0.01	-0.02	+0.21	-0.33	+0.01
Mg	-0.29	1.45	-1.29	-0.36	-0.55		+0.01	+0.07	+0.32	+0.06	+0.01
Ca	0.39	-0.03	1.54	+0.10	+0.01	-0.84		-0.01	-0.53	+0.18	-0.01
Fe	0.44	0.17	-0.04	-0.31	-0.08	+0.63	+0.01		+0.15	-0.08	-0.01
Mn	-0.11	0.73	-1.39	-0.04	+0.23	+0.62	+0.02	+0.04		-0.32	+0.01
Zn	0.30	-0.43	-0.41	+0.10	+0.63	-0.19	+0.01	+0.03	+0.55		+0.01
Cu	0.25	-0.02	+0.71	-0.03	-0.10	-0.16	-0.01	+0.04	-0.32	+0.14	

R² = 0.885