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19 **Abstract**

20 The aim of this research was: (1) to assess the effect of an integrated cultivation system of
21 native durum wheat (6 variants), differentiated by a nitrogen fertilization dose (0, 80, 120 kg·ha⁻¹)
22 and growth regulator use (Medax 350 SC, with growth regulator – GR, without growth regulator –
23 WGR) on changes in selected quality parameters (protein, lipid, and starch contents; hardness;
24 color) and electrical parameters (conductive – Z and capacitive – C_p, C_s) of the grain; and (2) to
25 determine the correlations between the examined quality traits and electrical properties of the grain
26 to indicate the possibility of using a non-invasive electrical method to assess grain quality.

27 The grain of durum wheat cultivated in the six variants tested differed mainly in the starch and
28 lipid contents, which indicates the feasibility of tailored optimization of grain production. The
29 highest contents of starch and total lipids, and the highest grain hardness were obtained in the
30 cultivation variants GR+0N and WGR+0N, whereas the highest protein content – upon wheat
31 fertilization with 120N. The study demonstrated a different strength of the correlations between the
32 tested parameters depending on the cultivation method (WGR-GR; N: 0, 80, 120 kg·ha⁻¹). In the
33 WGR+0N variant (environmentally friendly), the strongest correlation between grain quality traits
34 and electrical properties was obtained for both the conductive (Z) and capacitive (C_p, C_s)
35 parameters in the entire analyzed range of current frequencies. The GR application during
36 cultivation hampers the possibility of using electrical parameters to assess grain quality. In turn, the
37 quality of the grain produced WGR can be effectively assessed using the Z, C_p, and C_s parameters
38 in the entire measuring frequency range (1kHz-1MHz), while in the variant with GR, only
39 impedance (Z), measured at high frequencies (100kHz, 1MHz) can be used.

40

41 **Keywords:** durum wheat grain; agrotechnical parameters; quality evaluation; electrical method,
42 impedance, electric capacity

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45 **Introduction**

46 Durum wheat (*Triticum durum* Desf.) occupies about 8% of the global acreage intended for
47 wheat cultivation, and its production accounts for approximately 5% of the global wheat harvest
48 (Colasuonno et al. 2019). It is cultivated in a dry and hot climate, where its grain yield is diminished
49 by water shortage. Spring durum wheat is mainly grown worldwide, as it is the oldest form of this
50 cereal. Winter forms, that had been developed from the spring forms, are cultivated in the South-
51 Eastern Europe. After 1960, durum wheat cultivation shifted from the Mediterranean region more to
52 the north of Europe. This was due to significant breeding progress and registration of varieties in
53 such countries as Austria, Germany, Hungary, Czech Republic and Poland (Banach et al. 2021;
54 Alemu, 2017; Kabbaj et al. 2017).

55 Due to its exceptional technological properties (hard endosperm and high contents of gluten
56 and carotenoids) and nutritional value, durum wheat grain is used to make top-quality pasta (Morris
57 et al. 2015, Xiao Fu et al. 2018, Colasuonno et al. 2019).

58 Durum wheat species may gain in importance in Poland due to the ongoing climate changes
59 coupled with breeding progress in its cultivation and growing interest expressed by the food
60 industry (Polish National List of the Research Center for Cultivar Testing 2021). The cultivation of
61 this demanding wheat species and its grain yield are largely affected by weather conditions (Żuk-
62 Gołaszewska et al. 2016, Semenov et al. 2014). Despite these impediments, breeding and agro-
63 engineering works are undertaken regarding different varieties of durum wheat to produce the most
64 optimal ones for the north-eastern Europe (Żuk-Gołaszewska et al. 2016, Polish National List of the
65 Research Center for Cultivar Testing 2021). So far, a few winter and spring durum wheat varieties
66 have been introduced into the Polish National List of Agricultural Plant Varieties, these being:
67 Komnata, Ceres, SM Metis, SM Eris, SM Tetyda as well as SMH 87, respectively (Polish National
68 List of Agricultural Plant Varieties 2018, Polish National List of the Research Center for Cultivar
69 Testing 2019, 2020). An additional course of action is the production of plants in an integrated
70 system, the aim of which is to draw from the potential of sustainable economic, ecological, and

71 social development. The exploitation of the first two potentials is feasible through the conscious use
72 of innovative technologies and manufacturing techniques, continuous improvement of
73 environmentally friendly management practices, as well as implementation of biological progress.
74 The production of high-quality cereal grains and grain yield size are expected to be ensured by,
75 among others, agro-engineering factors, including the level of nitrogen fertilization and the use of
76 growth regulators (Banach et al. 2021).

77 The development of automation in integrated agricultural production has spurred the interest in
78 the electrical properties of grain and cereal products. In addition to using them in electro-
79 engineering, as an alternative to the conventional methods for process monitoring and analysis in
80 storage and processing practice (Łuczycka 2009; Nelson & Bartley 2000, Nelson & Trabelsi 2017),
81 research is also carried out on the possibility of replacing analytical methods of grain quality
82 assessment with electrical methods. However, the complex morphological structure of kernels,
83 chemical composition (protein, lipids, starch, minerals), water content (in cells, intercellular spaces,
84 and membranes), and the lack of repeatability of dimensions and other physical features require in-
85 depth research in this area. Our previous research addressing the use of an RCC substitute model of
86 food products showed that the electrical parameters, i.e. impedance and admittance, can be used to
87 identify the variety, geometric features, and grain moisture content (Majewska et al. 2008); to
88 distinguish cereal species (wheat, barley, rye, triticale, oat) and varieties (Banach et al. 2017); and
89 to determine the extent of barley grain damage (Banach et al. 2020). Promising results concerning
90 the use of electrical features of grain/seed products for their quality assessment were also achieved
91 in the case soybean (Jha et al. 2011), maize (Bansal et al. 2015), and wheat flours (Łuczycka et al.
92 2013).

93 Summing up, it needs to be stated that a global trend can be observed regarding the increasing
94 consumption of products made of durum wheat grain, and also that the use of integrated agricultural
95 practices of cereal grain cultivation is conducive to modeling the quality of their production, and
96 finally that the need to develop a quick method for assessing the quality characteristics of grain

using environmentally friendly electrical methods is a current challenge for scientists. Therefore, a study was undertaken that aimed at:

- ✓ evaluating the effect of an integrated cultivation system, differing in a nitrogen fertilizer dose and growth regulator use (with/without, GR/WHR) on changes in the selected quality traits (protein, lipid, and starch contents; hardness; color) and electrical properties (conductive and capacitive) of the grain of native durum wheat;
- ✓ determining correlations between the analyzed quality traits and electrical properties of durum wheat grain to identify the feasibility of employing a non-invasive electrical method for grain quality assessment.

Material and methods

➤ *Cultivation of durum wheat in an integrated system*

The experimental material included grain of durum wheat var. SMH 87 derived from a field experiment established in the north-eastern Poland (53°40'N, 19°50'E) – harvest 2016. Durum wheat cultivation in an integrated system (6 variants) was differentiated by a nitrogen fertilization rate and use of a growth regulator Medax 350 S.C. (with/without growth regulator; GR/WGR) expected to prevent lodging (preventive action). Nitrogen was applied in three doses: no fertilization (0N), 80 kg·ha⁻¹ (80N), and 120 kg·ha⁻¹ (120N). A detailed description of the fertilization scheme was provided in our previous research (Banach et al. 2021). After harvest, grain was cleaned of physical impurities and seed coat residues. Ca. 500 g of the grain were collected to glass bottles from each cultivation variant, and the bottles were stored in the climatic chamber (Memmert, USA) at air temperature of 20±0.1°C. The grain intended for research had a standardized moisture content of 14±0.5% (PN-EN ISO 712:2012).

➤ *Determination of the selected chemical components of the grain*

The grain comminuted with a WZ-1 laboratory grinder (Sadkiewicz Instruments, Poland) was determined for the contents of: total protein – with the Kjeldahl's method (PN-EN ISO 20483:

2014-02), total lipids – with the Soxhlet’s method, and total starch – with the polarimetric method acc. to the methodology described by Krelowska-Kulas (1993). Determinations were performed in 6 replications for each component, and the results were expressed per % of dry matter (d.m.).

➤ *Hardness measurements*

Hardness of single kernels placed furrow-down on a table was measured using a Universal Testing Device (Instron 5942; Instron Corp., USA). A uniaxial compression test (flat-truncated cone, $\varnothing=12.6$ mm; speed of the working head, 10 mm/min) was performed to measure the maximum compression force ($F_{\max}$) needed to reach 50% grain deformation, in 16 replications for each of the 6 grain samples from cultivation variants tested. The results of the tests were analyzed using the computer software Bluehill II.

➤ *Color measurements*

Color measurements of the grain were made using a Hunter Miniscan XE Plus colorimeter (HunterLab, USA), set to collect spectral data with illuminant A/observer D65/10°. Before the measurements, the colorimeter was calibrated using a black and white ceramic plate. Grain color was determined in the CIELab scale, measuring lightness (L^*), redness (a^*), and yellowness (b^*), in 12 replications.

➤ *Electrical measurements*

Electrical measurements were performed using a measuring system composed of the following devices (Fig. 1):

- a measuring sensor – a glass container (internal dimensions: L: $88.80 \times$ D: $49.20 \times$ H: 76.20 mm) with flat electrodes made of acid-proof steel having the surface area of ca. 68 cm^2 , attached adjacent to two opposite longer container’s walls,
- a metal container with a water jacket connected to a thermostat (PolyScience, USA),
- an LCR meter, type E4980a (Agilent, USA) with a measuring attachment.

Fig 1. The measurement system used for electrical properties examination of the wheat grain (A): 1- LCR meter, type E4980a 2- thermostat; 3 – measuring glass cell with plate electrodes, 4- examined wheat; 5- water jacket; (B) the internal view of the measuring cell with sample, water jacket and connecting cables

Before measurements, the experimental material with a standardized moisture content of $14 \pm 0.5\%$ was stored (temp. $20 \pm 0.1^\circ\text{C}/24\text{h}$) in tightly closed glass bottles in a climatic chamber (Mettmert ICP500, Germany). The LCR meter with wires was calibrated. The glass container was filled up with grain (ca. 250g) and placed in the metal container with a water jacket that was next thermostated to a temperature of $20 \pm 0.05^\circ\text{C}$ (Fig 1A). The wires fixed to the electrodes of the measuring sensor were connected to the wires of meter's attachment, mounted in the upper section of the thermostated system (Fig 1B), and measurements were performed. The electrical properties of the grain were determined based on the measurements of conductive parameters (impedance – Z) and capacitive parameters (C_p and C_s), performed at frequencies (f) of 1kHz, 100kHz, and 1MHz, and voltage of 200 mV. The measuring frequencies were selected based on the results of our previous investigations (Majewska et al. 2008, Banach et al. 2020). The electrical measurements were conducted in 12 replications for each of the 6 grain samples using an RCC substitute model of food products (serial-parallel resistance + capacitance) – Fig 2, which was also employed to determine change in the quality of animal and plant products in our earlier research (Banach et al.

167 2012, 2017, 2021; Banach & Żywica 2021, Żywica et al. 2012), and results were registered in an
 168 external memory of the meter.

169

170 Fig 2. RCC equivalent model for measuring of electrical properties food products (Z - impedance;
 171 R - resistance; C_s - series equivalent capacitance; C_p - parallel equivalent capacitance; M -
 172 measuring device)

173

174 ➤ *Statistical analysis*

175 The results of measurements were processed statistically using Statistica 13.3 software
 176 (StatSoft Inc., Tulsa, OK, USA). Data was analyzed employing procedures which enabled: (1)
 177 determining basic statistical measures (mean values $\pm$ standard deviation), (2) comparing the values
 178 of the analyzed traits of the grain produced using different agro-engineering factors, and (3)
 179 determining correlations between the analyzed physicochemical and electrical properties of the
 180 grain. The computations were performed at significance levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$.
 181 Furthermore, the Principal Component Analysis (PCA) was conducted to identify correlations
 182 between the quality traits and electrical properties of the grain of durum wheat grown without
 183 (WGR) and with the application a growth regulator (GR), on a two-dimensional plane (Ringnér,
 184 2008, Abdi and Williams, 2010).

185

186

187 **Results and discussion**

188 *Changes in the physicochemical properties (technological) of the grain*

189 Starch is the major storage polysaccharide accumulated in wheat grain, composed of two
190 fractions – linear amylose and branched-chain amylopectin. Starch granules are spherocrystalline
191 and their size is species-dependent (in wheat, it ranges from 10 to 24 μm), whereas their density
192 depends on the hydration degree. They feature double refraction and are coated with a thin
193 lipoprotein layer (Gąsiorowski 2004). Starch of durum wheat grain is strongly bound to proteins of
194 the endosperm, which results in its glassy and compact structure. In turn, a less compact structure
195 with numerous open spaces and physically discontinuous protein matrix is observed for starchy
196 kernels (Xiao Fu et al. 2018).

197 The starch content of durum wheat grain from particular variants of integrated cultivation
198 ranged from 60.9 to 65.1 % d.m. (Tab. 1). It was lower from the average values reported by
199 Lafiandra et al. (2014) for ripe wheat grain, i.e. 65 - 75%, but fitted the range expected by
200 Gąsiorowski (2004), i.e. 55 - 70 %. Wheat cultivation in the tested variants differentiated starch
201 content of the grain. The highest starch content was determined in the grain from the variant with
202 the growth regulator and without nitrogen fertilization (GR+0N). With nitrogen dose increase (N:
203 80 and 120 $\text{kg}\cdot\text{ha}^{-1}$), the starch content of the grain decreased significantly ($p<0.01$). In turn, wheat
204 cultivation in variants GR+80N and GR+120N resulted in a significant ($p<0.01$) increase in the
205 content of this chemical component (Tab. 1).

206 Lipids represent a large group of chemical compounds shearing the following common traits:
207 solubility in organic solvents and insolubility in water. They are a quantitatively minor but crucial
208 component of wheat grain. The total lipid content of wheat grain ranges from ca. 0.9 to 3.3 %;
209 however, the highest average content (2.8 % d.m.) can be found in durum wheat grain. The lipid
210 content is positively correlated with kernel hardness and color. Durum wheat varieties have higher
211 contents of both total lipids and polar lipids (glycolipids and phospholipids) compared to soft
212 wheats (Gąsiorowski 2004). The total lipid content of the grain analyzed in the present study

213 **Table 1. Changes in the physicochemical properties (starch, lipid and protein content; values $F_{\max}$ - maximum compression force) of the**
214 **durum wheat grain depending on growth regulator application (WGR, GR) and nitrogen fertilization (0, 80, 120 kg·ha⁻¹).**
215

Parameters	Without the application growth regulator (WGR)			With the application growth regulator (GR)			Significant differences WGR - GR		
	Fertilization [kg·ha ⁻¹]								
	0N	80N	120N	0N	80N	120N	0N	80N	120N
Starch [% s.m]	64.62±0.27 ^a	62.01±0.32 ^b	60.90±0.24 ^c	65.12±0.34 ^a	63.44±0.28 ^b	61.85±0.05 ^c	NS	p<0.01	p<0.01
Lipid [% s.m]	2.43±0.05 ^{aA}	2.31±0.01 ^b	2.22±0.09 ^{bB}	2.51±0.01 ^a	2.11±0.05 ^b	2.24±0.03 ^c	p<0.05	p<0.01	NS
Protein [% s.m]	12.717±0.530 ^a	14.157±0.388 ^b	14.425±0.382 ^b	11.450±0.418 ^a	14.022±0.504 ^{bB}	15.825±0.851 ^{Cd}	0.01	NS	NS
F _{max} [N]	131.87±17.98 ^a	126.47±10.66 ^a	122.87±19.88 ^a	120.90±9.08 ^a	120.51±14.22 ^a	134.38±9.57 ^b	NS	NS	NS
L*	53.92±0.54 ^a	53.27±0.79 ^a	52.11±0.64 ^a	53.49±1.04 ^a	52.93±0.48 ^a	52.84±0.79 ^a	NS	NS	NS
a*	8.78±0.72 ^a	8.92±0.55 ^a	8.88±0.21 ^a	8.67±0.71 ^a	8.82±0.60 ^a	8.69±0.64 ^a	NS	NS	NS
b*	28.42±0.51 ^a	28.39±0.57 ^a	27.91±0.54 ^a	28.14±0.63 ^a	27.35±0.74 ^a	27.87±0.62 ^a	NS	NS	NS

216 NS – no significant differences

a-d – mean values in columns indicated with various small letters are statistically significantly different at p<0.01;

A-B – mean values in columns indicated with various capital letter are statistically significantly different at p<0.05

217 a-a – mean values in columns indicated with the same small letters non statistically differences

218 ranged from 2.1 to 2.5% d.m., with the highest content determined in the grain from the variant
219 without nitrogen fertilization and with growth regulator (GR). The total content of lipids was more
220 significantly affected by nitrogen fertilization. The analysis of the effect of growth regulator use
221 (WGR-GR) showed that the cultivation variant had a significant ($p<0.01$; $p<0.05$) effect on lipid
222 content of the grain from the variants with nitrogen fertilization at 0 and 80 kg·ha⁻¹ (Tab. 1).

223 The total protein content of the grain (8-18 %) defines the functionality and processing options
224 of different wheat species and types. The main storage proteins of wheat grain, being at the same
225 the key indicators of its technological quality, include gluten proteins originally divided into
226 gliadins and glutenins (prolamines and glutelins). Durum wheat grain has a high total protein
227 content (11.5-18.5 % on average) and is characterized by different proportions of individual protein
228 fractions compared to the common wheat grain. The content of the gliadin protein fraction is higher
229 than that of the high-molecular fraction of glutenin proteins. Owing to this, dough made of semolina
230 is more plastic than elastic, which determines the high usability of durum wheat grain in the pasta
231 making industry (Gašiorowski 2004, De Santis et al. 2017, Dragov 2021).

232 The total protein content of the analyzed grain ranged from ca. 11.5 to 15.8 % d.m. It was most
233 beneficially influenced by the cultivation variant GR+120N and the least beneficially by the
234 GR+0N variant (Tab. 1). Also Obuchowski et al. (2007) reported a beneficial effect of nitrogen
235 fertilization (at 100 - 150 kg·ha⁻¹) on the total protein content of the grain of 4 durum wheat
236 varieties grown under Polish climate conditions. The contemporary durum wheat varieties require
237 higher rates of nitrogen fertilization (up to 100 - 120 kg·ha⁻¹) than the old varieties to reach their
238 maximum grain yield. Certain cultivars need even higher fertilization doses to increase their grain
239 protein percentages; however, these agricultural strategies are economically ineffective (Giuliani et
240 al. 2011, Mefleh et al. 2018).

241 The hardness of wheat grain is the most important indicator of its structural and mechanical
242 properties, including especially endosperm features (Xiao Fu et al. 2018). This property defines the
243 potential grain behavior during milling and affects such technological traits as: the extraction rate,

fraction size, and water absorption of pasta flour/semolina, starch damage degree, and starch susceptibility to enzymatic processes. One of the measures of wheat kernel hardness is their resistance to compression to the assumed deformation.

Grain hardness, expressed as the maximum compression force ($F_{\max}$) required for its 50% deformation, ranged from 120.5 to 134.4 N (Tab. 1). The analyzed durum wheat grain was harder than the grain of common wheat (68.0 - 109.5 N) and spelt grain (37.4 - 98.8 N) tested by Żuk-Gołaszewska et al. (2018). These differences point to the better cohesiveness of starch granules with protein and a lower number of free air compartments, which ultimately indicates potentially higher resistance of the analyzed durum wheat grain during milling (Morris et al. 2015, Xiao Fu et al. 2018). Significant and beneficial changes in hardness values were noted in the cultivation variant GR+120N (Tab. 1).

Grain color is another important technological trait of wheat. The yellow-amber color of semolina is caused by the carotenoid yellow pigment content in the entire grain. The high content of carotenoid pigments is especially valued in the case of durum wheat intended for top-quality semolina production as it determines pasta color. It is positively correlated with color parameter b^* (yellowness) in the CIE system (Żuk-Gołaszewska et al. 2018, Colasuonno et al. 2019). Grain color, expressed by color parameters L^* (52.1-53.9), a^* (8.7-8.9), and b^* (27.4-28.4) did not change significantly across the wheat cultivation variants (Tab. 1). Similar results were obtained by Obuchowski et al. (2007) who analyzed the effect of durum wheat fertilization with nitrogen on changes in color parameters (L^* , a^* , b^*) of pasta flour produced from its grain. Low variation (less than 10%) of color parameters of common wheat and spelt grain, cultivated in organic farming system for 3 years, was also reported by Żuk-Gołaszewska et al. (2018).

Changes in the electrical parameters of the grain

Among the multiple physical properties, the electrical properties of cereal grain enable the non-invasive identification of its quality traits, including structural changes of the grain, like e.g. damage

270 degree (Banach et al. 2020). However, due to heterogeneity, cellular structure, chemical
271 composition, and shape of various biological materials tested, a specific measurement technique
272 should be developed for each material type (Łuczycka 2009).

273 Like in the case of selected chemical components determined in this study, measurements of
274 the electrical parameters (Z , C_p , and C_s) of durum wheat grain demonstrated a significant effect of
275 agro-engineering factors (WGR-GR; N: 0-120 kg·ha⁻¹) on changes in their values. These changes
276 were additionally affected by the tested frequencies of the measuring current (1kHz-1 MHz).

277 Due to its cellular structure and chemical composition, cereal grain exhibits conductive and
278 dielectric (capacitive) properties. In the process of electric current conduction, the cytoplasm
279 exhibits the characteristics of a complex electrolyte (suspension), composed of proteins and amino
280 acids, nucleic acids, lipids, and carbohydrates as well as low-molecular-weight organic compounds,
281 mineral salts, and water. The electrical conductivity of the cytoplasm depends on the type,
282 concentration, and mobility of ions (Żywica 2010). Given the above, measurements were made for
283 one of the conductive parameters – impedance (Z), which is defined as complex resistance
284 ($Z^2 = R^2 + (X_l - X_c)^2$). The grain of wheat cultivated without the growth regulator and with nitrogen
285 fertilization at 80kg·ha⁻¹ (WGR+80N) had significantly the highest impedance values ($Z_{100kHz} =$
286 $3.36 \cdot 10^5 \Omega$; $Z_{1MHz} = 3.81 \cdot 10^4 \Omega$), whereas the grain from the WGR+0N variant had the lowest Z
287 values. The statistical analysis of the effect of the WGR-GR factor demonstrated significant
288 ($p < 0.01$; $p < 0.05$) differences between Z values (measured at 1kHz 100kHz; 1MHz) of the grain
289 produced with 0N and also between Z_{100kHz} values of the grain from the 120N variant (Tab.2).

290 These results point to a significant effect of protein content on the electrical conductivity and to the
291 feasibility of producing grain with an increased protein content in the WGR+0N variant
292 (environmentally-friendly, cost-effective) compared to the GR+0N variant. Increasing nitrogen
293 fertilization rates (80-120N) in both the WGR and the GR variant caused no differences in the
294 protein content of the grain, which is the main positive driver of grain yield and technological
295 quality (Obuchowski et al. 2007; Giuliani et al. 2011, Mefleh et al. 2018). When investigating the

296 **Table 2. Changes in the values (mean values $\pm$ standard deviation) of the electrical parameters (Z, Cp, Cs) durum wheat grain cultivated with the**
 297 **application (GR) and without application (WGR) of the growth regulator with different nitrogen fertilization (0, 80, 120 kg·ha⁻¹).**

Frequency	Without the application growth regulator (WGR)			With the application growth regulator (GR)			Significant differences WGR - GR		
	Fertilization [kg·ha ⁻¹]						0N	80N	120N
	0N	80N	120N	0N	80N	120N			
Z [Ω]									
1 kHz	16.00±5.29·10 ⁶ a	14.50±1.09·10 ⁶ a	11.50±1.08·10 ⁶ b	12.50±1.76·10 ⁶ a	14.30±2.15·10 ⁶ bB	11.5±3.74·10 ⁶ Ca	p<0.05	NS	NS
100 kHz	1.65±0.15·10 ⁵ a	3.36±0.12·10 ⁵ b	2.87±0.05·10 ⁵ c	2.92±0.34·10 ⁵ a	3.27±0.12·10 ⁵ b	2.97±0.14·10 ⁵ ca	p<0.01	NS	p<0.05
1 MHz	2.85±0.50·10 ⁴ a	3.81±0.12·10 ⁴ b	3.32±0.12·10 ⁴ c	3.30±0.37·10 ⁴ a	3.70±0.15·10 ⁴ b	3.37±0.16·10 ⁴ ca	p<0.05	NS	NS
Cp [F]									
1 kHz	1.19±0.05·10 ⁻¹¹ a	1.06±0.09·10 ⁻¹¹ b	1.32±0.13·10 ⁻¹¹ c	1.23±0.19·10 ⁻¹¹ a	1.07±0.17·10 ⁻¹¹ b	1.21±0.09·10 ⁻¹¹ ca	NS	NS	p<0.05
100 kHz	5.42±0.26·10 ⁻¹² a	4.71±0.16·10 ⁻¹² b	5.46±0.11·10 ⁻¹² ca	5.47±0.68·10 ⁻¹² a	4.84±0.19·10 ⁻¹² b	5.33±0.26·10 ⁻¹² ca	NS	NS	NS
1 MHz	4.83±0.23·10 ⁻¹² a	4.18±0.12·10 ⁻¹² b	4.78±0.17·10 ⁻¹² ca	4.87±0.58·10 ⁻¹² a	4.29±0.18·10 ⁻¹² b	4.71±0.23·10 ⁻¹² ca	NS	NS	NS
Cs [F]									
1 kHz	1.32±0.06·10 ⁻¹¹ a	1.15±0.09·10 ⁻¹¹ b	1.46±0.15·10 ⁻¹¹ c	1.37±0.21·10 ⁻¹¹ a	1.17±0.02·10 ⁻¹¹ b	1.33±0.11·10 ⁻¹¹ ca	NS	NS	p<0.05
100 kHz	5.52±0.26·10 ⁻¹² a	4.80±0.17·10 ⁻¹² b	5.61±0.08·10 ⁻¹² ca	5.57±0.71·10 ⁻¹² a	4.93±0.18·10 ⁻¹² b	5.41±0.26·10 ⁻¹² ca	NS	NS	p<0.05
1 MHz	4.86±0.24·10 ⁻¹² a	4.19±0.13·10 ⁻¹² b	4.82±0.16·10 ⁻¹² ca	4.90±0.58·10 ⁻¹² a	4.32±0.18·10 ⁻¹² b	4.71±0.21·10 ⁻¹² ca	NS	NS	NS

298 NS – no significant differences

a-c – mean values in columns indicated with various small letters are statistically significantly different at p<0.01;

A-C – mean values in columns indicated with various capital letter are statistically significantly different at p<0.05

299 a-a – mean values in columns indicated with the same small letters non statistically differences

effect of fertilization type in durum wheat cultivation, also Rossini et al. (2018) determined a lower protein content of the grain in the variant with organic fertilization compared to mineral fertilization; however, they did not notice a strong impact of this factor on protein and gluten percentage contents. Wheat grain yield and quality as well as nitrogen utilization effectiveness are influenced by environmental factors (Marinaccio et al. 2016, Di Mola et al. 2021). Our previous study (Banach et al. 2021) demonstrated that high-quality grain with desired flour quality parameters (flour extraction rate $\approx 64\%$; flour particle size $\approx 98\%$; $L^* \approx 92$) can be produced from spring durum wheat grown without the growth regulator and at $80 \text{ kg} \cdot \text{ha}^{-1}$ nitrogen fertilization. In addition, its results allowed concluding that this cultivation variant proved effective in reducing durum wheat production costs and diminishing natural environment pollution.

Solid state biophysics classifies cereal grain into the group of heterogeneous (layered) and weakly polarizable dielectrics, differing in mass. This is directly due to the high content of lipids in the cell wall and membrane. The size of the electric charge accumulated in the grain or the dipole moment is the factor that determines the behavior of the grain in the electric field. Therefore, the ability to accumulate an electric charge by durum wheat grains from the 6 cultivation variants was determined using capacitive parameters (strictly dependent on the geometric features, moisture content, chemical composition, and morphology of the grain).

The measurements of the capacitive parameters (C_p , C_s) of the grain showed different trends of changes than in the case of the Z values. In the WGR cultivation variant, significantly the highest C_p and C_s values were obtained at fertilization rates of 120N ($f=1\text{kHz}$, $f=100\text{kHz}$) and 0N ($f=1\text{MHz}$). In turn, wheat cultivation with GR contributed to the highest C_p and C_s values in the 0N variant (regardless of the measuring frequency). However, the statistical analysis of the effect of the WGR-GR factor demonstrated significant ($p<0.05$) differences only between the $C_{p1\text{kHz}}$ and $C_{s1\text{kHz}}$ and $C_{s100\text{kHz}}$ values of the grain from wheat fertilized with 120N (Tab. 2).

The analysis of correlations between the quality traits and electrical parameters of durum wheat grain produced without the growth regulator (WGR) showed that the nitrogen dose had a significant

effect on the strength of these correlations (Tab. 3). Significant ($p<0.001$; $p<0.01$; $p<0.05$) correlations were found for impedance (Z) and capacitance parameters (C_p , C_s) of the grain produced in the WGR+0N variant, regardless of the measuring frequency. Increasing the fertilization rate to 80N impaired the possibility of using electrical parameters (Z, C_p , C_s) for grain yield and quality assessment only to these measured at the higher frequencies tested ($f=100\text{kHz}$ and $f=1\text{MHz}$). At the highest nitrogen fertilization dose used in the study (120N), the strongest correlation was noted between $Z_{1\text{MHz}}$ and $C_{p100\text{kHz}}$ and $C_{s100\text{kHz}}$ (Tab. 3). The viability of capacitance parameters in grain yield and quality assessment was also demonstrated by Cseresnyés et al. (2021) and Di Mola et al. (2021). The recommendations to use the electrical parameters only at higher frequencies of the measuring current (100 kHz, 1 MHz) may be due to the facts that the increasing frequency is accompanied by a successive decrease in the electric permeability value (current streams flow through the cell), that the capacitive resistance of the membrane practically contains the resistance of the lipid layer, and, finally, that the intracellular substance is involved in the conduction of electricity (Żywica 2010).

The statistical analysis of results from the wheat cultivation variant with GR demonstrated stronger correlations between quality traits and electrical parameters of the grain with increasing nitrogen rates, indicating especially the viability of C_p and C_s parameters in grain quality assessment (Tab. 4). In the case of wheat grown in the GR+0N variant, the most significant ($p<0.001$) correlation was demonstrated between grain chemical composition (protein, lipid, and starch contents) and impedance (Z) measured in the entire tested range of current frequencies. In turn, the values of C_p and C_s parameters were correlated only with lipid and starch contents. These correlations are also confirmed by the earlier described phenomena (WGR cultivation variant). The quality traits of the grain from wheat grown in the GR+80N variant correlated with the values of electrical parameters measured at the higher frequencies tested ($Z_{100\text{kHz}}$, C_s and $C_{p100\text{kHz}}$; C_s and $C_{p1\text{MHz}}$). The correlations demonstrated in the GR+120N variant were similar to those noted for the GR+80N variant; however, they more strongly indicated the possibility of using the C_s parameter (Tab. 4) to evaluate

352 **Table 3. Analysis of the correlation between technological (lipid, protein, starch, hardness) and electrical (Z, Cs, Cs) parameters of hard wheat**
353 **grain cultivated without retardant (WGR) and at different nitrogen dose (0, 80, 120 kg·ha⁻¹)**

Quality parameters	Z1kHz	Z100kHz	Z1MHz	CS1kHz	CS100kHz	CS1MHz	Cp1kHz	Cp100kHz	Cp1MHz
WGR+0N									
Lipid [% s.m]	***	***	***	***	***	***	***	***	***
Protein [% s.m]	**	***	*	***	***	*	0.129	***	***
Starch [% s.m]	***	***	***	***	***	***	***	***	***
Hardness [N]	***	***	***	**	*	*	***	***	***
L*	**	**	**	0.734	0.943	0.763	**	**	**
a*	0.738	0.864	0.898	0.842	0.916	0.962	0.774	0.920	0.935
b*	*	*	*	0.218	0.235	0.249	*	*	*
WGR+80N									
Lipid [% s.m]	0.515	***	***	0.945	**	***	0.462	***	***
Protein [% s.m]	0.319	***	***	0.994	***	***	0.953	***	***
Starch [% s.m]	0.138	***	***	0.914	***	***	0.165	***	***
Hardness [N]	0.349	*	*	0.457	*	*	**	*	*
L*	0.367	0.089	0.075	0.436	0.083	0.077	0.690	0.830	0.686
a*	0.289	0.718	0.727	0.257	0.729	0.714	0.871	0.996	0.960
b*	0.092	0.117	0.126	0.100	0.122	0.123	0.248	0.340	0.369
WGR+120N									
Lipid [% s.m]	0.992	0.435	***	0.691	***	***	0.983	***	**
Protein [% s.m]	0.895	0.929	***	0.777	***	0.570	0.865	*	0.793
Starch [% s.m]	0.989	0.953	***	0.957	***	0.114	0.983	***	0.537
Hardness [N]	0.591	***	*	***	***	***	***	***	***
L*	0.770	0.965	0.651	0.171	0.845	0.854	0.301	0.145	0.089
a*	0.605	0.549	0.411	0.380	0.578	0.305	0.779	**	**
b*	0.700	0.916	0.796	0.988	0.975	0.974	0.928	0.780	0.819

354 *** - significance level p<0.001; ** - significance level p<0.01; * - significance level p<0.05

355 **Table 4. Analysis of the correlation between technological and electrical parameters (Z, Cs, Cs, measured at the frequency of 1kHz, 100kHz,**
 356 **1MHz) of hard wheat grain grown with retardant (GR) and differentiated nitrogen dose (0, 80, 120 kg·ha⁻¹)**

Quality parameters	Z _{1kHz}	Z _{100kHz}	Z _{1MHz}	CS _{1kHz}	CS _{100kHz}	CS _{1MHz}	Cp _{1kHz}	Cp _{100kHz}	Cp _{1MHz}
GR+0N									
Lipid [% s.m]	***	***	***	***	***	***	***	***	***
Protein [% s.m]	***	**	**	0.242	0.361	0.437	0.123	0.725	**
Starch [% s.m]	***	***	**	***	***	***	***	***	***
Hardness [N]	0.762	0.939	0.649	0.722	0.757	0.711	0.973	0.742	0.699
L*	*	0.132	**	0.206	0.185	0.202	0.143	0.190	0.196
a*	0.499	0.548	0.418	0.580	0.570	0.577	0.515	0.572	0.577
b*	0.479	0.250	0.447	0.977	0.911	0.965	0.678	0.928	0.993
GR+80N									
Lipid [% s.m]	**	***	0.086	***	***	**	**	***	**
Protein [% s.m]	0.201	***	0.084	*	*	*	0.774	**	**
Starch [% s.m]	0.073	***	0.356	***	**	*	***	**	*
Hardness [N]	0.312	**	*	0.096	**	***	0.091	**	***
L*	0.263	*	0.761	*	0.071	0.191	*	0.109	0.233
a*	0.431	*	0.093	0.095	*	*	0.092	*	*
b*	*	0.586	0.099	0.584	0.767	0.756	0.666	0.787	0.780
GR+120N									
Lipid [% s.m]	0.484	***	***	***	***	**	0.627	**	***
Protein [% s.m]	***	***	***	*	*	*	0.439	**	***
Starch [% s.m]	0.642	***	***	***	**	*	0.962	**	***
Hardness [N]	0.262	0.123	0.128	*	***	***	0.239	0.137	0.122
L*	*	***	***	0.060	***	***	**	***	***
a*	0.900	0.641	0.843	0.267	*	*	0.906	0.823	0.850
b*	***	***	***	0.708	*	**	***	***	***

357 *** - significance level p<0.001; ** - significance level p<0.01; * - significance level p<0.05

358

all grain quality traits tested in this study.

The Principal Component Analysis enabled discriminating a sub-set of electrical parameters (additional variables) from a large group of the evaluated physicochemical parameters and identifying the usability of the analyzed electrical parameters for quality assessment of the grain of durum wheat grown in Poland. In addition, only one agro-engineering factor was considered, i.e. wheat cultivation with/without GR, to verify the versatility of the proposed electrical method – Fig 3A, and Fig 3B (with no account taken of the nitrogen fertilization factor)

Fig. 3. Visualization of correlations between quality traits and electrical properties of the grain of durum wheat cultivated WGR (3A) and with the application of the GR (3B)

The matrix correlation between the analyzed parameters of the grain produced in the WGR and GR variants enabled discriminating two Principal Components explaining 83.90 % (Fig. 3A) and 72.90% (Fig. 3B) of the total variance of the analyzed parameters. In the first wheat cultivation variant – WGR (Fig. 3A), the visualization of the analyzed parameters (vector length, angle between vectors) onto a two-dimensional plane, defined by PC1 (68.46%) and PC2 (15.44%), demonstrated correlations between the chemical composition of the grain and its conductive (Z) and capacitive (C_p, C_s) parameters. Significant ($p < 0.05$) and the strongest positive correlations were found between: protein content and $Z_{1\text{kHz}-1\text{MHz}}$ ($0.839 < r < 0.900$); starch content and $C_{p1\text{kHz}-1\text{MHz}}$ ($0.807 < r < 0.912$) and $C_{s1\text{kHz}-1\text{MHz}}$ ($0.874 < r < 0.946$); as well as lipid content and $C_{p1\text{kHz}-1\text{MHz}}$ (0.624

379 $<r < 0.745$) and $C_{S1kHz-1MHz}$ ($0.700 <r < 0.785$). In turn, significant ($p < 0.05$) and the strongest negative
380 correlations were demonstrated between: protein content and $C_{p1kHz-1MHz}$ ($-0.817 <r < -0.897$) and
381 $C_{S1kHz-1MHz}$ ($-0.867 <r < -0.916$); starch content and $Z_{1kHz-1MHz}$ ($-0.846 <r < -0.930$); as well as lipid
382 content and $Z_{1kHz-1MHz}$ ($-0.664 <r < -0.763$). The positive correlations between protein content and Z
383 values are most likely due to the generally higher protein content in the grain from wheat grown in
384 the WGR variants (Tab. 3). Our previous study (Banach et al. 2017) demonstrated significant
385 correlations between impedance and admittance values and the chemical composition (including
386 especially lipid and starch contents) of the grain of various cereal species (wheat, barley, rye,
387 triticale, oats) and indicated the viability of conductive parameters (measured in a frequency range
388 of $f=100\text{ kHz}-2\text{ MHz}$) in discriminating cereal species and cultivars.

389 In the second variant of wheat cultivation – GR (Fig 3B), the visualization of the analyzed
390 parameters was not that explicit as in the WGR variant (Fig 3A). Significant ($p < 0.05$) and the
391 strongest correlation was found only between $C_{p1kHz-1MHz}$ ($0.903 <r < 0.925$) and $C_{S1kHz-1MHz}$ (0.902
392 $<r < 0.937$) parameters and protein content. In contrast, significant ($p < 0.05$) negative correlations
393 were determined only between impedance value and protein content, color (b^* and L^*), and
394 hardness. The values of the correlation coefficient were as follows: protein- Z_{100kHz} ($r = -0.933$); b^* -
395 Z_{1MHz} ($r = -0.801$); L^* - Z_{1MHz} ($r = -0.688$); and hardness - Z_{1MHz} ($r = -0.609$). Given the above, it was
396 concluded that the electrical method can be employed to assess the quality of durum wheat grain
397 produced in the WGR cultivation variant. A lack of explicit correlations between the analyzed traits
398 of grain from the GR variant points to the limited applicability of this method. The administration
399 of the growth regulator (GR variant) had a significant effect on differences in the chemical
400 composition of the grain, including especially contents of starch and lipids (Tab. 1), which
401 determine grain microstructure. According to Patel et al., (2006); Nilesh et al., (2012); and
402 Ropelewska et al., (2019), GR application elicits a positive effect on: thousand seed weight, bulking
403 density, width of common wheat grain, grain yield, and HI, and may improve technological
404 processes in the cereal processing industry. The grain from the GR+0N variant had a significantly

405 lower protein content than the WGR+0N grain. Contrary to the available literature data (Łuczycka
406 2009; Majewska et al. 2008; Żywica 2010; Banach et al. 2017, 2020), no explicit correlations were
407 found between the quality traits and electrical properties of the grain from wheat cultivated with
408 GR. Presumably, the application of a growth regulator (Medax 350 S.C.) induces changes in kernel
409 structure. Therefore, it seems advisable to identify deeper mechanisms underlying effects of this
410 agro-engineering factor to elucidate trends of these changes.

411

412 **Summary and conclusions:**

- 413 1. The cultivation of durum wheat in different variants of agro-engineering factors (GR-WGR and
414 nitrogen fertilization: 0, 80, 120 kg·ha⁻¹) enables modifying grain quality, including especially
415 starch and lipid contents. The highest contents of starch and lipids, and the highest hardness of
416 the grain can be achieved in wheat cultivation variants with or without growth regulator (GR of
417 WGR) without nitrogen fertilization (0N). In turn, the highest protein content of the grain can
418 be obtained upon nitrogen fertilization at 120 kg·ha⁻¹. These results suggest the feasibility of
419 tailored optimization of grain production in durum wheat processing.
- 420 2. The analysis of correlations between the quality traits and electrical parameters of the grain
421 demonstrated cultivation variant-dependent differences in the strength of these correlations. In
422 the grain from the WGR+0N variant (environmentally friendly), the strongest correlation was
423 found between the conductive and capacitive parameters, in the entire range of current
424 frequencies. Coupling the WGR cultivation variant with higher nitrogen fertilization rates (80
425 and 120 kg·ha⁻¹) caused strong correlations ($p < 0.001$), indicating the viability of capacitive
426 parameters (C_p and C_s) measured at higher frequencies (100kHz; 1MHz) or $Z_{1\text{MHz}}$ in grain
427 quality assessment. GR application during wheat cultivation impedes the use of electrical
428 parameters for grain quality evaluation; however, the feasibility of using C_s parameter at
429 $f=100\text{kHz}$ and $f=1\text{MHz}$ was strongly indicated in the GR+120N variant.

3. The agro-engineering factor of growth regulator (GR) application during native durum wheat cultivation hampers the use of the analyzed electrical method to assess its grain quality (chemical composition, hardness, and color). This type of assessment can only be made using one of the conductive parameters, i.e. impedance, measured at high frequencies (100 kHz; 1MHz). The quality of the grain produced in the WGR variant can be effectively evaluated using conductive (Z) and capacitive (C_p , C_s) parameters in the entire tested range of measuring current frequencies (1kHz-1MHz).

4. The cultivation of durum wheat in the integrated system, especially in the WGR variant, facilitates grain quality modeling and enables using a non-invasive electrical method for a rapid assessment of the quality traits of the grain, while raising no concerns over natural environment safety.

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