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Ammonium nitrate enriched with sulfur influences wheat yield and soil properties

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Abstract: The effect of fertilization with a new fertilizer on Polish market, a mixture of ammonium nitrate and ammonium sulfate (30% N, 6% S), was analysed in a three-year field experiment. The mixture commonly available on the market (26% N, 13% S) and ammonium nitrate, were used for comparison. Each fertilizer was applied in three doses: 150, 200 and 250 kg N/ha/year (simultaneously, 30, 40 and 50 kg S/ha were introduced with the mixtures). The highest mean (of the three years) grain yield (8.27 t/ha) was obtained after application of 200 kg N and 40 kg S/ha as the new fertilizer, with almost no significant effect of the type and dose of sulfur-containing fertilizers. Sulfur content in the grain was highest after the new fertilizer application; the content increased with increasing fertilizer dose. The highest mean protein (13.9–14.3%) and gluten (28.3–28.9%) content were recorded after application of 250 kg N/ha, and Zeleny sedimentation index (45.0–45.3 cm^3) – after application of 250 kg N and 50 kg S/ha, regardless of the fertilizer. Sulfur intensified the acidifying effect of ammonium nitrate and increased the content of sulfates in the soil.

Keywords: *Triticum aestivum* L.; macronutrient; sulfur deficiency; grain quality; nitrogen; mineral fertilizer

The global wheat-harvested area has not increased in the last 20 years and amounted to 227 million ha in 1997 and 219 million ha in 2017 (FAOSTAT 2019). However, the production has increased in that time from 615 million tons to 772 million tons. Maximization of yield, with keeping its high quality, is a result of progress in breeding, but also of proper agrotechnical operations, including balanced fertilization, adjusted to plant requirements, soil properties, and weather conditions.

In recent years, more and more attention has been devoted to fertilization of cereals, including wheat, with sulfur (whose content in soils is low and does not meet nutrient requirements of most plants) (Dostálová et al. 2015, Klikocka et al. 2016). In Central and Western Europe, a systematic reduction in the amount of sulfur returning to the soil surface has been observed since the end of the 20th century and that situation will continue until, at least, 2050 (Engardt et al. 2017). The same trend can be observed in North America. There is an exception – Asia, where sulfur dioxide is emitted to the environment in high doses (Smith et al. 2011, Klimont et al. 2013). However, some actions to reduce emissions from these sources are currently being taken (Smith et al. 2011, Klimont et al. 2013). The goal is to protect the environment, particularly to reduce acidification. However, as a result of reduction in sulfur deposition, most soils of

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agricultural use in Europe have a low content of sulfates (Scherer 2009). Currently, annual deposition of sulfur from the atmosphere onto the soil surface ranges from several to a dozen or so kilograms per hectare. Other causes of sulfur deficiency include: removal of sulfur with plant field, losses resulting from sulfate leaching into soil profile, reduction in the use of organic fertilizers and low-percentage mineral fertilizers that contain ballast (which includes sulfur).

Mineral fertilization influences the quality of wheat grain yield, taking into account parameters deciding on its technological value (Pilbeam 2015, Klikocka et al. 2016). Sulfur deficiency in soils translates into the necessity of fertilization with this element. The dose and form of sulfur should be chosen properly to satisfy plant requirements, and not to deteriorate soil properties, particularly by increasing its acidification.

The aim of the research was to determine the effect of fertilization with ammonium nitrate enriched with ammonium sulfate on quantity and quality of yield of winter wheat grain, as well as on selected soil properties. The effect of a new fertilizer available on the Polish market, containing 30% N and 6% S, was analysed.

MATERIAL AND METHODS

Field experiment. The field experiment was set up in 2014 at the experimental station of the University of Agriculture, located in Krakow-Mydlniki. The experiment was established on Stagnic Luvisol. The soil has heavy category (36% fraction < 0.02 mm), acid reaction (pH_{KCl} 4.88), low content of total sulfur (0.16 g/kg DM (dry matter)) and sulfate sulfur (8.92 mg/kg DM) and medium content of available phosphorus (63.4 mg/kg DM) and potassium (238 mg/kg DM). The experiment comprised of 10 treatments, each conducted in four replications (experimental plot = 7 m × 4 m = 28 m^2):

- I: no fertilization (control);
- II, III and IV: 150 kg N, 200 kg N and 250 kg N/ha, respectively – as ammonium nitrate (34% N);
- V, VI and VII: 150 kg N and 30 kg S/ha, 200 kg N and 40 kg S/ha, 250 kg N and 50 kg S/ha, respectively – as fertilizer A (a mixture of ammonium nitrate and ammonium sulfate, 26% N and 13% S); N dose was completed with ammonium nitrate;
- VIII, IX and X: 150 kg N and 30 kg S/ha, 200 kg N and 40 kg S/ha, 250 kg N and 50 kg S/ha, respectively – as fertilizer B (a mixture of ammonium nitrate and ammonium sulfate, 30% N and 6% S).

The experiment was conducted for three growing seasons, and winter wheat cv. Natula (a quality bread cultivar with very high technological parameters of the grain) was the test plant in all seasons. Phosphorus and potassium were applied at pre-sowing (each year 30.50 kg P/ha as 40% superphosphate and 83 kg K/ha as 60% potassium salt). Nitrogen was applied at the beginning of spring vegetation (dose of 50%), at the beginning of stem elongation phase (30%) and prior to heading (20%). Humidity and thermal conditions during the experiment are shown in Figure 1. Wheat was harvested at grain full maturity. After the harvest, soil samples were collected and dried.

Laboratory analyses. Sulfur content in dried and ground wheat grain was determined using a Vario MAX cube CNS elemental analyser (Elementar Analysensysteme GmbH, Langenselbold, Germany). Protein content was determined according to AOAC (2012), gluten content – ISO 21415-2, 2015, Zeleny sedimentation index – PN-EN ISO 5529, 2010, and falling number – ICC Standard 107/1 (1995).

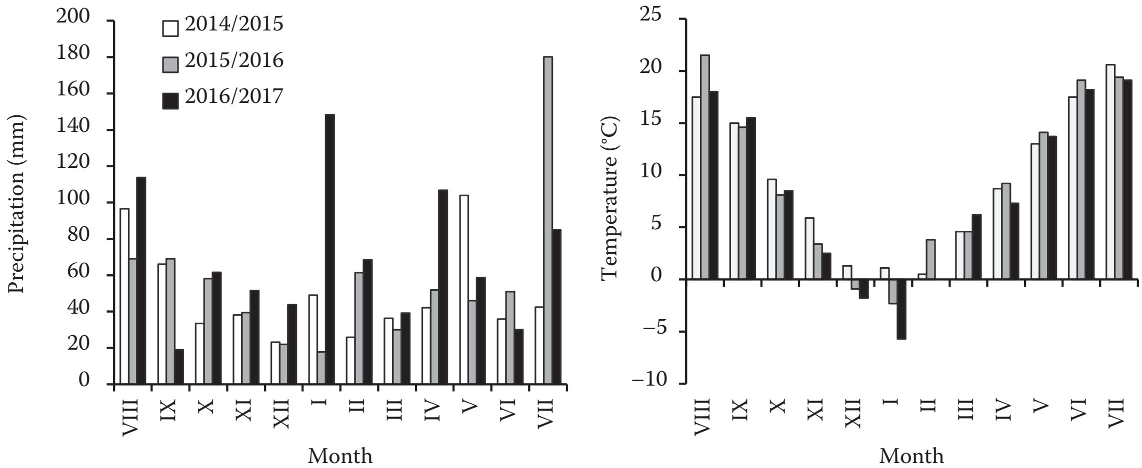

Figure 1. Total precipitation and mean air temperature during wheat growth

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Soil pH was determined by potentiometry, using 1 mol/L KCl solution (m/v 1:2.5) (Tan 2005). Sulfate sulfur content was determined by the ICP-OES method using an OPTIMA 7300 spectrometer (Perkin-Elmer, Waltham, USA); sulfates were rinsed with 0.03 mol/L acetic acid (30 min, 40 rpm, 1:10 m/v).

To characterize the soil properties before setting up the experiment, additional analyses were conducted. Granulometric composition was determined by the Bouyoucos-Casagrande's areometric method in the Prószyński's modification (Warzyński et al. 2018). Total sulfur was determined by the ICP-OES method after binding sulfur by magnesium nitrate, dry mineralization (12 h at 450°C) and after dissolving the residue in a nitric acid solution, and available forms of phosphorus and potassium were determined by the Egner-Riehm method (Ivanov et al. 2012), after extraction with pH 3.55 calcium lactate (90 min, 40 rpm, 1:50 m/v).

Statistical analysis. An analysis of variance was performed. The least significant differences (*LSD*) were calculated by using the Tukey's test ($\alpha = 0.05$). Principal component analysis (PCA) was applied to show relationships between the analysed parameters and treatments. The data analysis software system Statistica, ver. 13 (TIBCO Software Inc., Palo Alto, USA) was used.

RESULTS AND DISCUSSION

Amount of wheat grain yield and sulfur content in grain. A significant diversity in the amount of yield of winter wheat grain and sulfur content in grain in individual years of the experiment was observed (Table 1). Klikocka et al. (2016) showed the additive effect of sulfur fertilization on wheat yield. Similarly to the results obtained by Hřivna et al. (2015) and Klikocka et al. (2016), diversity between the years resulting from weather conditions was shown. The highest mean (of the three years of the research) yield was obtained after application of 200 kg N and 40 kg S/ha as fertilizer B. As a rule, no significant diversity in the amount of yield after sulfur fertilization was shown. The mean sulfur content in grain increased along with increasing the nutrient doses. The grain of plants fertilized with the two highest doses of fertilizer B had significantly highest sulfur content.

Wheat grain quality. Values of all the analysed quality parameters of winter wheat grain varied considerably in individual years (Tables 2 and 3). A significant correlation between years and treatments, and thereby their influence on the grain quality, was shown. Significantly the highest mean protein (13.9–14.3%) and gluten (28.3–28.9%) content were observed after application of 250 kg N/ha, regardless

Table 1. Yield of wheat grain and sulfur content in grain

Treatment	Yield (t/ha)				Sulfur (g/kg)			
	2015	2016	2017	mean	2015	2016	2017	mean
I	6.40	4.93	6.79	6.04	0.77	0.56	1.07	0.80
II	8.00	6.75	8.90	7.88	0.69	0.55	1.18	0.81
III	8.05	5.92	9.13	7.70	0.89	0.67	1.20	0.92
IV	7.60	6.78	9.37	7.86	0.94	0.67	1.28	0.96
V	8.00	7.61	8.97	8.20	0.92	0.67	1.26	0.95
VI	7.92	6.15	9.36	7.81	1.03	0.71	1.22	0.99
VII	8.10	6.55	9.68	8.11	1.16	0.79	1.30	1.08
VIII	8.20	6.47	9.37	8.01	1.13	0.71	1.30	1.04
IX	8.10	7.04	9.67	8.27	1.20	0.81	1.32	1.11
X	7.80	6.90	9.85	8.18	1.24	0.86	1.35	1.15
Mean	7.81	6.51	9.10	–	1.00	0.70	1.25	–
$LSD_{0.05}$	years = 0.10 years × treatment = 0.34			treatment 0.27	years = 0.02 years × treatment = 0.06			treatment 0.05

I – no fertilization; II – 150 kg N/ha; III – 200 kg N/ha; IV – 250 kg N/ha – as ammonium nitrate (34% N); V – 150 kg N and 30 kg S/ha; VI – 200 kg N and 40 kg S/ha; VII – 250 kg N and 50 kg S/ha – as fertilizer A (a mixture of ammonium nitrate and ammonium sulfate, 26% N and 13% S); N dose completed with ammonium nitrate; VIII – 150 kg N and 30 kg S/ha; IX – 200 kg N and 40 kg S/ha; X – 250 kg N and 50 kg S/ha – as fertilizer B (a mixture of ammonium nitrate and ammonium sulfate, 30% N and 6%S)

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Table 2. Content of protein and gluten in wheat grain

Treatment	Protein (%)				Gluten (%)			
	2015	2016	2017	mean	2015	2016	2017	mean
I	8.7	8.7	10.1	9.1	19.0	9.4	19.0	15.8
II	11.1	13.5	12.8	12.5	27.9	24.0	25.3	25.7
III	11.3	15.7	13.9	13.6	28.2	26.5	26.7	27.1
IV	11.5	16.5	14.9	14.3	29.0	28.7	29.1	28.9
V	11.2	13.8	13.3	12.7	28.0	21.4	26.3	25.2
VI	11.3	14.4	14.2	13.3	28.4	22.8	27.3	26.1
VII	11.5	15.8	14.6	14.0	28.9	26.5	29.5	28.3
VIII	11.2	13.5	12.9	12.5	28.1	22.6	25.1	25.3
IX	11.4	14.5	13.0	12.9	28.9	25.2	26.5	26.9
X	11.6	15.3	15.0	13.9	29.6	28.5	28.7	28.9
Mean	11.0	14.2	13.4	–	27.6	23.6	26.4	–
$LSD_{0.05}$	years = 0.2 years × treatment = 0.5			treatment 0.4	years = 0.3 years × treatment = 1.1			treatment 0.9

I – no fertilization; II – 150 kg N/ha; III – 200 kg N/ha; IV – 250 kg N/ha – as ammonium nitrate (34% N); V – 150 kg N and 30 kg S/ha; VI – 200 kg N and 40 kg S/ha; VII – 250 kg N and 50 kg S/ha – as fertilizer A (a mixture of ammonium nitrate and ammonium sulfate, 26% N and 13% S); N dose completed with ammonium nitrate; VIII – 150 kg N and 30 kg S/ha; IX – 200 kg N and 40 kg S/ha; X – 250 kg N and 50 kg S/ha – as fertilizer B (a mixture of ammonium nitrate and ammonium sulfate, 30% N and 6%S)

of the fertilizer used. Significantly the highest mean value of Zeleny sedimentation index (45.0–45.3 cm^3) was determined after application of 250 kg N and 50 kg S/ha as both sulfur-containing fertilizers. Along with the increase in nitrogen dose (regardless of the fertilizer), there was an increase in protein content,

Table 3. Values of Zeleny sedimentation index and falling number in wheat grain

Treatment	Sedimentation index (cm^3)				Falling number (s)			
	2015	2016	2017	mean	2015	2016	2017	mean
I	8.7	22.6	24.7	18.6	248	380	303	310
II	32.0	40.2	36.0	36.0	305	469	326	366
III	33.7	43.7	38.7	38.7	320	473	319	370
IV	37.0	46.2	43.5	42.2	310	439	322	357
V	34.0	41.2	38.2	37.8	316	432	337	361
VI	35.3	43.5	40.0	39.6	341	397	329	355
VII	37.0	55.7	43.2	45.3	338	423	333	365
VIII	31.7	46.0	33.1	36.9	287	435	304	342
IX	35.3	50.0	37.0	40.7	314	437	320	357
X	37.7	53.7	43.7	45.0	341	398	310	349
Mean	32.2	44.3	37.8	–	312	428	320	–
$LSD_{0.05}$	years = 0.9 years × treatment = 2.8			treatment 2.2	years = 7 years × treatment = 23			treatment 18

I – no fertilization; II – 150 kg N/ha; III – 200 kg N/ha; IV – 250 kg N/ha – as ammonium nitrate (34% N); V – 150 kg N and 30 kg S/ha; VI – 200 kg N and 40 kg S/ha; VII – 250 kg N and 50 kg S/ha – as fertilizer A (a mixture of ammonium nitrate and ammonium sulfate, 26% N and 13% S); N dose completed with ammonium nitrate; VIII – 150 kg N and 30 kg S/ha; IX – 200 kg N and 40 kg S/ha; X – 250 kg N and 50 kg S/ha – as fertilizer B (a mixture of ammonium nitrate and ammonium sulfate, 30% N and 6%S)

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gluten content and sedimentation index. The highest mean value of falling number (370 s) was recorded after fertilization with 200 kg N/ha as ammonium nitrate. However, the falling number was not, as a rule, much diversified between the fertilized treatments.

Grain of unfertilized wheat did not meet the qualitative requirements. Grain for the production of bread flour should contain at least 11.5% protein and 25% gluten (Kujawa 2014). To be of good baking value, the sedimentation index should not be lower than 30 cm^3, and the falling number should amount to 250–350 s. Sedimentation index indicates the quantity and quality of gluten. Grain with the falling number lower than 150 is characterized by a very high activity of amylolytic enzymes and intensive life processes.

Hřivna et al. (2015) showed no significant effect of sulfur fertilization on protein content in wheat grain. Järvan et al. (2012a,b) obtained an opposite effect. They also indicated that weather conditions modify protein content and baking parameters of flour. In contrast, Erekul et al. (2011) and Klikocka et al. (2016) did not show the effect of sulfur fertilization on protein content in wheat grain. Hovewer, Klikocka et al. (2016) draw attention to the improvement of protein quality as a result of the increase in the content of cystine and methionine. The results presented in this paper point to a significant increase in gluten content in grain along with increasing the nitrogen dose. A similar tendency was obtained by Erekul et al. (2012) and Klikocka et al. (2016), also in the case of sulfur fertilization. Erekul et al. (2012) showed the beneficial effect of nitrogen and sulfur fertilization on the value of sedimentation index. Value of the falling number presented in this paper was similar to that obtained by Erekul et al. (2012), who showed no distinct impact of nitrogen and sulphur fertilization on this parameter.

Soil properties. No significant diversity in soil pH in subsequent years of the research was recorded but the sulfate sulfur content in the soil underwent a significant decrease in subsequent years (Table 4). The significant interaction of years and fertilization on both parameters was confirmed. When analysing the mean pH values (of the three years of research), it was shown that the addition of ammonium sulfate intensified the acidifying effect of ammonium nitrate. The soil fertilized with 250 kg N and 50 kg S/ha as fertilizer B had the lowest pH value and the highest sulfate sulfur content. A significant increase in sulfate sulfur content, in comparison with the content in the control soil and the soil fertilized with ammonium nitrate, was shown after sulfur application. Generally, no significant diversity in sulfate sulfur content in the soil fertilized with sulfur-containing fertilizers was

Table 4. pH value and sulfate sulfur content in soil

Treatment	pH_{KCl}				Sulfate sulfur (mg/kg)			
	2015	2016	2017	mean	2015	2016	2017	mean
I	4.83	4.94	4.82	4.86	8.63	9.69	6.70	8.34
II	4.91	4.90	5.03	4.95	11.21	9.42	6.35	8.99
III	5.04	5.03	4.94	5.00	8.08	6.62	5.13	6.61
IV	5.11	5.07	4.66	4.94	7.94	6.23	6.82	7.00
V	4.89	4.91	4.92	4.91	10.02	11.11	10.15	10.43
VI	4.80	4.62	4.86	4.76	14.51	12.91	11.62	13.01
VII	4.75	4.81	4.82	4.79	13.77	12.13	13.86	13.25
VIII	4.75	4.92	5.03	4.90	13.32	13.58	8.10	11.66
IX	4.96	4.94	4.86	4.92	14.68	12.19	9.62	12.16
X	4.84	4.48	4.49	4.60	16.55	13.70	10.17	13.47
Mean	4.89	4.86	4.82	–	11.87	10.76	8.51	–
$LSD_{0.05}$	years = id years × treatment = 0.18			treatment 0.15	years = 0.78 years × treatment = 2.47			treatment 1.95

I – no fertilization; II – 150 kg N/ha; III – 200 kg N/ha; IV – 250 kg N/ha – as ammonium nitrate (34% N); V – 150 kg N and 30 kg S/ha; VI – 200 kg N and 40 kg S/ha; VII – 250 kg N and 50 kg S/ha – as fertilizer A (a mixture of ammonium nitrate and ammonium sulfate, 26% N and 13% S); N dose completed with ammonium nitrate; VIII – 150 kg N and 30 kg S/ha; IX – 200 kg N and 40 kg S/ha; X – 250 kg N and 50 kg S/ha – as fertilizer B (a mixture of ammonium nitrate and ammonium sulfate, 30% N and 6%S); id – insignificant differences

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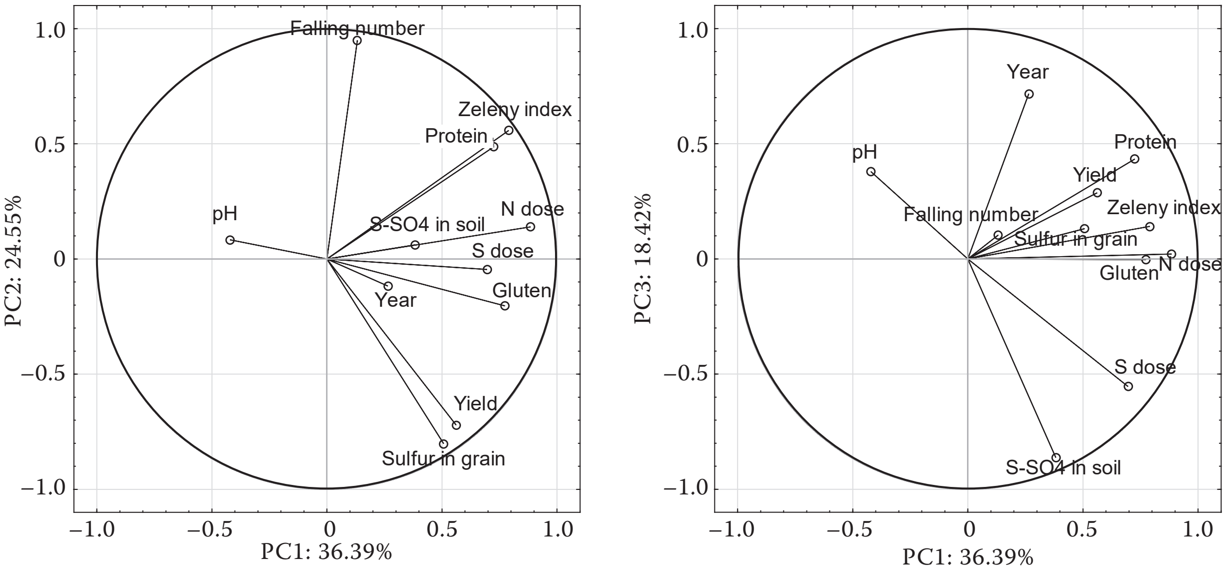

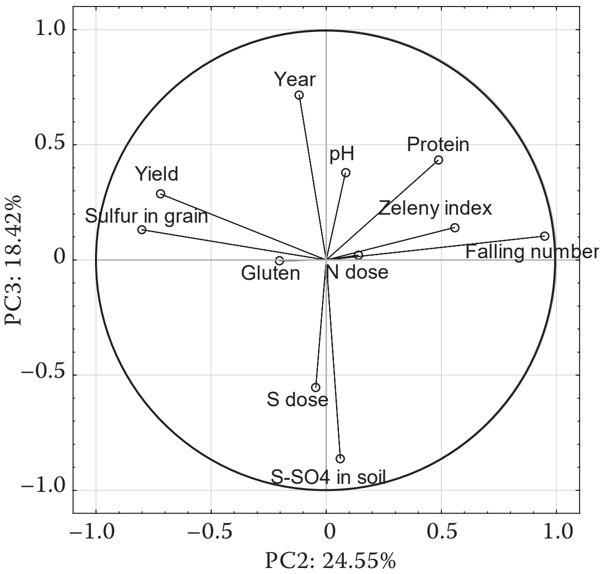

Figure 2. Principal component analysis (PCA) showing relationships between the examined parameters, years as well as nitrogen and sulfur doses

recorded. A change of the most available sulfur forms after mineral fertilization was stated also by Kulhánek et al. (2011). Gryzełko and Filipek-Mazur (2008) stated that mineral fertilization (with and without sulfur addition) caused a decrease in soil pH, which intensified in time. Negative effects of acidification can be reduced through liming (Lošák et al. 2012).

Principal component analysis. Sulfate sulfur content in soil was strongly positively correlated with the dose of sulfur (Figure 2). There was a strong positive correlation between wheat grain yield and sulfur content in grain as well as between nitrogen dose and grain quantity and quality (sedimentation index, content of protein and gluten). It was observed that the year of the experiment had an impact on the values for particular treatments.

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