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INFLUENCE OF HIGH-VOLTAGE ELECTRICAL DISCHARGE ON THE OIL BINDING CAPACITY OF SPELT CHAFF AND WHEY

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Summary

Oil binding capacity (OBC) is a key property in the formulation of oleogels (structured vegetable oils without trans or saturated fatty acids). Food industry by-products are promising structuring agents for oleogels, as they can bind oil. With appropriate treatment, OBC can be improved. The green technology known as High-Voltage Electrical Discharge (HVED) has shown potential for modifying the structure of materials for this purpose. In this study, spelt chaff and whey were treated with HVED under different conditions (time and frequency). HVED successfully enhanced OBC values for lignocellulosic material spelt chaff, while it did not have a significant effect on protein-rich material whey. The influence of the process parameters was determined by response surface methodology (RSM). The results showed that the highest OBC value for spelt chaff was achieved when treated for 15 minutes at 40 Hz. These findings suggest that HVED can be used as a green physical treatment for material modification, supporting the circular economy, sustainability, and the valorisation of by-products.

Keywords: oil binding capacity, high voltage electrical discharge, spelt chaff, whey, response surface methodology

Introduction

Nowadays, structuring edible oil by physical sorption onto materials has attracted interest in the scientific community. The resulting structured oil systems (oleogels) enable the development of novel food products with improved nutritional value, being lower in trans and saturated fatty acids. Therefore, the ability of materials to bind oil is a crucial property in formulating such oleogels. Oil sorption (absorption and adsorption), also known as oil binding capacity, is defined as the enrichment of a material with oil in the interfacial layer, followed by the penetration of oil into the solid phase (Rouquerol et al., 2012; Patel and Dewettinck, 2016). Consequently, food researchers are seeking suitable materials for this purpose. Wahid et al. (2026) proposed using underutilised by-products to develop cost-effective materials, thereby valorising by-products at the same time. In this way, the concept of a circular economy can be established through reduction, reuse, and recycling in the food supply chain (de Oliveira et al., 2021).

If appropriate physical treatment is applied, materials can be modified into more effective structuring agents for oleogel production by increasing oil binding capacity during treatment. Yin et al. (2021) reported that physical treatments such as ball milling or high-pressure homogenisation can create a loose, porous network structure that enhances oil binding capacity. They highlighted the importance of particle size and the microstructure of insoluble dietary fibre in relation to oil binding capacity. According to Krause et al. (2023), protein powders with small particle size and low density tend to adsorb more oil than those with high density.

Since High-Voltage Electrical Discharge (HVED) demonstrates potential for material modification, as reported by Ačkar et al. (2022), where starch was modified, it suggests that this physical treatment can increase oil binding capacity. HVED is considered an innovative green technology, which shows potential to extract various bioactive compounds from biological materials, including by-products from the food industry. This method offers several advantages over conventional extraction techniques, such as cost-effectiveness, reduced extraction times, and low operating temperatures. During HVED treatment, high energy is generated in the aqueous suspension positioned between a grounded electrode and a high-voltage needle electrode. An electron avalanche and several secondary phenomena – such as shock waves, cavitation, and liquid turbulence – are initiated by a plasma channel formed by a rapid electrical discharge, resulting in mechanical cell disintegration and electroporation. These secondary phenomena accelerate the extraction of biomolecules (Pastor et al., 2025; Boussetta et al., 2013). In addition to its extraction and modification potential, HVED may also offer the possibility of food decontamination (Kiš et al., 2020).

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Spelt (*Triticum spelta*) is one of the oldest known grains. In the past, spelt's popularity declined due to lower crop yields and the expensive dehulling process, compared to high-yielding common wheat (*Triticum aestivum*), where the hulls are separated from the kernel immediately at harvest. However, spelt is more resistant to drought and fungal pathogens than bread wheat, which is why it is becoming more significant in agriculture, as its resistance is suitable for organic farming systems. As environmental awareness has increased, spelt is receiving renewed attention because it requires less pesticide and fertiliser for cultivation. Additionally, spelt grains are superior in protein content, soluble dietary fibre, fat, and minerals. However, spelt has lower gluten quality, which is important for dough production. If the soil is rich in nutrients, spelt will produce lower yields compared to common wheat. After the dehulling process, spelt chaff is obtained as a by-product. As this material can be high in various mycotoxins, it is not recommended for use as feed or food without prior treatment. According to Wiwart et al. (2017), spelt chaff can be utilised in energy production due to its high calorific value (Kiš et al., 2017; Wiwart et al., 2017; Wanic et al., 2024).

Whey is a liquid by-product obtained during cheese production. In the production of one kilogram of cheese, approximately nine litres of whey remain as residue. Although whey has high nutritional value, particularly because of its proteins, significant investment is required for its valorisation. Large quantities in the ecosystem can negatively affect the environment if disposed of as waste, since the biological oxygen demand of whey is very high (40,000 mg/kg). Depending on the method of cheese production, whey can be either sweet if enzymes are used, or acidic if acid is used for coagulation. Besides water, which makes up 93% of whey, the main component is lactose, accounting for 70–72% of the dry matter. Whey proteins are present at 8–10%, while minerals make up 12–15% of the dry matter. With appropriate technology, whey can be converted into valuable products such as whey cheeses (e.g. Ricotta), beverages, whey protein isolate, etc. (Jelen, 2011; Slačanac and Lučan, 2017).The aim of this study was to determine the potential of high voltage electrical discharge as a physical treatment for modifying biowaste (spelt chaff and whey) to increase oil binding capacity. The goal is to achieve the highest possible outcome by optimising process parameters (HVED treatment time and frequency) with response surface methodology.

Materials and methodology

High voltage electrical discharge

Spelt chaff was obtained from EKO-JAZO (Croatia), while whey, dried into powder, was provided by Belje Plus (Croatia). Spelt chaff was ground into powder using an ultra centrifugal mill (ZM 200, Retsch, Germany). The prepared materials were modified using high voltage electrical discharge (HVED). Raw materials were suspended in ultrapure water. Based on preliminary research, 60 g of whey was suspended in 240 mL of water, and 20 g of spelt chaff in 280 mL of water. A grounded electrode and a high-voltage needle (point-to-plane geometry) were positioned 0.5 cm apart. The gas flow (synthetic air) was set at 2 m/s. After treatment, the suspension was centrifuged for 20 min at 3000 RPM, the supernatant was decanted, and the treated samples were oven-dried at 50 °C. Different frequencies and treatment times were tested.

Oil binding capacity

Oil binding capacity (OBC) was determined using AACC Method 88–04 (AACC, 1983). Material (2.5 g) is suspended in sunflower oil (30 mL). After 30 minutes, the resulting suspension was centrifuged at 3000 rpm for 15 minutes at ambient temperature. Excess oil was decanted, and the precipitate was weighed together with the Falcon tube. The value for oil binding capacity was calculated using Eq. (1), defined as the ratio of the precipitate mass after centrifugation to the total mass of the sample, indicating how much oil was bound to the sample.

$$OBC = \frac{(weight\ of\ precipitate\ after\ centrifugation)}{(weight\ of\ the\ sample)} \quad (1)$$

Statistical Analysis

To clarify the influence of the two variables (frequency and treatment time) on oil binding capacity, a second-order polynomial regression model is used, as shown in Eq. (2), in which:

Y – anticipated outcome of oil binding capacity; β_0 – intercept; β_1, β_2 – linear coefficients; β_{11}, β_{22} – quadratic coefficients; β_{12} – interaction coefficient; A, B – variables (HVED treatment time and frequency, respectively); ε – random error term.

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{12} AB + \varepsilon \quad (2)$$

Data analysis was conducted using R software (R Core Team, 2022). The significance level was set at a probability value of 0.05. The F-test, Shapiro-Wilk test, and ncvTest (non-constant variance score test) from the package „car“ (Fox and Weisberg, 2019) were used to assess the validity of the regression model. The ncvTest was used to detect heteroscedasticity in the regression model, while the Shapiro-Wilk test was applied to the studentized residuals to check for normality. The t-test was used to assess the significance of the regression coefficients. The F-test of overall significance was conducted to determine whether the regression model provided a better fit than a model with no independent variables. In this study, response surface methodology (RSM) was applied to identify the region in which the maximum value of the response function (oil binding capacity) is located. By employing an appropriate experimental design and an approximation model, the effects of two factors (HVED treatment time and frequency) and their interactions on the response were systematically explored. Based on the fitted model, the optimal region was determined in order to provide a foundation for more refined experimental design and subsequent investigation.

Results and discussion

Table 1. Experimental design and response values for oil binding capacity of spelt chaff (g/g)

Run	Factor 1 A: HVED treatment time (min)	Factor 2 B: Frequency (Hz)	Response: Oil binding capacity (g/g)	Run	Factor 1 A: HVED treatment time (min)	Factor 2 B: Frequency (Hz)	Response: Oil binding capacity (g/g)
1	15	60	5.60	29	15	40	7.86
2	15	60	5.43	30	15	40	7.58
3	15	60	6.78	31	15	40	7.98
4	15	60	6.89	32	15	40	7.20
5	15	40	7.91	33	10	50	8.68
6	15	40	7.76	34	10	50	8.73
7	15	40	8.39	35	10	50	8.71
8	15	40	7.87	36	10	50	8.32
9	25	40	6.19	37	15	40	8.80
10	25	40	6.77	38	15	40	8.57
11	25	40	7.16	39	15	40	8.64
12	25	40	6.98	40	15	40	8.14
13	10	30	7.90	41	15	40	8.20
14	10	30	8.02	42	15	40	8.24
15	10	30	7.73	43	15	40	8.55
16	10	30	7.90	44	15	40	8.57
17	20	30	7.98	45	15	40	8.69
18	20	30	8.12	46	15	40	8.12
19	20	30	8.54	47	15	40	7.96
20	20	30	8.48	48	15	40	8.20
21	15	20	7.64	49	20	50	8.53
22	15	20	7.59	50	20	50	8.06
23	15	20	6.61	51	20	50	7.98
24	15	20	6.72	52	20	50	7.96
25	5	40	5.97	53	15	40	7.54
26	5	40	5.67	54	15	40	7.44
27	5	40	7.42	55	15	40	7.24
28	5	40	7.13	56	15	40	7.01

Oil binding capacities for untreated samples were 5.74 ± 0.001 g/g for spelt chaff and 2.01 ± 0.01 g/g for whey. According to the results shown in Tables 1 and 2, whey had noticeably lower OBC values than spelt chaff after HVED treatment, indicating that HVED is less effective for protein-rich materials than for lignocellulosic materials. According to Sangnark and Noomhorm (2003), the oil binding capacity of

sugarcane bagasse increased after alkaline hydrogen peroxide treatment compared with the raw material, as a result of lignin destruction in the lignocellulosic material. Since Miranda et al. (2020) reported that plasma-in-water treatment caused removal of lignin from biomass, it suggests that HVED treatment caused partial removal of lignin in spelt chaff, thus increasing oil binding capacity.

Table 2. Experimental design and response values for oil binding capacity of whey (g/g)

Run	Factor 1 A: HVED treatment time (min)	Factor 2 B: Frequency (Hz)	Response: Oil binding capacity (g/g)	Run	Factor 1 A: HVED treatment time (min)	Factor 2 B: Frequency (Hz)	Response: Oil binding capacity (g/g)
1	14	30	2.27	25	14	50	2.39
2	14	30	2.36	26	14	50	2.39
3	14	30	2.33	27	14	50	2.38
4	14	30	2.29	28	14	50	2.31
5	16	60	2.38	29	14	50	2.47
6	16	60	2.51	30	14	50	2.39
7	16	60	2.28	31	14	50	2.27
8	16	60	2.28	32	14	50	2.30
9	14	50	2.55	33	12	60	2.72
10	14	50	2.72	34	12	60	2.68
11	14	50	2.26	35	12	60	2.24
12	14	50	2.34	36	12	60	2.27
13	14	50	2.68	37	10	50	2.20
14	14	50	2.84	38	10	50	2.28
15	14	50	2.84	39	10	50	2.24
16	14	50	2.69	40	10	50	2.18
17	14	50	3.20	41	16	40	2.61
18	14	50	3.08	42	16	40	2.61
19	14	50	2.84	43	16	40	2.31
20	14	50	2.71	44	16	40	2.32
21	14	50	2.41	45	12	40	2.32
22	14	50	2.46	46	12	40	2.39
23	14	50	2.45	47	12	40	2.84
24	14	50	2.37	48	12	40	2.87

Statistical Analysis

In the case of spelt chaff, the Shapiro-Wilk test ($W = 0.97227$, $p = 0.2228$) failed to reject the null hypothesis ($p > 0.05$), confirming that studentized residuals follow a normal distribution. The ncvTest confirmed homogeneity of variance for spelt chaff ($\chi^2 = 2.3624$, $Df = 1$, $p = 0.1243$). The residual analysis confirmed model adequacy, as both homoscedasticity and normality were achieved. The regression model for spelt chaff was statistically significant ($F(5, 50) = 7.473$, $p = 2.664 \times 10^{-5}$; $p < 0.001$). The linear and quadratic regression coefficients were also statistically significant ($p < 0.05$), while the interaction coefficient was not (Table 3). This indicates that the predictors had a significant effect on the response (OBC), but their effects were independent. Although the regression model assumptions were met, the regression model developed for spelt chaff explained only approximately 40% of the variability, as indicated by the low adjusted coefficient of determination ($R^2 = 0.3705$). This result suggests that predictors (HVED time treatment and frequency) were not the only parameters affecting changes in OBC. Variability in the OBC occurred by other factors beyond this study. This may be explained by the heterogeneous fibre sample whose particle size varied. Wang et al. (2020) stated that conventional methods for oil absorption capacity can encounter issues due to material loss during the decanting process and reabsorption of oil after centrifugation. According to Locke et al. (2006), point-to-plane geometry can be problematic since the volume of the plasma discharge active region is not uniform throughout the suspension, suggesting that not every particle is treated equally. All of these factors could explain why most of the variability was unexplained by the predictors.

The second-order polynomial equation for the oil binding capacity of spelt chaff is given in Eq. 3. Analysis of the fitted model indicated that the stationary point is a maximum. The optimum condition was achieved at 15.63 min (HVED treatment time) and 37.77 Hz (frequency). The corresponding predicted maximum value for oil

binding capacity was 8.243 g/g, as shown in Fig 1. and Fig 2. Compared to untreated spelt chaff, the oil binding capacity increased by 43.6%, indicating successful modification of spelt chaff.

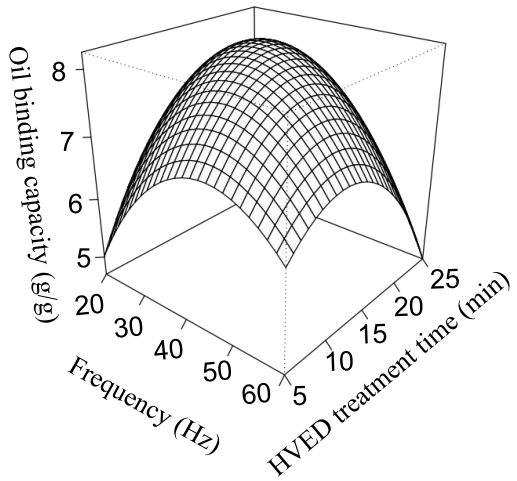

Figure 1. Response surface plot showing the effect of HVED treatment time and frequency on oil binding capacity of spelt chaff

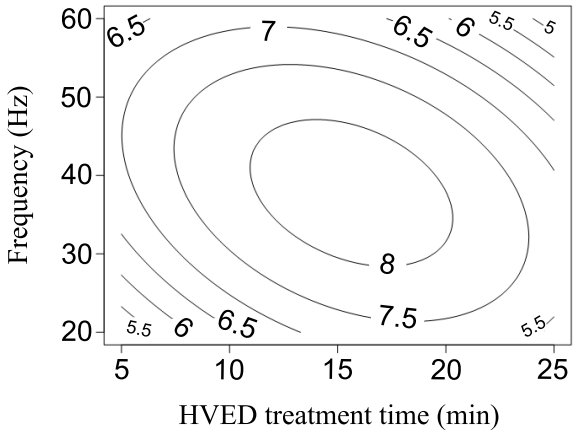

Figure 2. Contour plot showing the effect of HVED treatment time and frequency on oil binding capacity of spelt chaff

Table 3. Estimated regression coefficients with standard errors for oil binding capacity of spelt chaff

Coefficients	Estimate	Std. Error	t-value	p-value
(Intercept)	-1.8541813	2.429989	-0.763	0.449024
HVED treatment time (A)	0.5548533	0.157771	3.517	0.000939
Frequency (B)	0.3049932	0.074578	4.090	0.000157
A^2	-0.0125203	0.002719	-4.606	0.0000286
B^2	-0.0031421	0.000680	-4.623	0.0000269
A×B	-0.0043262	0.003342	-1.295	0.201413

$$Y = -1.8542 + 0.5549\,A + 0.3050\,B - 0.0125\,A^2 - 0.0031\,B^2 - 0.0043\,AB + \varepsilon \quad (3)$$

The F-test for the whey regression model ($F(5, 42) = 1.888$, $p = 0.1169$; $p > 0.05$) showed that the model with no independent variables fits the data as well as the regression model. In addition, the coefficients in the regression models for whey were not statistically significant ($p > 0.05$). Overall, HVED treatment in the case of protein-rich material whey did not show a statistically significant effect on oil binding capacity. Consequently, reliable response surface analysis could not be established in this case.

Conclusion

Under the conditions applied in this research, high-voltage electrical discharge (HVED) successfully increased oil binding capacity of spelt chaff. Using response surface methodology, the highest OBC value was observed at 15 min and 40 Hz, which was 43.6% higher compared to the untreated sample. In contrast, the oil binding capacity of whey was not significantly altered by HVED treatment, which may be due to structural differences between lignocellulosic and protein-rich materials. Overall, HVED, as a green physical treatment, is a promising non-thermal technology for enhancing the properties of selected food industry by-products, especially lignocellulosic materials, into potential structuring agents for oleogel production. Additional research is needed to determine if the lignin loss indeed occurred due to the application of HVED. It is also necessary to identify additional factors that influence OBC besides HVED treatment time and frequency, such as different HVED device geometries and the effect of particle size heterogeneity.

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