Decolorization of liquid sugar products by carbon sorbents

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Abstract

Introduction. This study aims to justify the use of carbon sorbents for adsorption purification (decolorization) of liquid sugar products and to determine the key patterns of the process.

Materials and methods. A sugar-containing product derived from sweet sorghum was used as the raw material in the study. To enhance the purification process and effectively remove coloring agents from the liquid sugar product, various carbon sorbents were utilized. These included novel carbon sorbent CS produced by modifying regenerated wood-based raw materials, and commercially available NORIT, and coconut shell-based activated carbon C607.

Results and discussion. It was established that the decolorization efficiency of the investigated sugar solutions using carbon sorbents depends on the duration of the process and the sorbent dosage, as described by mathematical relationships. High purification efficiency of sugar solutions from coloring substances is achieved with carbon sorbents at dosages of 0.5–1.5% relative to the product mass and a process duration of 20–30 minutes. An analysis of the decolorization kinetics of sugar solutions using the studied carbon sorbents was conducted. Based on a comparative analysis of the adsorption characteristics of the tested sorbents, it was found that the carbon sorbent (CS), at a dosage of 0.5–1.5%, achieved a decolorization efficiency of up to 80–85% and an adsorption capacity of 28–32 mg/g. This resulted in a reduction of solution color to 220–350 ICUMSA units, outperforming the corresponding values obtained with sorbents C607 and NORIT. The high efficiency of the CS carbon sorbent is attributed to its surface characteristics, particularly its micro- and mesoporous structure, which play a key role in determining the sorption kinetics of coloring substances during the liquid-phase purification of sugar-containing products.

Conclusion. The research results indicate the potential for the industrial implementation of carbon sorbent grade CS and its use for the purification of liquid sugar-containing products.

Introduction

Global trends in the development of the sugar industry are defined by key directions such as product range diversification, high quality of finished products, and environmental sustainability (Chorna et al., 2023). A relevant issue is the production of organic sugar, liquid sugars (sugar or invert syrup), as well as the manufacture of sugar-containing syrups from non-traditional plant raw materials, particularly from sweet sorghum (Abdelsalam et al., 2020; Husiatynska et al., 2023; Li et al., 2017; Thilagavathi et al., 2016). Liquid sugar products are becoming increasingly popular in the food and beverage industry due to their long shelf life and ease of use in the food industry (Khan et al., 1996; Mouelhi et al., 2014).

An important aspect of the quality of both crystalline sugar and liquid sugars is meeting organoleptic standards and color specifications. However, during the production of sugar-containing products, especially at the stage of concentration to syrup, reactions occur under the influence of high temperatures, resulting in the formation of intensely colored compounds (colorants) (Lohinova and Petrusha, 2023). The colorants in sugar production have a rather complex chemical structure that remains insufficiently studied, as continuous transformations occur within them. In general, colorants are divided into compounds formed as a result of the breakdown of hexoses and natural compounds present in the raw material that pass into the juice during the extraction or pressing process. These include plant pigments (chlorophylls, carotenoids, and xanthophylls), phenolic compounds, and flavonoids, which undergo complex chemical transformations during processing (Cabral et al., 2022; Zavaleta and Velasco, 2019). Because of a series of chemical reactions, high-molecular-weight compounds with colors ranging from yellow to dark brown are formed (Eggleston et al., 2009; Vercellotti et al., 2010). The intensity of color compound formation in juices and syrups depends on the quality of the raw materials, the duration and temperature of the technological process, the pH of the medium, the concentration of sugar-containing solutions, and the presence of non-sugar substances, which may act as catalysts or inhibitors of color formation.

The formation of color compounds can be classified into the following groups: melanins, melanoidins, products of alkaline-thermal transformation of hexoses, and caramels (Zhu et al., 2021; Zolfaghari et al., 2020). Their presence in sugar syrups leads to a deterioration in product quality and increased coloration, as well as an increase in the viscosity of intermediate products and a decline in the organoleptic properties of the final product due to the development of a bitter taste and a characteristic specific odor. The removal of color compounds is an extremely important task in the production of crystalline sugar, liquid sugar, invert syrup, and food syrups from sweet sorghum.

Currently, several methods are proposed and used for the purification of sugar-containing juices and syrups, including chemical treatment (Kibret, 2019); membrane filtration methods (including ultrafiltration) (Chibrikov et al., 2022); the use of adsorbents such as activated carbon and ion exchange purification (Xiao et al., 2022), among others. However, some of these methods pose potential health risks. For instance, residual amounts of sulfur dioxide during sulfitation or styrene and divinylbenzene monomers during ion-exchange purification may enter food solutions during processing, thereby potentially compromising food safety. Additionally, phosphate treatment removes only certain color compounds, mainly those with high molecular weight and a significant number of carboxylic groups (Kibret, 2019).

The use of carbon-based adsorbing materials, particularly activated carbon derived from agricultural waste, is becoming increasingly relevant for the decolorization of liquid sugar products. Due to its highly developed porous structure and large specific surface area, activated carbon possesses a high adsorption capacity for most contaminants and is widely used across various industries (Ahmad et al., 2010; Bello et al., 2017; Kosheleva et al., 2018). Its application is technologically simple, energy-efficient, relatively inexpensive, and poses no environmental risks. Owing to its ability to absorb and retain a wide range of pollutants, activated carbon serves as an effective adsorbent for the treatment and purification of drinking water, the removal of harmful substances from industrial wastewater, as well as the elimination of high-molecular-weight and colored compounds during the purification of various liquid food solutions (Ruiz-Velducea et al., 2024). Given the above, the use of a developed carbon sorbent based on renewable organic waste and its integration into the technological process of liquid sugar product manufacturing presents scientific and practical interest.

It should be noted that adsorption decolorization processes using activated carbon are widely applied in starch and syrup production. Both powdered and granular forms of activated carbon are used for this purpose. However, despite the significant advantages of activated carbon as a sorbent, its application is not widespread in sugar and liquid syrup production. This is likely due, largely, to economic factors, as food industries currently face a shortage of high-efficiency domestically produced sorbent materials. This necessitates the use of foreign analogues in technological processes, leading to increased production costs. At the same time, approximately 177.5 million tons of plant waste are generated annually in Ukraine, which could be used as raw material for the production of sorbent materials (Zhuk, 2022).

In the present study on the purification (decolorization) of colored compounds, a sugar-containing syrup derived from the stem juice of sweet sorghum was used. The sorghum stems were first cleaned of leaves and then pressed using a roller press to extract the raw juice, which was then used to produce food syrup.

Specifically, the stem sap has balanced nutritional value, containing easily absorbable sugars, comprising 53-85% sucrose and 15-54% fructose and glucose (Blatke, 2019; Rao et al., 2013). The sap contains bioactive substances: amino and organic acids, polyphenols, proteins, vitamins, minerals, and more (Eggleston et al., 2013). When sweet sorghum syrup is utilized in food product technologies, excellent taste and technological characteristics for new product types can be achieved. It can be considered a natural, safe, and complete substitute for sugar in food products.

This study aims to justify the use of carbon sorbents for the adsorption-based decolorization of liquid sugar products, particularly syrup obtained from sweet sorghum stem juice, and to determine the key patterns governing this process.

Materials and methods

Sugar syrup from sweet sorghum

The production of the syrup was carried out according to Hryhorenko et al. (2020), which involved thermal coagulation of non-sugars, a two-stage enzymatic hydrolysis of starch, separation of the coagulated precipitate by filtration with the addition of filter perlite, and additional ultrafiltration purification of the juice using a polyethylene terephthalate membrane with a pore diameter of 0.08–0.15 µm. The purified juice was then concentrated into syrup with a dry matter content of 70–75%.

The physicochemical characteristics of the syrup from sweet sorghum are presented in Table 1.

Table 1

Physicochemical characteristics of the syrup from sweet sorghum

Characteristics	Unit	Value
Dry matter (DM)	%	73.30 ± 0.03
Total sugars (TS)	% to product weight	65.54 ± 0.15
Reducing sugars (RS)	% to product weight	23.72 ± 0.05
Sucrose	% to product weight	41.82 ±. 0.04
Purity	% TS to DM	89.41 ± 0.11
H+ activity		5.12 ± 0.02

Carbon sorbents

The novel carbon sorbent (CS), and commercial available sorbents NORIT GAC 1240 and C607 18x40, supplied by Chemviron Carbon (USA), were used in the study.

The carbon sorbent (CS) was derived from pine pellets with the following specifications: diameter – 6 mm, length – 8–25 mm, moisture content – 7%, ash content – 0.7%, mechanical strength – 98%, bulk density – 0.6 g/cm³. The sorbent production technology involved carbonization in a quartz reactor followed by steam activation, as described in (Brey et al., 2024). This sorbent, further referred to as carbon sorbent (CS), was used in the purification (decolourisation) process of sugar syrup to compare its efficiency with known sorbents NORIT GAC 1240 and C607 18x40.

NORIT GAC 1240 is a coal-based granular activated carbon, while C607 18×40 is a coconut shell-based granular activated carbon. Both are suitable and commonly used for the decolorization of sugar syrups and other liquid sugar products.

Evaluation of the efficiency of colorant removal by carbon sorbents

To evaluate the potential of CS for the decolorization of syrup from sweet sorghum, a series of adsorption experiments were conducted. Each experiment was performed using an individual conical flask containing 100 NORIT of dye solution, to which CS was added. Adsorption of coloring compounds from the solutions was carried out under standard conditions. Fixed volumes, 100 ml, of the sugar-containing product were treated with carbon sorbent samples at dosages of 0.5%, 1.0%, and 1.5% by product mass. The test solutions were kept in a thermostat at 80 °C under constant stirring for 30 minutes. Product samples were taken at 10, 20, and 30 minutes to determine optical density and dry matter content.

Based on the experimental data, the following parameters were calculated: solution color intensity (ICUMSA units), decolorization efficiency (%), and adsorption capacity (A, mg/g). During the study, the following parameters were varied: type and dosage of the sorbent, and duration of the adsorption process. The study was conducted using traditional control and analysis methods commonly used in the sugar industry and accepted in international practice.

The content of total sugars (TS), reducing substances, and sucrose was determined using the Luff-Schoorl method (Asquieri et al., 2007; Dekker, 1950). The purity index was calculated as the ratio of the total sugars content in the product to the dry matter content multiplied by 100% (Hryhorenko et al., 2021).

Dry matter content (DM, % to the weight of the product) was determined at a temperature of 20 °C by the refractometric method (Asquieri et al., 2007) using refractometer RPL-3.

The activity of H^{+} ions was determined by the potentiometric method (Hryhorenko et al., 2021) using universal ionometer EV-74. The quantitative assessment of sugar solution decolorization was performed in accordance with the methodology of the International Commission for Uniform Methods of Sugar Analysis (ICUMSA) (Chai et al., 2016). The ICUMSA color value was then calculated using following formula (1):

$$C\ (\mathrm{ICUMSA}) = \frac{100 \times 1000 \times D}{l \times DM \times \rho} \qquad (1)$$

where: C is color intensity, opt. densityICUMSA units; D is optical density of the solution at 560 nm; l is cuvette length; DM is total solids content,%; p is true density of the solution g/ml.

Decolorization effect (%) was calculated using the following formula (2) (Wang et al., 2023):

$$\text{Decolorization effect} = \frac{(C1 - C2) \times 100}{C1} \qquad (2)$$

where: C1 and C2 are color intensity of the solutions before and after treatment with the carbon sorbent.

Sorption capacity (A, mg/g) was determined by the formula (Sych et al., 2017):

$$A = \frac{k \cdot (C_0 - C_t) \cdot V}{m} \qquad (3)$$

where: k is coefficient that accounts for the ratio between the concentration of coloring substances in the solution and its optical density; V is volume of the solution, ml; m is mass of the carbon sorbent, g; C_0 and C_t are concentrations of coloring substances (g/ml) before and after treatment with the carbon sorbent, respectively.

Taking into account the ratio that:

$$k = 1/Kl \text{ and } C = k \cdot D,$$

where K is the conversion coefficient, which equals 1150 for sugar and refined sugar products; l is cuvette length; D is optical density of the solutions; C is concentration of coloring substances, g/ml.

Accordingly, the Sorption capacity was calculated using the following formula:

$$A = \frac{1}{1150} \cdot \frac{l \cdot (D_0 - D_t) \cdot V}{m} \qquad (4)$$

where D_0 and D_t are optical density of the solutions before and after treatment with the carbon sorbent, respectively.

Characteristics of the structural-adsorptive and physicochemical properties of the studied carbon sorbents

The **textural characteristics** of the studied carbon sorbents were calculated from nitrogen adsorption/desorption isotherm curves using an automated Quantachrome analyzer (Nova 2200e, Quantachrome, USA) with Nova Win 2.0 software.

The **total surface area of the materials** (S total, m^2/g) was calculated using the Brunauer–Emmett–Teller (BET) method (Kotynska et al., 2025).

The **total pore volume** (V total) was calculated from the volume of adsorbed nitrogen converted to liquid at a relative pressure close to $P/P_0 = 1$ (Gregg et al., 1982; Kotynska et al., 2025).

To determine the sorption properties of the adsorbents, an aqueous solution of the dye (methylene blue) was used. The methods involved measuring the change in dye concentration after interaction with the adsorbent. The sorption activity of the studied samples was determined by the methylene blue sorption method following standard procedures using a KFK-3 photoelectric colorimeter (Tarnovsky et al., 2021).

Mathematical and statistical processing of experimental data

To obtain regression equations that adequately describe the adsorption purification process of sugar-containing solutions, methods of mathematical and statistical processing of experimental results were used (Castillo, 2007), along with the Mathcad Professional application software.

The main factors selected were: duration of the purification process (minutes), decolorization of the solutions (%), and carbon sorbents dosage (%). The variation of these factors was conducted within the ranges typical for the purification and decolorization technology of solutions of the sugar-containing product from sweet sorghum.

The research program was incorporated into the experimental design matrix as follows: base level — time: 20 min; sorbent dosage: 1%; variation interval — time: ±10 min; sorbent dosage: ±0.5%; upper level — time: 30 min; sorbent dosage: 1.5%; lower level — time: 10 min; sorbent dosage: 0.5%.

Results and discussion

Adsorption removal of colored compounds from sugar solutions using carbon sorbents

The key parameters investigated during the adsorption process included the type of adsorbent material, adsorbent dosage, contact time, and temperature. In addition, a comparative analysis was conducted to evaluate the relative performance of CS in comparison with other industrially manufactured adsorbents that are commercially available on the market, including NORIT GAC 1240 (further NORIT) and coconut-based charcoal, grade C607 18x40 (further C607), supplied by Chemviron Carbon (USA).

Characteristics of CS were compared with those of industrially manufactured adsorbents that are commercially available on the market, including NORIT and coconut-based charcoal, grade C607 (Table 2).

Table2

Characteristics of the carbon sorbents

Characteristics	C607	NORIT	CS
Bulk density, g/cm³	0.53	0.45	0.34
Adsorption capacity for methylene blue, mg/g	80	155	300
Total specific sorption pore volume, ml/g	0.48	0.55	1.28
Specific surface area, m²/g	1077	1100	1240

It is known (Hryhorenko et al., 2021; Husiatynska et al., 2023), that the purity and chemical composition of sugar-containing syrups depend on the quality of the raw materials, the efficiency of the purification processes, and are determined by the content of non-sugar substances, including colored compounds. Among the factors influencing the adsorption purification process, the following should be highlighted (Dubinin et al., 1987; Qureshi et al., 2008): contact time, sorbent dosage, temperature, concentration of sugar-containing solutions, and the physicochemical properties of the sorbent (such as surface area, and the presence of a significant number of meso- and micropores in the sorbent structure).

According to the characteristics of the carbon sorbent (CS), it can be assumed that the obtained material, due to its sufficiently high surface area and developed micro- and meso-porosity, may serve as an effective sorbent for medium- and large-sized molecules, particularly for high-molecular-weight compounds and colored substances in liquid-phase purification processes of sugar-containing products.

To confirm the effectiveness of using the carbon sorbent (CS), a series of studies was conducted to investigate the removal of coloring compounds from liquid sugar-containing products in comparison with industrial carbon sorbents. The results of the color intensity changes in sugar-containing solutions during a treatment period of 10–30 minutes and with sorbent dosages of 0.5–1.5% are presented in Table 3.

Table 3

Change in the color intensity of sugar solutions treated with carbon sorbents

Time, min	C607	NORIT	CS
	Color, ICUMA units		
Sorbent dosage, 0.5%			
10	615.67	585.23	552.60
20	580.35	562.43	323.89
30	402.66	341.89	292.27
Sorbent dosage, 1.0%			
10	569.99	433.60	347.99
20	402. 12	366.36	251.72
30	392.15	338.70	228.83
Sorbent dosage, 1.5%			
10	509.91	426.70	340.18
20	394.16	358.67	252.19
30	390.65	329.69	222.81

An increase in the process duration up to 30 minutes and sorbent dosage in the range of 0.5–1.5% (relative to product mass) led to a gradual decrease in colour intensity of the treated sugar-containing liquids for all tested sorbents.

For example, when purifying the initial solution with a color intensity of 1489.06 ICUMSA units using activated carbon, a 30-minute contact time and a sorbent dosage of 1.5% resulted in the following reductions in color intensity: 390.65 ICUMSA units for C607; 329.69 ICUMSA units for NORIT; and 222.81 ICUMSA units for CS.

At the same time, a favourable decolourisation dynamic was also observed at lower treatment durations (20 minutes) and carbon dosages of 1.0%, for all sorbents C607, NORIT, and CS.

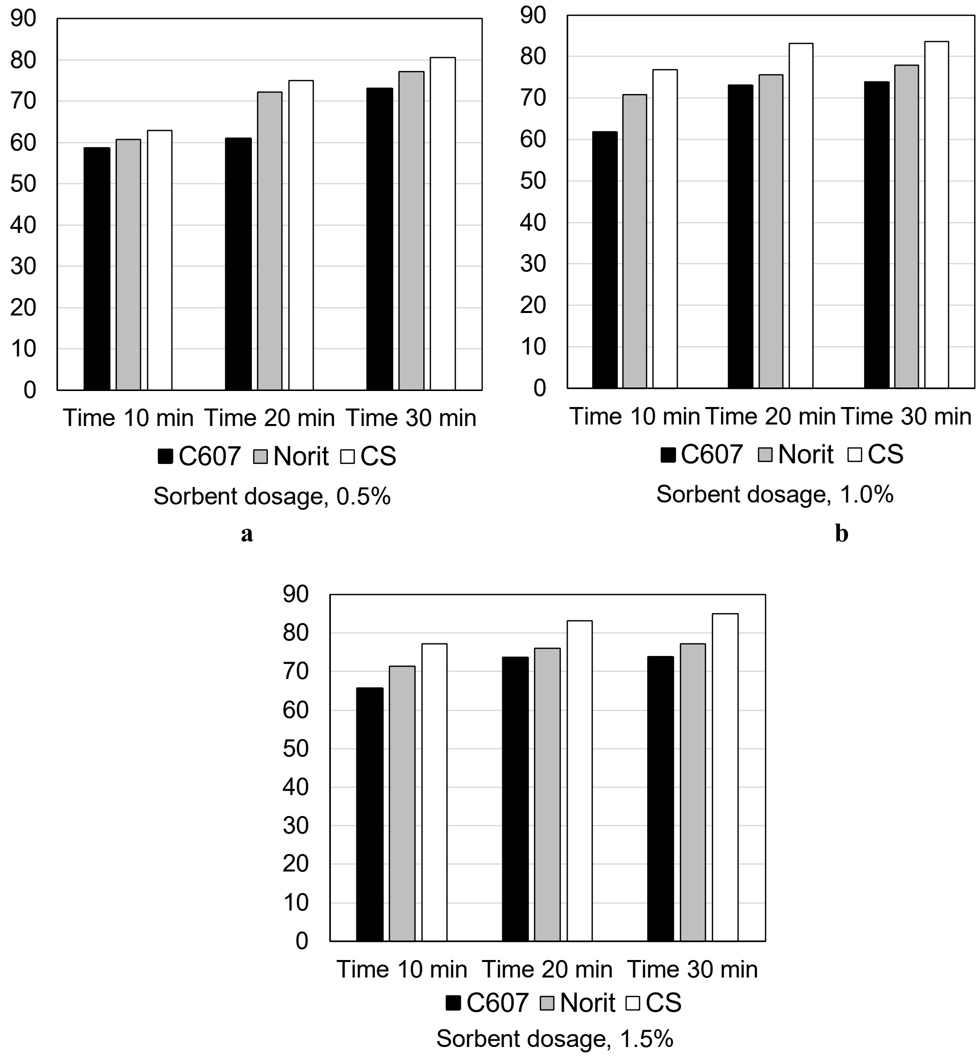

Figure 1. Decolorization effect of syrup at different process durations.
Dosage of sorbent, %: a – 0.5; b – 1.0; c – 1.5.

To determine the optimal parameters of adsorption purification, it is advisable to assess the process based on the decolorization effect achieved under varying process parameters. This was done by calculating the percentage reduction in solution color intensity before and after treatment with the tested carbon sorbents using formula (2). The diagrams showing the changes in the decolorization effect of sugar-containing solutions over a process duration of 10–30 minutes and sorbent dosages of 0.5–1.5% are presented in Figures 1 (a, b, c).

Based on the comparison of the adsorption characteristics of the carbon sorbent CS with commercial activated carbon samples (Fig. 1a, b, c), it was established that the decolorization effect achieved using sorbent CS was 80–85% at a dosage of 0.5–1.5%, which exceeds the corresponding performance of sorbents C607 and NORIT.

The data on the decolorization effect of the solutions (Fig. 1 a, b, c) correlate with the previously presented results on the change in color intensity of the solutions during purification with the studied carbon sorbents (Table 3), and are also consistent with findings reported by other researchers (Wang et al., 2023; Zolfaghari et al., 2020).

In particular, the use of an adsorbent synthesized from bagasse with the addition of hydroxyapatite enabled the decolorization of juice and syrup from sugarcane by 92.41% and 93.19%, respectively (Wang et al., 2023). Also, a combined method for the decolorization of the beet sugar syrup using activated carbon granules was proposed, which gave a decolorization performance at the level of 83.68% (Zolfaghari et al., 2020).

Mathematical and statistical analysis of experimental results

An important step in determining the optimal parameters for adsorption purification is obtaining mathematical relationships that allow for the prediction of decolorization efficiency of sugar solutions within the selected range of key process variables. As a result of the mathematical and statistical analysis of the experimental data, regression equations were obtained that adequately describe the influence of the studied factors on the purification and decolorization of solutions of the sugar-containing product from sweet sorghum when using the following substances as adsorbents:

NORIT:

$$\mathrm{Effect\ decolor} = 37.046 + 1.651 \cdot \mathrm{t} + 27.879 \cdot \mathrm{c} - 0.534 \cdot \mathrm{t} \cdot \mathrm{c} - 0.016 \cdot \mathrm{t}^2 - 5.608 \cdot \mathrm{c}^2$$

C 607:

$$\mathrm{Effect\ decolor} = 30.734 + 1.718 \cdot \mathrm{t} + 26.571 \cdot \mathrm{c} - 0.305 \cdot \mathrm{t} \cdot \mathrm{c} - 0.020 \cdot \mathrm{t}^2 - 6.886 \cdot \mathrm{c}^2$$

CS:

$$\mathrm{Effect\ decolor} = 26.588 + 2.227 \cdot \mathrm{t} + 46.291 \cdot \mathrm{c} - 0.540 \cdot \mathrm{t} \cdot \mathrm{c} - 0.029 \cdot \mathrm{t}^2 - 12.983 \cdot \mathrm{c}^2$$

t is process duration, minutes;
c is carbon sorbent dosage, %.

The obtained equations adequately describe the dependence of the decolorization effect of sugar-containing solutions at a temperature of 80 °C, within a process duration of 5–35 minutes, and a carbon sorbent dosage range of 0.3–1.7%.

He obtained regression equations can be used to analyze the decolorization process of sugar-containing solutions and to determine the optimal parameters for process duration and sorbent dosage when using the specified carbon sorbents.

The next stage of the mathematical and statistical analysis of the experimental results involved calculating the sorption capacity (A, mg/g) and conducting a comparative analysis of the decolorization kinetics solutions using the studied carbon sorbents. The calculated adsorption values under the investigated process durations, presented in Figures 2 (a, b, c), show that the sorption-kinetic decolorization properties of the studied carbon sorbents gradually increase with higher sorbent dosages and longer sorption times. For instance, at a dosage of 1.5% (relative to the product mass) and a process duration of 30 minutes, the sorption capacity (A, mg/g) was as follows: 28.02 mg/g for C607; 29.55 mg/g for NORIT; and 31.91 mg/g for CS.

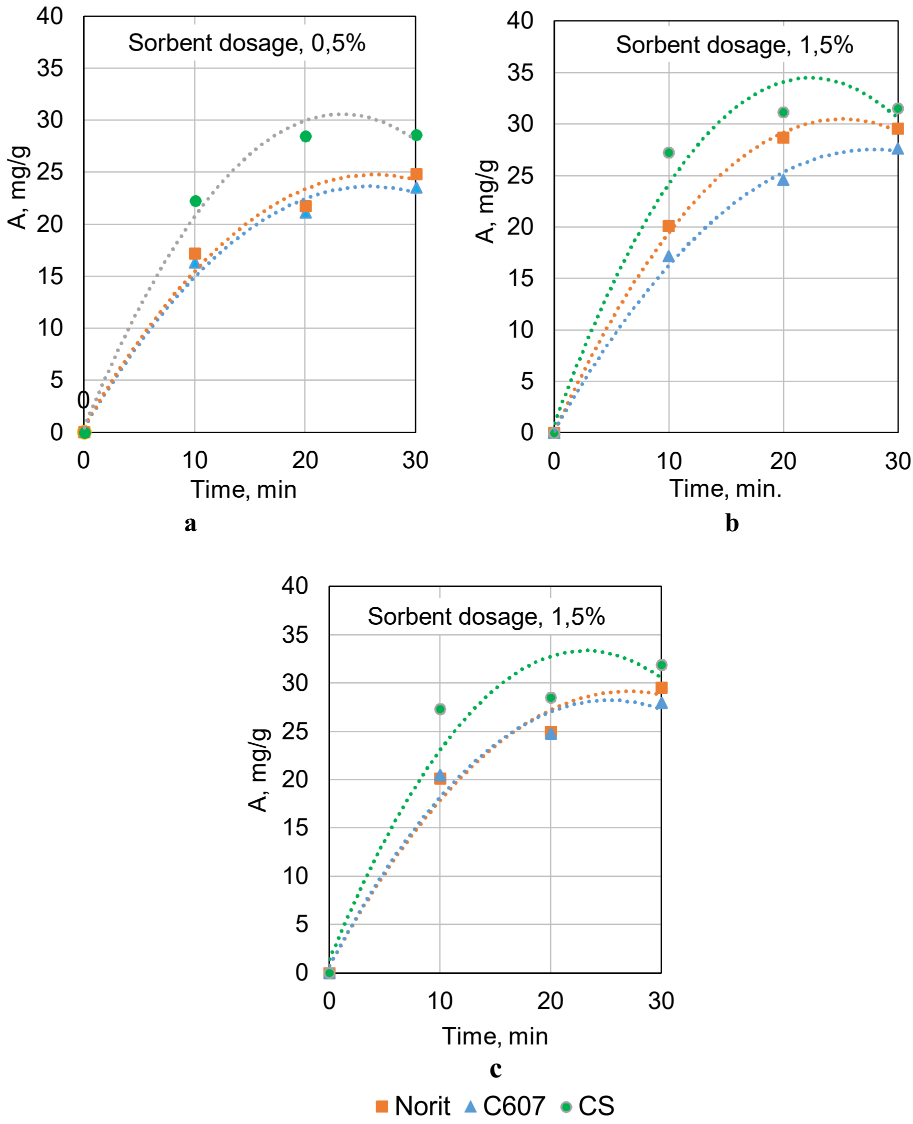

Figure 2. Change in colorant absorption (A) from sugar syrup at sorbents dosage of: 0.5% (a), 1.0% (b), and 1.5% (c).

Moreover, the data presented in Figures 2 (a, b, c) clearly illustrate the sorption-kinetic performance of the studied carbon sorbents in removing colorants from sugar-containing solutions. Accordingly, their performance may be ranked in the following order:

CS > NORIT > C607.

Conclusions

The carbon sorbent CS, obtained through the modification of renewable woody raw materials, demonstrated effective performance in purifying sugar-containing solutions from coloring compounds and, in terms of its properties, showed superior results compared to the commercial available C607 and NORIT sorbents.

The CS carbon sorbent possesses sufficient mechanical strength of the granules, indicating its practicality for long-term use and the possibility of reuse after regeneration.

The obtained results indicate the potential for industrial implementation of the CS carbon sorbent and its application in the purification of liquid sugar-containing products. Furthermore, based on its physicochemical characteristics, the sorbent shows promising potential for use in the purification of aqueous solutions in the chemical, food, and pharmaceutical industries, as well as for water treatment and wastewater purification from organic pollutants.

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