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PHOTOCATALYTIC DEGRADATION AND ADSORPTION OF REMAZOL DYE WASTE USING TiO_2/BIOCHAR COMPOSITE AT SMAN 3 MUARO JAMBI BATIK STUDIO

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Abstract:
This study aims to evaluate the effectiveness of Remazol batik wastewater treatment at SMAN 3 Muaro Jambi through degradation and adsorption using a TiO_2/biochar photocatalytic composite. The biochar was derived from cassava peel and employed under UV light irradiation, with UV-Vis spectrophotometry used for analysis. Treatment efficiency was assessed by varying the biochar mass (1–4 grams) and reaction time (1, 3, and 6 hours). The highest removal efficiency of 100% was achieved at 4 grams of biochar and 6 hours of exposure. The adsorption process followed the Freundlich isotherm model, indicating a multilayer adsorption mechanism on the biochar surface. These findings suggest that the TiO_2/biochar composite offers an effective, eco-friendly, and practical solution for small-scale batik wastewater treatment, particularly in educational and home industry settings.

Keywords: *batik wastewater, photocatalytic, biochar, TiO_2*

Abstrak:
Penelitian ini bertujuan untuk mengevaluasi efektivitas pengolahan limbah batik Remazol di SMAN 3 Muaro Jambi melalui proses degradasi dan adsorpsi menggunakan komposit fotokatalitik TiO_2/biochar. Biochar dibuat dari kulit singkong dan digunakan dalam proses iradiasi sinar UV, dengan analisis dilakukan menggunakan spektrofotometri UV-Vis. Efisiensi pengolahan diuji dengan variasi massa biochar (1–4 gram) dan waktu reaksi (1, 3, dan 6 jam). Hasil terbaik menunjukkan efisiensi penghilangan mencapai 100% pada massa biochar 4 gram dan waktu 6 jam. Proses adsorpsi mengikuti model isoterm Freundlich, yang mengindikasikan mekanisme adsorpsi berlapis pada permukaan biochar. Temuan ini menunjukkan bahwa komposit TiO_2/biochar merupakan solusi yang efektif, ramah lingkungan, dan aplikatif untuk pengolahan limbah batik skala kecil, khususnya di lingkungan pendidikan dan industri rumahan.

Kata kunci: limbah batik, fotokatalisis, biochar, TiO_2

INTRODUCTION

Batik is an Indonesian cultural heritage that holds not only aesthetic value but also high economic and social value. Each region in Indonesia has its own distinctive batik patterns, including Jambi Province, which is known for its Batik Jambi designs. In efforts to preserve and promote batik, the provincial government of Jambi has initiated various promotional and educational activities in schools, such as batik fashion shows, batik-making training, and batik ambassador competitions at the student level. One of the schools actively involved in these activities is SMAN 3 Muaro Jambi, which integrates batik-making as part of its extracurricular activities and student learning projects.

The batik-making activity at this school uses a synthetic dye, Remazol, in the dyeing process. The use of this dye generates liquid waste containing complex organic compounds that are non-biodegradable and difficult to break down naturally. Untreated batik waste that is directly disposed of into the environment poses a risk of lowering water quality and disturbing the balance of the surrounding aquatic ecosystem. The characteristics of this waste include high color intensity (50–2500 Pt-Co), Chemical Oxygen Demand (COD) ranging from 150 to 12000 mg/L, and Biological Oxygen Demand (BOD) reaching 80 to 6000 mg/L. At SMAN 3 Muaro Jambi, the batik waste is only collected in a simple container without further treatment, and some of it is disposed of into the drainage system that leads to ponds around the batik studio, potentially contaminating local water bodies.

Conventional management of batik waste has been carried out using various methods, such as adsorption, chlorination, ozonation, coagulation, flocculation, and reverse osmosis. These methods are quite effective, but they generally have high operational costs and can generate residues or secondary pollutants. Therefore, an alternative approach that is more efficient and environmentally friendly is needed. One method that has been developed is photocatalysis, a process of degrading organic compounds with the assistance of ultraviolet (UV) light and semiconductor catalysts. Photocatalysis has the advantage of accelerating chemical reactions without generating harmful by-products (Anggraini et al., 2021).

Titanium dioxide (TiO_2) is one of the most widely used photocatalysts due to its chemical stability, non-toxicity, and high effectiveness in degrading various types of organic pollutants. A study by Harun et al. (2018) showed that the use of TiO_2 as a photocatalyst could degrade Congo Red dye by more than 80%. A similar study by Aminullah (2019) demonstrated that at an initial concentration of 5 mg/L, the photocatalytic degradation of Remazol Yellow using TiO_2 achieved an effectiveness of 82.25% after 24 hours of exposure. However, the effectiveness of TiO_2 decreases at high waste concentrations due to its limited adsorption capacity.

To increase degradation efficiency, TiO_2 can be combined with adsorbent materials such as biochar. Biochar is activated carbon produced through the pyrolysis of biomass, characterized by a porous structure and high surface area, making it capable of adsorbing pollutants and enhancing photocatalytic reactions. One potential source of biochar is cassava skin, which has not been optimally utilized despite its abundance. Alfiany et al. (2013) stated that biochar from cassava skin has lower ash and moisture content compared to other raw materials. Jambi Province itself produces approximately 53,944 tons of cassava annually (BPS, 2016), making its skin a highly potential adsorbent raw material.

The combination of TiO_2 and biochar has been shown to improve waste degradation effectiveness. Li et al. (2016) reported that TiO_2/Biochar composites could remove more than 92% of Methyl Orange pollutants under visible light. Another study by Gonçalves et al. (2021) showed an efficiency of about 90% in degrading sulfamethoxazole and Methyl Orange using ZnO/Biochar. Laury (2022) also reported a degradation efficiency of 83% for Orange II Sodium dye, accompanied by an increase in solution pH. Based on these findings, the combination of TiO_2 and biochar shows great potential in processing dye waste, including batik waste.

This study aims to determine the extent of the reduction in the concentration of Remazol batik waste produced from the batik-making process at SMAN 3 Muaro Jambi and to analyze the degradation and adsorption activities that occur in this waste through a photocatalytic process using TiO_2/Biochar composites. The analysis was conducted using UV-Vis spectrophotometry and measurement of key parameters such as pH and reaction time. It is hoped that the results of this study can make a tangible contribution to the development of efficient and applicable small-scale wastewater treatment technology, especially in educational environments and home industries.

METHODS

This research is a laboratory-based experimental quantitative study aimed at evaluating the effectiveness of the TiO_2/Biochar photocatalyst in degrading Remazol batik waste through photocatalytic and adsorption processes. The study was conducted using an experimental approach with variations in biochar mass and treatment time to assess the reduction in batik waste concentration after treatment. The research was conducted from September to November 2024 at the Instrumentation Laboratory and Final Project Laboratory, Faculty of Science and Technology, Universitas Jambi, as well as at the IPA Laboratory of SMAN 3 Muaro Jambi. The research subjects consisted of Remazol batik waste samples obtained directly from the Batik Studio of SMAN 3 Muaro Jambi. The samples were collected using the wastewater sampling method in accordance with SNI 6989.59:2008 and stored in sterile 100 mL glass bottles for further analysis.

Research Procedures

This research was conducted in several stages:

(1) The TiO_2/Biochar activity test was conducted by taking 100 mL of Remazol and adding TiO_2/biochar catalyst from cassava skin with varying biochar masses of 1g, 2g, 3g, and 4g. The mixture was then exposed to UV light under a reactor and stirred using a stirrer for various irradiation times of 1 hour, 3 hours, and 6 hours. The mixture was then filtered, and its absorbance was measured using a UV-Vis spectrophotometer.
(2) For the adsorption test, the method used in this study was the Batch method. According to Anggraini (2013), this method is one of the best for reducing the concentration of Remazol in batik waste. The TiO_2/biochar adsorption test was conducted by taking 100 mL of Remazol and adding TiO_2/biochar catalyst from cassava skin with varying biochar masses of 1g, 2g, 3g, and 4g to the sample. The mixture was then stirred using a stirrer for 1 hour, 3 hours, and 6 hours in the dark or without light.

Data, Instruments, and Data Collection Techniques

The data collected consisted of the absorbance values of the wastewater before and after treatment, measured using a UV-Vis spectrophotometer. The main instruments used in this research included the UV-Vis spectrophotometer, UV photocatalytic reactor, pH meter, and orbital shaker. Data were collected by measuring the absorbance of the wastewater solution after the degradation and adsorption processes and analyzed to determine the efficiency and adsorption capacity.

Data Analysis Technique

The degradation data was analyzed using the photocatalytic efficiency formula (Sutanto, 2017):

$$Degradtion\ (\%) = \frac{Co - Ct}{Co}\ x\ 100\%$$

Explanation:
Co = Concentration before irradiation
Ao = Absorbance before irradiation
Ct = Concentration after irradiation
At = Absorbance after irradiation

Additionally, for the adsorption test (Liu et al., 2010), the following formula was used:

$$qe = \frac{(Co - Ce)V}{M}$$

$$\text{Adsorption efficiency (\%)} = \frac{(Co - Ce)}{Co}\ \text{x}\ 100\%$$

Explanation:
qe = Adsorption capacity (mg/g)
C_o = Concentration before the adsorption process (mg/l)
C_e = Concentration after the adsorption process (mg/l)

V = Sample volume (L)
M = Adsorbent mass (g)

To understand the adsorption characteristics, the Freundlich isotherm model was used:

$$\text{Log } Qe = \log Kf + (1/n) \log Ce$$

Explanation:

Qe = Amount of adsorbate on the surface (mg/g)
n = Constant
K = Adsorption capacity
Ce = Adsorbate concentration (mg/L)

And the Langmuir isotherm model:

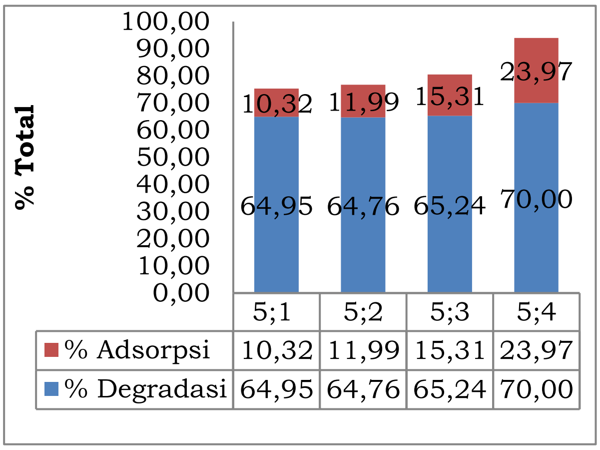
$$\frac{Ce}{Qe} = \frac{1}{Qm} Ce + \frac{1}{KlQm}$$

Explanation:

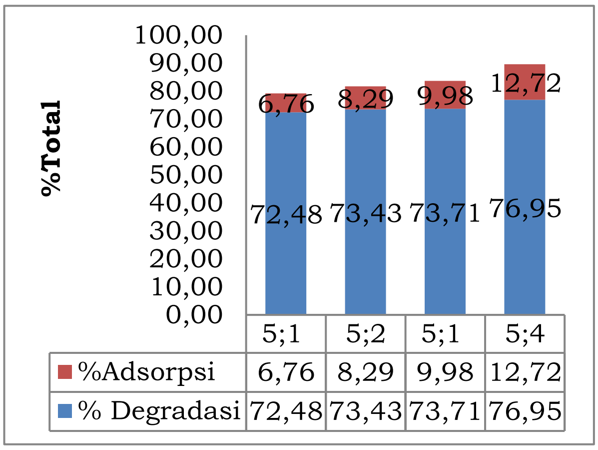
Q_e : Amount of adsorbate on the surface (mg/g)
Q_m : Adsorption capacity
K_l : Langmuir Constant
C_e : Adsorbate concentration (mg/L)

RESULTS AND DISCUSSION

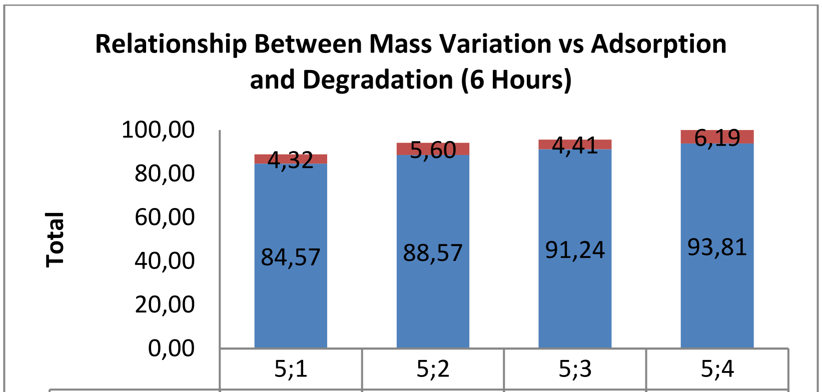
The total analysis shows that at a treatment time of 1 hour with a biochar mass of 1 gram, the total efficiency of the combination of degradation and adsorption reached 75.27%. At a biochar mass of 2 grams, the total value slightly increased to 76.75%. A biochar mass of 3 grams showed further improvement with a total efficiency of 80.55%, and a biochar mass of 4 grams achieved the highest efficiency of 93.97%. These results emphasize that increasing the biochar mass not only enhances the degradation process but also improves the overall adsorption capacity, making it more efficient in the contaminant removal process in the solution.



(a)



(b)



	5;1	5;2	5;3	5;4
% Adsorpsi	4,32	5,60	4,41	6,19
% Degradasi	84,57	88,57	91,24	93,81

(c)

Figure 1. Effect of biochar mass variation on the degradation and adsorption of Remazol with a constant TiO_2 mass (5 g) at the optimum pH over (a) 1 hour, (b) 3 hours, and (c) 6 hours

The total analysis at a treatment time of 3 hours shows that the combination of degradation and adsorption demonstrates an increase in efficiency with the increase in adsorbent mass. At a biochar mass of 1 gram, the total efficiency was recorded at 79.24%. When the biochar mass was increased to 2 grams, the total efficiency rose to 81.72%. At 3 grams, the efficiency reached 83.70%, and at 4 grams, the highest total efficiency of 89.67% was achieved. This data indicates that the system combining TiO_2 photocatalyst with biochar adsorbent becomes more effective in enhancing degradation and adsorption as the mass increases, showing that both processes work synergistically in contaminant removal.

The total effectiveness of the combined adsorption process by biochar and degradation by TiO_2 photocatalyst results in a more effective synergistic effect compared to using biochar or TiO_2 alone. At the treatment time with a biochar mass of 1 gram, the total effectiveness reached 88.89%, while at a biochar mass of 4 grams, it achieved the maximum value of 100.00%. This synergy occurs because pollutant molecules adsorbed on the biochar surface are more easily exposed to free radicals produced by TiO_2. This combination accelerates the degradation process, as pollutants that are held on the biochar surface become easier targets to be broken down by free radicals, increasing the rate and overall efficiency of pollutant degradation. With the increase in biochar mass, the surface area and number of pores available for adsorption also increase, thereby improving biochar's capacity to adsorb pollutants from the solution. This adsorption mechanism is highly influenced by the micropore and mesopore structure of biochar, which is capable of trapping pollutant molecules for a longer period.

Overall, the results from the treatment time indicate a positive correlation between the increase in biochar mass and the effectiveness of the TiO_2 photocatalytic system and biochar adsorbent in terms of degradation and adsorption. The increase in mass provides more active sites, allowing for better photocatalytic degradation and higher adsorption capacity, thus enhancing the overall system efficiency in contaminant treatment.

Managing Remazol batik waste using TiO_2 biochar is an innovative step in addressing environmental issues related to the batik industry. This is also in line with the research by Faza et al. (2021), which highlights the importance of monitoring parameters such as pH and turbidity to ensure that the waste produced is of good quality before disposal. By adopting this method, significant reductions in waste pollution are expected. This application is not only beneficial for the ecosystem but also supports the sustainability and long-term development of the batik industry.

Adsorption Isotherm

An adsorption isotherm is the relationship between the adsorbed substance and its concentration at constant temperature. The change in adsorbate concentration during the adsorption process, in accordance with the adsorption mechanism, can be studied through the determination of the adsorption

isotherm. The most commonly used isotherm models are the Langmuir isotherm and the Freundlich isotherm. To determine the pattern of the adsorption isotherm, tests were conducted using Remazol solution with different time intervals, namely adsorption at 1 hour, 3 hours, and 6 hours.
If the adsorption process follows the Langmuir isotherm model, the adsorption occurs in a monolayer. The Langmuir isotherm model assumes that the solid is homogeneous, and the adsorption occurring on the surface is localized adsorption. In this model, adsorbate molecules are adsorbed only at specific sites. This means that each site accommodates only one adsorbate molecule (Astuti, 2018).

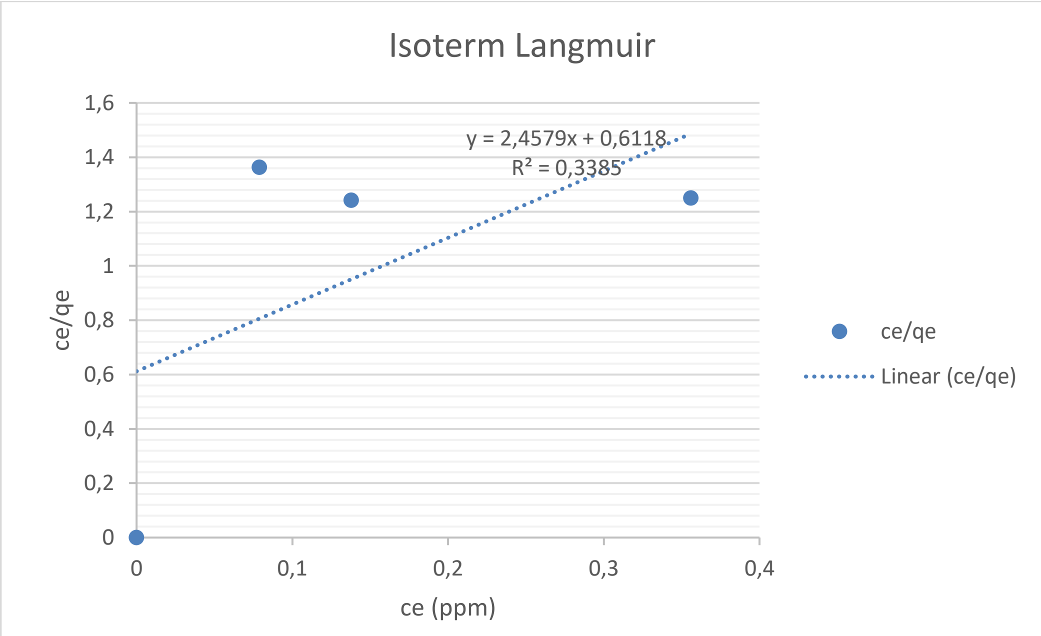


Figure 2. Langmuir Isotherm Curve

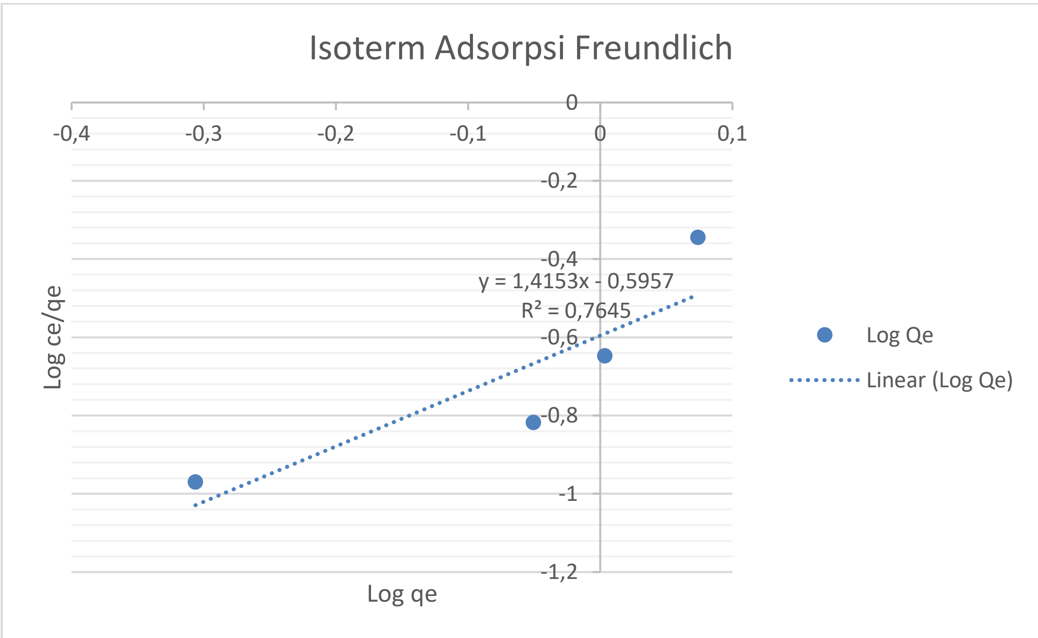


Figure 3. *Freundlich Isotherm Curve*

Table 1. Results of Adsorption Isotherm Calculations

Time Var	Langmuir			Freundlich		
	qm	K_l	R^2	n	K_f	R^2
3	0.1546	-3.979	0.262	0.7061	0,1719	0.7645

Based on Table 10, it was found that the adsorption isotherm model that best fits this study is the Freundlich isotherm model. This is evident from the fact that the linear regression value of the Freundlich isotherm is higher than that of the Langmuir isotherm, with regression values of 0.262 for Langmuir and 0.764 for Freundlich. This indicates that the adsorption follows the Freundlich adsorption model. The isotherm model obtained is consistent with the isotherm model in the study by Wahyuningsih (2018) regarding the use of cassava peel waste as an adsorbent for Remazol Brilliant Blue. The Freundlich isotherm model is based on the principle that adsorption occurs in a multilayer, where each adsorbate molecule occupies more than one adsorption site, both on the surface of the adsorbent and inside the adsorbent. In the Freundlich isotherm model, the adsorption sites on the surface of TiO_2/biochar have uniform energy. This means that each adsorbate molecule has an equal chance of binding to both the surface and within the adsorbent. The adsorption of Remazol by biochar is illustrated in Figure 26, where the adsorption process on the surface of the adsorbent forms a multilayer. The adsorbate will accumulate on the adsorbent surface forming the first layer, and then the adsorbate will continue to adsorb onto the adsorbent surface until it forms a multilayer.

This isotherm model shows that TiO_2/biochar is effective in removing pollutants from batik waste through multilayer adsorption, with the active adsorption sites distributed heterogeneously and occurring quickly while being able to re-act. The following is an illustration of the adsorption process that occurs on the surface of the adsorbent (Gamage et al., 2023).

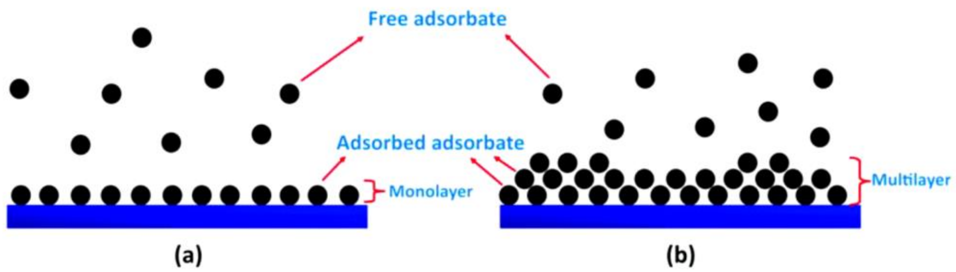


Figure 4. *Adsorption Process on the Adsorbent Surface (Gamage et al., 2023)*

CONCLUSION AND SUGGESTION

The greatest reduction in the concentration of Remazol batik wastewater through degradation and adsorption was achieved with a biochar mass of 4 grams and a contact time of 6 hours. Under these conditions, the initial Remazol concentration decreased from 20.76 ppm to 3.23 ppm, with degradation and adsorption efficiency reaching 100%. Isotherm analysis demonstrated that the adsorption process is best described by the Freundlich model, indicating multilayer adsorption with heterogeneous and uniformly distributed active sites on the biochar surface. These findings highlight the potential application of biochar as an effective and sustainable adsorbent for treating dye-contaminated wastewater, particularly in the batik industry. The results also provide valuable insights for developing low-cost, environmentally friendly wastewater treatment technologies that align with circular economy principles. Future studies are recommended to explore the reusability and regeneration capacity of biochar in repeated adsorption–desorption cycles, investigate the effects of different operating parameters such as temperature and agitation speed, and evaluate performance at a pilot or industrial scale to assess the feasibility of large-scale implementation.

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