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Research Article / Araştırma Makalesi

Physicochemical Characterization of Domestic Washing Machine Grey Water and Treatment with Granular Activated Carbon

Evsel Çamaşır Makinesi Gri Suyunun Fizikokimyasal Karakterizasyonu ve Granül Aktif Karbon ile Arıtımı

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Abstract

In this study, the physicochemical properties of domestic washing machine graywater were determined, and the treatment performance of granular activated carbon (GAC) was evaluated in a laboratory setting. Graywater samples were collected using different washing programs and analyzed for key parameters such as pH, electrical conductivity, suspended solids, chemical oxygen demand (COD), surfactants, total phosphate, and total nitrogen. Adsorption experiments conducted at different GAC doses (0.5–4 g/L) and contact times of 30–120 minutes revealed that the optimum conditions were 4 g/L GAC and 120 minutes of contact time. Under these conditions, COD removal was 32% and surfactant removal was 38%. Kinetic analyses showed a high fit to the pseudo-second-order model (R^2=0.98), and isotherm studies revealed that the Freundlich model reflects heterogeneous surface properties. In conclusion, the low removal rates obtained with GAC indicate that the current method is inadequate for the treatment of washing machine graywater and that the design and use of more effective new filter materials are needed.

Keywords: *Greywater, washing machine, physicochemical analysis, granular activated carbon, adsorption.*

Öz

Bu çalışmada, evsel çamaşır makinesi gri suyunun fizikokimyasal özellikleri belirlenmiş ve laboratuvar ortamında granül aktif karbon (GAK) ile arıtım performansı değerlendirilmiştir. Farklı yıkama programları kullanılarak gri su örnekleri toplanmış ve pH, elektriksel iletkenlik, askıda katı madde, kimyasal oksijen ihtiyacı (KOİ), yüzey aktif maddeler, toplam fosfat ve toplam azot gibi temel parametreler açısından analiz edilmiştir. Farklı GAK dozlarında (0,5–4 g/L) ve 30–120 dakika temas süresinde yürütülen adsorpsiyon deneyleri, optimum koşulların 4 g/L GAK ve 120 dakika temas süresi olduğunu göstermiştir. Bu koşullarda KOİ giderimi %32, yüzey aktif madde giderimi %38 olarak saptanmıştır. Kinetik analizler pseudo-second-order modeline (R^2=0,98) yüksek uyum göstermiş, izoterm çalışmaları ise Freundlich modelinin heterojen yüzey özelliklerini yansıttığını ortaya koymuştur. Sonuç olarak, GAK ile elde edilen düşük giderim oranları, çamaşır makinesi gri su arıtımında mevcut yöntemin yetersiz kaldığını ve daha etkili yeni filtre malzemelerinin tasarımına ve kullanımına ihtiyaç olduğunu göstermektedir.

Anahtar Kelimeler: *Gri su, çamaşır makinesi, fizikokimyasal analiz, granül aktif karbon, adsorpsiyon.*

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1. Introduction

The amount of wastewater (WW) generated as a result of increased water use due to urbanization, industrialization, and population growth is also constantly increasing [1]. This WW, generated by human activities, causes the spread of various pollutants that are harmful to the environment and human health [2]. Detergents are among the most significant pollutants contributing to industrial and domestic water pollution, particularly in large cities [3]. Domestic WW consists of gray water (showers, bathtubs, sinks, washing machines, and dishwashers) and black water WW from toilets) [4]. Detergents are surface-active agents that break down dirt and stains on laundry by lowering the surface tension of water [5,6]. The most commonly used surfactant in household and industrial laundry detergents is anionic linear alkyl benzene sulfonate (LAS) [7].

In regions experiencing water scarcity, treating greywater on-site for irrigation and toilet flushing is a viable alternative. The European Commission has reported that by 2050, encouraging graywater reuse and rainwater harvesting will reduce drinking water use by approximately 5% [7]. The composition of graywater coming from a washing machine varies depending on the soiling of the laundry, the washing method used, and the type and amount of detergent [7]. When washing clothes, washing machines consume a lot of water, detergent, and energy [8]. The volume of water used in a home washing machine for one cycle is 60 liters in Europe, while it is 140 liters in North America and Japan. In industrial laundries, daily water consumption reaches up to 400 m^3 [9]. Laundry WW may contain high doses of soaps and detergents for dirt and stain removal, as well as optional ingredients such as fabric softeners, washing soda, and bleach to increase wash efficiency [10]. Washing machine WW containing these toxic components has significant detrimental effects on the ecosystem, including biodiversity degradation, water and soil pollution [11,12]. For this reason, washing machine WW must be discharged into the receiving water environment after being treated [12]. Surfactants exceeding 0.5 mg/L can be harmful to health [13]. Therefore, some authorities in Türkiye and around the world have set certain limit values. The Water Pollution Control Regulation sets anionic surfactant concentrations in surface waters as 0.5 mg/L, 1 mg/L, 1.5 mg/L, and >1.5 mg/L for Class 1 (high quality), Class 2 (lightly polluted), Class 3 (polluted), and Class 4 (heavily polluted), respectively. In the European Union water quality criteria, the recommended value for methylene blue active substances is ≤0.3 mg/L. The World Health Organization has set the maximum concentration of anionic detergents in drinking water as 0.2 mg/L [14].

There are limited studies in the literature on the characterization of domestic laundry wastewater [15–17] Assessing the physicochemical parameters of greywater is a critical step in determining its reuse potential and treatment requirements [18]. Therefore, before greywater treatment, its physicochemical characterization should be determined. Identifying these parameters ensures the selection of the appropriate treatment method and sustainable water management [18]. The reuse of greywater through treatment has great potential for both water saving and environmental protection [19]. Greywater needs to be treated utilizing physical, chemical, and biological mechanisms before it can be utilized again [20]. In the last decade, various treatment methods such as coagulation and flocculation, wet air oxidation, membrane separation, ion exchange, ozonation, photocatalytic degradation, Fenton oxidation and other advanced oxidation processes have been developed for the removal of anionic surfactants in WW [16]. Among these methods, granular activated carbon (GAC) adsorption stands out due to its large surface area, high porosity and strong adsorption capacity against various pollutants [21].

A literature review reveals a limited number of studies on the treatment of washing machine wastewater. Most existing studies have been conducted on synthetic graywater samples containing detergents and do not fully reflect the complex nature of real domestic wastewater. However, the treatment of real washing machine wastewater provides more realistic and applicable results due to the many factors that vary in daily life, such as the types of detergent used, wash temperatures, fabric textures, soil loads, and microfiber release. Such studies allow for a more accurate assessment of treatment systems performance in the field, their reuse potential, and their contribution to sustainable water management. Therefore, this

study examined the treatment of a real graywater sample obtained from a household washing machine. First, the physicochemical characterization of the wastewater was conducted, followed by an investigation of the treatment efficiency using granular activated carbon.

2. Materials and Method

2.1. Sample collection

Graywater samples were collected from the washing machine of a family of five, including three children, in Adıyaman province. Five kilograms of white laundry was washed with liquid detergent at 60 °C for three hours. Immediately after washing, samples were taken from the washing machine's drain pipe and stored in sterilized glass jars at + 4°C. Samples were removed from the washing machine's drain pipe immediately after washing and stored in sterilized glass jars. Sampling was performed three times over a month, under the same conditions throughout. To minimize potential chemical and biological changes, all samples were analyzed within 24 hours of collection. All experiments were conducted in the Environmental Engineering Laboratory of Adıyaman University, Faculty of Engineering.

2.2. Physicochemical analysis

Collected greywater samples were subjected to a series of physicochemical analyses based on standard methods. The analyzed parameters were as follows:

- pH (Thermo Scientific Orion Star) and electrical conductivity (EC): measured using probes.
- Suspended Solids (SDS): determined by Standard Methods 2540 D Total Suspended Solids 103-105°C drying method) [22].
- Chemical Oxygen Demand (COD): measured using the titrimetric method described in Standard Methods r 5520-C [22].
- Surfactants: analyzed using the methylene blue active substances (MBAS) method [23]
- •Total phosphate (PO_4^{3-}) and total nitrogen (TN): analyzed using spectrophotometric methods after appropriate digestion procedures (Standard Methods 4500-P-N) [22].

Spectrophotometric measurements used in this study were made with an ultraviolet and ultraviolet visible (Hach Lange/DR 6000) spectrophotometer.

2.3. Treatment experiments with granular activated carbon

The granular activated carbon used in the adsorption experiments was commercially available. The carbon is coal-based, has an average surface area of approximately 800 m^2/g, and a particle size of 0.5–2 mm. Treatment experiments were conducted in batch mode in 1 liter Erlenmeyer flasks. A fixed volume of graywater (500 mL) was added to each flask, and experiments were conducted at different carbon doses (0.5, 1.0, 2.0, and 4.0 g/L). Contact times of 30, 60, 90, and 120 minutes were preferred. The stirring speed was maintained at 150 rpm throughout the experiments, and the temperature remained constant at room temperature (20–25°C). Initial and final concentrations were measured throughout the experiment, and the percentage removal was calculated using the following equation:

$$\%\text{Removal} = (C_0\text{-}C_t)/C_0 \times 100$$

Where C_0 represents the initial concentration (mg/L), and C_t represents the concentration at time t.

2.4. Isotherm and kinetic models

During isotherm studies, experiments were conducted at GAC concentrations ranging from 0.5 to 4.0 g/L, with detergent concentration, temperature (23°C), stirring speed, and time (120 min) held constant. Once the equilibrium concentration was reached, the samples were centrifuged at 6000 rpm for 5 minutes and then filtered.

3. Results and Discussion

3.1. Physicochemical properties of greywater

Physicochemical analyses of greywater samples before and after treatment with GAC are shown in Table 1.

Table 1. Physicochemical parameters of laundry WW before and after treatment with GAC

Parameters	Untreated	GAC treated
pH	9.7	7.4
Conductivity (µS/cm)	862	556
Suspended solids (mg/L)	78	53
COD (mg/L)	953	648
Surfactants (mg/L)	56	35
Total phosphate (mg/L)	10.5	7.2
Total nitrogen (mg/L)	11.7	8

Granular activated carbon treatment slightly improved greywater quality. pH decreased from alkaline (9.7) to a near-neutral level (7.4), while conductivity dropped from 862 to 556 µS/cm, indicating reduced dissolved ions. Suspended solids declined from 78 to 53 mg/L, and COD fell from 953 to 648 mg/L, showing partial removal of organic matter. These reductions remain below typical reuse standards [15]. When compared with other studies, the removal efficiencies observed here are lower than those reported for multi-step or combined treatment systems. For instance, Zhang et al. (2020) [24] found that coupling activated carbon adsorption with membrane filtration achieved COD removals above 70 %, while Braga et al. (2014) [16] reported surfactant removals exceeding 90% using advanced oxidation processes such as Fenton or photocatalytic degradation. Similarly, Boyjoo et al. (2013) [19] highlighted that integrated coagulation–filtration systems could reach COD reductions over 80%. These comparisons suggest that while GAC alone provides partial pollutant reduction, it cannot meet the stringent criteria for safe greywater reuse, especially where detergent concentrations are high. Furthermore, Jjagwe et al. (2021) [21] emphasized that the adsorption capacity of GAC depends strongly on precursor material and activation method; biochar-based carbons or chemically modified carbons can display higher surface area and functional groups, leading to improved removal of organics and surfactants. Incorporating such engineered adsorbents could therefore enhance performance beyond the 32 % COD removal observed in this work.

3.2. Presence of surfactants and nutrients

Surfactants, total phosphate, and total nitrogen decreased (56→35 mg/L, 10.5→7.2 mg/L, and 11.7→8 mg/L, respectively). These results demonstrate that GAC adsorbs a range of pollutants, though the reductions are moderate and further treatment may be required to meet strict reuse standards. The results obtained in this study, in which GAC removed approximately 30–40% of contaminants such as detergent-

derived surfactants, total phosphate, and total nitrogen, are consistent with the findings of similar studies. For example, a study using a single-stage saturated–unsaturated GAC biofilter in graywater treatment reported approximately 35% removal of surfactants [25]. The 31% reduction achieved for total phosphate is consistent with studies showing that phosphate is only partially retained by GAC, requiring additional processing for ultra-low concentrations [26]. Similarly, the approximately 32% reduction in total nitrogen is consistent with research indicating that GAC has a limited capacity to adsorb nitrogen species [27]. Higher removal rates have been reported in GAC systems enhanced with biological processes. For example, removals greater than 50% for surfactants have been recorded in GAC systems operated as dynamic biofilm reactors [28]. In a study where anionic surfactant removal was performed with powdered activated carbon, 60% removal was reported [29]. Kaleta and Elektorowicz (2013)[30] found that aluminum sulfate and ferric chloride coagulants removed anionic surfactant (AS) at 7.6% and 10%, respectively. Corona et al. (2021)[31] determined that GAC and graphite oxide adsorbed anionic surfactants at 28.23% and 37.32%, respectively. In these studies, the removal of anionic surfactants was investigated using many different adsorbents, and results similar to our findings were obtained. It can be said that surfactants removal efficiencies vary depending on parameters such as the type of adsorbent used, the amount of adsorbent, surfactant concentration and contact time. The moderate removal observed in the present study could be improved by bio-enhanced or multi-stage processes.

3.3. Effect of initial GAC concentration and contact time on removal rates

The average COD and surfactant removal percentages obtained from adsorption experiments using GAC are given in the Fig. 1.

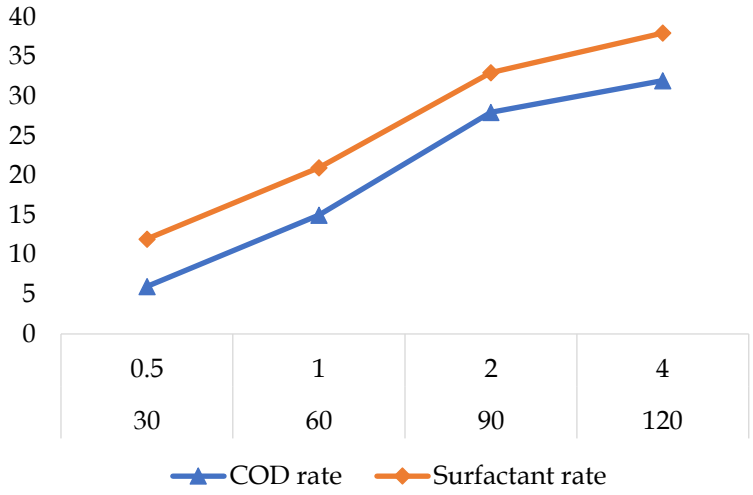


Fig. 1. Average COD and surfactant removal percentages depending on initial GAC concentration and contact time

Fig. 1 shows that both COD and surfactant removal percentages increase steadily with higher initial GAC concentrations and longer contact times. At the lowest conditions (0.5 g/L and 30 min), COD removal is about 6 % and surfactant removal about 12 %, indicating limited adsorption. As GAC dosage and contact time rise, removal efficiency improves significantly, reaching roughly 32 % COD and 38 % surfactant removal at 4 g/L and 120 min. Overall, the results demonstrate that both a greater amount of GAC and extended contact enhance pollutant removal, with surfactants consistently removed more effectively than COD throughout the tested range.

3.4. Adsorption isotherm and kinetic models

Isotherm models are used to understand the equilibrium relationship between the adsorbent surface and the adsorbate during the adsorption process. While the Langmuir isotherm assumes that the surface is

homogeneous and monolayer adsorption occurs, the Freundlich isotherm is assumed to be more suitable for heterogeneous surfaces [32]. In this study, the adsorption of COD in bleach by GAC was investigated with isotherms and kinetics models. In the isotherm study, C_e-C_e/q_e and log C_e-logq_e graphs were plotted for the Langmuir and Freundlich isotherms, respectively. Thus, the isotherm to which COD adsorption fits was determined by examining the R^2 values (Fig. 2). COD adsorption was shown to conform to the Freundlich isotherm (R^2: 0,985) when R^2 values were examined. The Freundlich isotherm is often used to describe surface heterogeneity. The Freundlich constant of "1/n < 1" indicates that the adsorbent is suitable for adsorption [33].

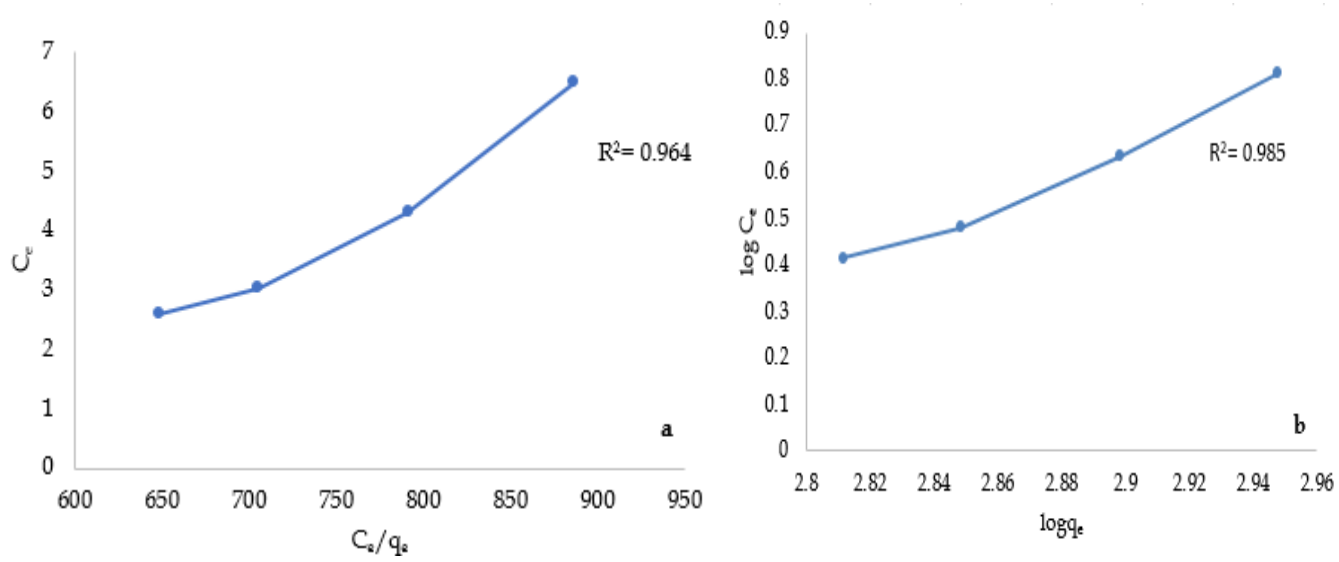


Fig. 2. Adsorption isotherms of COD: Langmuir (a) and Freundlich (b)

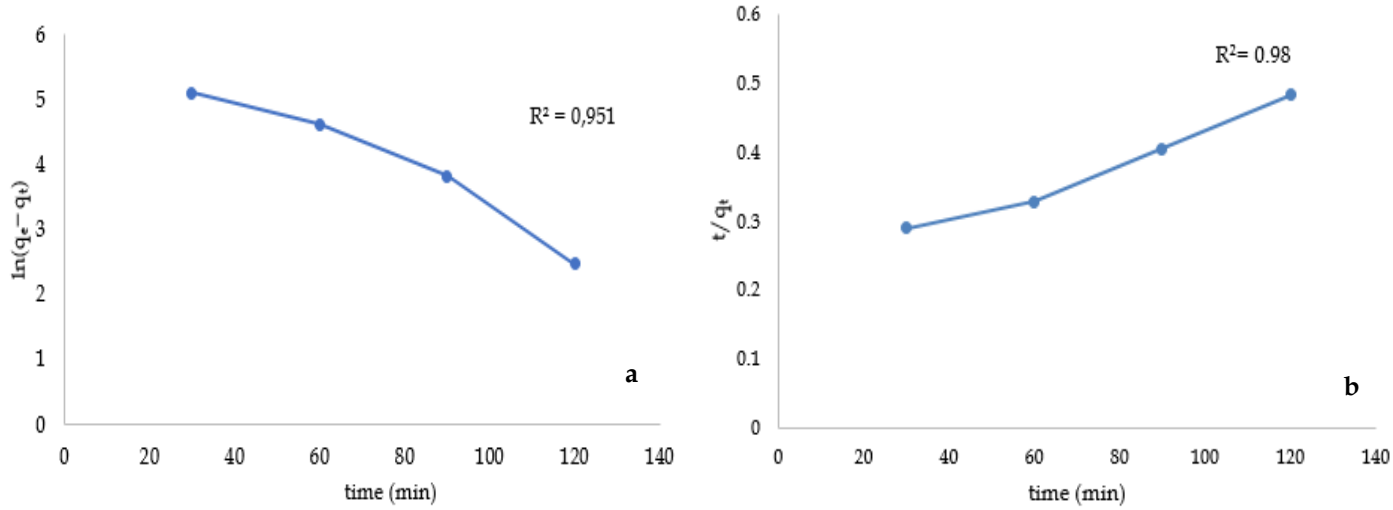


Fig. 3. Adsorption kinetics of COD: Pseudo first order (a) and Pseudo second order (b)

Furthermore, in this study, two different kinetic models were used to determine the rate of COD adsorption: pseudo-first-order and pseudo-second-order. According to Fig. 3, the R values of the pseudo-first-order and pseudo-second-order kinetic models were found to be 0.951 and 0.98, respectively. The pseudo-second-order kinetic model was found to be more suitable for the COD adsorption process due to its R^2 value being close to 1. The fit of the kinetic data to the pseudo-second-order model indicates that the adsorption mechanism is largely driven by chemical interactions [34]. There are studies in the literature that support our findings. Bautista Quispe reported that the adsorption of the anionic surfactant sodium

dodecyl sulfate (SDS) onto rice husk biochar conforms to the Freundlich isotherm model [35]. In another study, it was determined that the adsorption of COD and BOD from treated WW using activated carbon prepared from date palm waste fits a pseudo-second-order kinetic model [34].

4. Conclusion

This study showed that GAC treatment provides only moderate removal of pollutants from domestic washing machine greywater. From a sustainability perspective, single-step GAC treatment is attractive for its simplicity and low energy demand. However, the findings align with global recommendations that greywater treatment for reuse requires either advanced adsorbents or combined processes—such as GAC plus advanced oxidation, membrane filtration, or biological polishing—to achieve water quality standards set by the WHO and EU. Overall, this research confirms that GAC can serve as a preliminary step but not as a stand-alone treatment for greywater with high detergent loads. In future studies, it is planned to combine activated carbon, newly developed filter materials and physical treatment mechanisms for the treatment of washing machine WW obtained using different detergent forms and washing programs. In conclusion, this study is a preliminary study on the removal of surfactant contaminants from graywater generated after washing in washing machines using activated carbon. The findings from this study will guide future studies and inform the development of strategic approaches for more effective water resources management.

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Contribution Statement

Aysel Alkan Uçkun: Investigation, methodology, project management, writing-editing. Şeyma Akkurt: Methodology, investigation, writing-editing. Özgür Özdemir: Investigation, methodology. Şerif Çitil: Investigation, methodology.

Conflict of Interest

The authors of the article declare that they have no personal or financial conflicts of interest with any institution, organization, or individual.

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