



Examining the Kinetics and Equilibrium of Crystal Violet Dye Removal Using Olive Pomace as a Function of Time

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Abstract:

Synthetic dyes released into water bodies represent a growing environmental problem, since many resist natural breakdown and persist in aquatic systems for long periods. Crystal violet, a cationic dye of the triphenylmethane family, is widely used in textiles, printing inks, and biomedical staining, and it can pose ecological and health hazards even at very low concentrations. Developing inexpensive, renewable, and effective materials for removing it from water has therefore become a research priority. This study examines how effectively untreated dry olive pomace — a widely available Mediterranean agro-industrial by-product - removes crystal violet from aqueous solution under simple batch conditions. In each experiment, 1 g of dry olive pomace was mixed with 20 mL of a 1×10^{-5} M crystal violet solution and held at 23 ± 2 °C for contact periods reaching 144 h; the dye remaining in solution was measured spectrophotometrically at 557.3 nm, its wavelength of maximum absorbance. Equilibrium behaviour was examined using the linear forms of the Langmuir and Freundlich isotherms, and the uptake rate was modelled with the pseudo-first-order (PFO) and pseudo-second-order (PSO) equations. Of the two isotherms, the Langmuir model gave the closer fit ($R^2 = 0.9981$) with a favorable separation factor ($RL = 0.3135$), consistent with monolayer coverage on a surface of largely uniform energy, while the Freundlich model also described the data reasonably well ($R^2 = 0.9955$). For the kinetics, the pseudo-second-order equation reproduced the experimental trend more closely ($R^2 = 0.9998$) than the pseudo-first-order

equation ($R^2 = 0.9938$), pointing to chemisorption — bonding between dye molecules and functional groups on the pomace surface — as the step controlling the overall rate. Overall, these results show that raw, unmodified olive pomace performs well as a cheap and eco-friendly biosorbent for crystal violet, and converting this residue into a wastewater-treatment material offers a practical way to combine agricultural-waste valorization with the goals of a circular bioeconomy.

Keywords: Olive pomace; Crystal violet dye; Biosorption; Adsorption isotherms; Reaction kinetics; Agricultural waste; Wastewater treatment.

المخلص

تمثل الأصباغ الاصطناعية التي تصل إلى المسطحات المائية مشكلة بيئية متنامية، إذ يقاوم كثير منها التحلل الطبيعي ويبقى في الأنظمة المائية لفترات طويلة، ويُعد البنفسجي البلوري (Crystal violet)، وهو صبغة كاتيونية من عائلة ثلاثي فينيل ميثان ($C_{19}H_{16}$)، مستخدماً على نطاق واسع في صناعة النسيج وأحبار الطباعة والصبغ البيولوجي الطبي، وقد يشكل خطراً بيئياً وصحياً حتى عند تركيزات منخفضة جداً. لذا أصبح تطوير مواد رخيصة ومتجددة وفعالة لإزالة الملوثات من المياه أولوية بحثية، تتناول هذه الدراسة مدى فعالية تفل الزيتون الجاف غير المُعالج، وهو منتج ثانوي زراعي-صناعي متوفر بكثرة في منطقة البحر الأبيض المتوسط، في إزالة صبغة البنفسجي البلوري من المحلول المائي في ظل ظروف تجريبية دفعية (batch) بسيطة. في كل تجربة، تم خلط 1 غرام من تفل الزيتون الجاف مع 20 مل من محلول البنفسجي البلوري بتركيز 10×10^{-5} مولار، وحُفظ الخليط عند درجة حرارة 23 ± 2 درجة مئوية لفترات تلامس وصلت إلى 144 ساعة؛ وقيست كمية الصبغة المتبقية في المحلول طيفياً عند طول موجي 557.3 نانومتر، وهو الطول الموجي الأقصى للامتصاص. وقد دُرِس سلوك التوازن باستخدام الصيغ الخطية لمتساويات الحرارة لانغموير وفرندليتش، بينما نُمِذَج معدل الامتصاص باستخدام معادلتَي الرتبة الأولى الزائفة (PFO) والرتبة الثانية الزائفة (PSO) ومن بين المتساويتين الحراريتين، أعطى نموذج لانغموير التطابق الأقرب ($R^2 = 0.9981$) مع معامل فصل مناسب ($RL = 0.3135$)، بما يتوافق مع تكون طبقة أحادية على سطح متجانس الطاقة إلى حد كبير، في حين وصف نموذج فرندليتش البيانات أيضاً بشكل جيد نسبياً ($R^2 = 0.9955$). أما من ناحية الحركية، فقد عكست معادلة الرتبة الثانية الزائفة الاتجاه التجريبي بدقة أكبر ($R^2 = 0.9998$) مقارنة بمعادلة الرتبة الأولى الزائفة ($R^2 = 0.9938$)، مما يشير إلى أن الامتزاز الكيميائي، أي الترابط بين جزيئات الصبغة والمجموعات الوظيفية على سطح التفل، هو الخطوة المتحكم فيها في المعدل الإجمالي للعملية. بشكل عام، تُظهر هذه النتائج أن تفل الزيتون الخام غير المُعالج يؤدي أداءً جيداً كمادة ماصة حيوية رخيصة وصديقة للبيئة لإزالة صبغة البنفسجي البلوري، وأن تحويل هذا المخلف إلى مادة لمعالجة مياه الصرف الصحي يوفر وسيلة عملية للجمع بين الاستفادة من المخلفات الزراعية وأهداف الاقتصاد الحيوي الدائري.

الكلمات المفتاحية: تفل الزيتون؛ صبغة البنفسجي البلوري؛ الامتزاز الحيوي؛ متساويات الامتزاز الحراري؛ حركية التفاعل؛ المخلفات الزراعية؛ معالجة مياه الصرف الصحي.

1. Introduction

Industrial effluents from the textile, leather, paper, printing, cosmetic, pharmaceutical, and food sectors are a major source of synthetic dyes entering rivers and lakes, whether through direct discharge or after incomplete treatment. Worldwide dye production now exceeds 100,000 distinct commercial products, and a substantial share ends up in receiving waters because dye-fibre fixation is never complete and treatment infrastructure is often inadequate. Because dyes absorb light strongly even at low concentration, their presence in water reduces light penetration, disrupts photosynthesis, harms aquatic organisms, and creates broader ecological

risk; a recent global review of dye-laden wastewater underlined that controlling this pollution and finding practical remediation methods remains a difficult, unresolved water-quality challenge [1].

Crystal violet (also known as methyl violet 10B) is a cationic dye of the triphenylmethane family, used extensively in textile dyeing, biological staining, veterinary medicine, printing inks, and laboratory diagnostics. Its stable aromatic structure makes it resistant to natural degradation, allowing it to persist in aquatic environments for prolonged periods. It has also been described as a mitotic poison with mutagenic, cytotoxic, carcinogenic, and genotoxic potential, and is regarded as a biohazard requiring careful handling and disposal [2]; removing it from contaminated effluent is therefore an important environmental priority.

Numerous treatment approaches exist for removing dyes from wastewater, including coagulation–flocculation, advanced oxidation, membrane separation, electrochemical methods, biodegradation, photocatalysis, and adsorption. Adsorption stands out for its operational simplicity, high efficiency, and low cost, and newer engineered materials such as biochar–ferrite composites have reported crystal-violet uptake capacities above 300 mg g⁻¹ [3]. While activated carbon remains the standard commercial adsorbent, its high production and regeneration costs have pushed research toward cheaper lignocellulosic alternatives derived from agricultural residues — an approach that a recent comprehensive review confirmed is expanding rapidly as a class of dye-removal materials [4].

Agricultural and food-processing residues are attractive as adsorbents because they are inexpensive, renewable, biodegradable, and naturally rich in hydroxyl, carboxyl, phenolic, and carbonyl groups capable of binding dye molecules. Olive pomace — the solid material left after oil is pressed from olives — is generated in enormous quantities across Mediterranean countries, and its disposal is a recurring economic and environmental burden in olive-growing regions such as Libya. Because it is largely composed of cellulose, hemicellulose, lignin, pectin, protein, and phenolic compounds, it is well suited as a natural biosorbent, and repurposing it in this way supports both waste valorization and circular-bioeconomy goals within the olive-oil sector [5].

Recent studies point consistently to the ability of olive by-products to bind cationic dyes. Powdered olive leaves removed crystal violet with a Langmuir capacity of 181.1 mg g⁻¹ and followed pseudo-second-order kinetics [6], and olive pomace chemically modified with sodium hexametaphosphate achieved an even greater capacity of roughly 271 mg g⁻¹ for the same dye [7]. Comparable agricultural residues have shown similar effectiveness against both cationic and anionic dyes, generally fitting Langmuir- or Freundlich-type monolayer models combined with pseudo-second-order kinetics [8, 9]; olive-kernel powder, for example, was recently found to remove basic violet 10, a xanthene dye related to crystal violet — through a Freundlich-controlled, pseudo-second-order pathway [10]. Together, these reports suggest that even unmodified olive residues can perform on par with more elaborately engineered biosorbents. Libyan agricultural waste has shown similar promise: dried green pea husk and its charcoal form were reported to remove Congo red dye effectively, with equilibrium data consistent with both the Langmuir and Freundlich models [11], reinforcing the case for using local agro-waste such as olive pomace in the region's wastewater-treatment efforts.

Isotherm and kinetic models remain central tools for interpreting adsorption mechanisms and for scaling up biosorbent performance. Broadly speaking, the Langmuir model treats adsorption as occurring in a single layer on sites of uniform energy, whereas the Freundlich model allows for a heterogeneous surface; correspondingly, the pseudo-first-order and pseudo-second-order kinetic equations are commonly applied to characterize adsorption rates and identify the rate-determining step.

This study set out to test how effectively locally sourced, untreated dry olive pomace removes crystal violet dye from aqueous solution, with particular attention to the equilibrium isotherms

and kinetic behaviour that govern the process, and to assess its suitability as a low-cost, sustainable adsorbent for industrial wastewater treatment.

2. Materials and Methods:

2.1 Materials:

Dry olive pomace (OP) — the solid residue left after mechanically pressing oil from olives — was collected from local farms, air-dried, ground, and used as-is, without any chemical or physical modification, so that its natural biosorption capacity could be assessed. The crystal violet (methyl violet 10B) used as the model cationic dye throughout the study was supplied by Al-Kuwaifeya Chest Diseases Hospital. Distilled water was used for all solutions, and analytical-grade reagents were used throughout.

2.2 Preparation of Crystal Violet Solutions:

A 1×10^{-3} M stock solution of crystal violet (molar mass 407 g mol^{-1}) was prepared and diluted in two stages to reach the working concentration used in the adsorption tests: 25 mL of stock was first brought to 250 mL to give an intermediate 1×10^{-4} M solution, and 25 mL of that intermediate solution was again diluted to 250 mL to give the final 1×10^{-5} M working solution. Scanning the solution with a UV–Visible spectrophotometer identified 557.3 nm as the wavelength of maximum absorption (λ_{max}), where the working solution gave an absorbance reading of 0.335; this wavelength was used to track residual dye concentration throughout the experiments.

2.3 Batch Adsorption Experiments:

For each batch test, 1 g of dry olive pomace was placed in a stoppered container with 20 mL of the 1×10^{-5} M crystal violet solution. Containers were kept at 23 ± 2 °C, and the dye concentration remaining in solution was tracked spectrophotometrically at successive time intervals over a maximum period of 144 h. As is typical for adsorption processes, a greater mass of biosorbent exposes more binding sites and therefore tends to raise removal efficiency. Percentage removal and the amount adsorbed at time t (q_t) and at equilibrium (q_e) were calculated from the equations below:

$$\% \text{ removal} = [(C_0 - C_t) / C_0] \times 100 \quad (1)$$

$$q_e = [(C_0 - C_e) V] / m \quad (2)$$

$$q_t = [(C_0 - C_t) V] / m \quad (3)$$

Here, C_0 , C_t and C_e (mol L^{-1}) denote, respectively, the initial, time- t , and equilibrium dye concentrations; V (L) is the solution volume; and m (g) is the adsorbent mass. Percentage removal was plotted against contact time to visualize how the process evolved (Figure 1).

2.4 Adsorption Isotherm Models:

Equilibrium behaviour was analyzed using two classical isotherm equations, Langmuir and Freundlich. The Langmuir model describes adsorption as a single layer of molecules occupying a fixed number of identical, non-interacting sites, and is commonly used to represent adsorption in aqueous and wastewater systems [12]. Its linear form is:

$$q_e = q_m - (1 / KL)(q_e / C_e) \quad (4)$$

C_e is the equilibrium dye concentration (mol L^{-1}), q_e is the equilibrium adsorption capacity (mol g^{-1}), and q_m and KL — the maximum adsorption capacity and the Langmuir affinity constant — are obtained, respectively, from the intercept and slope of a plot of C_e/q_e against C_e . A related, dimensionless separation factor, RL , captures the favourability of the isotherm:

$$RL = 1 / (1 + KL C_0) \quad (5)$$

Values of RL above 1 indicate an unfavourable process, RL equal to 1 corresponds to linear adsorption, RL of 0 signals an irreversible process, and values between 0 and 1 indicate a favourable process.

Freundlich's isotherm, originally formulated for gas-phase and solute adsorption, is commonly applied in environmental chemistry to represent adsorption onto heterogeneous surfaces. Its linear form is:

$$\log q_e = \log K_f + (1/n) \log C_e \quad (6)$$

K_f represents the Freundlich distribution coefficient, and n is an empirical parameter reflecting adsorption intensity and the degree of surface heterogeneity; both are obtained from the slope and intercept of a plot of $\log q_e$ against $\log C_e$.

2.5 Adsorption Kinetics:

Understanding how quickly adsorption proceeds, and what governs that rate, is central to evaluating any biosorption system. Two kinetic models — pseudo-first-order (PFO) and pseudo-second-order (PSO) — were fitted to the time-course adsorption data; both can be derived from a general rate expression:

$$dq/dt = k_n (q_e - q)^n \quad (7)$$

Solving Equation (7) for $n = 1$, subject to the initial condition $q = 0$ at $t = 0$, gives the pseudo-first-order expression:

$$q = q_e (1 - e^{-k_1 t}) \quad (8)$$

where k_1 (h^{-1}) denotes the pseudo-first-order rate constant and t (h) is the contact time. The pseudo-second-order model, first proposed by Ho and McKay (1998)[13] to describe dye uptake from solution, treats chemisorption — valence-type bonding between adsorbate and adsorbent — as the rate-limiting step, and is expressed as:

$$dq/dt = k_2 (q_e - q)^2 \quad (9)$$

which, upon integration and linearization, gives:

$$t/q = 1/h + (1/q_e) t \quad (10)$$

Here k_2 ($\text{g mol}^{-1} \text{h}^{-1}$) is the pseudo-second-order rate constant, and $h = k_2 q_e^2$ ($\text{mol g}^{-1} \text{h}^{-1}$) represents the initial adsorption rate. Values of q_e , k_1 , k_2 and h were extracted from the appropriate linear plots, and the two kinetic models were compared using their correlation coefficients (R^2).

3. Results and Discussion:

3.1 Effect of Contact Time on Crystal Violet Removal:

Figure 1 shows how the percentage removal of crystal violet by dry olive pomace changed over a 144 h contact period. As is typical for lignocellulosic biosorbents, uptake was fastest during the early stages, when most of the pomace surface's binding sites were still unoccupied and readily available to dye molecules, and then slowed progressively as those sites filled and the system approached equilibrium. This gradual approach to equilibrium over an extended contact period matches the fairly long half-life (30.7 h) and characteristic time constant ($\tau = 44.2$ h) derived from the pseudo-first-order analysis in Section 3.3, and shows that while the initial phase of biosorption is quick, complete equilibration of the dye–pomace system takes considerably longer.

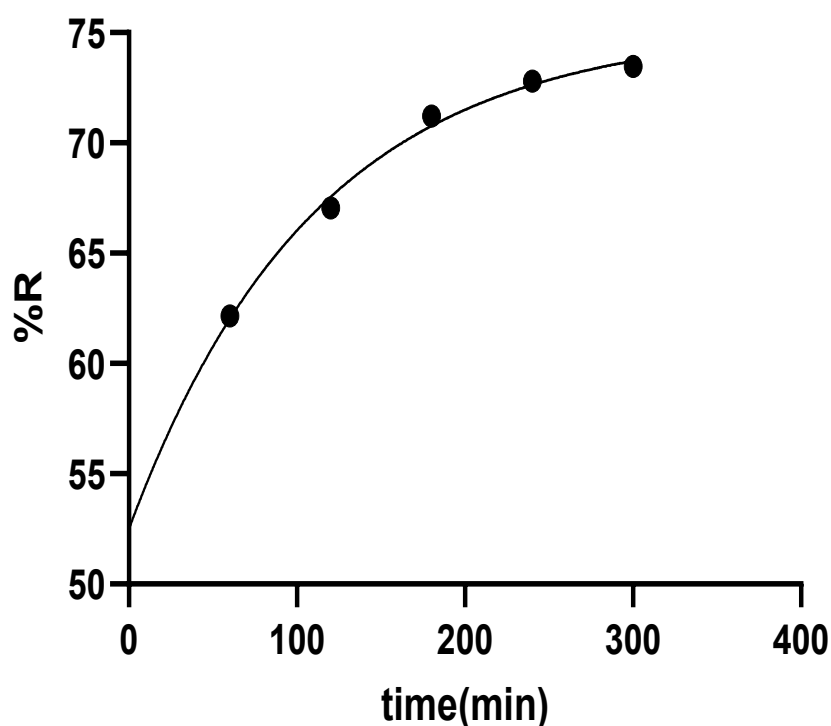


Figure 1. Percentage removal of crystal violet dye by dry olive pomace over contact time.

3.2 Adsorption Equilibrium Studies:

Equilibrium data for crystal violet biosorption onto untreated olive pomace were fitted to the Langmuir and Freundlich isotherms to gain insight into the adsorption mechanism, the nature of the biosorbent surface, and the adsorbate–adsorbent interaction.

Table 1 lists the resulting Langmuir parameters, and Figure 2 shows the corresponding linear plot. The fit to the Langmuir equation was very good, with a correlation coefficient of $R^2 = 0.9981$, consistent with monolayer coverage on a surface of roughly uniform energy. A fairly large Langmuir constant ($K_L = 2.19 \times 10^5 \text{ L mol}^{-1}$) points to strong binding between crystal violet and the pomace's active sites, and a separation factor of $RL = 0.3135$ — falling between 0 and 1 — confirms that adsorption is favourable under the conditions tested.

Table 1. Langmuir adsorption isotherm parameters for crystal violet biosorption onto olive pomace.

qm (intercept)	K_L	R^2	RL	Slope
4.819×10^{-8}	2.19×10^5	0.9981	0.3135	4.567×10^{-6}

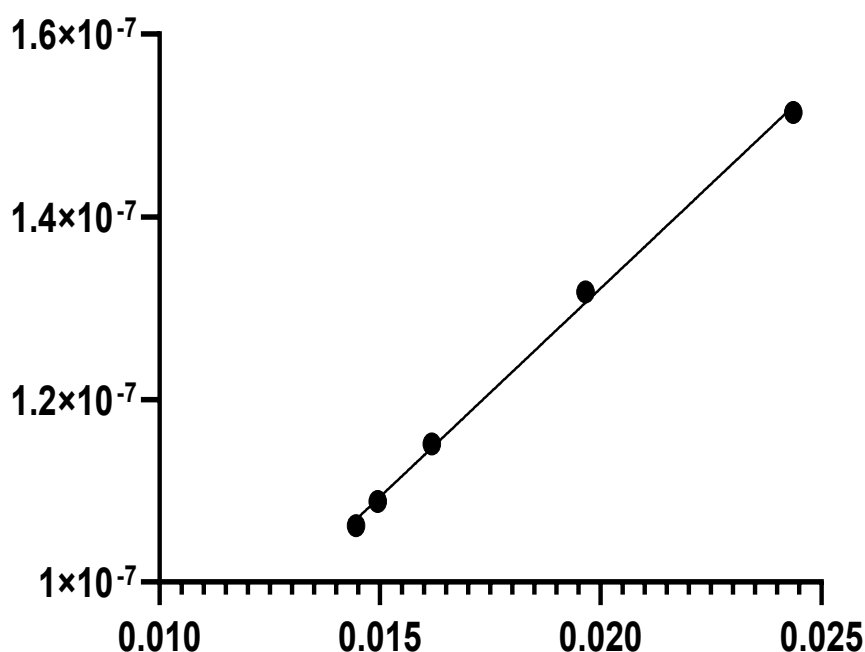


Figure 2. Linear Langmuir isotherm plot (C_e/q_e versus C_e)

This close fit to the Langmuir model is likely related to the abundance of oxygen-containing groups — hydroxyl, phenolic, carboxyl — naturally present in olive pomace's lignocellulosic structure. These groups can engage in electrostatic attraction, hydrogen bonding, and π – π interactions with the aromatic rings of crystal violet, favouring efficient single-layer adsorption; similar Langmuir dominance has been reported for crystal violet biosorption onto related olive materials, including olive leaves powder and chemically treated olive pomace [6, 7].

Table 2 and Figure 3 present the Freundlich isotherm results. This model also described the equilibrium data reasonably well, with $R^2 = 0.9955$, though somewhat less accurately than the Langmuir equation.

Table 2. Freundlich adsorption isotherm parameters for crystal violet biosorption onto olive pomace

n	K_f	R²	Intercept	Slope
–0.471	1.349×10^{-18}	0.9955	–17.87	–2.123

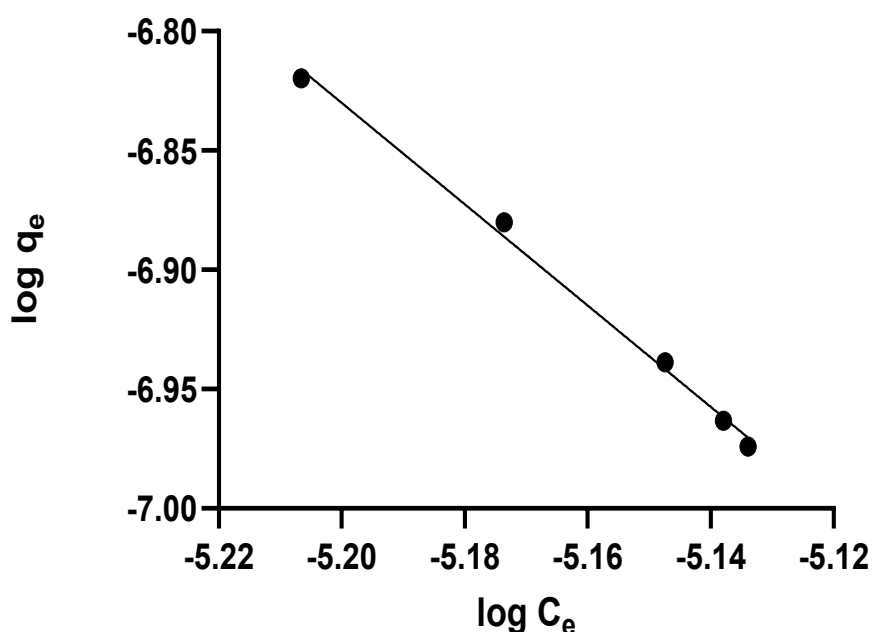


Figure 3. Linear Freundlich isotherm plot ($\log q_e$ versus $\log C_e$)

The Freundlich model's slightly weaker fit implies that, despite some heterogeneity in the pomace surface, monolayer coverage — rather than multilayer build-up — dominates the adsorption process. The exponent n came out negative (-0.471) here, which falls outside the $0 < 1/n < 1$ range normally associated with favourable multilayer adsorption, so this value should be read with caution; it most likely reflects the fact that only a single dye concentration (1×10^{-5} M) was tested, rather than any real shift in adsorption behaviour, and points to the value of examining a broader concentration range in future work. Taken together, both isotherms describe the data adequately, but the clearly stronger fit of the Langmuir model confirms that monolayer adsorption is the dominant mechanism in crystal violet removal by olive pomace.

3.3 Adsorption Kinetics:

The pseudo-first-order (PFO) and pseudo-second-order (PSO) models were used to characterize the rate of dye uptake and identify the controlling mechanism; the resulting parameters appear in Tables 3 and 4, with the corresponding linear plots shown in Figures 4 and 5.

Table 3. Pseudo-first-order kinetic parameters for crystal violet biosorption onto olive pomace.

q_e	k_1	Half-life (h)	τ (h)	R^2
2.10×10^{-7}	2.26×10^{-2}	30.7	44.2	0.9938

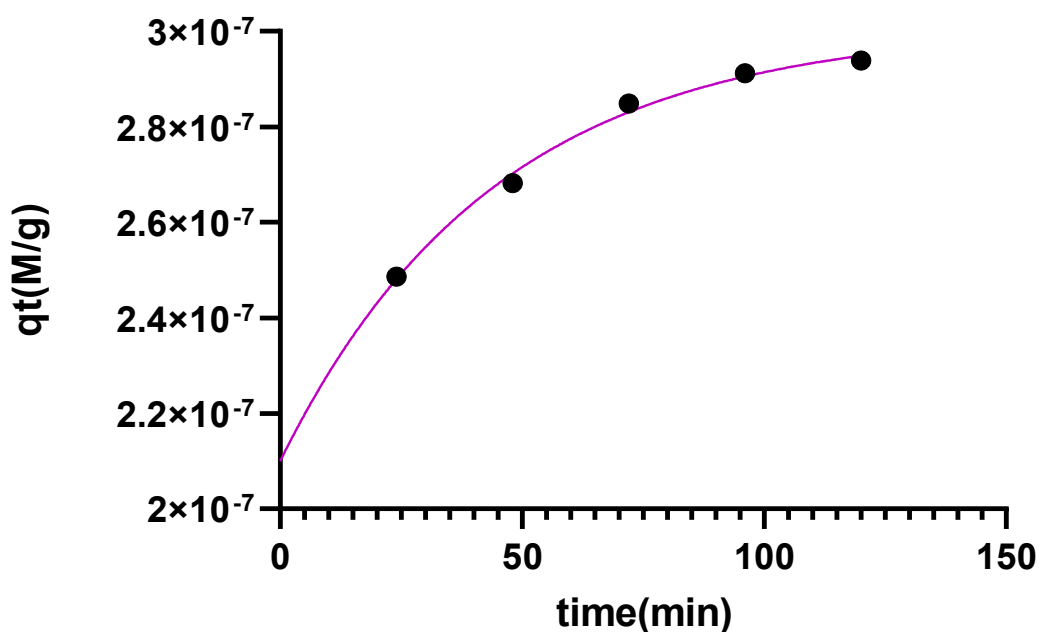


Figure 4. Pseudo-first-order kinetic plot

Table 4. Pseudo-second-order kinetic parameters for crystal violet biosorption onto olive pomace.

Intercept	Slope	R ²	qe (exp)	K ₂	h
5.23×10^7	3.225×10^6	0.9998	3.10×10^{-7}	1.99×10^5	1.91×10^{-8}

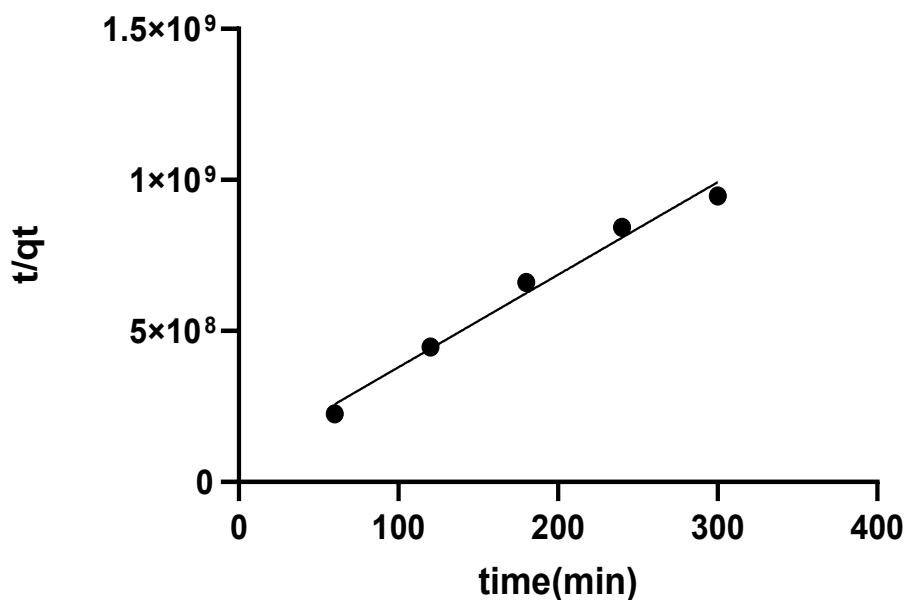


Figure 5. Pseudo-second-order kinetic plot

The pseudo-first-order fit was reasonably good ($R^2 = 0.9938$), so it captures the general shape of the adsorption curve. However, the fairly long half-life (30.7 h) and time constant ($\tau = 44.2$ h) indicate that first-order diffusion alone cannot fully explain the uptake behaviour observed across the full 144 h contact period.

By comparison, the pseudo-second-order model gave a near-perfect fit ($R^2 = 0.9998$), well above that of the pseudo-first-order equation. This strong agreement points to chemisorption — bonding between crystal violet molecules and functional groups on the pomace surface — as the main driver of the process, meaning the overall rate depends chiefly on how many active sites remain available rather than on external mass transfer alone. Pseudo-second-order kinetics has repeatedly been reported as the dominant pathway for crystal violet and related cationic dyes adsorbed onto olive-based and other agricultural biosorbents [6, 8, 10], supporting the broader idea that chemisorption-controlled kinetics is a common feature of dye uptake by lignocellulosic agro-waste.

Taken as a whole, the equilibrium and kinetic results both indicate that untreated olive pomace is an effective, environmentally sound biosorbent for removing crystal violet. The combination of a strong Langmuir fit and dominant pseudo-second-order kinetics reflects a robust interaction between dye molecules and the pomace surface, underscoring the value of this agro-industrial by-product as an affordable wastewater-treatment material.

3.4 Comparison with Previous Studies:

To put these results in context, the present findings were benchmarked against recent studies on cationic-dye adsorption by olive-derived and other agricultural materials. The strong Langmuir fit obtained here ($R^2 = 0.9981$) matches results reported for related olive residues: olive leaves powder, for instance, reached a maximum Langmuir capacity of 181.1 mg g^{-1} for crystal violet with pseudo-second-order kinetics [6], while olive pomace chemically activated with sodium hexametaphosphate achieved a still-higher capacity of about 271 mg g^{-1} for the same dye [7]. This comparison suggests that although untreated olive pomace may have somewhat lower maximum capacity than chemically modified variants, it still shows comparable equilibrium behaviour without the added expense and complexity of chemical activation.

The dominance of pseudo-second-order kinetics found here fits a wider pattern reported for agricultural biosorbents treating cationic and related dyes, including native agro-waste materials used for anionic-dye removal [8] and olive-kernel powder applied to basic violet 10, a xanthene dye structurally similar to crystal violet [10]. This consistency across independent studies supports the view that basic/cationic dye adsorption onto lignocellulosic agro-residues is generally governed by interactions between dye molecules and surface functional groups rather than by simple diffusion. Even sophisticated, high-surface-area materials engineered specifically for crystal violet removal — such as the biochar–ferrite composite reported by Mehta et al. (2025)[3] — rely on the same Langmuir/pseudo-second-order combination observed in this work, showing that olive pomace's mechanistic behaviour is consistent with the broader dye-biosorption literature despite the large gap in engineering sophistication and cost.

Relative to commercial activated carbon, untreated olive pomace brings several practical benefits: it is cheap, renewable, biodegradable, and widely available in olive-growing regions like Libya, and needs no chemical or thermal pre-treatment before use. Employing this residue lowers the cost of wastewater treatment while also supporting the sustainable use of an abundant agro-industrial by-product, in keeping with the waste-to-resource strategies increasingly promoted in the olive-oil sector [5]. Overall, the present findings show that untreated olive pomace performs comparably to several modified or engineered biosorbents described in the recent literature, while retaining the cost and environmental benefits that come with using raw agricultural residues, supporting its potential use in large-scale treatment of dye-laden industrial wastewater.

That said, a few results here diverge from earlier work and call for cautious interpretation. The negative Freundlich exponent ($n = -0.471$) found in this study lies outside the $0 < 1/n < 1$ range normally regarded as ideal for favourable multilayer adsorption, unlike most isotherm studies

on olive- and agro-waste-derived biosorbents, which typically report positive Freundlich exponents alongside a dominant Langmuir fit [6, 7, 11]; this is most likely explained by the single-concentration design used here rather than any genuine change in mechanism, and points to the need for multi-concentration isotherm work in future studies. Similarly, the pseudo-second-order rate constant obtained in this work ($k_2 = 1.99 \times 10^5 \text{ g mol}^{-1} \text{ h}^{-1}$) cannot be compared directly, in absolute numbers, with the mass-based rate constants ($\text{g mg}^{-1} \text{ min}^{-1}$) reported in most published work [3, 6], since the present analysis used molar rather than mass-based concentrations; even so, the qualitative finding — that pseudo-second-order, chemisorption-controlled kinetics dominates the process — holds consistently across all the studies cited, which strengthens confidence in the mechanistic picture presented here.

4. Conclusion:

This study shows that untreated dry olive pomace, an abundant and inexpensive agro-industrial residue, works effectively as a biosorbent for removing crystal violet dye from water. Equilibrium data were best represented by the Langmuir isotherm ($R^2 = 0.9981$, $RL = 0.3135$), pointing to favourable, monolayer adsorption on a fairly uniform surface, while the pseudo-second-order kinetic model ($R^2 = 0.9998$) gave the closest description of how uptake changed over time, indicating that chemisorption controls the overall rate. Combined with the growing body of recent research on olive-derived biosorbents, these findings support olive pomace as a sustainable, low-cost substitute for commercial activated carbon in treating dye-contaminated wastewater, while also helping manage agricultural waste and advancing circular-bioeconomy goals in olive-producing regions. Future studies should test a wider range of initial dye concentrations, solution pH, and temperature, and should include desorption and reuse experiments, to better establish how well untreated olive pomace would perform at a larger scale.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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