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An overview of equilibrium, kinetic and thermodynamic studies for the sequestration of Maxilon dyes

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ABSTRACT

Maxilon dyes are a class of cationic dyes containing different aliphatic and aromatic radicals. Contamination of water by this class of dyes causes serious environmental concern to both man and other animals and plants. Adsorption as a process has been studied by various researchers for Maxilon dye uptake. This work represents a review of published literature discussing the adsorption of Maxilon dyes using various adsorbents. Adsorption operating parameters, kinetic and isotherm models, and thermodynamic models were discussed herein. In the study, it was observed that adsorption parameters such as contact time, adsorbent dosage, solution pH, and temperature affect the uptake of Maxilon dyes. The highest reported uptake of Maxilon dyes by the various adsorbents is 1830 mg/g for Maxilon blue using hydrolyzed (styrene-*alt*-maleic anhydride) chitosan. For the adsorption of the Maxilon dyes, the pseudo-second order kinetic model was shown to provide the best fit. The Langmuir and Freundlich isotherm models best describe the adsorption of the Maxilon dyes. There were also some proposals for the future. In conclusion, adsorption was found to be an effective approach for removing Maxilon colours from water and wastewater.

Introduction

Population development and industrialization have resulted in the release of a variety of poisonous gases and liquid effluents, as well as the production of millions of tons of solid garbage, which harm the environment on a regular basis (Dahdouh et al., 2020; Iwuozor et al., 2022; Adeniyi et al., 2022). Wastewater from industries largely consists of organic compounds, inorganic compounds, and heavy metals (Aragaw and Angerasa, 2020; Iwuozor et al., 2022). Water pollution as a result of industrial effluents discharged into water bodies is one of the most dangerous ecological issues facing the whole world. Huge quantities of dangerous dyes are dumped into bodies of water daily by industries such as plastic, printing, food, paper, plastic, and cosmetics, industries, thus causing damage to the water and threatening the lives of aquatic organisms and, by extension, human beings (Doğan et al., 2006; Ali et al., 2020; Iwuozor and Gold, 2018; Adeniyi et al., 2022). The textile industry, in particular, emits a large quantity of dyes into the environment. The industry consumes a large amount (about 200 L) of water to produce 1 kg of textile dye, thereby releasing large amounts of wastewater that contains unusual volumes of dyes, organic and inorganic salts, as well as acids and heavy metals (Emgili et al., 2017). An estimated 30 % of dyes are lost during the dying process and 20 % of the lost dyes enter the wastewater, from which they are released to water bodies, mostly without proper treatment (Chan et al., 2017; Ferrero and Periolatto, 2011). It has been reported that wastewater from the textile industry is the most dangerous of all industrial effluents (Demirbaş and Alkan, 2015).

Colorant characteristics were previously taken from natural sources like animals and vegetables. With the exception of a few inorganic dyes, practically all dyes on the market today are synthetic (Awwad et al., 2019). There are almost 10,000 different commercial dyes and pigments available (Ferrero and Periolatto, 2011). Synthetic dyes are a type of

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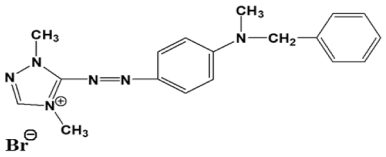
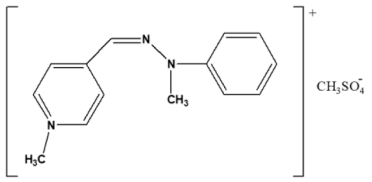
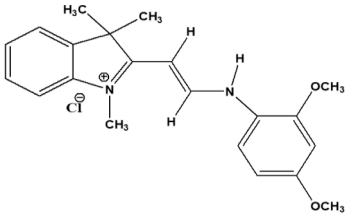
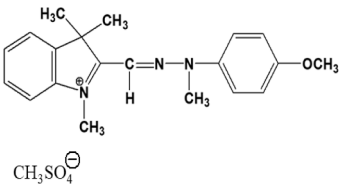
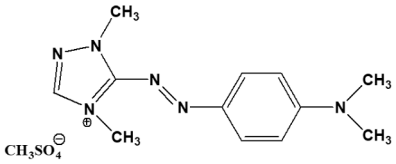
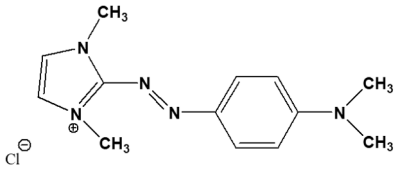
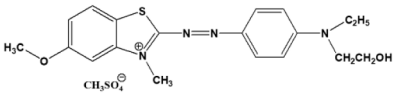
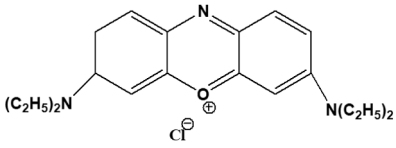
Table 1
Physicochemical properties of Maxilon dyes.

Maxilon Dyes	IUPAC name	Molecular formula	Molecular structure	Molecular weight ($gmol^{-1}$)	Refs
Maxilon Yellow 4GL (Basic Yellow 87)	*N*-methyl-N-[(E)-(1-methylpyridine-1-ium-4-yl) methylideneamino]aniline;methyl sulphate	$C_{15}H_{19}N_3O_4S$		337.4	(Information, N.C.f.B., PubChem Compound Summary for CID 9576503, Basic Yellow 87., 2022)
Maxilon Yellow 3GL (Basic Yellow 11)	2,4-dimethyl-N-[(E)-2-(1,3,3-trimethylindol-1-ium-2-yl) ethenyl]aniline;chloride	$C_{21}H_{25}ClN_2O_2$		372.9	(Information, N.C.f.B., PubChem Compound Summary for CID 6436295, Basic Yellow 11., 2022)
Maxilon Golden Yellow (Basic Yellow 28)	4-methoxy-*N*-methyl-N-[(E)-(1,3,3-trimethyliodol-1-ium-2-yl) methylideneamino]aniline;methyl sulphate	$C_{21}H_{27}N_3O_5S$		433.5	(Information, N.C.f.B., PubChem Compound Summary for CID 9570625, Basic Yellow 28., 2022)
Maxilon Red GRL (Basic Red 46)	*N*-benzyl-4-[(2,4-dimethyl-1,2,4-triazol-4-ium-3-yl)diazenyl]-*N*-methylaniline;bromide	$C_{18}H_{21}BrN_6$		401.3	(Information, N.C.f.B., PubChem Compound Summary for CID, 2022)
Maxilon Red BL-N (Basic Red 22)	4-[(2,4-dimethyl-1,2,4-triazol-4-ium-3-yl)diazenyl]-N,*N*-dimethylaniline;methyl sulphate	$C_{13}H_{20}N_6O_4S$		356.4	(Information, N.C.f.B., PubChem Compound Summary for CID 73759884, Basic red 22., 2022)
Maxilon SL (Basic Red 51)	4-[(1,3-dimethylimidazole-1-ium-2-yl)diazenyl]-N,*N*-dimethylaniline;chloride	$C_{13}H_{18}N_5Cl$		297.8	(Information, N.C.f.B., PubChem Compound Summary for CID, 2022)
Maxilon Blue GRL (Basic Blue 41)	2-[*N*-ethyl-4-[(6-methoxy-3-methyl-1,3-benzothiazol-3-ium-2-yl)diazenyl]aniline]ethanol; methyl sulphate	$C_{20}H_{26}N_4O_6S_2$		482.6	(Information, N.C.f.B., PubChem Compound Summary for CID 83008, Basic blue 41., 2022)
Maxilon Blue 5G	–	$C_{20}H_{28}N_3OCl$		361.5	(Souza et al., 2011)

organic chemical with a complicated aromatic structure that can offer industrial items dazzling color (Alkaim et al., 2015). This complex aromatic structure of commonly used dyes allows them to resist biodegradation and photo-degradation (Ali et al., 2020; Aljebori and Alshirifi, 2012). About 7×10^5 tons of dyestuffs are used in the textile industry annually (Bingul and Adar, 2021), and approximately 100 tons are discharged into the aquatic environment (Boudechiche et al., 2019). Chemical oxygen demand, color, total organic carbon, and biological oxygen demand concentrations are all high in wastewater-containing dyes, such as Maxilon dyes (Bingul and Adar, 2021; Çiner, 2018).

Maxilon dyes are a class of cationic dyes containing different aliphatic and aromatic radicals (de Almeida, 1960). Contamination of water by this class of dyes causes serious environmental concern as their colour tends to persist even after treatment, impeding light penetration and thereby affecting the photosynthetic activities of aquatic flora (Aljeboree et al., 2014; Aljeboree and Alkaim, 2019; Barka et al., 2009; Konicki et al., 2017). This class of dyes is carcinogenic, mutagenic, and teratogenic, while also posing a threat to humans, fishes, and

Table 2
Adsorption Capacities of different adsorbents for aqueous Maxilon dyes uptake.

Maxilon Dyes	Adsorbent	Highest RE (%)	Qmax (mg/g)	Adsorbent dosage (g/L)	Contact time (min)	Temp. (°C)	pH	Method of Qmax determination	Refs.
Maxilon blue	Hydrolyzed (styrene-*alt*-maleic anhydride) Chitosan	–	1830	–	–	–	–	Experiments	(Ali et al., 2020)
Maxilon blue	Sulphonated (styrene-*alt*-maleic anhydride) Chitosan	–	702.0	–	–	–	–	Langmuir	(Ali et al., 2020)
Maxilon blue	Multiwall carbon nanotubes		260.7	–	–	50	10	Experiments	(Alkaim et al., 2015)
Maxilon blue	Activated Carbon/Clay	–	175.9	–	–	50	6.0	Langmuir	(Aljeboree et al., 2020)
Maxilon blue	Bentonite	–	95.82	–	–	37	4.7	Langmuir	(Koyuncu, 2009)
Maxilon blue	AC/Clay	–	66.91	–	–	50	6.0	Experiments	(Aljeboree et al., 2020)
Maxilon blue	Coconut shell activated carbon	–	46.56	–	–	30	3.0	Experiments	(Aljeboree et al., 2017)
Maxilon blue	Coconut shell activated carbon	–	46.53	–	–	30	3.0	Experiments	(Aljeboree et al., 2017)
Maxilon blue	Ultrasonic acid modified	–	44.62	–	–	25	7.0	Experiments	(Kalipci et al., 2016)
Maxilon blue	Zirconium-based MOF	46.60	25.99		–	25	5.0		(Hasanzadeh et al., 2019)
Maxilon blue	Raw clay	–	19.45	–	–	25	7.0	Experiments	(Kalipci et al., 2016)
Maxilon blue	Date stone activated carbon	–	12.02	–	60	30	6.0	Experiments	(Alqaragully, 2014)
Maxilon blue	Iron-oxide nanoparticles	45.00	0.230	–	–		9.0	Langmuir	(Yakar et al., 2020)
Maxilon blue (GRL)	White marble	–	–	–	–	25	3.0	Experiments	(Aljebori and Alshirifi, 2012)
Maxilon golden yellow	*Ziziphus lotus stones* Activated carbon	79.00	424.0	0.6	180	20	8.0	Langmuir	(Boudechiche et al., 2019)
Maxilon golden yellow	Sulphonated waste poly methacrylate	95.38	222.2	0.4	45	20	6.0	Langmuir	(Dahdouh et al., 2020)
Maxilon golden yellow	Newspaper pulp	–	91.51	2.0	180	20	6.0	Langmuir	(Laib et al., 2019)
Maxilon golden yellow	Smectite-rich natural clay	97.00	76.92	–	40	–	–	Langmuir	(Chaari et al., 2019)
Maxilon golden yellow	Clinoptilolite	–	59.60	–	–	20	6.3	Langmuir	(Yener et al., 2006)
Maxilon golden yellow	Amberlite XAD-4	–	6.600	–	–	20	–	Experiments	(Yener et al., 2006)
Maxilon Goldgelb	Granular activated carbon	–	305.2	–	–	–	–	Experiments	(Meshko et al., 2001)
Maxilon Goldgelb	Natural zeolite	–	55.86	–	–	–	–	Langmuir	(Meshko et al., 2001)
Maxilon red	Natural clay	–	344.8	–	–	25	–	Langmuir	(Nassar and Farrag, 2012)
Maxilon red	Activated pine sawdust	99.35	312.5	–	–	45	5.8	Langmuir	(Şentürk and Yıldız, 2020)
Maxilon red	Wurtzite Zn	97.00	175.0	–	–	25	7.0	Langmuir	(Mekatel et al., 2021)
Maxilon Red	Activated sludge	–	123.2	–	–	–	–	Langmuir	(Basibuyuk and Forster, 2003)
Maxilon red	Boron waste	99.80	74.83	2.0	90	25	9.0	Experiments	(Olgun and Atar, 2009)
Maxilon red	Waste sludge	97.00	58.52	–	–	–	5.0	Langmuir	(Sarioglu and Aşkal, 2018)
Maxilon Red	Walnut shell	–	58.21	–	–	45	8.0	Experiments	(Deniz, 2014)
Maxilon red	Potato starch	–	28.57	–	–	–	–	Langmuir	(Irinislimane and Belhaneche-Bensemra, 2017)
Maxilon red	Sugarcane stalk powder	95.10	20.96	0.05	60	–	7.2	Langmuir	(El-Sayed et al., 2013)
Maxilon red	Sorghum	–	16.75	–	–	–	–	Langmuir	(Irinislimane and Belhaneche-Bensemra, 2017)
Maxilon red	Oak corn starch	–	12.67	–	–	–	–	Langmuir	(Irinislimane and Belhaneche-Bensemra, 2017)
Maxilon red	Nigde grape molasses soil + Fenton reagent	> 90.00	7.686	–	–	30	3.0	Langmuir	(Çiner, 2018)
Maxilon red	Silica	96.00	3.030	0.1	–	24	–	Langmuir	(Koyuncu, 2009)
Maxilon Shwarz	Granular activated carbon	–	159.0	–	–	–	–	Experiments	(Markovska et al., 2001)
Maxilon Shwarz	Natural zeolite	–	14.91	–	–	–	–	Experiments	(Markovska et al., 2001)
Maxilon Yellow	Amidated pectin	–	571.4	–	–	–	–	Langmuir	(Nesic et al., 2014)

(*continued on next page*)

Table 2 (*continued*)

Maxilon Dyes	Adsorbent	Highest RE (%)	Qmax (mg/g)	Adsorbent dosage (g/L)	Contact time (min)	Temp. (°C)	pH	Method of Qmax determination	Refs.
Maxilon yellow	Reed	–	140.0	–	–	12	6.0	Langmuir	(Boudrahem et al., 2015)
Maxilon Yellow	Conch shells	–	78.22	–	–	40	–	Experiments	(El Ouahabi et al., 2018)
Maxilon yellow	Boron waste	99.70	74.80	2.0	28	25	9.0	Experiments	(Olgun and Atar, 2009)
Maxilon yellow	Calcined eggshells	> 90.00	28.87	–	–	15	–	Experiments	(Slimani et al., 2014)
Maxilon yellow	hydromagnesite stromatolite	–	25.18	–	–	20	8.0	Experiments	(Karakuş et al., 2020)
Maxilon yellow	Natural phosphate	–	16.77	–	–	25	–	Langmuir	(Barka et al., 2009)
Maxilon yellow	*Salvia officinalis*	56.00	11.79	–	–	25	6.5	Experiments	(Bingul and Adar, 2021)
Maxilon yellow	Beneficiated Kaolin	–	1.896	1.0	60	30	6.0	Experiments	(Aragaw and Angerasa, 2020)
Maxilon yellow	Raw kaolin	–	1.842	1.0	60	30	6.0	Langmuir	(Aragaw and Angerasa, 2020)
Maxilon yellow	Calcined Kaolin	–	1.742	1.0	60	30	6.0	Langmuir	(Aragaw and Angerasa, 2020)

microorganisms (Zermane et al., 2010; Zhu et al., 2016; Yakar et al., 2020). They have the potential to kill a huge number of aquatic species, disrupt ecological equilibrium, and reduce the receiving water body's ability to self-clean (Köktürk et al., 2021). Even at very low quantities, their presence in water is highly apparent and unwanted (Demirbaş et al., 2015). As a result of its negative environmental impacts, the treatment of maxilon dye(s)-containing wastewater has gained some - attention in recent times, with various methods being proposed and used for its treatment before discharge. Coagulation, flotation, chemical oxidation, solvent extraction, filtration, and reverse osmosis are all examples of such traditional methods. (Ogunlalu et al., 2021; Iwuozor et al., 2021; Iwuozor, 2019; Iwuozor et al., 2021). These methods, however, frequently produce waste (sludge) and do not completely remove the dyes (Emenike et al., 2022; Ighalo et al., 2021; Ighalo et al., 2022).

Adsorption, on the other hand, has grown in popularity as a purification and separation process on a large scale in recent decades and has become a desirable alternative for industrial (waste) water treatment, particularly in the removal of chemically and biologically stable organic compounds such as Maxilon dyes (Igwegbe et al., 2021; Adeniyi and Ighalo, 2019; Ighalo et al., 2022; Iwuozor et al., 2021). Adsorption is a complicated process that is largely influenced by the surface chemistry of the adsorbent and the adsorbate, as well as the process factors that exist between the two phases (Ighalo et al., 2021; Emenike et al., 2022; Ighalo et al., 2022). Because of its ease of implementation, convenience, low cost, and non-toxicity of the adsorbents used, it is favoured over other wastewater treatment technologies (Iwuozor et al., 2021; Ighalo et al., 2022; Ighalo et al., 2022; Iwuozor et al., 2022). The following adsorbents have been used in the removal of Maxilon dyes from wastewater: clay (Chaari et al., 2019; Cheknane et al., 2010), sugarcane stalk powder (El-Sayed et al., 2013), walnut shell (Deniz, 2014), waste sludge (Sarioglu and Aşkal, 2018), pine sawdust (Şentürk and Yıldız, 2020a; Şentürk and Yıldız, 2020b), amongst others.

Although researchers have examined the adsorptive elimination of Maxilon dyes from wastewater, to the best of the authors' knowledge, there is presently no review study on Maxilon dyes or their mitigation through the process of adsorption, and this work intends to address that gap. This work was aimed at reviewing the progress made thus far in the treatment of Maxilon dyes-contaminated wastewater using the adsorption technique. It studies the properties of Maxilon dyes and discusses the factors that affect their adsorption. It also gives an insight into its isotherm, kinetic, and thermodynamic modelling. This study will particularly benefit future researchers in understanding the conditions required for effective Maxilon dye removal.

Maxilon dyes and the environment

Maxilon dyes are a class of basic monoazo dyes. The most colorful class of soluble synthetic dyes used in the textile industry is basic dyes (also known as cationic dyes) (Şentürk and Yıldız, 2020). One or more azo groups (R_1-N═N-R_2) with polyaromatic rings are usually replaced by sulfate groups in these dyes (Şentürk and Yıldız, 2020). Because of their strong interaction with many surfaces of both natural and synthetic fibers, they are used in the dyeing of leather, wool, silk, nylon, leather, cotton, and acrylics (Errais et al., 2011). The extensive use of this azo-dye group has revealed that most of their reaction products are highly carcinogenic (Şentürk and Yıldız, 2020a). The presence of aromatic and other functional groups makes the dyes stable and non-biodegradable. Thus, they remain in water bodies for a long time, causing serious deleterious effects on all aquatic flora and fauna, and reaching man through various means, including bio-magnification. A recent study by Köktürk et al. (2021) showed that Maxilon Blue 5G causes toxicity, teratogenicity, and genotoxicity in zebrafish embryonic development. The dye can cause irreversible damage to embryos or larvae owing to oxidative stress, as well as developmental defects such as tail deformity, microphthalmia, curved body axis, and sac edema, according to the study (Köktürk et al., 2021). Maxilon dyes that have been reported in literature with profound environmental impact include Maxilon Blue 5G, Maxilon Blue GRL, Maxilon Red GRL, Maxilon Red BL-N, Maxilon Red SL, Maxilon Yellow 4GL, Maxilon Golden Yellow, and Maxilon Yellow 3GL. Table 1 presents the physicochemical properties of these dyes alongside their chemical structures.

Batch equilibrium studies

Adsorbent performance for the removal of Maxilon dyes is usually measured in terms of percentage removal efficiency (RE%) and adsorption capacity (Qmax), which are presented in Table 2. These parameters were presented based on the different kinds of Maxilon dyes with their corresponding pH, adsorbent dosage, temperature, and method of determination (sorted in decreasing order of adsorption capacity for each pollutant type). The method by which the adsorption capacity was determined is also stated. It is either determined directly by experiments or via isotherm modelling (Ighalo and Eletta, 2020; Iwuozor et al., 2022). The highest reported uptake of Maxilon dyes by the various adsorbents as shown in Table 2 is 1830 mg/g for Maxilon blue using hydrolyzed (styrene-*alt*-maleic anhydride) chitosan (Ali et al., 2020). The implications of some of the process parameters that affect the adsorption of Maxilon dye are outlined below.

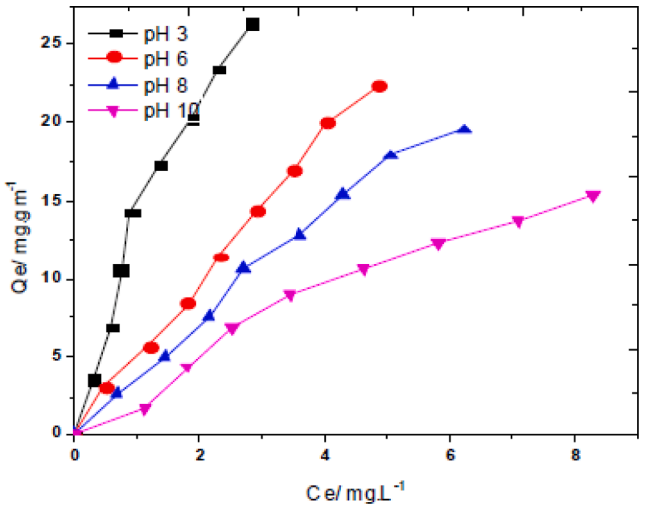


Fig. 1. Effect of pH on the adsorption of Maxilon Blue on the surface of Coconut shell (Aljeboree et al., 2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

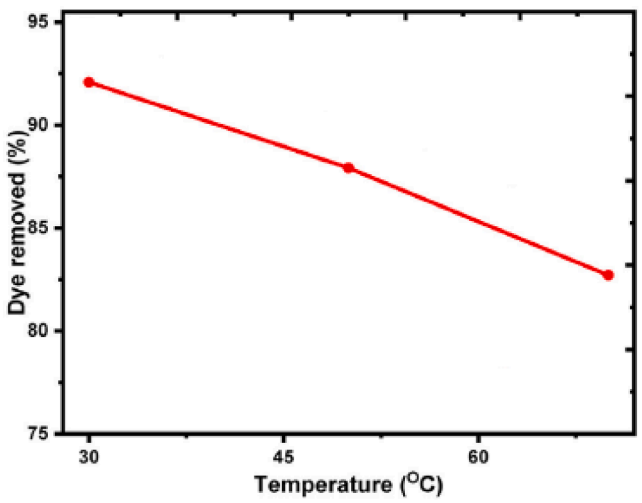


Fig. 2. Effect of time for Basic Yellow adsorption onto raw kaolin adsorbent (Aragaw and Angerasa, 2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The solution pH

The adsorbent capacity of an adsorption process is mostly determined by its solution pH (Iwuozor et al., 2022; Aljebori and Alshirifi, 2012; Aljeboree and Alkaim, 2019; Peter et al., 2019). The effect of solution pH on the adsorption of Maxilon yellow using sulphonated waste poly methyl methacrylate was investigated by Dahdouh et al. (2020). When the pH of the solution was between 2 and 8, the authors observed an increase in adsorption capacity. The maximum adsorption capacity for Maxilon yellow was found at a pH of around 6. The cationic form of Maxilon yellow in aqueous solution, which increases electrostatic interaction with the adsorbent and, therefore, greater adsorption at pH 6 and higher, where the adsorbent's surface charge becomes negative, is the likely explanation for this. (Dahdouh et al., 2020). In another research by Aljeboree et al. (2020), it was observed that the uptake of Maxilon blue by coconut shell activated carbon decreased as the solution pH increased (Fig. 1). The reduced adsorption seen at alkaline pH could be due to greater competition between anions on the dyes' surface and excess hydroxyl ions produced for the adsorbent's adsorption sites (Aljeboree et al., 2020). El-Sayed et al., 2013 investigated the pH effect on the uptake of Maxilon red (GRL) from aqueous solution by natural sugarcane stalk powder. They discovered that the maximum adsorption of the dye into the solvent was low at lower pH values, and that the greatest adsorption was achieved at pH 4.8. When the pH was adjusted from 4.8 to 1.9 within a pH range of 1.9 to 10.8, the percentage removal was shown to decrease. This is due to the positive charge on the adsorbent's surface at pH < 4.8, as evidenced by its point of zero charge (pHpzc). As a result, there is competition between the dye cations and the protons at the adsorption sites. However, at pH levels beyond the adsorbent's point of zero charge, there is increased electrostatic attraction between the negative charge on the adsorbent's surface and the dye cations, resulting in better adsorption. The influence of pH on Maxilon blue adsorption was examined by Aljeboree et al., 2017. They discovered that as the pH increased from 3 to 10, the adsorption of Maxilon blue decreased. The largest adsorption occurred at pH 3 and that the lowest dye uptake occurred at pH 10. Due to the extinction of hydrogen ions, higher electrostatic repulsion between the anions on the dye and the adsorbent surface occurs at alkaline pH. However, at an acidic pH, the adsorbent's functional group becomes protonated, resulting in enhanced adsorption (Aljeboree et al., 2017).

Effect of temperature

Temperature, like other important factors, has an impact on dye uptake by the adsorbent because it affects the adsorbent's equilibrium capacity as a function of the adsorbate. When the absorption of dye by the adsorbent decreases as the temperature rises, the adsorption reaction is called exothermic; when the uptake of dye by the adsorbent increases, it is called endothermic (Alqaragully, 2014). The effect of temperature on the adsorption of Maxilon blue onto white marble was examined by Aljebori and Alshirifi, 2012. They discovered that as the solution temperature increased from 303 to 343 K, the dye's equilibrium adsorption capacity dropped. This could be due to a breakdown in the physical link between the dye and the active sites of the adsorbent. As a result of the exothermic action of the environment, desorption of the adsorbed dyes is accelerated (Aljebori and Alshirifi, 2012; Alqaragully, 2014). In another research conducted by Aljeboree et al., 2017, a decrease in adsorption of Maxilon blue onto coconut shell activated carbon with increasing temperature within a range of 10–40 ^{0}C was reported. A plausible reason for this observation is the increase in solubility of the dye which results into an enhanced interaction between the solvent and Maxilon blue relative to the interaction between the adsorbent and the dye. This may also be attributed to the disruption of the intermolecular hydrogen bond that exists between coconut shell activated carbon and Maxilon blue which contributes strongly to the dye uptake (Aljeboree et al., 2017). In a study by Aragaw and Angerasa, 2020 using raw kaolin as the adsorbent (shown in Fig. 2), a decrease in the removal efficiency from 94.79 to 85.41 % was reported when the temperature increased from 30 to 70 ^{0}C. This implies that the adsorption process was exothermic and invariably suggests the expansion of the kaolin's pore which reduces its ability to retain the dye molecules with increasing temperature. Interestingly, Barka et al., 2009 reported a reverse trend in their research. They discovered that the uptake of Maxilon yellow by natural phosphate increased as the temperature was increased. While this reflects the endothermic nature of the process, the expansion of the natural phosphate's internal structure and the increased mobility of the dye, which allows for more penetration into the active areas of the adsorbent, are possible explanations (Barka et al., 2009).

Effect of adsorbent dosage

Adsorbent dose is particularly important in the adsorption process since it serves as a benchmark for evaluating adsorbent performance and process economics (Gorzin and M. Bahri Rasht Abadi, , 2018; Kuang

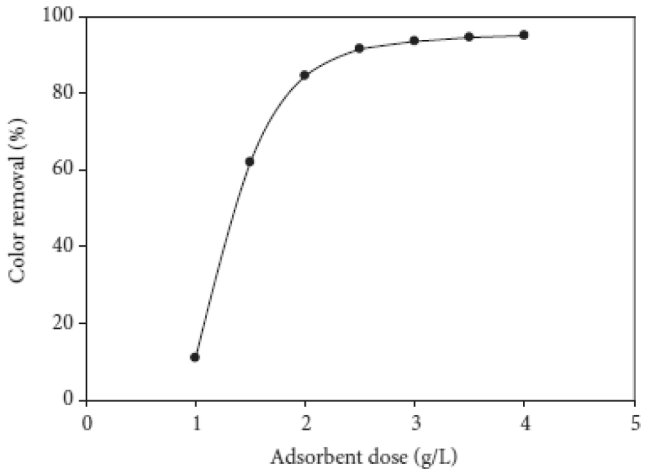


Fig. 3. Sugarcane stalk powder's effect as an adsorbent dosage on the color removal of Maxilon Red (El-Sayed et al., 2013).

et al., 2020; Alao et al., 2022). Aragaw and Angerasa, 2020 studied the influence of Ethiopian kaolin dosage on Maxilon golden yellow GL elimination efficiency. With an increase in adsorbent dosage from 0.1 to 2 g, they reported a percentage rise of 22.92–97.5 %, 17.92–96.87 %, and 3.33–94.38 % for beneficiated, raw, and calcined kaolin, respectively. The availability of accessible adsorption sites on the adsorbent surface is suggested by the increase in removal efficiency with increasing dosage (Aragaw and Angerasa, 2020). Also, another possibly reason for this is the heightened availability of exchangeable sites on the kaolin at higher concentration of adsorbent (Yao et al., 2014). Further, at a higher dosage of 2 g, the adsorption efficiency remained constant under the same operating conditions. This could be due to adsorption sites overlapping due to adsorbent surface crowding or the attainment of equilibrium between the adsorbed Maxilon golden yellow and the unadsorbed dye on the kaolin surface (Yao et al., 2014; Kumar et al., 2010). Fig. 3 shows the effect of adsorbent dosage as investigated by El-Sayed et al., 2013, where the adsorption on Maxilon red by sugarcane stalk powder was found to increase from 11.25 to 95.10 %. The increase in adsorption recorded within the dose range of 1.0–4.0 g/L could be attributable to the sugarcane stalk powder's increased surface area and the availability of adsorption sites. Similar findings were observed in another investigation by Boudechiche et al., 2019, When the adsorbent dosage was changed within a range of 0.2–0.7 g/L, the authors reported an increase in the adsorption effectiveness of Maxilon golden yellow from 59 to 100 percent at pH 8. This was attributable to the adsorbent's increased contact surface area and the existence of adsorption sites. The authors did report a maximum adsorption efficiency at 0.6 g/L adsorbent dosage (Boudechiche et al., 2019). According to Aljebori and Alshirifi, 2012, the removal efficiency of Maxilon Blue GRL increases with increasing dosage. The rise in removal percentage with a significant increase in adsorbent dosage from 2.5 to 20 g/L can be due to the greater surface area and sorption sites offered by the additional adsorbent, which enables Maxilon Blue GRL absorption (Aljebori and Alshirifi, 2012).

Effect of contact time

Several studies have established that contact time is crucial in determining the removal efficacy of an adsorption process (Yao et al., 2014; Amenaghawon et al., 2022). The effect of contact time (up to 180 min) in the removal of Maxilon golden yellow was studied by Boudechiche et al., 2019. They observed a drastic increase in adsorption with removal percentage 35 % within the first 5 min. Afterwards, there was a slow increment in the removal efficiency up till 90 min. At 180 min, equilibrium adsorption was attained with a removal efficiency of

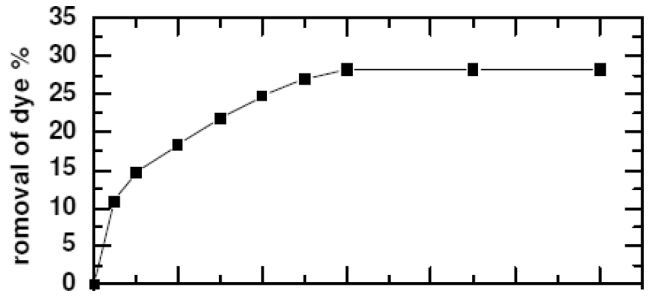


Fig. 4. Effect of contact time on the adsorption of Maxilon Blue by white marble (Aljebori and Alshirifi, 2012).

79 %. The minor increase in removal efficiency after the first 5 min indicates that dye molecules on the adsorbent's surface are competing for accessible sites at increasing concentrations (Boudechiche et al., 2019). Aljebori and Alshirifi, 2012 examined the effect of contact duration on the removal of Maxilon blue GRL by white marble (Fig. 4). They noticed an increase in dye uptake with increasing contact duration throughout a range of 0–120 min, until equilibrium was reached at 60 min. The initial increase was rapid, which could be ascribed to the multiple adsorption sites accessible on the adsorbent surface. The creeping growth observed at a later time, on the other hand, could be owing to the solute–solute repulsion between the bulk and solid phases, resulting in a delayed equilibrium. This phase, which is marked by slow internal diffusion, is regarded to be the rate-determining step (Aljebori and Alshirifi, 2012). El-Sayed et al. (2013) also found that as contact duration increased, the percentage of Maxilon red GRL removed by sugarcane stalks increased rapidly. As a result, until equilibrium is attained, the removal efficiency drops. The largest percentage of dye removed was recorded after 60 min of contact time, indicating that dye removal is dependent on dye concentration (El-Sayed et al., 2013).

Equilibrium isotherm and kinetics modelling

In the sorption process, the orientation of the adsorbent surface, the geometry of functional groups, and the interacting forces between adsorbate all play a role in the interaction between adsorbent and adsorbate. When an equilibrium condition is reached, the adsorbate's behavior and distribution between liquid and solid phases is explained by the adsorption isotherm. This serves to emphasize the porous solid's character (Igwegbe et al., 2021), and the information may subsequently be used to design and create industrial-scale adsorption processes. With only a few exceptions, such as Hill (Deniz, 2014), Temkin (Aljeboree and Alkaim, 2019), and Fritz-Schlunder (Aljeboree et al., 2017), the classical models of Freundlich and Langmuir were shown to be the best-fits in the majority of the studies under consideration. This observation indicates prevalence in adsorption uptake of Maxilon dyes unto various adsorbents as either monolayer (homogenous) or multilayer (heterogenous). Perhaps ease in computation as they consider just two parameters make them more preferred (Igwegbe et al., 2021). Linear and non-linear methods via regression technique can be used in describing isotherm models (Aniagor and Menkiti, 2018). The optimum fit for linear regression models is determined by how close their respective coefficients of determination (R^2) are to unity, but the non-linear regression model is an iterative approach that use applicable computer

Table 3
Predominant isotherm and kinetic model type for Maxilon dye uptake.

Model Type	Langmuir Isotherm	Freundlich Isotherm	Pseudo-Second Order
Linear	$\frac{1}{q_e}=\frac{1}{q_t K_l C_e}+\frac{1}{q_t}$	$In(q_e)=InK_F+\frac{1}{n}InC_e$	$\frac{t}{q_t}=\frac{1}{K_2 q_e^2}+\frac{t}{q_e}$
Non-linear	$q_e=\frac{q_{max}K_l C_e}{1+K_l C_e}$	$Qe = KFC^{1/n}$	$q_e=\frac{K_2 q_e^2 t}{1+K_2 q_e t}$

Table 4
Best-fit isotherm and kinetic models for Maxilon dyes uptake.

Maxilon dye	Adsorbent	Isotherm models			Kinetic models			Ref.
		Best fit	Model type	R^2	Best fit	Model type	R^2	
Maxilon Blue (GRL)	AC from Apricot stone with Clay	Langmuir	Non-linear	0.9889	–	–	-	(Aljeboree et al., 2020)
	AC from Corn cob	Temkin	Non-linear	0.9974	–	–	-	(Aljeboree and Alkaim, 2019)
	Multiwall carbon nanotubes (MWCNTs)	Freundlich	Non-linear	0.9874	–	–	-	(Alkaim et al., 2015)
Basic Yellow 28	Reed	Langmuir	Non-linear	0.9480	PSO	Linear	0.9990	(Boudrahem et al., 2015)
	Raw Ethiopian kaolin	Langmuir	Linear	0.9990	PSO	Linear	0.8260	(Aragaw and Angerasa, 2020)
	Beneficiated Ethiopian kaolin	Langmuir		0.9960	PSO		0.9010	
	Calcined Ethiopian kaolin	Freundlich		0.9980	PFO		0.8860	
	AC from *Ziziphus lotus* stones	Langmuir	Non-Linear	0.9942	PSO	Linear	0.9910	(Boudechiche et al., 2019)
	Natural phosphate rock	Langmuir	Non-linear	0.9970	PSO	Non-linear	0.9950	(Barka et al., 2009)
Maxilon Red (BLN)	Activated sludge	Langmuir	Linear	0.9960	PSO	Linear	0.9990	(Basibuyuk and Forster, 2003)
Maxilon Red BL-3	Natural clay	Langmuir	Linear	0.9990	PSO	Linear	0.9880	(Nassar and Farrag, 2012)
Maxilon Red GRL	Grape molasses soil	Langmuir	Linear	0.9950	–	–	-	(Çiner, 2018)
	Sugarcane stalks powder	Langmuir	Linear	0.9994	PSO	Linear	0.9990	(El-Sayed et al., 2013)
	Walnut shell	Hill	Non-linear	0.9960	PSO	Non-Linear	0.9850	(Deniz, 2014)
	Kaolinite	Langmuir	Linear	0.9990	–	–	-	(Karaoğlu et al., 2009)
Maxilon yellow 4GL	Kaolinite	Langmuir	Linear	0.9990	–	–	-	(Karaoğlu et al., 2009)
	Spent *Salvia officinalis*	Freundlich	–	0.9725	PSO	Non-linear	0.9850	(Bingul and Adar, 2021)
Tar-Chromium Green 3G	Diatomite	Freundlich	Linear	0.9800	–	–	-	(Koyuncu, 2012)
Maxilon Red 3GL	AC from Peach stone shells	Langmuir						(El-Khouly et al., 2017)
			Non-linear	0.9970	–	–	-	
	Peach stone shells modified with CeO_2	Langmuir	Non-linear	0.9890	–	–	–	
	Peach stone shells modified with ZnO	Langmuir	Non-linear	0.9880	–	–	–	
Maxilon blue	Sulphonated styrene-*alt*-maleic anhydride	Langmuir	Linear	0.9600	PSO	Linear	0.9000	(Ali et al., 2020)
	Hydrolyzed styrene-*alt*-maleic anhydride	Freundlich	Linear	0.9200	PSO	Linear	1.0000	
Maxilon Blue GRL	Coconut Shells-Activated Carbon	Fritz-Schlunder	Non-Linear	0.9989	–	Non-Linear	0.9895	(Aljeboree et al., 2017)
Maxilon Red GRL	Grape molasses soil	Langmuir	Linear	0.9950	–	–	-	(Çiner, 2018)
Basic Yellow	Smectite Natural Clay	Langmuir	–	0.9960	–	–	-	(Chaari et al., 2019)
	Sulphonated waste Poly Methyl Methacrylate	Langmuir	Linear	0.9993	PSO	Linear	0.9979	(Dahdouh et al., 2020)
Maxilon Blue 5G	Expanded Perlite	–	–	–	PSO	Linear	0.9900	(Demirbaş and Alkan, 2015)
Maxilon Blue GLR	Sepiolite	Langmuir	Linear	0.9992	PSO	Linear	0.9990	(Doğan et al., 2006)
Maxilon Yellow	*Salvia Officinalis*	Freundlich	Linear	0.9725	PSO	Linear	0.9850	(Bingul and Adar, 2021)

software to estimate parametric data (Aniagor and Menkiti, 2018; Aniagor et al., 2021). Here, the smallest possible error value is desired as it correlates to R^2 tending to unity (Aniagor et al., 2021). It should be noted that the linear regression is somewhat bias and less accurate as a result of varying y-axis; Langmuir model $\frac{1}{q_e}$ compared to Freundlich model $In(q_e)$ as seen as seen in Table 3.

Adsorption kinetics is another important parameter that should be considered during adsorption process design for probing the controlling mechanism and choosing the optimum operating conditions of an adsorption system (Aniagor and Menkiti, 2018). The best-fitting kinetic model is the Pseudo-Second order model (PSO), as seen in Table 4. Although it has been reported that PSO mathematically over-fits adsorption data, for instance, Tran et al. (2017) reported over-fitting anomalies in the PSO model, it can be concluded that PSO is the best fit kinetic model for the adsorption of Maxilon dyes. This invariably leads to the conclusion that chemisorption is the mechanism driving the adsorption characterized by electron transfer from the adsorbate to the adsorbent. However, Kajjumba et al. (2018) argued against this conclusion, noting that the adsorption mechanism cannot be determined solely through fitting a PSO model. Another observed event is the bias towards a higher R^2 value that occurs in PSO models for kinetic data close to equilibrium. The majority of the research under consideration concentrate on examining kinetic data from the beginning to the end of the adsorption process (Aniagor and Menkiti, 2018). However, Simonin (2016) has critiqued this strategy for producing bias and unfairly promoting the PSO model. Another phenomenon observed was the role played by the adsorbent type. Though much information was not presented here, it would seem likely that modified adsorbents had a better data fit, i.e., R^2 value, as compared to unmodified variants. For instance, in the study by Aragaw and Angerasa, 2020 using Ethiopian kaolin for the removal of basic yellow dye, the results showed that beneficiated kaolin had higher values ($R^2 = 0.901$) versus raw ($R^2 = 0.826$). The results contrast with that obtained by El-Khouly et al., 2017, where a higher value was reported ($R^2 = 0.997$) for AC from unmodified peach stone shells compared to ($R^2 = 0.989$) and ($R^2 = 0.988$) for CeO_2 and ZnO modified peach stone shells, respectively. Therefore, more research need to be conducted taking the effect of adsorbent modification on isotherm modelling into account in future studies. Table 4 summarizes the isotherm and kinetic modeling data from numerous studies on the removal of Maxilon dye using various adsorbents.

Thermodynamic studies

The analysis of an adsorption system's thermodynamics helps to reveal its effect on particular components of the adsorption process relating to energy. The thermodynamic parameters include the Gibb's free energy, ΔG°, Enthalpy change, ΔH°, and the Entropy change, ΔS°. The ΔH° parameter represents the adsorption process's responsiveness to variations in thermal energy (temperature rise or reduction). A negative value indicates an exothermic adsorption mechanism, with lower temperatures promoting the uptake of Maxilon dyes (Ogemdi;

Table 5
Summary of thermodynamics modelling for Maxilon dyes.

Maxilon dye Type	Adsorbent	Thermodynamics				Refs.
		Temp (K)	ΔG°C (kJ/mol)	ΔH ° (kJ/mol)	ΔS ° (J/mol·K)	
Red GRL	Activated Clay	298	−7.329	−17.13	−32.84	(Mekatel et al., 2021)
Golden Yellow GL	Sulphonated waste poly methacrylate	298	−6.910	−45.00	−130.0	(Dahdouh et al., 2020)
Yellow 4GL	*Salvia officinalis*	298	−0.586	−16.45	−53.30	(Aljebori and Alshirifi, 2012)
Blue GRL	White marble	308	9.586	10.12	1.743	(Bingul and Adar, 2021)
Blue 5G	Turkey green clay	308	66.63	15.20	−167.3	(Nas (2019))

Zhul-quarnain et al., 2018). The endothermic process is the inverse of the exothermic process. According to Table 5, both possibilities for Maxilon dye uptake have been observed, and this is dependent on the Maxilon dye (adsorbate), the adsorbent, and the corndition upon which the adsorption process took place (Balarak et al., 2021; Igwegbe et al., 2020). The variation in Gibbs free energy (ΔG°) reveals the process's spontaneity (Hevira et al., 2021; Hevira et al., 2020). From Table 5, the negative and positive results reported suggest the Maxilon dye uptake process was both spontaneous and non-spontaneous. During the adsorption process, the change in standard entropy (ΔS°) emphasizes the degree of disorderliness in the system at the adsorbent-adsorbate interphase.

Conclusion and future perspectives

The elimination of Maxilon dyes from the aquatic environment was investigated in this study. Maxilon dyes have been mitigated using a variety of adsorbents. Several operating parameters, such as contact time, adsorbent dosage, solution pH, and temperature, were found to influence the adsorption process. The highest reported uptake of Maxilon dyes by the various adsorbents is 1830 mg/g for Maxilon blue using hydrolyzed (styrene-*alt*-maleic anhydride) chitosan. The Langmuir and Freundlich isotherm models best describe the adsorption of Maxilon dyes. For the kinetic modeling of Maxilon dyes, the pseudo-second order was shown to be the best fit. In this study, the thermodynamic modeling of Maxilon dye uptake was also studied.

From this study, it was observed that the goal of most of the researchers of Maxilon dye was to obtain the maximum capacity of the dye with the aid of various adsorbents. Few studies have been carried out on the thermodynamic studies and mechanism of Maxilon dye uptake. These studies are very important in understanding the Maxilon dye adsorption process. More research is also needed to enhance the large-scale application of Maxilon dye absorption from industrial wastewater through economically feasible adsorbent regeneration studies and column adsorption studies. The study of competitive adsorption is also encouraged, as it is helpful in investigating the effect other ions that are usually present in the wastewater have on the adsorption of Maxilon dye.

Disclosure statements

Compliance with ethical standards

This article does not contain any studies involving human or animal subjects.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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