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ORIGINAL RESEARCH ARTICLE

Methoxy-Functionalized Monoazo Dyes: Synthesis, Characterization, and Evaluation of Dyeing Performance on Nylon Fabrics

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ABSTRACT
Synthesis of new monoazo acid dyes derived from 2-amino-4,5-dimethoxy benzoic acid using H-acid, J-acid, Tobias acid, Gamma acid, and 1-naphthol, and their utilization in dyeing of textile fabric is attempted in this article. The synthesized dyes were purified by recrystallization, and their melting points were between the range of 152-257 °C. The dyes were characterized using UV-Visible, FT-IR, and LC-MS spectroscopic techniques. The suitability of the prepared dyestuffs for dyeing of nylon 6,6 fabrics has been investigated. The UV-Visible spectrophotometric evaluation of the synthesized dyes in different solvents was carried out to determine their absorption maxima and molar extinction coefficients. The dyes showed absorption within the visible region (460-554 nm) and the molar extinction coefficients (ε) ranged from 2.141×10^4 to 3.336×10^4 $L \cdot mol^{-1} \cdot cm^{-1}$. The dyes were also tested for their dyeing build-up on nylon 6,6 fabrics. The dyes exhibited very good percentage exhaustion (50-93%) on nylon 6, 6 with dark, intense hues of purple and orange. The dyed fabrics demonstrated good to excellent fastness to washing (3-5), very good to excellent fastness to light (4-7), as well as good to excellent fastness to perspiration (3-5).

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INTRODUCTION
Azo compounds are a unique class of chemical compounds that have drawn attention in scientific research. These compounds are characterized by the functional group (-N=N-) uniting two symmetrical and/or asymmetrical identical or non-azo alkyl or aryl radicals (Benkhaya et al., 2020). Aromatic azo dyes are the most widely used class of coloring materials due to their extensive applications across various fields of science and technology (Saçmacı et al., 2012). Azo compounds possess importance in the synthesis of organic dyes and are continuously receiving attention in textile, cosmetic, and pharmaceutical research. Over the years, investigations have been carried out on the synthesis and spectroscopic properties of this group of dyes.

Monoazo acid dyes are synthesized by a simple diazotization and coupling method. They contain one azo group in their dye structure (-N=N-). Different routes and modifications are used to obtain the desired color properties, yield, and particle size of the dye for improved dispersibility (Shankarling et al., 2018).

Conventionally, acid dyes are widely used for the dyeing of silk, wool, and nylon fabrics under acidic conditions. Also, in the coloration of leather, paper, cosmetics, etc. Acid dyes are structurally classified as azo, anthraquinone, nitro, and triphenyl methane dyes (Jinfang *et al.*, 2019)

Among the many aromatic amines used as diazo precursors, 2-amino-4,5-dimethoxybenzoic acid (DMA) has attracted considerable research attention for the synthesis of monoazo dyes due to its electron-donating methoxy substituents, which enhance color intensity and bathochromic shifts (Saçmacı et al., 2012). Several studies have reported the synthesis and spectroscopic characterization of DMA-based azo dyes, exploring their structural, optical, and theoretical properties (Rahman et al., 2011; Al-Suwaidan et al., 2020).

Recent research has extended this interest to functionalized monoazo and disazo systems incorporating DMA or related methoxy-substituted precursors, designed to enhance color strength, dye exhaustion, and environmental compatibility (Dhar et al., 2022; Anwar et al., 2022). Applications have also been demonstrated for methoxy-functionalized monoazo dyes, which exhibit improved color strength, brightness, and wash fastness on various substrates, including cotton, silk, and wool (Nisa et al., 2020; Tadele et al., 2023).

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However, few studies have specifically investigated methoxy-functionalized monoazo dyes on nylon 6,6 fabrics, especially comparative studies involving multiple coupling components under uniform synthetic conditions. Existing reports often focus on cotton or wool substrates, leaving a clear knowledge gap regarding dye-fiber interactions, exhaustion behavior, and color fastness on nylon (Yadav et al., 2023).

This underscores the need for a systematic study of methoxy-substituted monoazo dyes with enhanced affinity for nylon 6,6, characterized comprehensively by UV-Vis, FTIR, and LC-MS spectroscopy, and evaluated for dyeing performance, exhaustion, and fastness properties under controlled acid-dyeing conditions.

In this study, new monoazo acid dyes were synthesized from 2-amino-4,5-dimethoxybenzoic acid (DMA) by coupling with H-acid, J-acid, Tobias acid, Gamma acid, and 1-naphthol. The dyes were characterized using UV-Visible, FTIR, and LC-MS Spectroscopic techniques; their percentage exhaustion and fastness properties were also assessed.

MATERIALS AND METHODS

Materials

Analytical-grade chemicals and reagents from Sigma-Aldrich were used for this research. These include 2-amino-4,5-dimethoxybenzoic acid, concentrated hydrochloric acid, sodium nitrite, dimethylformamide (DMF), absolute ethanol, sodium hydroxide, acetic acid, acetone, H acid, J acid, Gamma acid, Tobias acid, and 1-naphthol. All were used without further purification. Nylon 6,6 fabrics were obtained from Sabo, Samaru Zaria.

Synthesis of dyes D1- D5

Diazotization

2-Amino-4,5-dimethoxybenzoic acid (0.98 g, 0.005 mol) was dissolved in 10 mL of distilled water in a beaker fitted with a magnetic stirrer, then placed in an ice bath. Concentrated hydrochloric acid (0.77 mL) was then added, and the temperature of the resulting amine dispersion was maintained between 0 and 5 °C using an ice slurry. A freshly prepared sodium nitrite solution (0.35 g in 30 mL of distilled water) was added dropwise over 30 minutes with continuous stirring. The mixture was stirred further for 60 minutes to ensure complete formation of the diazonium salt (Ameuru et al., 2014).

Coupling Reaction

The coupling reaction was performed using H-acid (1.5 g) dissolved in 15 mL of sodium hydroxide (NaOH) solution. The solution was cooled to 0–5 °C in an ice bath and kept under magnetic stirring. The freshly prepared diazonium salt solution was then added dropwise over 45 minutes while maintaining the same temperature range. Stirring continued for an additional hour to ensure complete coupling. The resulting dye (D1) was filtered, thoroughly washed with distilled water, and dried in an oven at 40 °c. Dyes D2, D3, D4, and D5 were prepared following an identical procedure, using J-acid, Tobias acid, Gamma acid, and 1-naphthol, respectively, as coupling components (Ameuru et al., 2014).

Purification of the Dyes

The synthesized dyes were purified by recrystallization (three successive times) using ethanol as the solvent. A measured amount of each dye was dissolved in a minimal volume of ethanol and heated gently until fully dissolved. The hot solution was filtered through a funnel fitted with filter paper, and the filtrate was allowed to crystallize. The obtained crystals were collected and dried at ambient temperature (Yusuf et al., 2014).

Determination of the percentage yield of dyes

The percentage yield of the synthesized dyes was determined using the formula shown below:

$$\% \text{ Yield} = \frac{\text{Actual mass of product}}{\text{Theoretical mass of product}} \times 100 \quad \text{.... Eqn. 2.1}$$

Melting point of the dyes

The melting points of the synthesized dyes were determined using the open capillary method with a Gallenkamp melting point apparatus. A small quantity of each dye sample was introduced into a capillary tube and inserted into the apparatus. The temperature was gradually increased while the samples were continuously monitored, and the temperature at which each dye melted was recorded.

Spectroscopic Analysis

UV-Visible absorption measurements

The wavelengths of maximum absorption (λ_max) of the synthesized dyes were determined in various solvents: ethanol, ethanol with hydrochloric acid (HCl), dimethylformamide (DMF), and acetone. Each dye sample (0.001 g) was dissolved in 5 mL of the respective solvent. The absorption spectra were recorded using a UV-Visible spectrophotometer (Jenway 6405).

Infra-red spectra of the dyes

Each of the dye samples was presented for an Infrared scan using an Infrared spectrophotometer (Agilent Technologies Cary 360) to determine the functional groups present in the dyes.

Liquid chromatography-mass spectrometry (LC-MS)

The LC–MS characterization of the synthesized methoxy-functionalized monoazo dyes was performed on a reverse-phase C18 column (4.6 × 150 mm, 5 μm) under gradient elution conditions. The mobile phase consisted of water

containing 0.1 % formic acid (solvent A) and acetonitrile containing 0.1 % formic acid (solvent B). The elution began with 90 % solvent A and 10 % solvent B, gradually increasing to 60 % solvent B over 10 minutes, followed by an isocratic hold for 5 minutes before returning to the initial composition. The flow rate was maintained at 0.4 mL min^{-1}, and the column temperature was set at 35 °C.

Mass spectrometric detection was carried out using an electrospray ionization (ESI) source operated in both positive and negative ionization modes. The ion source conditions were as follows: capillary voltage 3.8 kV, nebulizer gas pressure 35 psi, drying gas flow 10 L min^{-1}, drying gas temperature 320 °C, and fragmented voltage 130 V. The mass spectra were recorded in full-scan mode over an m/z range of 50–1000 **(**El-Seify et al., 2022**)**. The relative mass-to-charge (m/z) ratios were used to verify the molecular weights of the synthesized compounds.

Molar extinction coefficient

The molar extinction coefficient (Ɛ) was calculated using the relation:

$$A = \varepsilon Cl$$

Where,

Ɛ = Extinction Coefficient

A = Absorbance at λ_{max}

C = Concentration of dye in mol/dm^3

l = Path length in cm (Juliana *et al.,* 2022)

General procedure for dyeing of nylon 6.6 fabrics

The Nylon 6,6 fabric (1.0 g) was dyed at a liquor ratio of 50:1 using dye concentrations of 1%, 3%, and 5% on the weight of fabric (o.w.f). The dyeing process started at 40 °C, with the temperature gradually increased to 100 °C over 15 minutes. Dyeing was then maintained at this temperature for an additional 60 minutes. The pH of the dye bath was adjusted and maintained at **4.5 ± 0.2** using acetic acid to facilitate optimal dye uptake. After dyeing, the fabric was removed from the tub, thoroughly rinsed with tap water, and air-dried at ambient temperature (Agho et al., 2017).

Measurement of dyeing properties

Dye bath exhaustion

The percentage of dye bath exhaustion (%E) for each substrate was calculated using the equation below (Jae-Hong Choi *et al.,* 2008).

$$\% E = A_o - A_1 \times 100/(A_o) \quad \text{..... Eqn. 2.2}$$

where A_o and A_1 are the absorbance at λ_{max} of the dye bath before dyeing and after dyeing, respectively.

Color fastness

The color fastness to washing, light, and perspiration was carried out in accordance with ISO test No. 3, ISO 105-X12: 2016, and ISO 105-B02: 2014, respectively.

RESULTS AND DISCUSSION

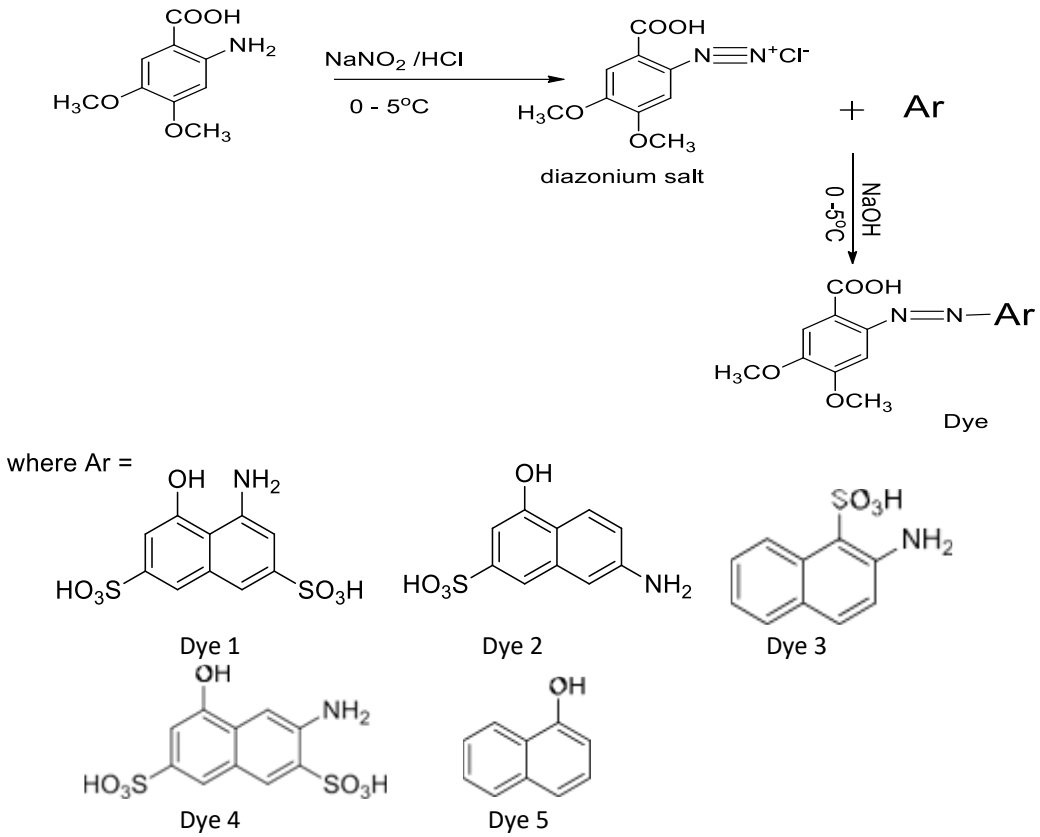
UV-Visible Spectrophotometry and Molar Extinction Coefficient (ε) of the Dyes

The UV-Visible spectra of the synthesized dyes (D1 - D5) exhibited absorption bands in the visible region (460 - 554 nm), which are characteristic of **π→π*** electronic transitions associated with the azo (–N=N–) chromophore (Benkhaya *et al.,* 2020). The observed λmax variation among the dyes reflects differences in chromophoric environments and substituent effects, particularly the influence of electron-donating methoxy groups and differing coupling components (Dhar *et al.,* 2022; Yadav *et al.,* 2023).

A noticeable bathochromic shift (red shift) was recorded upon acidification with HCl, especially for dyes D2 and D3, where λmax increased by 17 - 44 nm. This behavior can be attributed to protonation of the azo nitrogen or of auxochromic groups, leading to an extended conjugation system and increased electron delocalization (Saçmacı *et al.,* 2012; Rahman *et al.,* 2011). Such red shifts in acidic media are typical of azo dyes containing strong donating substituents, which facilitate intramolecular charge transfer upon protonation (Nisa *et al.,* 2020).

In contrast, dyes D1, D4, and D5 displayed only minor shifts (2-5 nm), suggesting limited electronic interaction or restricted protonation in an acidic medium, a trend consistent with observations in structurally related monoazo systems, where steric hindrance reduces resonance stabilization (Anwar *et al.,* 2022).

The molar extinction coefficients (ε) in DMF ranged from 2.141×10^4 to 3.336×10^4 $L \cdot mol^{-1} \cdot cm^{-1}$, indicating strong chromophoric absorption and high tinctorial strength. These ε values are consistent with previously reported ranges for structurally similar methoxy-substituted monoazo dyes, confirming the dyes' intense coloration and extensive π-conjugation (Tadele *et al.,* 2023; Al-Suwaidan *et al.,* 2020). The high ε values demonstrate that electronic transitions within the azo chromophore are efficient and that the conjugation between the aromatic rings and the –N=N– linkage is effectively delocalized, which is a defining feature of highly absorbing azo dyes (Benkhaya *et al.,* 2020; Dhar *et al.,* 2022).



Reaction Scheme 3.1: Synthesis of the Dyes

Table 3.1: Molecular structure of the dyes

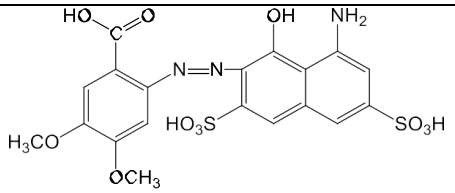
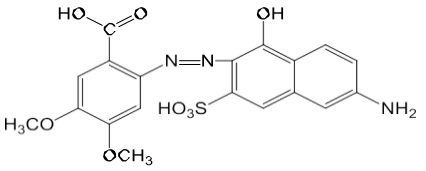
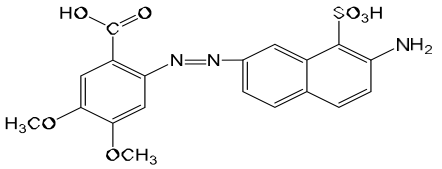
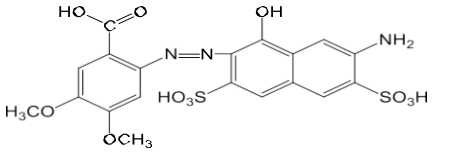
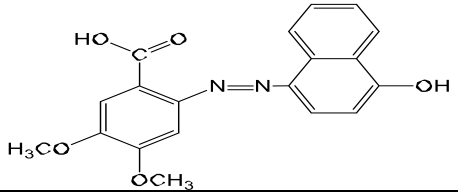
Dyes	Structure
D1	
D2	
D3	
D4	
D5	

Table 3.2: Physical Properties of the Synthesized Dyes.

Dye no	Molecular formula	Molecular weight(g/mol)	Melting point (°C)	Percentage yield (%)	Color of the synthesized dyes
1	$C_{19}H_{17}N_3O_{11}S_2$	527	152-154	84	Purple
2	$C_{19}H_{17}N_3O_8S$	447	223-227	90	Burnt Orange
3	$C_{19}H_{17}N_3O_7S$	431	200-205	93	Orange
4	$C_{19}H_{17}N_3O_8S$	447	253-257	70	Maroon
5	$C_{19}H_{16}N_2O_5$	352	174-176	91	Dark Purple

Table 3.3: Infrared Spectra of Synthesized Dyes

Functional Group Dye No.	OH Str.	NH Str.	CH Str.	C=C Str.	N=N Str.	C-N Str.	C-O Str.	OH Bend
1	3574		2974	1602	1461	1371	1293	1416
2	3365	3075	2940	1640	1401		1263	
3	3753	3004	2944	1658	1435	1338	1241	1405
	3652			1591				
4	3529		2922	1595	1490	1382	1278	
5	3652	3529	2937	1640	1461	1356	1263	1405
				1591	1438	1308		

Table 3.4: Wavelength of Maximum Absorption and Molar Extinction Coefficient of the Dyes

Dyes no	λmax in Ethanol (nm) (a)	λmax in Ethanol+ HCl (nm) (b)	λmax in DMF (nm)	λmax in Acetone (nm)	Molar Extinction Coefficient in (DMF) x 10^4 ($L/mol^{-1}cm^{-1}$)	Change in λmax (b-a)
1	551	554	525	538	3.263	3
2	490	507	487	485	3.336	17
3	485	529	460	475	3.198	44
4	527	532	537	530	2.141	5
5	493	495	489	484	2.974	2

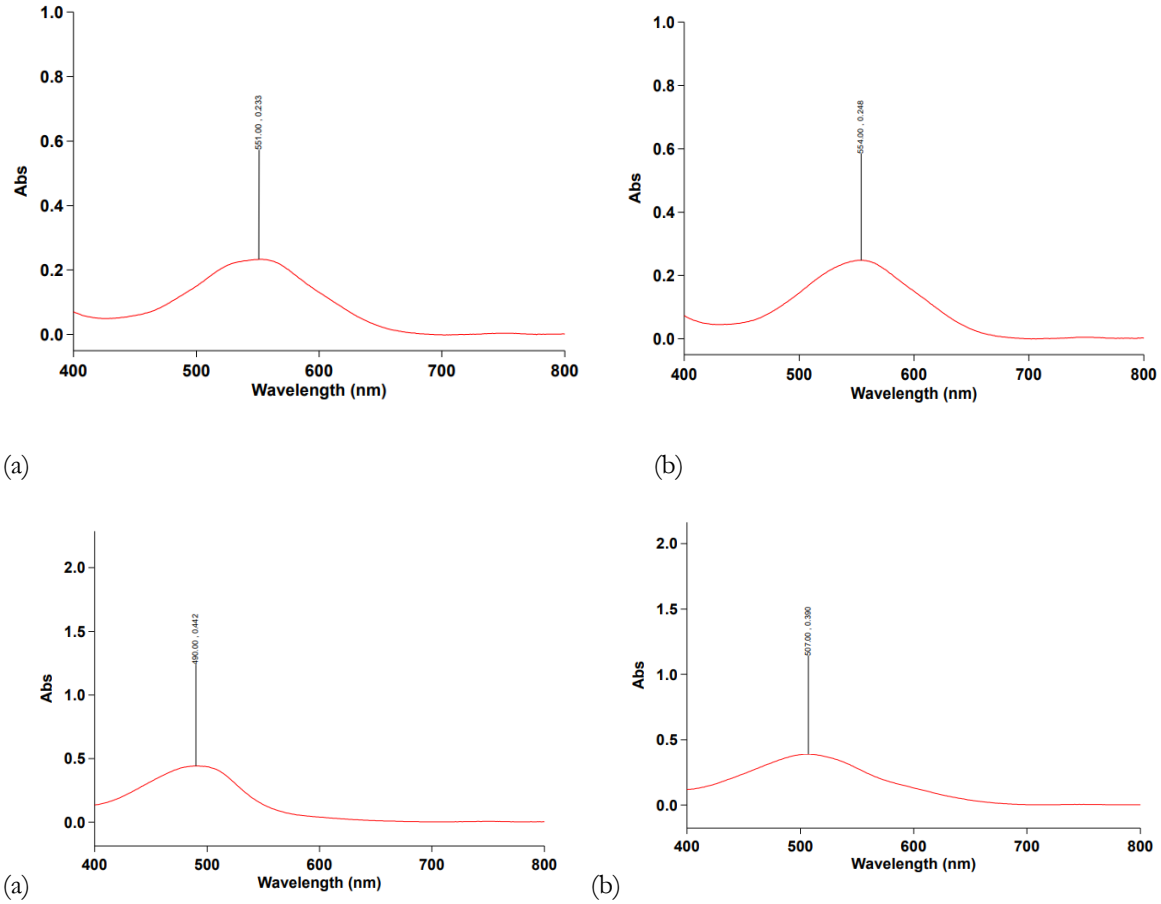


Figure 3.1: Absorption spectra of Dyes D1&D2 in (a) Ethanol (b) Ethanol + HCl

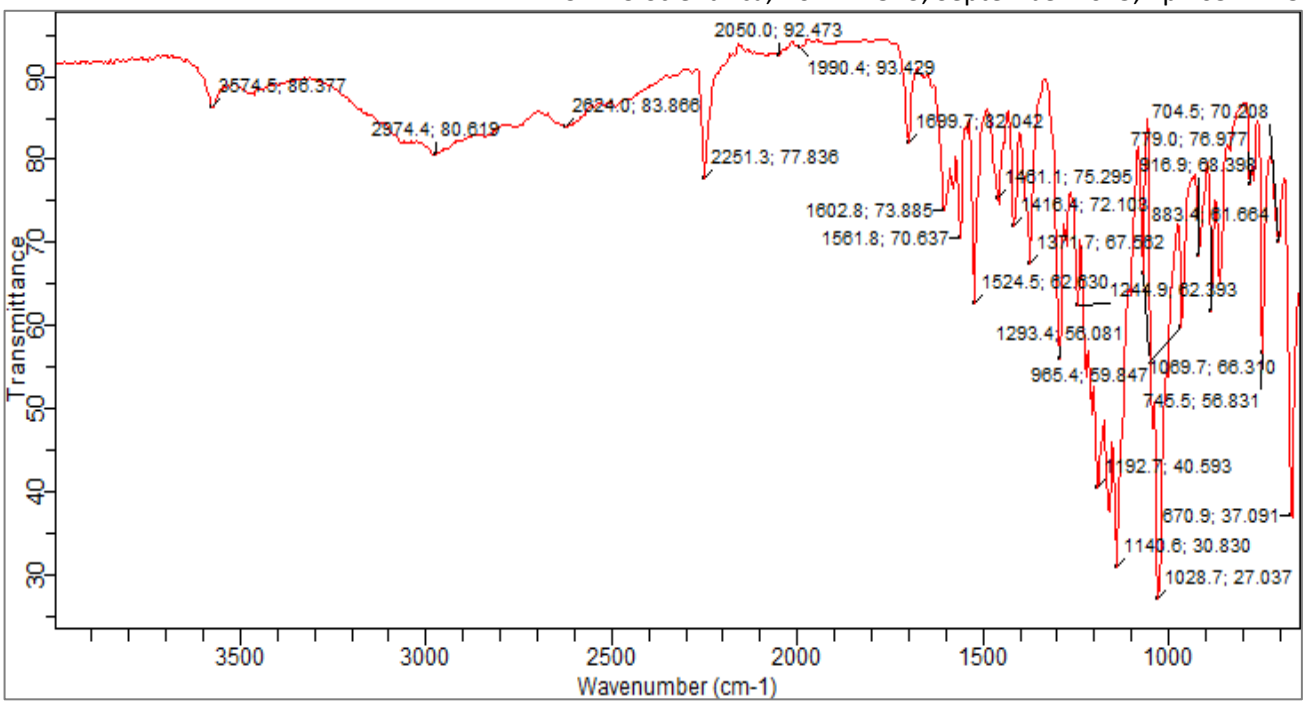


Figure 3.2: FTIR Spectra of Dye D1

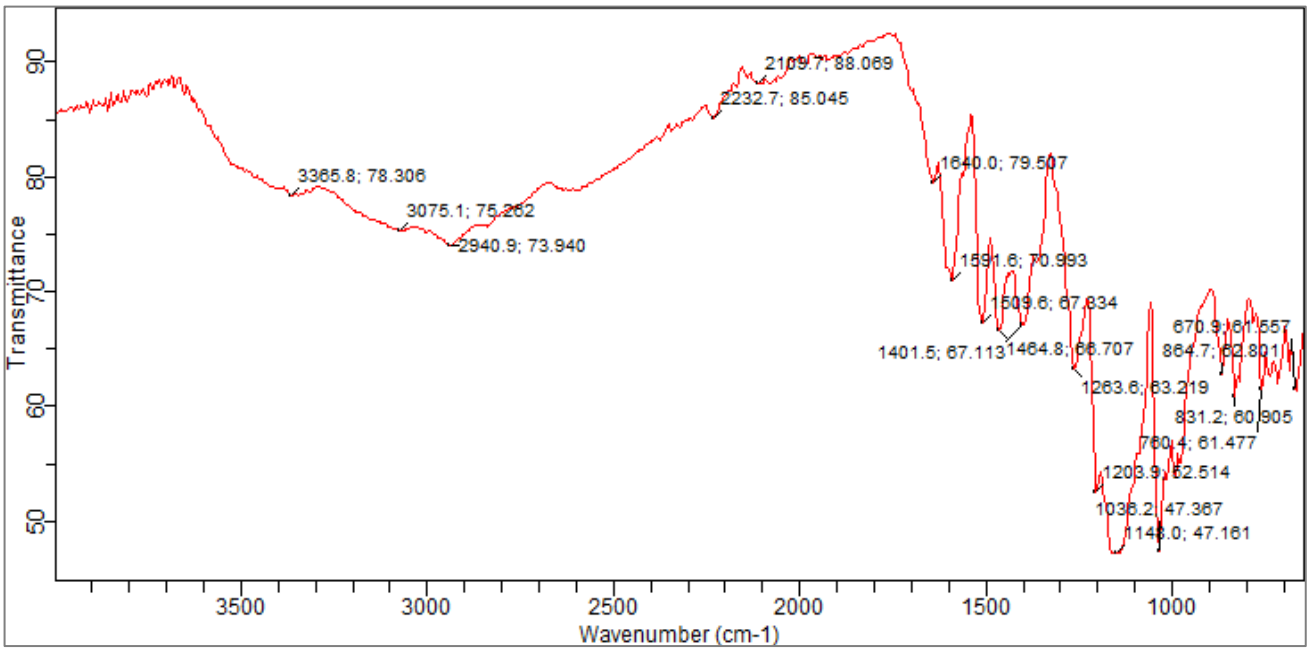


Figure 3.3: FTIR Spectra of Dye D2

IR Spectra of the dyes

The synthesized dyes exhibited strong and broad absorption bands between 3529–3753 cm^{-1}, corresponding to O-H stretching vibrations and indicating the presence of hydroxyl groups in the dye molecules (Adeniyi et al., 2023). The bands in the 3000-3075 cm^{-1} range are attributed to N-H stretching vibrations of amine groups (Omar et al., 2023). These broad absorptions indicate hydrogen bonding and intermolecular interactions involving hydroxyl and amino functionalities. The peaks at 2920–2974 cm^{-1} are linked to C-H stretching vibrations of aromatic structures typical of sp^2-hybridized C–H bonds in benzene derivatives (Omar et al., 2023). Absorptions around 1590–1658 cm^{-1} are characteristic of C=C stretching in aromatic rings, and the bands between 1400–1490 cm^{-1} relate to azo (–N=N–) stretching vibrations (Abdullmajed et al., 2011; Adeniyi et al., 2023). Peaks in the 1260–1370 cm^{-1} range are associated with C–N and C–O stretching vibrations, arising from aromatic amine and methoxy substituents, respectively (Adeniyi et al., 2023). whereas O-H bending vibrations are observed around 1400 cm^{-1} supporting the existence of phenolic or carboxylic groups in the molecular framework (Omar et al., 2023).

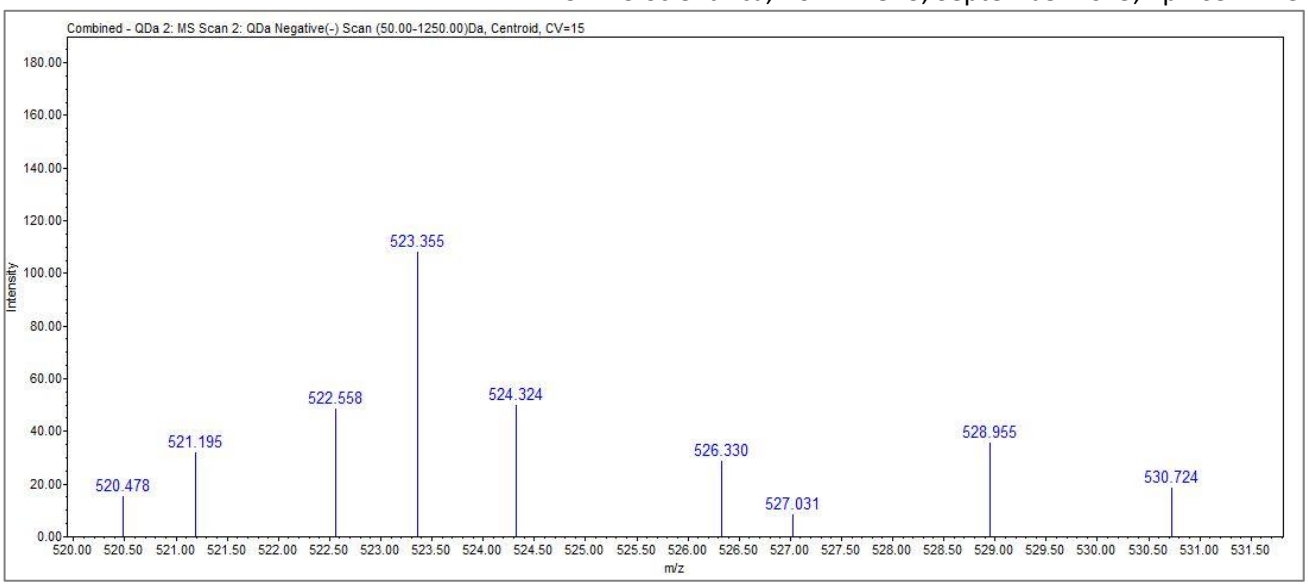


Figure 3.4: LC-MS spectrum of Dye D1

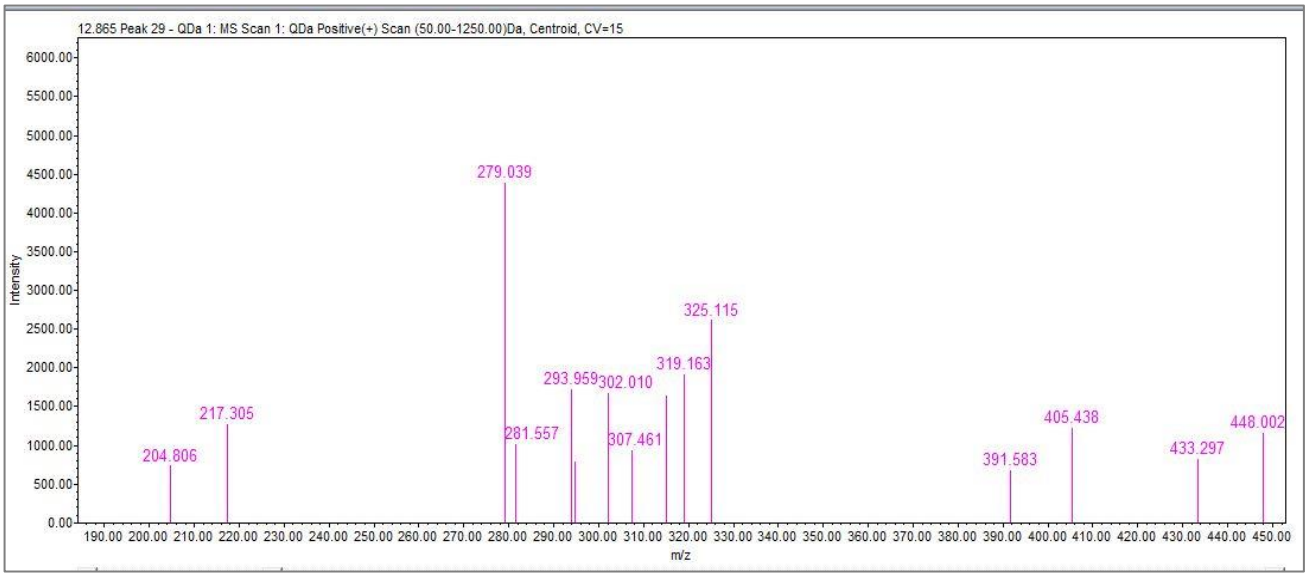


Figure 3.5: LC-MS spectrum of Dye D2

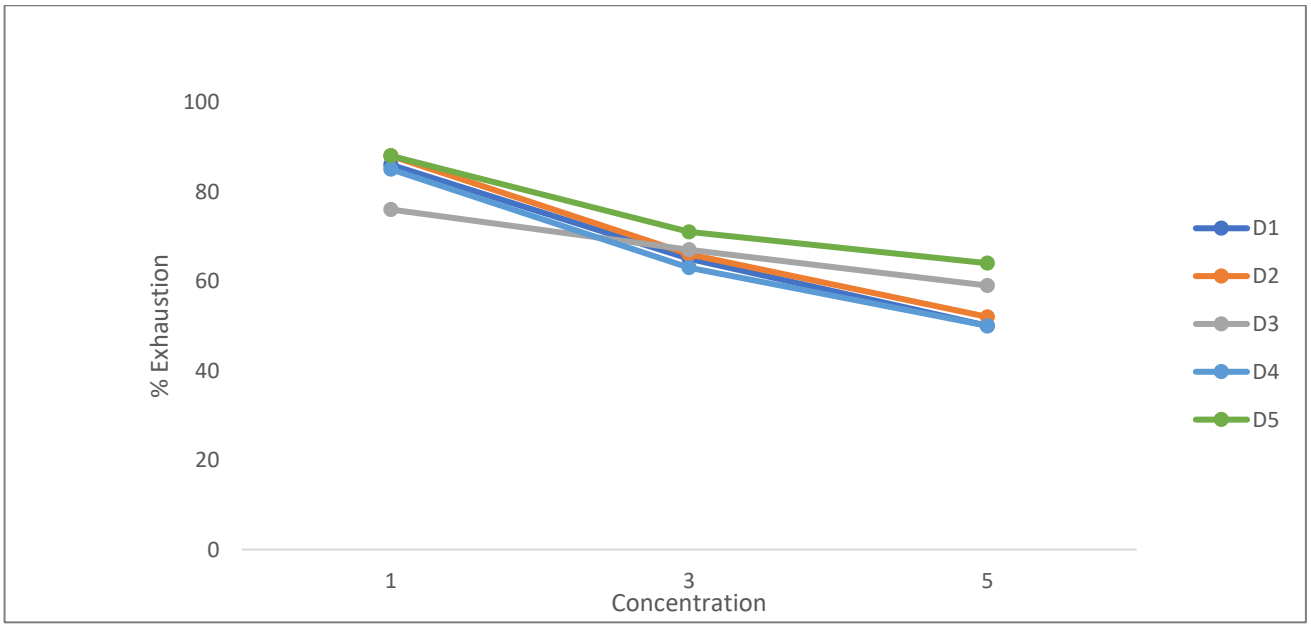


Fig 3.6: % Exhaustion of monoazo acid dyes D1-D5 on nylon 6.6 using various concentrations

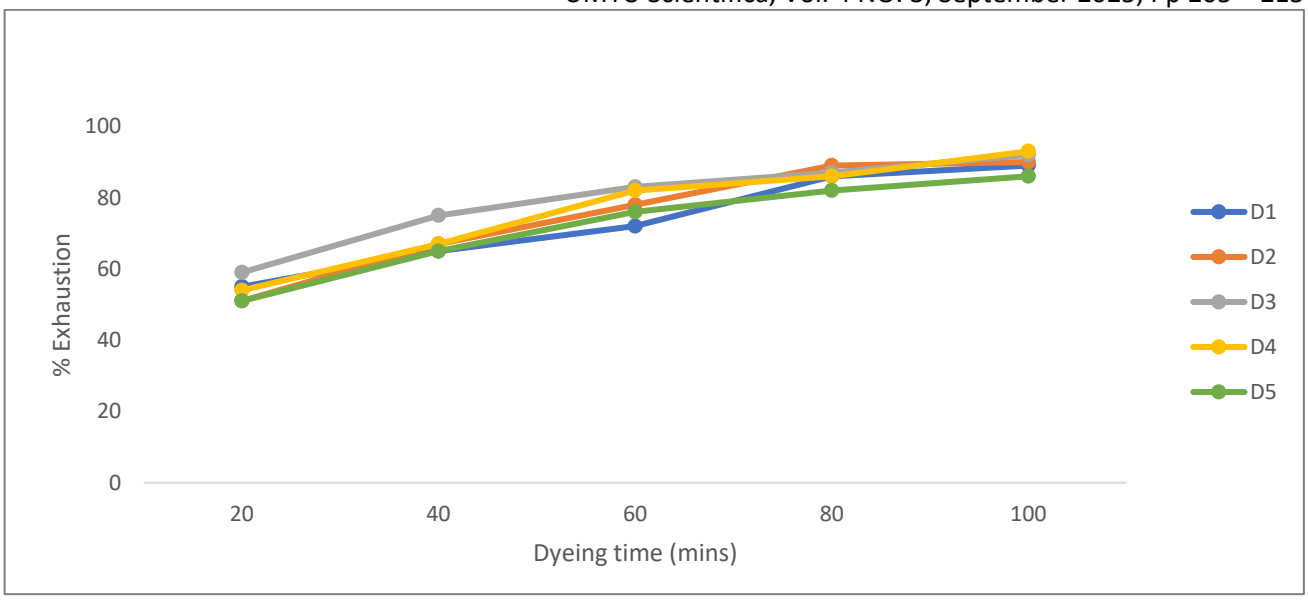


Fig 3.7: % Exhaustion of monoazo acid dyes D1-D5 on nylon at 3% o.w.f. with varying dyeing time.

Table 3.5: Fastness Properties of the Synthesized Dyes on Nylon 6,6 fabric at 1, 3, and 5% shade.

Dye Shade (%)	Dye No.	Fastness				
		Wash		Perspiration		Light
		Change in color	Degree of staining	Acid	Alkaline	
1	D1	3-4	4	3-4	4	4
	D2	3	3	4	4	6
	D3	3	4	3	4	4
	D4	4	4	5	5	5
	D5	4	4	3	4	4
3	D1	3	3	4	3-4	5
	D2	4	4	4	5	6
	D3	4	4	4	4	5
	D4	3	3	4-5	5	6
	D5	4-5	4-5	3-4	5	4
5	D1	4	4	4	5	5
	D2	4	4	3-4	4	7
	D3	3	3	4	5	5
	D4	4	3	3	4	7
	D5	3	3	5	5	5

Table 3.6: Fastness Properties of the Synthesized Dyes on Nylon 6,6 Fabric at 60, 80, and 100 minutes Dyeing Time.

Dyeing time(mins)	Dye No.	Fastness				
		Wash		Perspiration		Light
		Change in color	Degree of staining	Acid	Alkaline	
60	D1	4	4	4	4	5
	D2	3	3	3-4	4	6
	D3	3	3	4-5	4	5
	D4	3-4	3	4	4-5	6
	D5	3	4	3	4	4
80	D1	3	3	3	4	6
	D2	3	4	4	4	6
	D3	3	3	4	4	6
	D4	4	4	3-4	4	7
	D5	3	4	4	5	5
100	D1	4	3	4	3-4	7
	D2	3	3	4	5	7
	D3	3	3	4	5	6
	D5	4	3	4-5	4	7
	D5	3	3	4	3-4	5

Liquid Chromatography- Mass Spectroscopy (LC-MS) of the Dyes

The mass spectrometric analysis of the synthesized dyes confirmed their proposed molecular structures. The spectrum of dye D1 exhibited a prominent molecular ion peak (M^+) at m/z 530, which closely corresponds to the calculated molecular weight of 527 g mol^{-1}, indicating successful synthesis and the structural integrity of the compound. Minor peaks observed between m/z 520–528 can be attributed to natural isotopic variants and in-source fragmentation, particularly the cleavage of weak bonds within the azo linkage or adjacent aromatic substituents (Holčapek et al., 2007; Benkhaya et al., 2020).

Similarly, dye D2 displayed a dominant molecular ion signal at m/z = 448, consistent with its theoretical molecular mass of 447 g mol^{-1}, further confirming the formation of the intended monoazo dye. The narrow peak distribution and the clear dominance of the molecular ion reflect the high stability and conjugation of the dye molecule, which reduce extensive fragmentation during ionization (Souto et al., 2010).

The limited fragmentation observed in both spectra is typical of methoxy-substituted azo dyes, in which electron-donating methoxy and hydroxyl groups stabilize the azo chromophore via resonance delocalization, thereby enhancing molecular ion stability (Dhar et al., 2022; Yadav et al., 2023). The minor fragment ions detected are likely due to cleavage of the azo (–N=N–) bond or loss of methoxy or hydroxyl substituents, which are known fragmentation pathways for such dyes (Holčapek et al., 2007; Millbern, 2024).

Effect of Concentration

The effect of dye concentration on the exhaustion of the synthesized dyes (D1–D5) on nylon 6,6 fabric is presented in Figure 3.6. The results show that dye exhaustion decreases progressively with increasing dye concentration from 1% to 5% o.w.f. At lower concentrations (1%), the percentage exhaustion was highest, indicating efficient dye uptake due to greater dye -fibre affinity and availability of active sites on the fibre surface (Abd El-Aal & Koraïem, 2017; Shanker et al., 2019). However, as the concentration increased, the exhaustion declined, due to saturation of binding sites and increased competition among dye molecules in the dye bath (Behera et al., 2022). Among the dyes, D5 exhibited the highest exhaustion across all concentrations, suggesting stronger fiber-dye interactions and better substantivity. This could be attributed to the favorable balance of hydrophobic and hydrogen-bonding interactions conferred by the methoxy substituents, which enhance the diffusion and binding of the dye into the nylon matrix (Khan et al., 2020; Sharma & Gupta, 2019).

Effect of Time

The influence of dyeing time on the exhaustion of dyes D1–D5 on nylon 6,6 fabric is presented in Figure 3.7. The results show a steady increase in dye exhaustion with prolonged dyeing time from 20 to 100 minutes**,** indicating enhanced diffusion of dye molecules into the fiber as contact time increased (Gürses et al., 2016; Saçmacı et al., 2012). Equilibrium exhaustion was generally reached after about 80–100 minutes**,** beyond which only slight changes were observed. Among the dyes, D3 and D4 showed comparatively higher exhaustion values, suggesting faster dye-fiber interaction and greater substantivity due to their more planar molecular structure and better alignment within the amorphous regions of the nylon polymer (Behera et al., 2022; Khan et al., 2020).

Fastness to washing

The wash fastness test was carried out according to ISO test No. 3, and the results are presented in Tables 3.5 and 3.6. The dyed samples were investigated at different shade depths (1, 3, and 5%). Also, at dyeing times of 60, 80, and 100 minutes. It was observed that dyes D1-D5 showed good to very good fastness to washing (3-5), which can be attributed to the presence of polar functional groups such as hydroxyl and carboxylic acid moieties that enhance hydrogen bonding and ionic interactions between the dye molecules and nylon fiber (Khan et al., 2020; Shanker et al., 2019).

The overall good washing fastness of the dyes on nylon 6,6 fabrics may also result from their high diffusion and fixation within the amorphous regions of the fiber during dyeing. Once the dyes penetrate the polymer matrix, migration or leaching becomes limited, leading to improved wash fastness performance (Gürses et al., 2016; Behera et al., 2022). Similar observations have been reported for other methoxy-substituted monoazo acid dyes applied on polyamide substrates, where the molecular planarity and hydrogen-bonding capabilities promote strong fiber-dye adherence (Abd El-Aal & Koraïem, 2017).

Fastness to light

The light fastness ratings of the dyed nylon fabrics are presented in Tables 3.5 and 3.6. Dyes D1–D5 displayed good to excellent light fastness (4-7)**,** which can be attributed to the molecular planarity and resonance stabilization of the azo chromophore system. The presence of electron-donating substituents such as methoxy groups is known to improve photostability by delocalizing charge and reducing photodegradation of the azo linkage (Sakoma et al., 2012; Sharma & Gupta, 2019).

Also, compact molecular packing within the fiber matrix provided shielding against ultraviolet (UV) radiation, further enhancing resistance to photofading (Benkhaya et al., 2020; Khan et al., 2020). These results are consistent with previous studies reporting that dyes containing methoxy or hydroxyl substituents generally demonstrate superior light fastness due to improved conjugation and intramolecular hydrogen bonding (Gürses et al., 2016).

Fastness to perspiration

The fastness to perspiration of the dyed fabrics under both acidic and alkaline conditions was rated good to excellent, with values ranging from 3 to 5 on the gray scale, and predominant scores of 4–5 for most samples. This behavior may be attributed to the semi-crystalline nature of nylon 6,6, which restricts dye desorption and migration under wet or acidic/alkaline conditions (Behera et al., 2022; Gurses et al., 2016).

The strong intermolecular forces, particularly hydrogen bonding and ionic interactions between the dye and the amide groups of the fiber contribute significantly to this high perspiration fastness (Khan et al., 2020). Comparable findings have been reported by Shanker et al. (2019), who noted that azo dyes with polar substituents exhibit excellent fastness on nylon fabrics due to their enhanced substantivity and fiber affinity.

CONCLUSION

In this study, an efficient and simple protocol for the synthesis of monoazo acid dyes derived from 2-amino-4,5-dimethoxy benzoic acid and various coupling components (H-, J-. Tobias, Gamma-acid, and 1-naphthol) was successfully developed. Data obtained by various analytical techniques proved the synthesis of the claimed novel dyestuffs. Variation in the coupling components produced notable bathochromic and hypsochromic shifts, reflecting the influence of substituent effects and conjugation on the dyes' electronic transitions. When applied to nylon 6,6 fabrics, the dyes produced bright purple to orange shades with good to excellent wash, light, and perspiration fastness**.** The high percentage exhaustion values further demonstrated strong dye-fiber affinity and good solubility, indicating the suitability of the synthesized dyes for nylon dyeing applications.

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