ISSN 2616-5880 Vol. 7, Issue 1: 102-107, DOI: 10.25236/AJMC.2026.070114

Optimization of Reaction Conditions for the Synthesis of HC Yellow 2 Dye

Yiqiu Shen

Hong Kong International School, 1 Red Hill Road, Tai Tam, Hong Kong, China
jolinnn2007@gmail.com

Abstract: *2-Nitro-N-(2-hydroxyethyl) aniline (HC Yellow 2) is a widely used dye and intermediate for hair coloring, textile dyeing, and printing. Therefore, investigating an efficient synthesis of HC Yellow 2 is of academic and practical importance. The reaction proceeds through nucleophilic aromatic substitution (S_NAr) reaction between ethanolamine and nitro-substituted aryl halides (2-chloronitrobenzene or 2-bromonitrobenzene), promoted by potassium carbonate or catalyzed by copper(I) chloride. Literature-reported conditions using potassium carbonate at 160 °C may lead to product decomposition. At the same time, the copper-catalyzed method has low efficiency and safety concerns related to heavy-metal catalysts. In this study, we investigated and optimized the reaction conditions for the synthesis of HC Yellow 2 dye by comparing different substrates, potassium carbonate loadings, and catalysts. The effects of these conditions on product yield were evaluated. The results showed that 1 equiv. of potassium carbonate at 80 °C provided the best performance, and an isolated yield of 86.3% was obtained. Copper(I) chloride and zinc acetate catalysis were relatively inefficient by comparison. Based on the above results, proper control of both the base loading and the reaction temperature is essential to prevent product decomposition and achieve high yields of HC Yellow 2.*

Keywords: *HC Yellow 2 dye, nucleophilic aromatic substitution (S_NAr) reaction, potassium carbonate*

1. Introduction

1.1 Background and Significance of HC Yellow 2

Synthetic dyes are necessary fine chemicals in modern industry and daily-use consumer products that have better tinting strength, colour uniformity and chemical stability than natural pigments. Synthetic colourants do not have the natural origin of natural pigments, but by selecting synthetic raw materials reasonably, their excellent tinting strength, tunable chromatic performance and broad application versatility can be fully realised. They are widely used in cosmetic hair colour, textile printing and dyeing, leather finishing and packaging colour, and have formed a mature and stable industrial supply chain [1-3,7]. HC Yellow 2 is an all-purpose aromatic nitroamine dye and essential chemical intermediate that is highly water-soluble, has mild colouring properties, and good light-fastness and wash-fastness. It has mild irritation to the skin and a good colour-matching property, so it is often used as a colourant for semi-permanent and temporary hair dyes [3, 9]. HC Yellow 2 also has many uses as an intermediate in the production of functional dyes and fine chemicals, so it is used widely in textile auxiliaries and other industrial colorants. With the development of green chemistry and rising environmental demands around the world, new low-energy, high-efficiency, low-residue and environmentally friendly production routes for dyes are urgently needed[10]. Therefore, to address the deficiencies of the traditional HC Yellow 2 in its synthesis process and reduce costs and improve product safety, it is both feasible in theory and practice.

1.2 Limitations of the Potassium Carbonate-Assisted Method

The potassium carbonate-assisted way has simple operations, low-cost reagents and is metal-free; thus, the product purity is high. Potassium carbonate is a weak inorganic base that neutralises hydrogen halide by-products to shift the reaction equilibrium away from products and generate more nucleophiles for the forward reaction [5]. However, this protocol is still a high-temperature process at 160 °C and is not suitable for substrates. Prolonged high-temperature heating causes thermal decomposition and oxidation of HC Yellow 2 because of the relatively low thermal stability of nitro and amino functional groups. Cleavage of the molecular bond produces dark-coloured impurities, reduces the yield of products, and makes the colour less uniform; thus, it is unsuitable for cosmetic-grade dyes. In a high-temperature

ISSN 2616-5880 Vol. 7, Issue 1: 102-107, DOI: 10.25236/AJMC.2026.070114

environment, the speed of evaporation and decomposition for readily volatile raw materials will be relatively high; thus, there will be material loss and higher production costs. At the same time, a large quantity of alkaline waste and wastewater are generated and need to be treated. Excessive ethanolamine can promote a second nucleophilic substitution at high temperatures, generating diarylamine by-products and complicating purification [11, 12].

1.3 Limitations of the Copper-Catalyzed Method

Copper(I) chloride catalytic systems are relatively low-temperature alternatives for this reaction, operating around 100-120 °C via transition-metal activation [5-8]. The copper catalyst coordinates with substrate halogen atoms and ethanolamine amino groups to reduce the activation energy of SNAr reactions and inhibit thermal decomposition. Although it is energy-efficient, the two problems of this catalytic route are a low product yield and hazardous heavy-metal residues. Catalyst deactivation often occurs in the reaction due to active-site coverage by halide salts and polymeric by-products; thus, substrate conversion is reduced. Copper catalysis may promote the oxidation and polymerisation of the amine substrate to form macromolecular impurities, thus reducing the yield and purity of the product. Most significantly, the remaining copper ions are very dangerous to people using cosmetics. Heavy metal residues in skin-contact hair dyes can cause irritation and allergic reactions, fail to meet the strict heavy metal limits in the EU Cosmetics Regulation and US FDA [13]. Copper residues will reduce the light- and storage-stability of the dye, cause colour fading, and result in non-compliant products.

1.4 Influence of Key Reaction Parameters

Other reasons for a low-yield reaction or a poor-quality product may be missing. Substrate Structure affects reactivity; 2-bromonitrobenzene has higher SNAr activity than 2-chloronitrobenzene, but it is more expensive to produce, so a trade-off must be made between high-efficiency conversion and cost. An insufficient amount of base and catalyst will slow down the reaction; otherwise, over-alkylation or other side reactions may occur [14]. The previous post-treatment methods were extraction, crystallization and filtration repeatedly; thus, 10-15% of the product was lost, and trace impurities such as ethanolamine and unreacted nitroarenes remained. Residual impurities can reduce the efficiency of dye and cause skin irritation or damage to cells [15].

1.5 Objectives of This Study

Given the obvious defects of the existing synthetic route, such as harsh reaction conditions, low yield, poor stability and possible safety risks, systematic optimisation of the HC Yellow 2 synthesis conditions is required urgently. In this study, the type of aryl halide substrate, potassium carbonate equivalent (0.5–2.0 equiv), and mono/combined application of copper(I) chloride and zinc acetate catalysts were all systematically varied. A mild, efficient, low-residue and eco-friendly synthetic route is proposed in this paper to improve the yield and purity of HC Yellow 2, reduce production costs, and eliminate heavy-metal safety risks. In addition, the relationship between reaction parameters and product stability has been determined to provide robust theoretical support and practical reference for the industrial-scale production and high-quality quality control of HC Yellow 2.

The target compound HC Yellow 2 was synthesized via nucleophilic aromatic substitution (SNAr) between 2-halonitrobenzene and ethanolamine, with potassium carbonate as base under heating conditions. The synthetic route is shown in Figure 1.

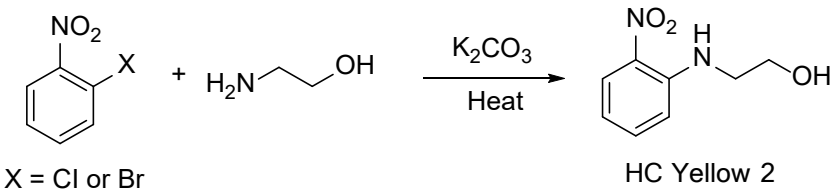

Figure 1. Synthetic route of HC Yellow 2

ISSN 2616-5880 Vol. 7, Issue 1: 102-107, DOI: 10.25236/AJMC.2026.070114

2. Materials and Methods

2.1 General Information

2.1.1 Materials and Reagents

All reagents used are of analytical grade as listed above: 2-chloronitrobenzene, 2-bromonitrobenzene, ethanolamine, potassium carbonate, cuprous chloride and zinc acetate were purchased from a commercial company and used directly without any extra purification or drying. Deionized water was used for all the following processing steps.

2.1.2 Reaction Setup and Equipment

All the reactions were carried out in round-bottom flasks with magnetic stir bar, and based on the scale of the reaction, a flask of about 25 mL or 50 mL was selected. The reaction systems were operated under open-air conditions without inert gas protection. Heating was provided by Heidolph MR Hei-Tec heating magnetic stirrer, with the temperature controlled by a hot-plate with contact thermometer, and magnetic stirring was maintained throughout each run.

2.1.3 Reaction Monitoring

During the reaction, progress was continuously monitored via thin-layer chromatography (TLC) using a commercial silica gel G60 plate as the stationary phase and a developing solvent system of n-hexane–ethyl acetate (1:4, v/v).A UV lamp (254 nm) was used to observe the migration and disappearance of spots for each component to determine how much starting material had been consumed and how much target product had formed. When the TLC showed that the starting-material spot had completely disappeared or was no longer changing significantly, it was determined that the reaction had reached its end, and heating and stirring were immediately discontinued.

2.1.4 Product Isolation and Purification

Crystallisation was employed to separate and purify the target product; otherwise, column chromatography or multiple recrystallisations would have been needed. The reaction has been completed; now, it will be transferred to a conical flask while hot. Add approximately two to three times the volume of the reaction mixture of deionized water slowly while stirring, and a large amount of solid will precipitate. Then, put the mixture in an ice-water bath to cool, and after about 1-2 hours, it will have crystallized. Suction filtration was used to collect the precipitated crystals with a Büchner funnel, and the filter cake was washed several times using a small amount of cold deionized water or a suitable solvent to remove residual inorganic salts and unreacted amine compounds.

2.1.5 Yield Calculation and Reproducibility

Dry the crude product to a constant weight in an IR lamp or a vacuum oven at 40-50 °C. Precisely weigh the final mass on an analytical balance and calculate the molar yield according to the amount of nitro-substituted aryl halide used. Yield data are based on the initial amount of this starting material, and for each condition, at least two parallel experiments were carried out to ensure reproducibility. All of the above experiments were carried out in a well-ventilated chemical fume hood and met the relevant chemical safety requirements.

2.2 Typical Procedure for the Synthesis of HC Yellow 2

In a 50-mL round-bottom flask, 2-chloronitrobenzene (1.58 g, 10 mmol) and ethanolamine (1.22 g, 20 mmol) were dissolved in ethanol. Potassium carbonate (1.38 g, 10 mmol, 1.0 eq.) was added as the base. Mix the two and, at 80 °C, stir for 8 hours. Finish the (TLC monitoring), then cool the reaction mixture to room temperature and dilute it with water (20 mL); filter the precipitate to obtain it. Wash the solid with cold ethanol and dry in a vacuum oven to obtain HC Yellow 2 as an orange-red solid (1.57 g, 86.3% yield), mp 72.0-73.5 °C [4].

2.3 Optimization and Screening Experiments

To determine the best reaction conditions, a series of experiments were conducted on a 10 mmol scale of the nitro-substituted aryl halide with 2 equivalents of ethanolamine (20 mmol), and three factors were systematically varied: (i) the amount of potassium carbonate (0, 0.5 and 1.0 equivalents); (ii) the aryl halide substrate (2-chloronitrobenzene versus 2-bromonitrobenzene); and (iii) the catalyst (none, 10 mol%

ISSN 2616-5880 Vol. 7, Issue 1: 102-107, DOI: 10.25236/AJMC.2026.070114

CuCl, or 10 mol% $Zn(OAc)_2$). Unless otherwise noted, all the reactions were carried out at 80 °C with a magnetic stirrer and observed by TLC. At the end of this process, the product was purified using the standard crystallization workup in Section 2.1.4, and the isolated yield was recorded. The specific conditions and corresponding results are as follows: Table 1.

2.4 Product Characterization

The isolated product was identified by the above methods. Visually observe and record the appearance and colour of an orange-red solid. A WRS-2C capillary melting-point apparatus was used to measure the melting point; it was 72.0-73.5 °C and in line with the data in [4]. Thin-layer chromatography (n-hexane–ethyl acetate 1:4, visualised at 254 nm) of the purified material showed a single major spot, indicating good purity, and the complete disappearance of the starting-material spot showed full conversion. ^{1}H and ^{13}C NMR spectra were recorded on AVANCE III 400 spectrometer.

2.5 Typical Procedure for the Synthesis of HC Yellow 2.

In a 50-mL round-bottom flask, 2-chloronitrobenzene (1.58 g, 10 mmol) and ethanolamine (1.22 g, 20 mmol) were dissolved in ethanol. Potassium carbonate (1.38 g, 10 mmol, 1.0 equiv.) was used as the base. At 80 °C, the mixture was stirred for 8 hours and then increased the temperature. Complete the observation of TLC, then cool the reaction mixture to room temperature and dilute it with water (20 mL), and finally filter to obtain the precipitate. Wash the solid with cold ethanol and dry in a vacuum oven to obtain HC Yellow 2 as an orange-red solid (1.57 g, 86.3% yield), mp 72.0-73.5 °C.[4] ^{1}H NMR (400 MHz, DMSO-*d6*) δ 3.36-3.40 (m, 2H), 3.62-3.66 (m, 2H), 5.09-5.12 (br, 1H), 6.64-6.69 (m, 1H), 7.01-7.05 (m, 1H), 7.48-7.53 (m, 1H), 8.02-8.05 (m, 1H), 8.18-8.21 (br, 1H). ^{13}C NMR (101 MHz, THF) δ, 45.11, 59.47, 115.07, 115.75, 126.62, 131.39, 137.13, 145.86.

3. Results and Discussion

Table 1. Optimisation of the Reaction Conditions for the Synthesis of HC Yellow 2 Dye[a]

Entry	K_2CO_3 (equiv.)	Catalyst (10 mol%)	X	Temp. (°C)	Time (hr)	Yield[b] (%)
1	1		Cl	80	8	86.3
2	0.5		Cl	80	12	80.4
3	0		Cl	80	15	68.7
4	1		Br	80	8	~50[c]
5		CuCl	Cl	80	8	~50[c]
6		$Zn(OAc)_2$	Cl	80	8	65.8

a. All the reactions used 10 mmol of a nitro-substituted aryl halide and 2 equivalents of ethanolamine (20.0 mmol).
b. Isolated yields.
c. Estimated by TLC.

Systematically explore the synthesis of HC Yellow 2 through nucleophilic aromatic substitution (SNAr) reactions of ethanolamine with nitro-substituted aryl halides in this study. The three main factors were potassium carbonate loading, substrate halogen type and transition-metal catalysts. The indices of evaluation were isolated yield, cost and safety for cosmetics.

Effect of K_2CO_3 Addition. 2-Chloronitrobenzene (10 mmol) was used as the electrophile at 80 °C for 8 h, and 1.0 equivalent of K_2CO_3 provided the best results; complete substrate conversion was achieved (TLC, hexane–ethyl acetate 1:4), and after water precipitation, ice-cooling crystallisation and vacuum drying, a yield of 86.3% was obtained for the isolated product. Lowering the base to 0.5 equivalent reduced the yield to 80.4% even after extending the reaction for 12 hours; unreacted starting material was still present in TLC because there was insufficient base to neutralise the generated HCl, leading to the protonation of ethanolamine and suppression of the SNAr equilibrium. Omitting K_2CO_3 entirely (Entry 3) resulted in poor performance; even after 15 h at 80 °C, a significant amount of raw material remained, and raising the temperature to 90 °C for an extra 4 hours caused side reactions (dark impurities on TLC) and dropped the isolated yield to 68.7%. Therefore, stoichiometric carbonate is needed for high-efficiency conversion.

Effect of Substrate Halogen. Under the best-case base condition (1 eq.). K_2CO_3, 80 °C), and replacing

ISSN 2616-5880 Vol. 7, Issue 1: 102-107, DOI: 10.25236/AJMC.2026.070114

2-chloronitrobenzene with equimolar 2-bromonitrobenzene (Entry 4) unexpectedly worsened the result. Bromide is a better leaving group in classical SNAr theory, but the higher reactivity of the C-Br bond led to over-substitution under our mild metal-free conditions. TLC showed many polar by-products (diarylamine over-alkylation products) at various times during the reaction, and the crude product had significant dark viscous impurities. Based on the intensity of TLC spots, the estimated yield was about 50%, and therefore, brominated substrates were not suitable for this low-temperature method.

Effect of Metal Catalysts. At 80°C and 1 eq. K_2CO_3: Add 10 mol% of either CuCl or $Zn(OAc)_2$. CuCl (Entry 5) also showed several impurity spots in TLC that were similar to those of the high-temperature carbonate process; thus, radical-induced oxidation and cross-coupling had occurred. The semi-quantitative yield was about 50%. $Zn(OAc)_2$ (Entry 6) was used to reduce the amount of dark polymeric impurities somewhat and increase the yield to 65.8%, but this was still much lower than in the metal-free system. Both catalysts contain heavy-metal impurities and are therefore unsuitable for cosmetic-grade dyes. Therefore, neither catalyst improved the efficiency under our conditions; instead, they introduced side reactions and safety risks.

Conclusion. The optimal protocol is: 2-Chloronitrobenzene (10 mmol), 1 equivalent of K_2CO_3, no catalyst, 80 °C for 8 h, and HC Yellow 2 was obtained in an isolated yield of 86.3%. This metal-free, mild and economically feasible way does not require high temperatures, produces fewer by-products and avoids heavy-metal contamination, thus being suitable for industrial-scale production.

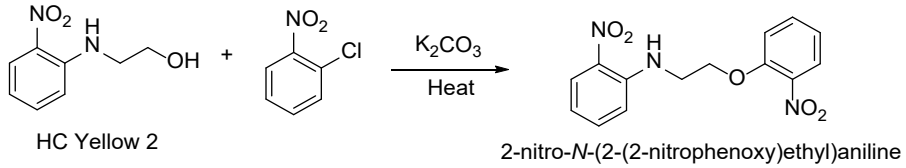

Figure 2. Proposed main side reaction during the synthesis of HC Yellow 2.

The main side reaction was analyzed according to literature reports.[5] As shown in Figure 2, HC Yellow 2 may undergo a further S_NAr substitution with the starting material 2-chloronitrobenzene to generate 2-nitro-N-(2-(2-nitrophenoxy) ethyl) aniline during the reaction. The experiments suggest that this side reaction is not apparent at 80 °C. However, when the reaction temperature exceeds 90 °C or when copper catalysis is used, by-products are clearly generated. Therefore, the relatively optimized conditions are 80 °C for 8 hours using 1 equiv. of potassium carbonate as the base promoter.

4. Conclusion

In this study, we systematically investigated the effect of potassium carbonate dosage (ranging from 0.5 to 2.0 equivalents) and various catalytic systems (including no catalyst, copper(I) chloride alone, zinc acetate alone, and a combination of the two) on the synthesis yield of 2-nitro-N-(2-hydroxyethyl)aniline (HC Yellow 2), and based on these findings, we optimized the reaction temperature and post-treatment crystallization conditions. The experimental results show that when 1 equivalent of potassium carbonate is used as the base and the reaction is carried out at 80 °C, the isolation yield of the target product is highest, reaching 86.3%, and the product purity is good (as verified by TLC and melting point determination).The above optimal conditions cleverly avoid the potassium carbonate-promoted side reactions mentioned in the literature at high temperatures (160 °C); otherwise, high temperatures would lead to the denitration of the product or degradation of the hydroxyethyl side chain, significantly reducing the yield. Cuprous chloride or zinc acetate were added as catalysts in contrast, but neither alone nor in combination with others increased the yield; instead, in some experiments, a darkening of the product colour or an increase in impurity spots was observed. It is believed that this may be due to metal-ion-induced radical side reactions or competition for coordination with ethanolamine, thereby disrupting the SNAr reaction pathway. In addition, an excess of potassium carbonate (e.g., 2 equivalents) is also detrimental to the reaction; this may be due to too strong a base that promotes the secondary decomposition of the product, and therefore, precise control over the quantity of base must be maintained. The above results confirm that potassium carbonate can be used to promote the SNAr reaction without a metal catalyst, and it has also been found that a low temperature (80 °C) and an equal amount of base are necessary to balance the speed of the reaction with the stability of the product. The results of this study provide reliable data support for the green and efficient synthesis of HC Yellow 2, and offer an excellent process route for industrial application; that is to say, it can avoid heavy-metal catalyst residues and reduce energy consumption and post-treatment steps. Future work may further explore other organic

ISSN 2616-5880 Vol. 7, Issue 1: 102-107, DOI: 10.25236/AJMC.2026.070114

bases or phase-transfer catalysts to achieve higher yields at lower temperatures.

References

[1] Corbett, J. F. An Historical Review of the Use of Dye Precursors in the Formulation of Commercial Oxidation Hair Dyes. Dyes Pigm. 1999, 41, 127–136.
[2] Lutamyo Nambela, Liberato Venant Haule, Quintino Mgani, A review on source, chemistry, green synthesis and application of textile colorants, Journal of Cleaner Production, 2020, 246, 119036.
[3] Fernandes, B.; Cavaco-Paulo, A.; Matamá, T. A Comprehensive Review of Mammalian Pigmentation: Paving the Way for Innovative Hair Colour-Changing Cosmetics. Biology 2023, 12, 290.
[4] He, L.; Michailidou, F.; Gahlon, H. L.; Zeng, W. Hair Dye Ingredients and Potential Health Risks from Exposure to Hair Dyeing. Chem. Res. Toxicol. 2022, 35, 901–915.
[5] McManus, J. M.; Herbst, R. M. Tetra- and Pentacyclic Benzimidazole Compounds as Analogs of Some Indole Alkaloids. J. Org. Chem. 1959, 24, 1042–1044.
[6] Rezaeivala, M.; Keypour, H.; Tamizi, S.; Fatemikia, H.; Alkorta, I.; Ferrer, M.; Gable, R. W. Synthesis and Characterization of Two Novel Fused Macrocyclic Ligands: Experimental and Theoretical Studies. J. Mol. Struct. 2023, 1290, 135936.
[7] Venkatesan, G.; Dancik, D. Y.; Sinha, A.; Bigliardi, M.; Srinivas, R.; Dawson, T.; Valiyaveettil, S.; Bigliardi, P.; Pastorin, G. Facile Synthesis of Oligo Anilines as Permanent Hair Dyes: How Chemical Modifications Impart Colour and Avoid Toxicity. New J. Chem. 2019, 43, 16188–16199.
[8] Westerheide, L.; Müller, F. K.; Than, R.; Krebs, B.; Dietrich, J.; Schindler, S. Syntheses and Structural Characterization of Dinuclear and Tetranuclear Iron(III) Complexes with Dinucleating Ligands and Their Reactions with Hydrogen Peroxide. Inorg. Chem. 2001, 40, 1951–1961.
[9] Cui, H.; Xie, W.; Hua, Z.; Cao, L.; Xiong, Z.; Tang, Y.; Yuan, Z. Recent Advancements in Natural Plant Colorants Used for Hair Dye Applications: A Review. Molecules *2022,* 27*, 8062.*
[10] Martínez, J.; Cortés, J.F.; Miranda, R. Green Chemistry Metrics, A Review. Processes *2022,* 10*, 1274.*
[11] Diego López-Carballeira, Tomáš Polcar, Computational selection of singlet fission colorants, Computational and Theoretical Chemistry, Volume 1229,2023,114343.
[12] Juliana M. Prado, Priscilla C. Veggi, Grazielle Náthia-Neves, M. Angela A. Meireles, Extraction Methods for Obtaining Natural Blue Colorants, Current Analytical Chemistry; 2020, 16, 5.
[13] Greif M., Maibach H.I., United States cosmetic ingredient labeling, Contact Dermatitis; 1977, 3, 94–97.
[14] P.S.F. Ramalho, O.S.G.P. Soares, J.L. Figueiredo, M.F.R. Pereira, Catalytic reduction of NO over copper supported on activated carbon, Catalysis Today, 2023, 418, 114044, 0920-5861.
[15] Gallardo-Garrido C., Cho Y., Cortés-Rios J., Vasquez D., Pessoa-Mahana C.D., Araya-Maturana R., Pessoa-Mahana H., Faundez M., Nitrofuran drugs beyond redox cycling: Evidence of Nitroreduction-independent cytotoxicity mechanism, Toxicology and Applied Pharmacology; 2020, 401, 115104.