The development of Friedländer hetero-annulation through a single electron transfer and energy transfer pathway using methylene blue (MB⁺)

Farzaneh Mohamadpour

The radical Friedländer hetero-annulation of 2-aminoaryl ketone and -methylene carbonyl compound was used to develop a green tandem approach for the metal-free synthesis of polysubstituted quinolines. At room temperature in an ethanol solvent, photo-excited state functions generated from MB⁺ were used as single-electron transfer (SET) and energy transfer (EnT) catalysts, utilizing visible light as a renewable energy source in the air atmosphere. The purpose of this research is to increase the use of a nonmetal cationic dye that is both inexpensive and widely available. High yields, energy-effectiveness, high atom economy, time-saving features of the reaction, and operational simplicity, and the least amount of a catalyst are the benefits of this study. As a result, a wide range of ecological and long-term chemical properties are obtained. Polysubstituted quinolines’ turnover number (TON) and turnover frequency (TOF) have been calculated. Surprisingly, such cyclization can be accomplished on a gram scale, indicating that the process has industrial potential.

The use of photo-redox catalysts in organic synthesis for the formation of C–C and C–heteroatom bonds via a single-electron transfer (SET)/photo-induced electron transfer (PET) pathway has increased dramatically in recent years. They are essential in a wide range of procedures, from small to large-scale. Various flow reactors1 utilizing visible light and dual photosensitized electrochemical processes2 have been created as a result of technological advancements, resulting in more affordable, green, and efficient reactions. MB⁺ is a cationic dye in the thiazine dye class. MB⁺ has a singlet lifetime of τ₁ ~ 1.0 ns, as well as an absorbance of near 650–670 nm (668 nm) and a molar absorbance (ε = 94,000)3,4. The triplet 3MB⁺* is a significantly more stable excited state5, with a triplet lifespan of τ₃ ~ 32 μs5,6. (More content and discussions about photoredox cycle catalyzed by dye7 have been added to the supporting information file).

Furthermore, because visible light irradiation has enormous energy reserves, lower prices, and renewable energy sources, green chemists consider it a dependable method for environmentally friendly organic chemical synthesis8–10. As visible light sources, compact fluorescent bulbs and light-emitting diodes are commonly used in many conversions.

The structures that make up quinolines have piqued the interest of biochemists and synthetic organic chemists due to their biological and pharmacological actions (Fig. 1). Quinolines have been described in the scientific literature as inhibit acetylcholinesterase11, butyrycholinesterase family of enzymes12, antifilarial13, antiparasitic14, tyrosine kinase inhibitory agents15, HMG-CoA reductase inhibiting16, antitubercular17, antifungals18,19, antihypertensive20,21, antiallergic, antiinflamatory22–24, antibacterial25–28, antimalarial29,30, anticancer30–33, antiproliferative34 and antiasthmatic35,36. Quinoline nucleus can also be found in a variety of natural products37–39. Numerous strategies are available, including DSIMHS40, Zn(OTf)₂41, NiO NPs42, Zr(NO₃)₄43, I₂44, PEG-bound sulfonic acid45, trifluoroacetic acid46, propylsulfonic silica47, HClO₃SiO₂48, Chitosan-SO₃H49, oxalic acid50, Ag₃PW₁₂O₄51, ImBuSO₃H52, MNP@PEG-ImHSO₄53. Metal catalyst limitations, expensive reagents, harsh reaction conditions, monotonous unacceptable yields, environmental risks, workup processes, and long reaction times have all resulted from these methods. Furthermore, it is difficult to separate a homogeneous catalyst from the reaction mixture.

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We’ve been attracted by the hunt for easy, efficient, and environmentally acceptable techniques to synthesizing biologically active chemicals utilizing photocatalysts because of the aforementioned problems and our concern for environmentally favorable operations. Given prior and ongoing attempts to manufacture polysubstituted quinolines, it’s critical to investigate environmentally friendly photocatalysts in green environments to ensure that these heterocyclic compounds are properly synthesized. This research focuses on the utilization of MB⁺, a metal-free cationic dye photo-redox catalyst, in the aforementioned photochemical synthesizing technique. Finally, a green tandem strategy for the metal-free synthesis of polysubstituted quinolines was developed using the radical Friedländer hetero-annulation of 2-aminoaryl ketone and -methylene carbonyl molecule. Photo-excited state functions produced from MB⁺ as single-electron transfer (SET) and energy transfer (EnT) catalysts were employed at room temperature in an ethanol solvent, exploiting visible light as a renewable energy source in the air atmosphere. The goal of this study is to increase the usage of an inexpensive and widely available nonmetal cationic dye. The benefits of this study include excellent yields, energy efficiency, high atom economy, time-saving aspects of the reaction, operational simplicity, and the use of the least amount of a catalyst. Furthermore, the use of organic solvents under reflux conditions, as well as the need for column chromatography to purify the products, is a source of environmental pollution. The products were produced with simple filtration and recrystallization with ethanol in this study, with no need for column chromatographic separation. Surprisingly, gram-scale cyclization is possible, indicating that the technique has industrial potential. This is a successful one-pot reaction that was carried out in a very efficient, cost-effective, and simple manner.

Figure 1. Compounds with biologically active quinolines rings.
**Experimental General.** All substances’ physical properties are determined using electrothermal 9100 equipment. On a Bruker (DRX-300) device, the spectra (1HNMR) were also recorded using nuclear magnetic resonance with CDCl₃ as the solvent. We purchased the reagents in bulk from the chemical companies Fluka, Merck, and Acros and used them exactly as they were.

*General procedure for preparation of polysubstituted quinolines (3a–r).* MB⁺ (1 mol%) was added to a mixture of 2-aminoaryl ketone (1, 1.0 mmol) and -methylene carbonyl compound (2, 1.5 mmol) in EtOH (3 mL) and stirred at room temperature under white LED (12 W) irradiation. TLC was used to monitor the reaction’s progress, with n-hexane/ethyl acetate as the eluent (3:2). Following the reaction, the resulting material was screened and washed with water, and the crude solid was crystallized again from ethanol to produce the pure substance without further purification. Even if we could produce the aforementioned compounds using gram scale methods, we wanted to see if we could scale up to the level required for pharmaceutical process R&D. In one experiment, 50 mmol 2-aminobenzophenone was mixed with 75 mmol acetylacetone. The large-scale reaction went off without a hitch and finished in just 6 min, with the product collected using simple filtration, rinse with water and then recrystallize with ethanol. This material’s 1HNMR spectrum indicates that it is spectroscopically pure.

After comparing spectroscopic data, the commodities were classified. After comparing spectroscopic data, the commodities were classified (1HNMR).

1-(2-Methyl-4-phenylquinolin-3-yl)ethanone (3k).

![Structure of 3k](image)

Yield: 94%; M.p. 110–112 °C; 1HNMR (300 MHz, CDCl₃): 2.03 (3H, s, CH₃), 2.65 (3H, s, CH₃), 7.39–7.46 (6H, m, ArH), 7.53 (1H, d, J = 7.2 Hz, ArH), 7.64–7.66 (1H, t, J = 7.2 Hz, ArH), 8.02 (1H, d, J = 8.4 Hz, ArH).

1-(6-Chloro-2-methyl-4-phenylquinolin-3-yl)ethanone (3l).

![Structure of 3l](image)

Yield: 97%; M.p. 152–154 °C; 1HNMR (300 MHz, CDCl₃): 2.01 (3H, s, CH₃), 2.69 (3H, s, CH₃), 7.36–7.41 (2H, m, ArH), 7.50–7.59 (5H, m, ArH), 8.04 (1H, d, J = 8.4 Hz, ArH).

**Results and discussion**

To begin, the reaction of 2-aminobenzophenone (1.0 mmol) and dimedone (1.5 mmol) in EtOH (3 mL) at room temperature was studied under LED irradiation. There was a trace of 3a at rt in 3 mL EtOH for 40 min with no photocatalysts (Table 1, entry 1). Methylene blue, erythrosin B, acenaphthenequinone, rhodamine B, alizarin, riboflavin, Na₂ eosin Y, xanthene, rose Bengal, phenanthrenequinone, 9H-xanthen-9-one (Fig. 2) were all tested in identical conditions to promote the reaction. This reaction progressed in 55–94% yields while achieving the acceptable matched product 3a (Table 1). According to the findings, methylene blue fared better in such a response. The yield was increased to 94% by using 1 mol% MB⁺ (Table 1, entry 4). THF, toluene, DMSO and DMF all had lower product yields, as shown in Table 2. In H₂O, H₂O/EtOH (1:1), MeOH, EtOAc, CH₃CN, and solvent-free conditions, the reaction rate and yield were increased. The reaction was carried out in EtOH at an excellent yield and rate. Under identical conditions, a yield of 94% was obtained, as shown in Table 2 (entry 2). Different light sources were used to screen the yield, demonstrating the effect of white light (Table 2). There was a minuscule of 3a without using the light source, according to the test control. According to the findings, visible light and MB⁺ are required for the successful synthesis of product 3a. Furthermore, the improved settings were determined by illuminating white LEDs of varying intensities (10, 12, and 18 W). The best results, according to the researchers, were obtained when white LED (12 W) were used (Table 2, entry 2). A wide range of substrates were investigated under the right conditions (Table 3 and Fig. 3). It is worth noting that the methylene carbonyl compounds had no effect on the reaction's outcome (Table 3). The reaction patterns of 2-aminobenzophenone and 5-chloro-2-aminobenzophenone were comparable (Table 3). Table 4 also includes turnover number (TON) and frequency of turnover information (TOF). The greater the TON and TOF numerical values, the less catalyst
is used and the greater the yield, and the catalyst becomes more effective as the value increases. $^1$HNMR data of some of known products has also been compared to literature (Table S1). (In the supporting information file, Table S1 has been added.)

Figure 4 denotes the preferred mechanism. Photoexcited modes derived from methylene blue can act as a single-electron transfer (SET) and energy transfer (EnT) catalyst. The ground-state MB and the intermediate (A) are regenerated by an electron transfer (ET) between the MB radical and the -methylene carbonyl compound (2). A reactive intermediate (B) is formed when this radical anion (A) is nucleophilically added to 2-aminoaryl ketone (1). A single-electron transfer (SET) mechanism promotes the production of the cation radical (C) by visible light-triggered $^*$MB$^+$. The dehydrated cyclized is then added for a total of 3.

Table 5 compares the catalytic capability of various catalysts discussed in this literature for the synthesis of polysubstitutedquinolines. It could have a variety of applications, including the use of a small amount of photocatalyst, a fast reaction time, and the absence of by-products when exposed to visible light. The atom-economic protocol is extremely successful at multigram scales and has significant industrial implications. These materials stand out in terms of efficiency and purity.

**Conclusion**

The photo-excited state functions generated by MB$^+$ can be used to metal-free manufacture polysubstitutedquinolines via radical Friedländer hetero-annulation of 2-aminoaryl ketone and -methylene carbonyl compound via a single-electron transfer (SET)/energy transfer (EnT) method, according to the findings. This procedure employs visible light as a renewable energy source in an EtOH solvent and air atmosphere at room temperature. The use of the least amount of catalyst, excellent yields, an efficient side of the reaction, secure reaction conditions, a renewable energy source, and a quick procedure without the use of toxic solvents or catalysts are the most noticeable features of this green protocol. No chromatographic purification was required. According to a multigram scale reaction of model substrates, this reaction can be scaled up without compromising the outcome. As a result, this process provides additional benefits in terms of meeting industrial requirements and addressing environmental concerns.
Figure 2. In this study, photocatalysts were put to the test.
Table 2. Table of solvent and visible light optimization for 3a synthesis. Reaction conditions: 2-aminobenzophenone (1.0 mmol) and dimedone (1.5 mmol) were added to MB+ at room temperature (1 mol%). Significant values are in bold.
Using photoexcited MB⁺ as a catalyst, this photocatalyst produces polysubstituted quinolines.

| R₁ NH₂ | O | Ph |   | R² | O | N | R³ |
|-------|---|----|---|----|---|---|----|
| 1     |   |    |   |    |    |   |    |
| 2     |   |    |   |    |    |   |    |

| MB⁺ (1 mol%) | White LED (12 W) | EtOH, rt | Air atmosphere | 3a-r |
|--------------|------------------|----------|----------------|------|

Table 3. Using photoexcited MB⁺ as a catalyst, this photocatalyst produces polysubstituted quinolines.

Figure 3. Polysubstituted quinoline synthesis.
Table 4. Calculated turnover number (TON) and turnover frequency (TOF).

| Entry | Product | TON  | TOF | Entry | Product | TON  | TOF |
|-------|---------|------|-----|-------|---------|------|-----|
| 1     | 3a      | 94   | 13.4| 10    | 3j      | 97   | 13.8|
| 2     | 3b      | 92   | 13.1| 11    | 3k      | 94   | 15.6|
| 3     | 3c      | 97   | 19.4| 12    | 3l      | 97   | 13.8|
| 4     | 3d      | 96   | 19.2| 13    | 3m      | 92   | 10.2|
| 5     | 3e      | 93   | 18.6| 14    | 3n      | 90   | 9   |
| 6     | 3f      | 96   | 13.7| 15    | 3o      | 93   | 15.5|
| 7     | 3g      | 95   | 13.5| 16    | 3p      | 94   | 15.6|
| 8     | 3h      | 93   | 13.2| 17    | 3q      | 95   | 19 |
| 9     | 3i      | 96   | 13.7| 18    | 3r      | 93   | 18.6|

Figure 4. A mechanistic method for producing polysubstituted quinolines has been proposed.
| Entry | Compound | Catalyst | Conditions | Time/yield (%) | References |
|-------|----------|----------|------------|---------------|------------|
| 1     | ![Compound Image] | DSIMHS | Solvent-free, 70 °C | 25 min/89 | 40 |
| 2     | ![Compound Image] | Zn(OtF)₂ | Solvent-free, MW | 5 min/86 | 41 |
| 3     | ![Compound Image] | NiO NPs | EtOH, Reflux | 2.5 h/94 | 42 |
| 4     | ![Compound Image] | Zr(NO₃)₄ | H₂O, Reflux | 30 min/98 | 43 |
| 5     | ![Compound Image] | Trifluoroacetic acid | Solvent-free, 100 °C | 15 min/92 | 44 |
| 6     | ![Compound Image] | MB⁺ | Visible light irradiation, EtOH, rt | 7 min/94 | This research |
| 7     | ![Compound Image] | DSIMHS | Solvent-free, 70 °C | 40 min/90 | 40 |
| 8     | ![Compound Image] | Zn(OtF)₂ | Solvent-free, MW | 5 min/88 | 41 |
| 9     | ![Compound Image] | NiO NPs | EtOH, Reflux | 2 h/93 | 42 |
| 10    | ![Compound Image] | Zr(NO₃)₄ | H₂O, Reflux | 25 min/98 | 43 |
| 11    | ![Compound Image] | Trifluoroacetic acid | Solvent-free, 100 °C | 15 min/95 | 44 |
| 12    | ![Compound Image] | MB⁺ | Visible light irradiation, EtOH, rt | 7 min/92 | This research |

Table 5. Comparison of the catalytic ability of some of the catalysts in the manuscript to produce 3a, 3b. Reaction conditions: 2-aminobenzophenone/5-chloro-2-aminobenzophenone and dimedone.

Data availability
All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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References
1. Politano, F & Oksdath-Mansilla, G. Light on the horizon: Current research and future perspectives in flow photochemistry. Org. Process Res. Dev. 22, 1045–1062 (2018).
2. Verschueren, R. H. & De Borggraeve, W. M. Electrochemistry and photoredox catalysis: A comparative evaluation in organic synthesis. Molecules 24, 2122 (2019).
3. Romero, N. A. & Nicewicz, D. A. Organic photoredox catalysis. Chem. Rev. 116, 10075–10166 (2016).
4. Whang, T. J., Huang, H. Y., Hsieh, M. T. & Chen, J. J. Laser-induced silver nanoparticles on titanium oxide for photocatalytic degradation of methylene blue. Int. J. Mol. Sci. 10, 4707–4718 (2009).
5. Patel, R. L., Sharma, A., Sharma, S. & Sharma, A. Visible light-mediated applications of methylene blue in organic synthesis. Org. Chem. Front. 8, 1694–1718 (2021).
6. Pitt, S. P., McTriernan, C. D. & Sciano, J. C. Understanding the kinetics and spectroscopy of photoredox catalysis and transition-metal-free alternatives. Acc. Chem. Res. 49(49), 1320–1330 (2016).
7. Miyabe, H. Organic reactions promoted by metal-free organic dyes under visible light irradiation. In Visible-Light Photocatalysis of Carbon-Based Materials (IntechOpen, 2017).
8. Mohamadpour, F. Visible light irradiation promoted catalyst-free and solvent-free synthesis of pyrano [2,3-d] pyrimidine scaffolds at room temperature. J. Saudi Chem. Soc. 24, 636–641 (2020).
9. Mohamadpour, F. Catalyst-free and solvent-free visible light irradiation-assisted Knoevenagel-Michael cyclocondensation of aryl aldehydes, malononitrile, and resorcinol at room temperature. Monatshefte für Chemie-Chem. Mon. 152, 507–512 (2021).
10. Mohamadpour, F. Catalyst-free, visible light irradiation promoted synthesis of spiroacenaphthylenes and 1H-pyrazolo[1,2-b] phthalazine-5,10-diones in aqueous ethyl lactate. J. Photochem. Photobiol. A 407, 113041 (2021).
11. Heilbronn, E. D. Inhibition of cholinesterases by tetrahydroaminacrin. Acta Chem. Scand. 15, 1386–1390 (1961).
12. Maayani, S., Weinstein, H., Ben-Zvi, N., Cohen, S. & Sokolovsky, M. Psychotomimetics as anticholinergic agents—I: 1-Cyclohexylpiperidine derivatives: Anticholinesterase activity and antagonistic activity to acetylcholine. Biochem. Pharmacol. 23, 1263–1281 (1974).
13. Srivastava, S. K., Chauhan, P. M., Bharduri, A. P., Fatima, N. & Chatterjee, R. K. Quinolones: Novel probes in antifilarial chemotherapy. J. Med. Chem. 43, 2275–2279 (2000).
14. Muscia, G. C., Bollini, M., Carnevale, J. P., Bruno, A. M. & Asis, S. E. Microwave-assisted Friedländer synthesis of quinolines of the synthesis of fungal cell wall polymers. Bioorg. Med. Chem. 11, 1531–1550 (2003).
15. Singh, M., Singh, M. P. & Ablordepey, S. In vitro studies with liposomal cryptolepine. Drug Dev. Ind. Pharm. 22, 377–381 (1996).
20. Ebiou, M. et al. Pharmacologic profiles of GA0113, a novel quinoline derivative angstogenins II AT1-receptor antagonist. *J. Cardiovasc. Pharmacol.* 34, 526–532 (1999).

21. Murugananthan, N., Sivakumar, R., Anbalagan, N., Gunasekaran, V. & Leonard, J. T. Synthesis, anticonvulsant and antihypertensive activities of 8-substituted quinoline derivatives. *Biol. Pharm. Bull.* 27, 1683–1687 (2004).

22. Roma, G., Di Braccio, M., Grossi, G., Mattioli, F. & Ghia, M. 1, 8-Naphthyridines IV. 9-Substituted N, N-dialkyl-5-alkylamino or cycloalkylamino)[1,2,4] triazolo [4,3-a][1,8] naphthyridine-6-carboxamides, new compounds with anti-aggressive and potent anti-inflammatory activities. *Eur. J. Med. Chem.* 35, 1021–35 (2000).

23. Savini, L., Chiasserini, L., Pellerano, C., Filippelli, W. & Falcone, G. Synthesis and pharmacological activity of 1,2,4-triazolo [4,3-a] quinolines. *Il Farmaco.* 56, 939–945 (2001).

24. Johnson, J. V., Rauckman, B. S., Baccanari, D. P. & Roth, B. 2, 4-Diamino-5-benzylpyrimidines and analogs as antibacterial agents. *J. Med. Chem.* 32, 1942–9 (1989).

25. Chen, Y. L., Fang, K. C., Sheu, J. Y., Hsu, S. L. & Tseng, C. C. Synthesis and anti-inflammatory activities of 8-substituted quinoline derivatives. *J. Med. Chem.* 44, 2374–2377 (2001).

26. Sadana, A. K., Mirza, Y., Aneja, K. R. & Prakash, O. Hypervalent iodine mediated synthesis of 1-aryl[1H]tetrazol-1,4-diamino-5-benzylpyrimidines and analogs as antibacterial agents. *Eur. J. Med. Chem.* 38, 533–536 (2003).

27. Kidwai, M., Bhushan, K. R., Sapra, P., Saxena, R. K. & Gupta, R. Alumina-supported synthesis of antibacterial quinolines using microwaves. *Bioorg. Med. Chem.* 8, 69–72 (2000).

28. Kayiree, M. G. et al. Synthesis and antibacterial activity of new 4-alkoxy-4-aminopyrimidine and 4-alkylthiopyrimidines. *Eur. J. Med. Chem.* 33, 55–63 (1998).

29. Billker, O. et al. Identification of xanthurenic acid as the putative inducer of malaria development in the mosquito. *Nature* 392, 289–292 (1998).

30. Perezna, A. et al. New benzo [5,6] pyrazolino [1,2-b] quinolines as cytotoxic agents. *Bioorg. Med. Chem. Lett.* 14, 2363–2365 (2004).

31. Lamazet, C. et al. Expeditious synthesis and cytotoxic activity of new cyanindolo [3,2-c] quinolines and benzimidazo [1,2-c] quinozinelines. *Bioorg. Med. Chem. Lett.* 10, 2183–2185 (2000).

32. Kaczmarek, Ł. et al. Synthesis and cytotoxic activity of some novel indolo [2,3-b] quinoline derivatives: DNA topoisomerase II inhibitors. *Bioorg. Med. Chem.* 7, 2457–2464 (1999).

33. Martirosyan, A. R. et al. Differentiation-inducing quinolines as experimental breast cancer agents in the MCF-7 human breast cancer cell model. *Biochem. Pharmacol.* 65, 1729–1738 (2004).

34. Kolokythas, G., Pouli, N., Marakos, P., Pratsinis, H. & Kletsas, D. Design, synthesis and antiproliferative activity of some new azapyranoxanthene aminoderivatives. *Eur. J. Med. Chem.* 41, 71–79 (2006).

35. Heitsch, H. Non-peptide antagonists and agonists of the bradykinin B2 receptor. *Curr. Med. Chem.* 9, 913–928 (2002).

36. Dubé, D. et al. Quinolines as potent 5-lipoxygenase inhibitors: Synthesis and biological profile of L-746,530. *Bioorg. Med. Chem. Lett.* 8, 1255–1260 (1998).

37. Ma, Z. Z., Hano, Y., Nomura, T. & Chen, Y. J. Two new pyrroloquinazolinoquinoline alkaloids from *Peganum nigellastrum*. *Heterocycles* 46, 541–6 (1997).

38. Ma, Z. Z., Hano, Y., Nomura, T. & Chen, Y. J. Alkaloids and phenylpropanoids from *Peganum nigellastrum*. *Phytochemistry* 53, 1075–1078 (2000).

39. Mak, Z. Z., Hano, Y., Nomura, T. & Chen, Y. J. Two new quinazoline-quinoline alkaloids from *Peganum nigellastrum*. *Heterocycles* 46, 1883–1889 (1999).

40. Shirini, F., Yahyazadeh, A., Mohammadi, K. & Kahligh, N. G. Solvent-free synthesis of quinoline derivatives via the Friedländer reaction using 1, 3-disulfonic acid imidazolium hydrogen sulfate as an efficient and recyclable liquid ion catalyst. *C. R. Chim.* 17, 370–376 (2014).

41. Lekhok, K. C., Bhuyan, D., Prajapati, D. & Boruah, R. C. Zinc trflate: A highly efficient reusable catalyst in the synthesis of functionalized quinolines via Friedlander annulation. *Mol. Divers.* 14, 841–846 (2010).

42. Reddy, B. P., Inyavaran, P., Sarveswari, S. & Vijayakumar, V. Nickel oxide nanoparticles catalyzed synthesis of poly-substituted quinolines via Friedlander hetero-annulation reaction. *Chin. Chem. Lett.* 25, 1595–1600 (2014).

43. Zoliğol, M. A., Salehi, P., Ghaderi, A. & Shiri, M. A. Catalytic and green procedure for Friedlander quinoline synthesis in aqueous media. *Catal. Commun.* 8, 1214–1218 (2007).

44. Wu, J., Xia, H. G. & Gao, K. Molecular iodine: A highly efficient catalyst in the synthesis of quinolines via Friedländer annulation. *Org. Biomol. Chem.* 4, 126–129 (2006).

45. Zhang, X. L., Wang, Q. Y., Sheng, S. R., Wang, Q. & Liu, X. L. Efficient Friedländer Synthesis of quinoline derivatives from 2-aminoaryketones and carbonyl compounds mediated by recyclable PEG-supported sulfonic acid. *Synth. Commun.* 39, 3293–3304 (2009).

46. Shaaban, A., Soleimani, E. & Badri, Z. Trifluoroacetic acid as an efficient catalyst for the synthesis of quinoline. *Synth. Commun.* 37, 629–635 (2007).

47. Garella, D. et al. Fast, solvent-free, microwave-promoted Friedländer annulation with a reusable solid catalyst. *Synth. Commun.* 40, 120–128 (2009).

48. Narasimhulu, M. et al. Silica supported perchloric acid: A mild and highly efficient heterogeneous catalyst for the synthesis of poly-substituted quinolines via Friedländer hetero-annulation. *J. Mol. Catal. A* 266, 114–117 (2007).

49. Reddy, B. S., Venkateswarlu, A., Reddy, G. N. & Reddy, Y. R. Chitosan-SO3H: An efficient, biodegradable, and recyclable solid acid functionalized liquid acid as dual solvent-catalyst. *Polycycl. Aromat. Compd.* 40, 1223–1237 (2020).

50. Fallah-Mehrjardi, M., Karimi, A. M. & Banita, S. H. Binding of polyethylene glycol imidazolium hydrogen sulfate to magnetic nanoparticles and its application as a novel recyclable solid acid catalyst in the Friedländer synthesis of quinolines under solvent-free conditions. *Polycycl. Aromat. Compd.* https://doi.org/10.1080/10406046.2019.1786416 (2020).

51. Mohamadpour, F. New role for photoexcited organic dye, Na2 eosin Y via the direct hydrogen atom transfer (HAT) process in photochemical visible-light-induced synthesis of spiroacenaphthenylines and 1H-pyrazolo[1,2-b]phenazine-5,10-diones under air atmosphere. *Dyes Pigments* 194, 109628 (2021).

52. Mohamadpour, F. A new role for photoexcited Na2 eosin Y as direct hydrogen atom transfer (HAT) photocatalyst in photochemical synthesis of dihydroxynaphtho[2,3-c]pyrazole scaffolds promoted by visible light irradiation under air atmosphere. *J. Photochem. Photobiol. A* 418, 113428 (2021).
56. Mohamadpour, F. Photoexcited Na₂ eosin Y as direct hydrogen atom transfer (HAT) photocatalyst promoted photochemical metal-free synthesis of tetrahydrobenzo[b]pyran scaffolds via visible light-mediated under air atmosphere. J. Taiwan Inst. Chem. Eng. 129, 52–63 (2021).
57. Friedlaender, P. Ueber o-Amidobenzaldehyd. Ber. Dtsch. Chem. Ges. 15, 2572–2575 (1882).

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