Volume 14, Issue 1, 142406 (1-8)

Iranian Journal of Catalysis (IJC)

https://doi.org/10.57647/j.ijc.2024.1401.06

Cascades synthesis of N-aryl oxindole nitrone derivatives using isatine oximes and arylboronic acids catalyzed by copper acetate under mild conditions

Rita S. Adam*

Department of Engineering of Environmental and Pollution Technology, Engineering Technical college, Southern Technical University, Basra, Iraq.

***Corresponding author:** dr.ritaadam@stu.edu.iq

Original Research

Received:
08 January 2024
Revised:
20 Febuary 2024
Accepted:
02 March 2024
Published online:
30 March 2024

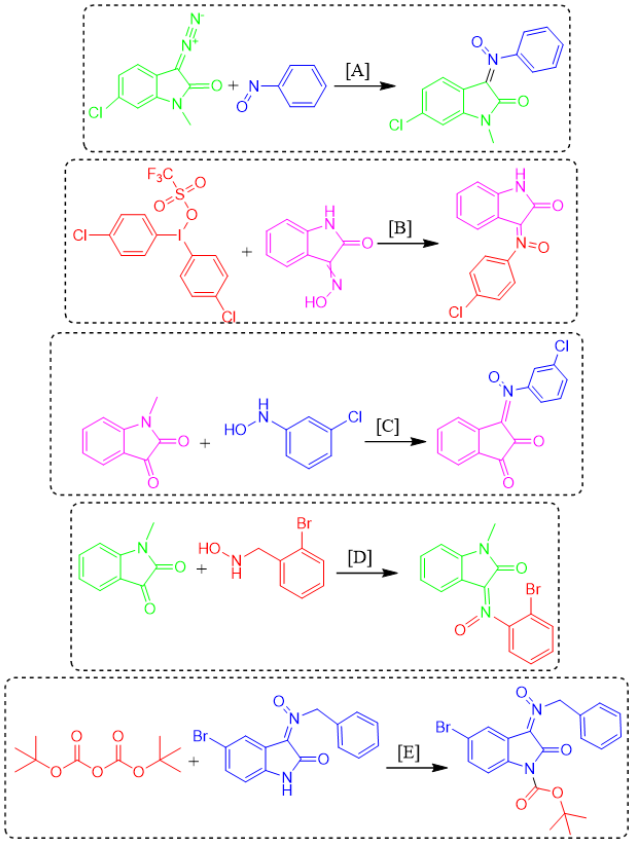
Abstract:

Cu-catalysis was employed to create numerous (E)-5-bromo-N-aryl oxindole nitrones with satisfactory to excellent coupling efficiencies. This process involved the reaction of N-unprotected 5-bromoisatin-3-oximes with aryl-boronic acids under moderately reactive conditions. Remarkably, the reaction exhibited tolerance towards various aryl-boronic acids containing diverse functional sensitivity subgroups (73% to 97% yields and 2 to 6 h). Extensive research has demonstrated that the (C=O) group present in 5-bromoisatin-3-oximes can serve as an inhibitory molecule or ligand, playing a crucial role in the generation of (E) oxindole nitrones.

Keywords: Synthesis; Copper acetate; Catalyst; Nitrones; Cascade reaction; Isatin

1. Introduction

Nitrones are readily available compounds and extremely valuable substrates for targeted organic synthesis. Nitrones, which act as potent intermediates in organic synthesis, have found widespread application in the development of synthetic methodologies for the production of biologically active compounds and natural products. Numerous refined samples have been extended to prepare nitrones from several starting compounds (Scheme 1). The obtained nitrones are extremely valuable for synthesizing nitrogen compounds that are biologically significant [1–7]. In addition, the synthesis of nitrones are categorized into four classes: 1) Oxidation reaction including oxidation of N-R-alpha-amino acids, N,N-disubstituted NH_2OH, Secondary amines, Isoxazolidines, and Imines; 2) Reaction of monosubstituted NH_2OH including reactions with aldehydes, ketones, allenes, acetylene, and alkenes; 3) Reaction of oximes; and 4) Other methods including from aryloxaziridines, nitro compounds, N-hydroxylamides, and nitroso compounds (Fig. 1). Nitrones exhibit distinctive characteristics that demonstrate essential transformation reactions, encompassing interactions with radicals, or nucleophiles, functionalization of carbon-hydrogen bonds, and various cyclo-addition reactions. Selective carbon-carbon bond formations are of utmost importance in organic syntheses because of their remarkable capacity to take place in a diastereo- and enantioselective manner. These reactions hold significant importance in various organic synthesis processes. Nitrones offer several advantages over imines due to their ease of handling, inherent stability, wide availability, and rapid reactivity. Several approaches have been documented for the synthesis of N-Aryl Oxindole Nitrone Derivatives using various strategies involving nitroso compounds. These methodologies were as follows a) a reaction with electron-deficient alkynes catalyzed by gold [13], b) a reaction with diazooxindoles promoted by silica gel, without the use of solvents [8], c) a reaction catalyzed by proline involving α,β-unsaturated aldehydes at the γ-position [14], a reaction facilitated by proline with benzaldehydes [15], and a reac-



Scheme 1. The General approach for the providing of N-aryl-isatin keto-nitrones a) Silicagel, solvent-free, 10 h, 60°C, 90% [8]. b) Stage 1: KOH in methanol. 0.083 h, 25°, Stage 2: methanol, 25°, 90% [9]. c) Trifluoroacetic acid, 1,2-Dichloroethane, Molecular sieve, inert atmosphere, 99% [10], d) Acetic acid, 20°C, methanol, 86% [11]. e) dmap in chloromethane, 2 h, 0-20°C, inert atmosphere, 83% [12].

tion involving the coupling of N-nosylhydrazones [16]. In modern synthetic chemistry, the oxidative cross-coupling reaction has emerged as a valuable technique for constructing C–C or C–X (heteroatom) bonds [17–21]. In addition, different metallic catalysts such as Li_2CO_3 [22]; metal-free [9]; copper (II) bromide [11]; $Yb(NTf_2)_3$ [10]; silica-gel [8]; and etc. [23–25] were used for the synthesis of oxindole nitrone derivatives. Herein, we reported the synthesis of several (E)-5-bromo-N-aryl oxindole nitrones using copper acetate as a catalyst from the reaction of arylboronic acid and N-unprotected-5-bromoisatin-3-oximes (Scheme 2).

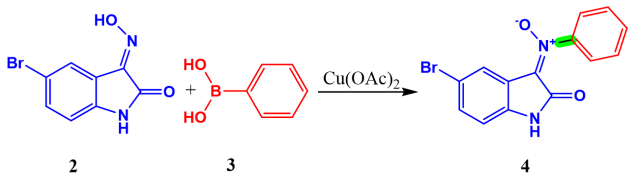
2. Experimental

2.1 General

The collection of proton NMR spectroscopic data was carried out in $CDCl_3$ at a frequency of 300 MHz, with $(CH_3)_4Si$ (tetramethylsilane) TMS serving as the internal standard. All reactions were conducted under atmospheric conditions. The proton NMR data is reported in terms of chemical shift (ppm), and multiplicity (d: doublet, s: singlet, t: triplet, m: multiplet, q: quartet,). For the aryl-boronic acids, we sourced them from Sigma-Aldrich, and a well-documented technique was followed to synthesize the unique compound.

2.2 The General approach for the synthesis of (E)-5-bromo-3-(hydroxyimino)indolin-2-one (2)

The reaction mixture containing 5-bromo-1H-indole-2,3-dione (8.3 mmol) (1), NH_2OH (8.4 mmol), K_2CO_3 (9.1 mmol), and 40 mL of methanol was heated under reflux at a low temperature during 3 h. Afterward, it was allowed to decrease temperature to room temperature overnight. Once the (E)-5-bromo-3-(hydroxyimino)indolin-2-one reached



Scheme 2. Production of (E)-5-bromo-N-aryl oxindole nitrone derivatives using copper acetate.

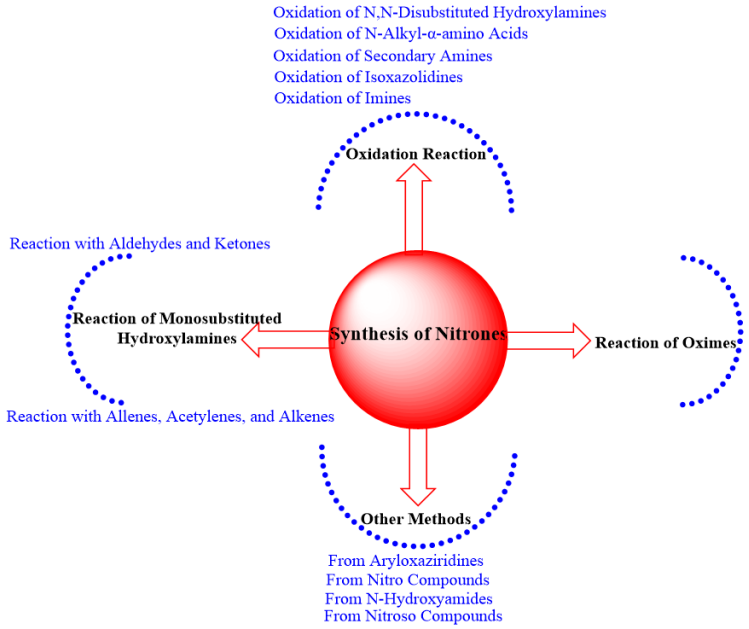


Figure 1. Different aspects of the synthesis of nitrones.

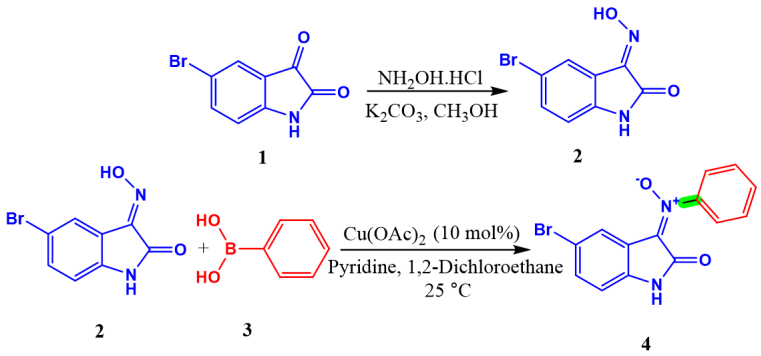
25°C, it was extracted using 30× 5 mL of dichloromethane. The organic phase was then isolated and dehydrated using anhydrous MgSO4. The solvent was evaporated at a lower temperature below 20°C, and the resulting crucial product was transferred to column chromatography using a mixture of ethyl acetate and n-hexane in a ratio of 1:3 (v/v) to separate the isomers. 1H NMR (300 MHz, $CDCl_3$) = 13.57 (s, 1H), 10.77 (s, 1H), 8.04 (s, 1H), 7.44 (d, J = 8.1 Hz, 1H), 6.77 (d, J = 8.1 Hz, 1H), 97% yield, yellow solid powder.

2.3 The General approach for the synthesis of (E)-5-bromo-2-oxo-N-phenylindolin-3-imine oxide derivatives (4)

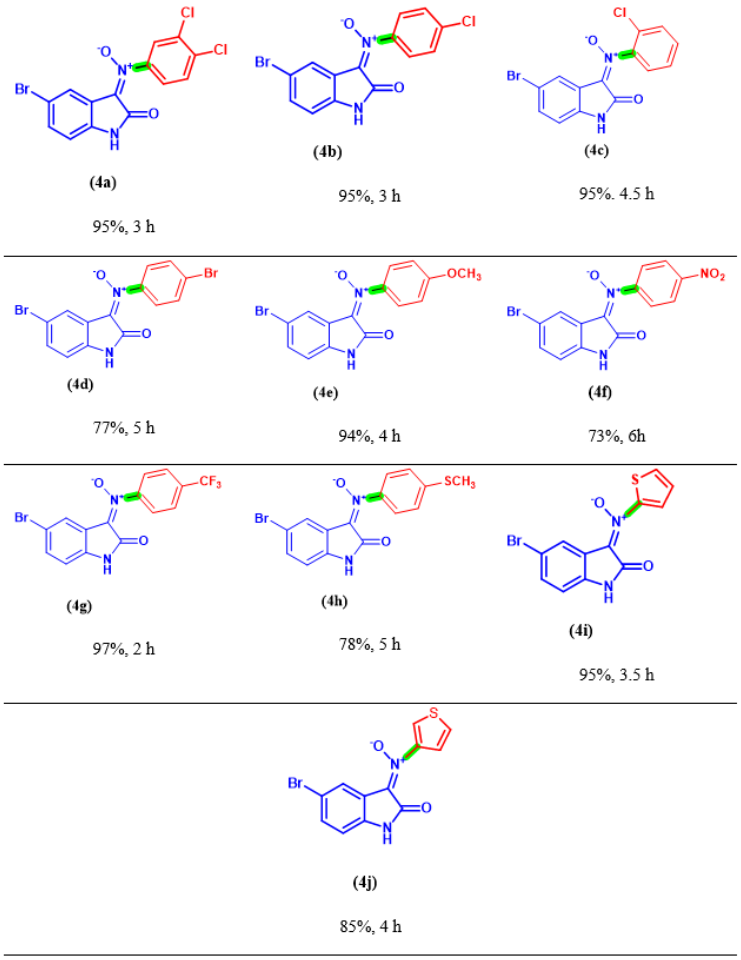
Following the addition of 0.3 mmol of (E)-5-bromo-3-(hydroxyimino)indolin-2-one (2) and 0.45 mmol of arylboronic acid (3) to a 25 mL flask, 3.0 mL of dichloroethane and 0.9 mmol of pyridine were injected into the flask in the presence of air. Subsequently, 0.03 mmol of $Cu(OAc)_2$ (10 mol%) was introduced. The oxime 2 was completely consumed by heating the reaction mixture at 25°C with vigorous stirring for an appropriate time, following the puncturing of the septum with a ventilation needle. The reaction was turned off by adding 10 mL of water, and the resulting liquid was subjected to 3 extractions to remove dichloroethane. Na_2SO_4 was employed to dehydrate the filtered organic mixture. Upon evaporation of the solvent under vacuum, (E)-5-bromo-2-oxo-N-phenylindolin-3-imine oxide derivatives (4) were obtained, which were subsequently purified using flash chromatography with an eluent mixture of petroleum ether and ethyl acetate, ranging from a ratio of 1:10 to 1:6.

2.4 Spectroscopic information of synthesized compounds

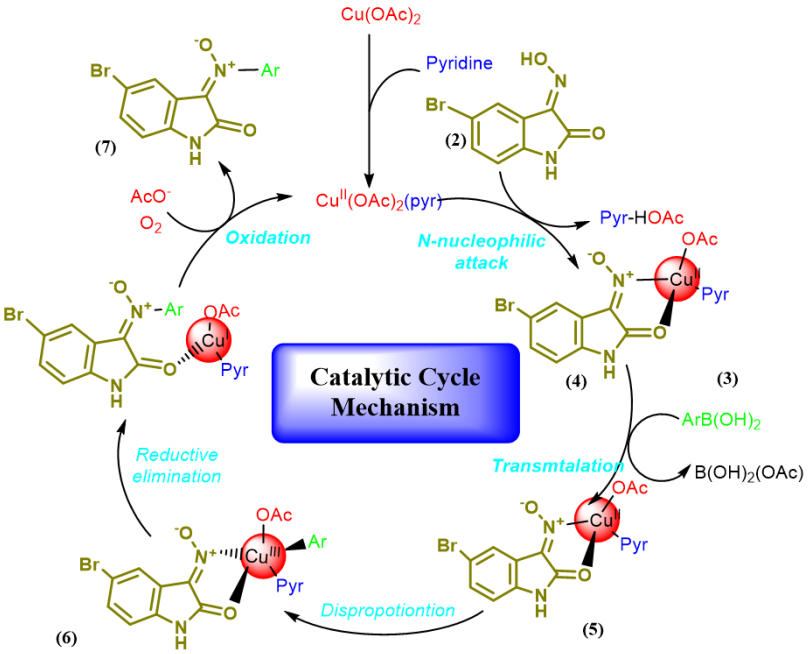
(E)-5-bromo-N-(3,4-dichlorophenyl)-2-oxo-indolin-3-imine-Oxide (4a): Solid orange (95%); m.p. 205–206°C. 1H - NMR (300 MHz, $CDCl_3$): δ = 10.76 (s, 1 H), 8.10 (m, 2 H), 8.16 (d, 1 H), 7.55 (d, 1 H), 7.64 (dd, 1 H), 7.55 (d 1 H) 7.50 (dd, 1 H) ppm. ^{13}C - NMR (125 MHz, $CDCl_3$): δ =165.07, 146.55, 141.95, 137.67, 135.60, 132.47, 132.24,131.32,126.58, 124.02, 123.56, 121.92, 118.86, 114.3 ppm.



Scheme 3. Synthesis of (E)-5-bromo-2-oxo-N-phenylindolin-3-imine oxide derivatives using $Cu(OAc)_2$.

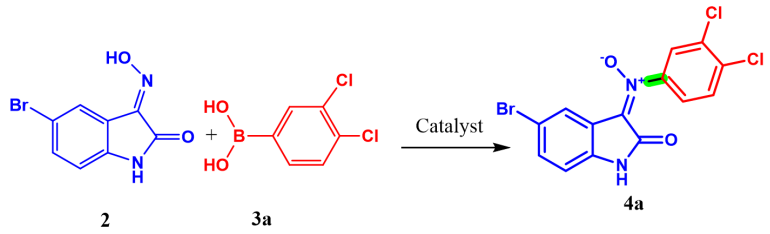


Scheme 4. Synthesis of (E)-5-bromo-2-oxo-N-phenylindolin-3-imine oxide derivatives.



Scheme 5. Plausible mechanism of the reaction.

Table 1. Optimization reaction conditions for 4a[a].



2 **3a** **4a**

Entry	Catalyst	Amount of catalyst (mol%)	Solvent	T (°C)	Molar ration (2):(3)	Base	Yield (%)[b]
1	$Cu(OAc)_2$	10	H_2O	25	1:1	Pyridine	35
2	$Cu(OAc)_2$	10	$CHCl_3$	25	1:1	Pyridine	40
3	$Cu(OAc)_2$	10	CH_2Cl_2	25	1:1	Pyridine	50
4	$Cu(OAc)_2$	10	DCEc	25	1:1	Pyridine	65
5	$Cu(OAc)_2$	10	EtOH	25	1:1	Pyridine	40
6	$Cu(OAc)_2$	10	CH_3CN	25	1:1	Pyridine	50
7	$Cu(OAc)_2$	10	DCE	45	1:1	Pyridine	65
8	$Cu(OAc)_2$	10	DCE	25	1:1.25	Pyridine	80
9	$Cu(OAc)_2$	10	DCE	25	1:1.5	Pyridine	95
10	$Cu(OAc)_2$	10	DCE	25	1:1.75	Pyridine	93
11	$Co(OAc)_2$	10	DCE	25	1:1.5	Pyridine	60
12	$Fe(OAc)_2$	10	DCE	25	1:1.5	Pyridine	60
13	$Cu(OAc)_2$	5	DCE	25	1:1.5	Pyridine	80
14	$Cu(OAc)_2$	15	DCE	25	1:1.5	Pyridine	90
15	$Cu(OAc)_2$	10	DCE	25	1:1.5	Et_3N	68
16	No catalyst	-	DCE	25	1:1.5	Pyridine	–

a) General reaction conditions: compound (2): 0.3 mmol, compound (3a): 0.45 mmol, Solvent: 3 mL, 4 h.
b) Isolated yield.
c) 1,2-dichloroethane (DCE).

(E)-5-bromo-N-(4-chlorophenyl)-2-oxo-indolin-3-imine-Oxide (4b): Solid yellow (95%); m.p. 182–183°C. ^{1}H - NMR (300 MHz, CDCl$_3$): δ = 10.72 (s, 1 H), 8.9 (m, J = 8.1 Hz, 3 H), 7.51 (m, J =7.5 Hz, 3 H), 7.64 (dd,1 H) ppm. ^{13}C - NMR (125 MHz, CDCl$_3$): δ = 164.79, 145.9, 141.92, 138.11, 135.19, 132.25, 130.01(d), 125.77(d), 124.08, 121.91, 118.87,114.27 ppm.

(E)-5-bromo-N-(2-chlorophenyl)-2-oxo-indolin-3-imine Oxide (4c): Solid yellow (95%); m.p. 195–196°C. ^{1}H - NMR (300 MHz, CDCl$_3$): δ = 10.76 (s, 1 H), 8.10 (dd, 1H), 8.0 (m,1H), 7.99 (d, 1H),7.49-7.51 (m, 3H), 7.64 (d, 1 H) ppm. ^{13}C- NMR (125 MHz, CDCl$_3$): δ = 164.86, 147.16, 141.9, 135.00, 132.33, 132.21, 130.95, 127.99, 127.78,126.29,124.1,121.53,114.29,118.87 ppm.

(E)-5-bromo-N-(4-bromophenyl)-2-oxoindolin-3-imine Oxide (4d): Solid yellow (77%); m.p. 182–183°C. ^{1}H NMR (300 MHz, CDCl$_3$): δ = 10.67 (s, 1 H), 8.08 (m,3H) 7.61-7.65 (m, J = 7.63 Hz, 3 H), 7.5 (dd, 1 H), ppm. ^{13}C NMR (125 MHz, CDCl$_3$): δ= 164.79, 146.63, 141.92, 138.11, 132.81(d), 132.25, 125.41, 125.41, 125.06, 124.08, 121.91, 118.87, 114.27 ppm.

(E)-5-bromo-N-(4-Methoxyphenyl)-2-oxo-indolin-3-imine Oxide (4e): Solid yellow (94%); m.p. 177–179°C. ^{1}H-NMR (300 MHz, CDCl−3): δ = 10.72 (s, 1 H), 8.09 (m, 3 H), 7.64(dd, 1 H), 7.50 (dd, 1 H), 7.05 m, 2 H), 3.78 (s, 3 H) ppm. ^{13}C- NMR (125 MHz, CDCl$_3$): δ = 164.79, 163.58, 141.10, 141.92, 138.11, 132.25, 132.25, 125.92, 124.08, 121.94, 118.87, 114.27, 113.67, 55.35 ppm.

(E)-5-bromo-N-(4-nitro phenyl)-2-oxo-indolin-3-imine Oxide (4f): Brown solid (73%); m.p. 144 –143°C. ^{1}H-NMR (300 MHz, CDCl−3): δ = 10.67 (s, 1H), 8.38 (m, 2H), 8.31 (m, 2 H) ,7.64 (dd,1H), 7.50 (dd, 1 H) ppm. ^{13}C - NMR (125 MHz, CDCl$_3$): δ = 164.82, 153.34, 150.48, 141.92, 138.11, 132.25, 125.37, 125.37, 125.29, 125.29, 124.08, 121.95, 118.78 , 114.27 ppm.

(E)-5-bromo-2-oxo-N-((4-triflouromethyl) phenyl) indolin-3-imine oxide (4g): Yellow Solid (97%); m.p. 236–237°C. ^{1}H- NMR (300 MHz, CDCl−3): δ = 10.75 (s, 1 H), 8.10 (m, 3 H), 7.61 (m,3 H), 7.50 (dd, 1 H), 6.80 (d, 1 H) ppm. ^{13}C- NMR (125 MHz, CDCl$_3$): δ = 164.78, 145.21, 141.91, 138.98, 136.78, 126.92, 126.92, 125.07, 125.07, 125.07, 125.07, 125.07, 125.07, 125.07, 124.66 123.24, 114.60, 113.96 ppm.

(E)-5-bromo-N-[4-(Methylthio)phenyl]-2-oxo-indolin-3-imine oxide (4h): Yellow Solid (78 %); m.p. 188 –190°C. ^{1}H- NMR (300 MHz, CDCl$_3$): δ = 10.75 (s, 1 H), 8.10 (dd, 1 H), 8.04 (m, 2 H), 7.64 (dd, 1 H), 7.50 (m, 1 H), 7.39 (m, 2 H), 2.5(s, 3 H) ppm. ^{13}C- NMR (125 - MHz, CDCl−3): δ = 164.79, 145.20, 141.92, 140.28, 138.11, 132.25, 127.15, 124.08, 124.24, 121.91, 118.87, 114.27, 15.52 ppm.

(E)-5-bromo-2-oxo-N- (thiophen-2-yl) indolin-3-imine oxide (4i): Yellow Solid (95%); m.p. 215–216°C. ^{1}H -NMR (300 MHz, CDCl$_3$): δ = 10.76 (s, 1 H), 8.10 (dd, 1 H), 7.80 (dd, 1 H), 7.64 (dd, 1 H), 7.53 (m, 1 H), 7.49 (m, 1 H), 7.23 (dd, 1H) ppm.^{13}C-NMR (125MHz, CDCl$_3$): δ =165.06, 149.88, 141.91, 136.38, 135.20, 132.25, 127.66, 125.77, 124.14, 121.74, 118.81, 114.27 ppm.

(E)-5-bromo-2-oxo-N-(thiophen-3-yl) indolin-3-imine oxide (4j): Solid yellow (85%); m.p. 165–166°C. ^{1}H- NMR (300 MHz, CDCl$_3$): δ = 10.76 (s, 1 H), 8.36 (t, 1 H), 8.10 (dd,

1 H), 7.73 (dd, 1 H), 7.64 (m, 2 H), 7.5 (dd, 1 H), ppm. ^{13}C- NMR (125 MHz, $CDCl_3$): δ = 165.3, 143.39, 141.93, 137.94, 133.10, 132.3, 130.29, 124.16, 123.28, 122.84, 118.9, 114.27 ppm.

3. Result and discussion

In order to produce (E)-5-bromo-2-oxo-N-phenylindolin-3-imine oxide derivatives (4) by $Cu(OAc)_2$, the reaction of arylboronic acid (3) and N-unprotected-5-bromoisatin-3-oximes (2) was performed (Scheme 3). For optimization of the reaction conditions, we conducted the synthesis of (E)-5-bromo-N-(3,4-dichlorophenyl)-2-oxo-indolin-3-imine-Oxide (4a) as a representative example by reacting arylboronic acid (3) with N-unprotected-5-bromoisatin-3-oximes (2). The obtained results were shown in Table 1. Initially, (E)-5-bromo-3-(hydroxyimino)indolin-2-one (2), and 3,4-dichlorophenylboronic acid (3a) were selected as a model reaction for the investigation of some important parameters including type of the catalyst, amount of the catalyst, type of the solvent, the temperature of the reaction, the molar ratio of the substrates, and type of base or acid scavenger. First, the model reaction was checked using several solvents including water, chloroform, 1,2-dichloroethane (DCE), dichloromethane, ethanol, and acetonitrile (Table 1, entries 1-6). These experiments displayed that the DCE was the best solvent for this reaction. Also, the reaction temperature was investigated and the obtained results showed that the room temperature was the best temperature for the performance of the model reaction (Table 1, entry 7). In addition, the molar ratio of the starting materials was investigated and our experiments show that the optimum molar ratio was 1:1.5 for compound (2), and compound (3a) (Table 1, entries 8-10). Furthermore, another factor was type of the catalyst such as cobalt acetate, and iron acetate (Table 1, entries 11, and 12). These tests revealed that copper acetate was the best catalyst for this reaction. In continuation of the optimization of the reaction conditions, the quantity of the catalyst was checked (Table 1, entries 13, and 14). The best amount of the catalyst was 10 mol% based on the compound (2). In addition, the type of the base was also checked and pyridine was the best base for the model reaction (Table 1, entry 15). Finally, to show the efficiency of the presence of the copper acetate, the model reaction was conducted under catalyst-free conditions. But after a long time of the reaction, no desired product was obtained (Table 1, entry 16).

After optimized reaction conditions, the generality and scope of the preparation of (E)-5-bromo-2-oxo-N-phenylindolin-3-imine oxide derivatives were checked using the reaction of arylboronic acid (3) and N-unprotected-5-bromoisatin-3-oximes (2) by copper acetate in DCE as solvent (Scheme 4). Furthermore, the impact of electron-withdrawing and electron-donating groups on the phenylboronic acid derivatives was assessed. However, it was observed that these groups had no significant influence, either positive or negative, on the reaction yield and duration. A proposed mechanism for the Cu-catalyzed coupling of substrates 2 and 3 (Scheme 5) has been put forward [26–30]. In this mechanism, the nitrogen atom in an n-oxide link within compound 2 undergoes nucleophilic addition to the pyridine molecule, resulting in the formation of a nitrone. This nitrone shares a similar property with the (Z) and (E) chalcone oxime isomers. The carbonyl group within the nitrone acts as a ligand, interacting with the Cu species to stabilize intermediate 4. Through trans-metalation with arylboronic acid 3, intermediate 4 is converted into intermediate 5. Subsequently, oxidation of intermediate 5 using oxygen leads to the formation of copper III species 6. The reductive elimination of intermediate 6 releases the CuI species, resulting in the formation of N-aryl-isatin keto-nitrone 7. Finally, in the presence of oxygen, CuI is oxidized to Cu II, thereby completing the catalytic cycle [31].

4. Conclusion

We have developed a method to produce (E)-N-aryl-isatin keto-nitrones by combining isatin oximes with aryl-boronic acids using copper catalysts under mild conditions. The carbonyl functional group in oximes can act as a ligand to control the relative nucleophilicity of O and N, facilitating the synthesis of the required (E)-nitrones. This approach allows for the utilization of a wide range of substrates, exhibits good tolerance towards functional groups, and enables the use of readily available materials. Consequently, this technique is highly suitable for the large-scale synthesis of N-unprotected N-aryl-isatin keto-nitrones.

Acknowledgment
Financial support from the University of Basra is greatly appreciated.

Ethical Approval
This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval does not applicable.

Availability of Data and Materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests
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.

References

[1] LL Anderson. "Diverse applications of nitrones for the synthesis of heterocyclic compounds.". *Asian J. Org. Chem*, **5**:9–30, 2016. DOI: https://doi.org/10.1002/ajoc.201500211.

[2] WM Shi, XP Ma, GF Su, and DL Mo. "New developments of ketonitrones in organic synthesis.". *Org. Chem. Front*, **3**:116–130, 2016. DOI: https://doi.org/10.1039/C5QO00122F.

[3] DB Huple, S Ghorpade, and RS Liu. "Recent advances in gold-catalyzed N-and O-functionalizations of alkynes with nitrones, nitroso, nitro and nitroxy species.". *Adv. Synth. Catal*, **358**:1348–1367, 2016. DOI: https://doi.org/10.1002/adsc.201600018.

[4] J Yang. "Recent developments in nitrone chemistry: some novel transformations.". *Synlett*, **23**:2293–2297, 2012. DOI: https://doi.org/10.1055/s-0032-1317096.

[5] M Chiacchio, SV Giofre, R Romeo, G Romeo, and U Chiacchio. "Isoxazolidines as biologically active compounds.". *Curr. Org. Synth*, **13**:726–749, 2016.

[6] H Pellissier. "Asymmetric 1, 3-dipolar cycloadditions, tetrahedron.". *Advances in Colloid and Interface Science*, **63**:3235–3285, 2007. DOI: https://doi.org/10.1016/j.tet.2007.01.009.

[7] KR Braun, TH Freysoldt, and F Wierschem. "1, 3-Dipolar cycloaddition on solid supports: nitrone approach towards isoxazolidines and isoxazolines and subsequent transformations.". *Chem. Soc. Rev*, **34**:507–516, 2005. DOI: https://doi.org/10.1039/B311200B.

[8] YH Zhang, MY Wu, and WC Huang. "Silica gel-promoted practical synthesis of oxindole–nitrones from diazooxindoles and nitrosoarenes under solvent-free conditions.". *RSC Adv*, **5**:105825–105828, 2015. DOI: https://doi.org/10.1039/C5RA21874H.

[9] SY Wu, XP Ma, C Liang, and DL Mo. "Synthesis of N-aryl oxindole nitrones through a metal-free selective N-arylation process.". *J. Org. Chem*, **82**:3232–3238, 2017. DOI: https://doi.org/10.1021/acs.joc.6b02774.

[10] HB Yang and M Shi. "Yb(NTf2)3-catalyzed [3 + 3] cycloaddition between isatin ketonitrones and cyclopropanes to construct novel spiro[tetrahydro-1,2-oxazine]oxindoles.". *Org. Biomol. Chem*, **10**:8236–8243, 2012. DOI: https://doi.org/10.1039/C2OB26413G.

[11] YR Chen, G Zhan, W Du, and YC Chen. "Regioselective asymmetric formal (32) cycloadditions of nitrone ylides from isatins and enals.". *Adv. Synth. Catal*, **358**:3759–3764, 2016. DOI: https://doi.org/10.1002/adsc.201600805.

[12] G Zhan, ML Shi, WJ Lin, Q Ouyang, W Du, and YC Chen. "Direct asymmetric aza-vinylogous-type michael additions of nitrones from isatins to nitroalkenes.". *Chem. A Europ. J*, **23**:6286–6289, 2017. DOI: https://doi.org/10.1002/chem.201701290.

[13] RR Singh and RS Liu. "Gold-catalyzed 1,2-iminonitronation of electron-deficient alkynes with nitrosoarenes to afford α-imidoyl nitrones.". *Chem. Commun*, **50**:15864–15866, 2014. DOI: https://doi.org/10.1039/C4CC06962E.

[14] AJ Fraboni and SE Brenner-Moyer. "Dienamine-catalyzed nitrone formation via redox reaction.". *Org. Lett*, **18**:2146–2149, 2017. DOI: https://doi.org/10.1021/acs.orglett.6b00770.

[15] M Choi, M Viji, D Kim, YH Lee, J Sim, YS Kwak, K Lee, H Lee, and JK Jung. " Metal-free approach for the L-proline mediated synthesis of nitrones from nitrosobenzene.". *Tetrahedron*, **74**:4182–4187, 2018. DOI: https://doi.org/10.1016/j.tet.2018.06.001.

[16] T Liu, Z Liu, Z Liu, D Hu, and Y Wang. "Coupling of N-nosylhydrazones with nitrosoarenes: transition-metal-free approach to (z)-N-arylnitrones.". *Synthesis*, **50**:1728–1736, 2018. DOI: https://doi.org/10.1055/s-0036-1591757.

[17] XP M, WM Shi, XL Mo, XH Lia, LG Li, CX Pan, B Chen, GF Su, and DL Mo. "Synthesis of α, β-unsaturated N-aryl ketonitrones from oximes and diaryliodonium salts: Observation of a metal-free N-arylation process.". *J. Org. Chem*, **80**:10098–10107, 2015. DOI: https://doi.org/10.1021/acs.joc.5b01716.

[18] D Kontokosta, DS Mueller, DL Mo, WH Pace, RA Simpson, and LL Anderson. "Copper-mediated synthesis of N-alkenyl-α, β-unsaturated nitrones and their conversion to tri and tetrasubstituted pyridines.". *Beilstein J. Org. Chem*, **11**:2097–2104, 2015. DOI: https://doi.org/10.3762/bjoc.11.226.

[19] DL Mo, DA Wink, and LL Anderson. "Preparation and rearrangement of N-vinyl nitrones: synthesis of spiroisoxazolines and fluorene-tethered isoxazoles.". *Org. Lett*, **14**:5180–5183, 2012. DOI: https://doi.org/10.1021/ol3022885.

[20] I Nakamura, M Okamoto, Y Sato, and M Terada. "Synthesis of azepine derivatives by rhodium-catalyzed tandem 2, 3-rearrangement/heterocyclization, angew.". *Chem*, **124**:10974–10977, 2012. DOI: https://doi.org/10.1002/ange.201205285.

[21] I Nakamura, T Onuma, R Kanazawa, Y Nishigai, and M Terada. "Efficient synthesis of N-alkylated α,β-unsaturated ketonitrones via Cu-catalyzed rearrangement.". *Org. Lett*, **16**:4198–4200, 2014. DOI: https://doi.org/10.1021/ol501889g.

[22] Y Jung, JE Hong, JH Kwak, and Y Park. "Single-step approach toward nitrones via pyridinium ylides: The DMAP-catalyzed reaction of benzyl halides with nitrosoarenes.". *J. Org. Chem*, **86**:6343–6350, 2021. DOI: https://doi.org/10.1021/acs.joc.1c00158.

[23] JJ David, AMM Stephen, RS Robin, SL Sebastian, J Palanichamy, and P Kalivel. "Comparative study on the electrocatalytic activity of dissimilar electrode combinations for the treatment of textile effluent by electrocoagulation process and their subsequent reuse.". *Iran. J. Catal*, **3**:341–358, 2023. DOI: https://doi.org/ijc.2023.1991117.2022.

[24] E Fadavipoor and R Badri. "Imidazolium hydrogen sulphate supported on copper oxide nanoparticles as an efficient simple heterogeneous acidic catalyst for multi-component synthesis of 1, 4- dihydro Pyrano [2, 3-c] pyrazoles derivatives.". *Iran. J. Catal*, **2**:165–174, 2021.

[25] AO Moghanlou, M Pourshahi, S Atabak, and NM Tarighi. "The use of recyclable magnetic nanocatalyst $Fe3O4@SiO_2$-$(CH_2)_3$-Pyridine-2-(1H)-tetrazole-Cu(II) in the synthesis of bis-coumarin derivatives under green conditions.". *Iran. J. Catal*, **2**:187–199, 2023. DOI: https://doi.org/10.30495/ijc.2023.1982870.2000.

[26] PF Larsson, CJ Wallentin, and PO Norrby. "Mechanistic aspects of sybmol.". *ChemCatChem*, **6**:1277–1282, 2014. DOI: https://doi.org/10.1002/cctc.201301088.

[27] AS Reddy, KR Reddy, DN Rao, CK Jaladanki, PV Bharatam, PY Lam, and P Das. "Copper (ii)-catalyzed Chan-Lam cross-coupling: chemoselective N-arylation of aminophenols.". *Org. Biomol. Chem*, **15**:801–806, 2017. DOI: https://doi.org/10.1039/C6OB02444K.

[28] KA Kumar, P Kannaboina, CK Jaladanki, PV Bharatam, and P Das. "Copper-catalyzed N-arylation of tautomerizable heterocycles with boronic acids and its application to synthesis of oxygenated carbazoles.". *ChemistrySelect*, **1**:601–607, 2016. DOI: https://doi.org/10.1002/slct.201600147.

[29] AE King, TC Brunold, and SS Stahl. " Mechanistic study of copper-catalyzed aerobic oxidative coupling of arylboronic esters and methanol: insights into an organometallic oxidase reaction.". *J. Am. Chem. Soc*, **131**:5044–5045, 2009. DOI: https://doi.org/10.1021/ja9006657.

[30] AE King, BL Ryland, TC Brunold, and SS Stahl. "Kinetic and spectroscopic studies of aerobic copper (II)-catalyzed methoxylation of arylboronic esters and insights into aryl transmetalation to copper (II).". *Organometallics*, **31**:7948–7957, 2012. DOI: https://doi.org/10.1021/om300586p.

[31] VH Duparc, GL Bano, and F Schaper. "Chan–evans–lam couplings with copper iminoarylsulfonate complexes: scope and mechanism.". *ACS Catal*, **8**:7308–7325, 2018. DOI: https://doi.org/10.1021/acscatal.8b01881.