

RAPID COMMUNICATION

Rapid, efficient and eco-friendly procedure for the synthesis of quinoxalines under solvent-free conditions using sulfated polyborate as a recyclable catalyst

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Abstract. An efficient and inexpensive sulfated polyborate catalyst was applied for the rapid synthesis of quinoxaline derivatives from various substituted *o*-phenylenediamines and 1,2-diketones/ α -hydroxy ketones using sulfated polyborate is described. The catalyst has the advantage of Lewis as well as Bronsted acidity and recyclability without significant loss in catalytic activity. The key advantages of the present method are high yields, short reaction times, solvent-free condition, easy workup, and ability to tolerate a variety of functional groups, which give economical as well as ecological rewards.

Keywords. Sulfated polyborate; *o*-phenylenediamines; 1,2-diketone; α -hydroxy ketones; quinoxaline.

1. Introduction

The importance of quinoxaline and its derivatives has been reported in the literature.¹ Quinoxaline derivatives are valuable for their wide spectrum of biological activities *viz* antiviral,² anticancer,² antibacterial,³ antidepressant,⁴ antiameobic,⁵ anticonvulsant,⁶ antimalarial,⁷ anti-inflammatory-antioxidant,⁸ antiprotozoal activity,⁹ and activity as kinase inhibitors.¹⁰ They are basic scaffolds for various insecticides, herbicides, and fungicides.³ In addition, several antibiotics such as actinomycin, echinomycin, levomycin and triostins bear quinoxaline nucleus.¹¹ Quinoxaline moiety is also part of bioactive natural products like Izumiphenazine-C.¹² Other applications of quinoxaline as fluorescent dyes,¹³ electroluminescent materials,¹⁴ organic semiconductors,¹⁵ cavitands,¹⁶ DNA cleaving agents¹ have been reported. Because of such a widespread applications of quinoxaline compounds in medicinal as well as industrial fields, it remains an attractive target for an organic chemist to develop new synthetic methods for the preparation of quinoxaline derivatives.

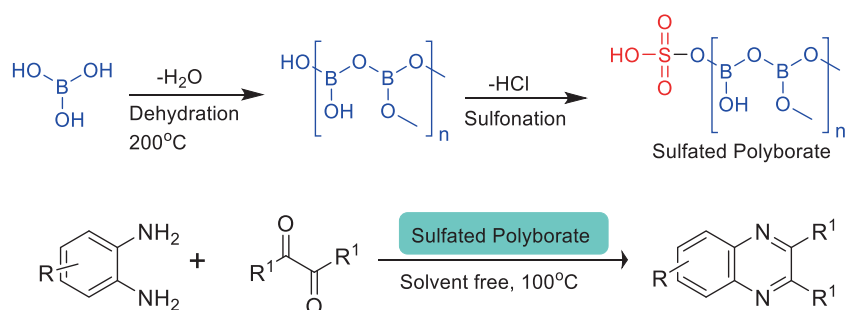
The most common methods for the synthesis of quinoxaline is condensation of aromatic 1,2-diamines with 1,2-dicarbonyl compounds in refluxing ethanol or acetic acid for 2–12 h with 34–85% yields.¹⁷ Over the years, various improved methods have been developed using grinding,¹⁸ microwave,¹⁹ sonication,²⁰ ball mill

heating,²¹ catalytic and reagent systems. Many catalysts and reagents have also been reported such as sulfamic acid,²² CuSO₄·5H₂O,²³ amidosulfonic acid,²⁴ polyaniline sulfate,²⁵ *p*-TSA,²⁶ ionic liquid (Hbim)BF₄,²⁷ Mn octahedral molecular sieves,²⁸ Ga(OTf)₃,²⁹ Montmorillonite K-10,³⁰ Keggin-type heteropolyacids (H₄SiW₁₂O₄₀),³¹ Amberlyte-15,³² SnCl₂,³³ SnCl₂/SiO₂,³⁴ Zr(DS)₄,³⁵ ZrO₂ mixed metal oxide,³⁶ iodine,³⁷ silica bonded S-sulfonic acid,³⁸ silica supported SbCl₃,³⁹ Zn[(L)proline],⁴⁰ etc. Recently, many new improved methods were also reported using silica gel,⁴¹ alumina,⁴² Sm(OTf)₂,⁴³ KHSO₄,⁴⁴ silica sulfuric acid in PEG,⁴⁵ glycerol,⁴⁶ CeCl₃·7H₂O in glycerin,⁴⁷ triethylamine/O₂,⁴⁸ FeCl₃/morpholine,⁴⁹ Ga(ClO₄)₃,⁵⁰ *p*-TSA/H₂O,⁵¹ graphite,⁵² sulfated TiO₂,⁵³ and PEG-400.⁵⁴

Furthermore, many of these methods have some synthetic advantages individually, but still suffer from one or more limitations, such as the use of toxic organic solvents, long reaction times, requiring anhydrous conditions, use of expensive or corrosive reagents, strong acids, strong oxidants, and toxic or expensive catalysts, harsh reaction conditions, tedious workup and most importantly unsatisfactory yields. Thus, development of a safe, environmentally benign, mild, efficient, and high yielding rapid reaction procedure using cost effective and recyclable catalyst for the preparation of quinoxalines is desirable.

A literature search revealed that boric acid catalyzes many important organic transformations at a temperature above 100°C.^{55–57} Boric acid dehydrates

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Scheme 1. Schematic representation of sulfated polyborate catalyzed quinoxaline synthesis.

above 100°C and converts to its polymeric forms, which presumably are the active species catalyzing the reaction.^{58,59} Dehydrative polymerization liberates water molecules which may hamper the progress of the reactions. This inspired us to develop a polymeric boric acid catalyst with mild Bronsted acidity. To accomplish this, boric acid was dehydrated at 200°C to convert it into its polymeric Lewis acid form and then sulfonated using chlorosulphonic acid to introduce the mild Bronsted acid character. Boron is an electron deficient element and electron withdrawing effect of adjacent sulfate enhances its Lewis acidity, hence, it has both Lewis as well as Bronsted acid characters (Scheme 1).

The development of a novel methodology which serves green chemistry purpose by maximizing efficiency and minimizing waste is currently in demand. To achieve these objectives, herein we report sulfated polyborate as a mild, efficient and eco-friendly catalyst for synthesis of quinoxalines under solvent-free condition with high yields and short duration of times. The catalyst was prepared from readily available boric acid, as economic and non-toxic starting material. This is the first report on the use of sulfated polyborate for the synthesis of quinoxalines (Scheme 1). The catalyst is environmentally benign due to its mild acidity and non-toxic nature.

2. Experimental

2.1 Materials and methods

Melting points of all the compounds were recorded by Analab ThermoCal melting point apparatus in the open capillary tube and are uncorrected. The FTIR spectra (KBr) were recorded on Shimadzu FTIR Affinity-1 Fourier Transform Infrared spectrophotometer. ¹H NMR spectra were recorded on MR400 Agilent Technology NMR spectrometer using tetramethylsilane (TMS) as an internal standard and DMSO-d₆ or CDCl₃ as a solvent. Chemicals and solvents used were of LR grade and purchased from SD fine, Avra Synthesis and Spectrochem and used without purification. The purity determination of the starting materials and reaction monitoring

were accomplished by thin layer chromatography (TLC) on Merck silica gel G F₂₅₄ plates.

2.2 Preparation of sulfated polyborate

Sulfated polyborate catalyst was prepared from boric acid as reported in the literature.⁶⁰

2.3 General procedure for the synthesis of quinoxaline derivatives

To a mixture of substituted *o*-phenylenediamines derivative (2.0 mmol) and 1,2-diketone / α -hydroxy ketone (2.0 mmol), was added sulfated polyborate (10 wt%). The reaction mixture was stirred at 100°C in an oil bath. The reaction was monitored by thin layer chromatography (TLC). After completion of the reaction, the mixture was cooled to room temperature and quenched by water. The resultant product was filtered/extracted with EtOAc to get the product. Crude products were either recrystallized from ethanol or purified by column chromatography using silica as the stationary phase and EtOAc: pet. ether as mobile phase. The products obtained were known compounds and were identified by melting point and ¹H and ¹³C NMR spectroscopy. The spectral data were compared with the literature values.

The catalyst was prepared and characterized by various analytical techniques such as potentiometric analysis, Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM) energy dispersive X-ray spectroscopy (EDAX).⁶⁰

3. Results and Discussion

The acidity of the catalyst was determined by potentiometric titration in a mixture of water and glycerine (2:1) against standard 0.1 N NaOH solution and the total concentration of H⁺ was found to be 19.5 mmol/g which is due to both SO₃H as well as associated B–O–H.

FTIR spectrum of the catalyst showed the presence of a band at 3221 cm⁻¹ corresponding to O–H stretching of B–O–H and at 1469 cm⁻¹ for B–O stretching, and bands at 1294 cm⁻¹ for O = S = O asym. stretching, 1068 cm⁻¹ for sym. stretching, 1004 cm⁻¹ for S = O

stretching of the SO_3H group. Powder XRD pattern showed significant peaks positioned at $2\theta = 28.1^\circ$ which confirms the presence of B–O bonds in the crystal structure of the catalyst. EDAX shows boron: oxygen: sulfur signal ratio of 30.32: 68.73: 0.96 wt% over different areas.

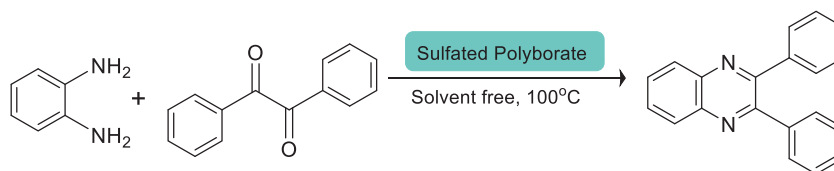
Recently, we have reported the efficiency of sulfated polyborate as a catalyst for one-pot multicomponent synthesis of 3,4-dihydropyrimidin-2(1H)-ones/thiones via Biginelli⁶⁰ reaction and synthesis of α -aminophosphinates via Kabachnik-Fields reaction⁶¹ both under solvent-free conditions. Its ease of preparation, high stability, mild acidity, and reusability prompted us for exploration of its potential to catalyze other useful reaction transformations.

In continuation of the development of greener, eco-friendly catalysts for the synthesis of various heterocycles, herein, we report sulfated polyborate used as a catalyst for synthesis of quinoxalines from aromatic 1,2-diamines and 1,2-diketone/ α -hydroxy ketone with good to excellent yields (Scheme 2).

Initially, we designed our study to investigate the suitability of sulfated polyborate as a catalyst at different reaction conditions for synthesis of the quinoxaline derivatives. An equimolar mixture of *o*-phenylenediamines, a representative substrate and benzil were used

(Scheme 2). The effect of the catalyst loading on time and yields of the reaction was assessed (Table 1, entries 2–6). In the absence of the catalyst, the reaction proceeded at 100°C but it required longer time with poor yield (Table 1, entry 1), while increased catalyst loading resulted in an increased product yield with significant reduction in reaction time. (Table 1, entries 2–5). The catalyst loading beyond 10 wt% was not advantageous (Table 1, entries 6). Hence, a 10 wt% catalyst loading was optimum for further study.

Temperature played a significant role in the synthesis of quinoxaline (Table 1, entries 5, 7 and 8). The temperature effect was observed at ambient, 70°C and 100°C in presence of sulfated polyborate as a catalyst. The reaction proceeded at 70°C but took longer reaction time with a lower yield (Table 1, entry 7). The reaction did not proceed at room temperature (Table 1, entry 8), while it proceeded at 100°C with increased product yield in a shorter reaction time (Table 1, entry 5). Therefore, 100°C was chosen as optimum temperature for the reaction. The effect of different solvents on yield and time of the reaction was assessed (Table 1, entries 9–14). None of the solvents presented an advantage over solvent-free condition. Therefore, the solvent-free condition was regarded as the best for the cost and ecological benefits.



Scheme 2. Synthesis of quinoxaline from *o*-phenylenediamines and benzil.

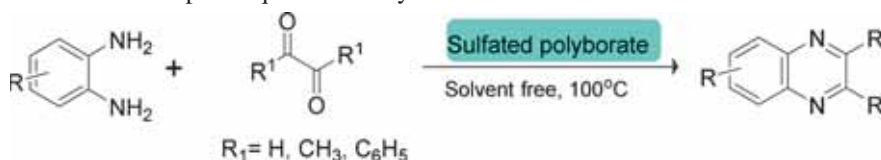
Table 1. Catalyst loading, temperature and solvent optimization study.

Entry	Catalyst (wt%)	Solvent	Temperature ($^\circ\text{C}$)	Time (min)	Yield ^a (%)
1.	0	solvent-free	100	320	52
2.	2.5	solvent-free	100	60	84
3.	5.0	solvent-free	100	30	90
4.	7.5	solvent-free	100	10	96
5.	10.0	solvent-free	100	5	99
6.	15.0	solvent-free	100	5	99
7.	10	solvent-free	70	60	50
8.	10	solvent-free	RT	60	NR ^b
9.	10	water	Reflux	60	95
10.	10	ACN	Reflux	60	91
11.	10	THF	Reflux	60	85
12.	10	Ethanol	Reflux	60	89
13.	10	Toluene	Reflux	60	93
14.	10	DMSO	100	60	94

^aIsolated yield, ^bNo reaction.

Table 2. Efficiency of sulfated polyborate in comparison with polyborate and boric acid.

Entry	Catalyst	Conditions	Time (min)	Yield ^a (%)
1.	Sulfated polyborate	solvent-free/100°C	5	99
2.	Polyborate	solvent-free/100°C	30	97
3.	Boric acid	solvent-free/100°C	40	96

^aIsolated yield.**Table 3.** Substrate scope for quinoxaline synthesis.

Entry	1,2-Diamine (R)	Diketone (R ¹)	Time (min)	Yield ^a (%)	Melting point (°C)	
					Obtained	Literature
1.	H	C ₆ H ₅	5	99	126–128	128–129 ⁵²
2.	6-CH ₃	C ₆ H ₅	5	98	113–115	112–114 ⁵²
3.	5-CH ₃	C ₆ H ₅	5	97	118–120	120–121 ⁶²
4.	6-C ₄ H ₉	C ₆ H ₅	7	97	80–82	83 ⁶³
5.	6-Cl	C ₆ H ₅	5	96	122–124	124–126 ⁶²
6.	6-NO ₂	C ₆ H ₅	10	95	187–189	188–190 ⁵²
7.	H	CH ₃	3	99	111–113	109–110 ⁶²
8.	6-CH ₃	CH ₃	3	98	93–95	94–95 ⁶²
9.	5-CH ₃	CH ₃	3	98	74–76	76–77 ⁶²
10.	6-C ₄ H ₉	CH ₃	3	97	liquid	NA ^b
11.	6-Cl	CH ₃	3	96	94–96	92–93 ⁶²
12.	6-NO ₂	CH ₃	7	96	132–134	130–132 ⁶⁴
13.	H	H	3	99	31–33	29–30 ⁶⁷
14.	6-CH ₃	H	3	98	liquid	liquid ⁶⁷
15.	5-CH ₃	H	3	98	liquid	18–20 ⁶⁸
16.	6-C ₄ H ₉	H	3	97	liquid	NA ^b
17.	6-Cl	H	3	97	64–66	63–64 ⁶⁵
18.	6-NO ₂	H	5	96	172–173	174 ⁶⁶

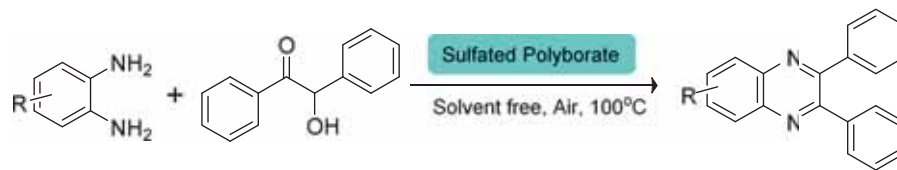
^aIsolated yields, ^bNot Available in literature.

Herein, the comparison of sulfated polyborate with polyborate and boric acid is shown in Table 2, which revealed that sulfated polyborate showed advantages over its precursors with respect to time and yields (Table 2).

To study the scope and generality of the present protocol, the optimized reaction conditions were applied for the synthesis of a variety of quinoxaline derivatives from substituted *o*-phenylenediamines and 1,2-diketones in the presence of a sulfated polyborate catalyst (Table 3, entries 1–18, Table 4, entries 1–6). All the substrates gave excellent yields in short reaction times. All reactions proceeded very cleanly and no undesirable side reactions were observed, while the reaction time for a 100% conversion of

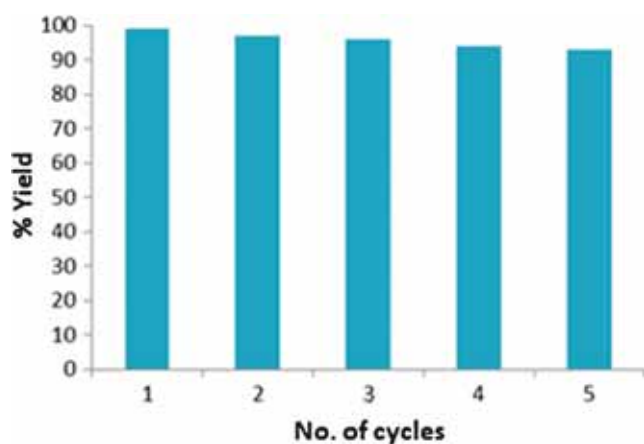
the substrates and reaction yields of products were highly dependent on the substituent. It was observed that *o*-phenylenediamines with either electron donating groups or electron withdrawing groups gave the corresponding products in good to excellent yields. The differences in the yields were very small but substrates having electron-withdrawing groups gave lower yields in increased reaction times compared to substrates having electron-donating groups (Table 3, entries 1–18). On the other hand, structurally diverse 1,2-diketone had no significant effect on the yields and the reaction times.

The optimized protocol was also applied to the reaction of α -hydroxy ketone, benzoin with substituted *o*-phenylenediamines for the synthesis of quinoxalines derivatives. The reaction gave lower yield with longer

Table 4. Quinoxaline synthesis using benzoin under solvent-free condition.

Entry	1,2-Diamine (R)	Time (min)	Yield ^a (%)	Melting point (°C)	
				Obtained	Literature
1.	H	20	96	126–128	128–129 ⁵²
2.	6-CH ₃	20	95	113–115	112–114 ⁵²
3.	5-CH ₃	20	93	118–120	120–121 ⁶²
4.	6-C ₄ H ₉	20	94	80–82	83 ⁶³
5.	6-Cl	20	92	122–124	124–126 ⁵²
6.	6-NO ₂	30	89	187–189	188–190 ⁵²

^aIsolated yields.

**Figure 1.** Reusability of the catalyst.

reaction time presumably due to subsequent air oxidation of 2,3-diphenyl-1,2-dihydroquinoxaline, an intermediate, to give 2,3-diphenylquinoxaline (Table 4, entries 1–6).

The reusability of the catalyst in the model reaction under solvent-free conditions at 100°C was evaluated. After completion of each cycle of the reaction, the catalyst was recovered by adding water and the product was filtered off. The filtrate was evaporated under reduced pressure to recover the catalyst quantitatively. The recovered catalyst was reused four times with no significant loss in a catalytic activity (Figure 1).

4. Conclusions

In conclusion, sulfated polyborate is a mild, efficient, eco-friendly and inexpensive catalyst for the synthesis of quinoxalines of various substituted *o*-phenylenediamines and 1,2-diketones/ α -hydroxy ketones under optimal conditions. Mild reaction conditions, shorter reaction times, higher yields, ease of workup, recyclability of the

catalyst and environment-friendliness are the key features of the present protocol. Moreover, this method has the ability to tolerate a wide variety of substituents.

Supplementary Information (SI)

Full experimental details, ¹H and ¹³C NMR spectra of compounds are available in Supplementary Information at www.ias.ac.in/chemsci.

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References

- Hegedus L S, Greenberg M M, Wendling J J and Bullock J P 2003 Synthesis of 5,12-dioxocyclam nickel(II) complexes having quinoxaline substituents at the 6 and 13 positions as potential DNA bis-intercalating and cleaving agents *J. Org. Chem.* **68** 4179
- Corona P, Vitale G, Loriga M, Paglietti G and Paola M 1998 Quinoxaline chemistry. Part 11. 3-Phenyl-2 [phenoxy- and phenoxy-methyl]-6(7) or 6,8-substituted quinoxalines and IV- [4- (6 (7) -substituted or 6 &disubstituted-3-phenylquinoxalin-2-yl) hydroxy or hydroxymethyl] benzoylglutamates. Synthesis and evaluation of *in vitro* anticancer activity and enzymatic inhibitory activity against dihydrofolate reductase and thymidylate synthase *Farmaco* **53** 480
- Seitz L E, Suling W J and Reynolds R C 2002 Synthesis and antimycobacterial activity of pyrazine and quinoxaline derivatives *J. Med. Chem.* **45** 5604
- Sarges R, Howard H R, Browne R G, Lebel L A, Seymour P A and B K Koe 1990 4-Amino[1,2,4]triazolo [4,3-a] quinoxalines. A novel class of potent adenosine receptor antagonists and potential rapid-onset antidepressants *J. Med. Chem.* **33** 2240

- Budakoti A, Bhat A R and Azam A 2009 Synthesis of new 2-(5-substituted-3-phenyl-2-pyrazolinyl)-1,3-thiazolino[5,4-b]quinoxaline derivatives and evaluation of their antiameobic activity *Eur. J. Med. Chem.* **44** 1317
- Wagle S, Adhikari A V and Kumari N S 2009 Synthesis of some new 4-styryl tetrazolo[1,5-a]quinoxaline and 1-substituted-4-styryl[1,2,4]triazolo[4,3-a] quinoxaline derivatives as potent anticonvulsants *Eur. J. Med. Chem.* **44** 1135
- Guillon J, Grellier P, Labaied M, Sonnet P, Leger J M, Deprez-Poulain R, Forfar-Bares I, Dallemagne P, Lemaitre N, Pehourcq F, Rochette J, Sergheraert C and Jarry C 2004 Synthesis, antimalarial activity, and molecular modeling of new pyrrolo[1,2-a]quinoxalines, bispyrrolo[1,2-a]quinoxalines, bispyrido[3,2-e] pyrrolo [1,2-a]pyrazines and bispyrrolo[1,2-a]thieno[3,2-e]pyrazines *J. Med. Chem.* **47** 1997
- Burguete A, Pontiki E, Hadjipavlou-Litina D, Villar R, Vicente E, Solano B, Ancizu S, Pérez-Silanes S, Aldana I and Monge A 2007 Synthesis and anti-inflammatory/antioxidant activities of some new ring substituted 3-phenyl-1-(1,4-di-N-oxide-quinoxalin-2-yl)-2-propen-1-one derivatives and of their 4,5-dihydro-(1H)-pyrazole analogues *Bioorg. Med. Chem. Lett.* **17** 6439
- Hui X, Desrivot J, Bories C, Loiseau P M, Franck X, Hocquemiller R and Figadère B 2006 *Bioorg. Med. Chem. Lett.* Synthesis and antiprotozoal activity of some new synthetic substituted quinoxalines *Med. Chem. Lett.* **16** 815
- He W, Myers M R, Hanney B, Spada A P, Bilder G Galzcinski H, Amin D, Needle S, Page K, Jayyosi Z and Perrone M H 2003 Potent quinoxaline-based inhibitors of PDGF receptor tyrosine kinase activity. Part 2: The synthesis and biological activities of RPR127963 an orally bioavailable inhibitor *Bioorg. Med. Chem. Lett.* **13** 3097
- Dell A, William D H, Morris H R, Smith G A, Feeney J and Roberts G C K 1975 Synthesis and antimycobacterial activity of pyrazine and quinoxaline derivatives *J. Am. Chem. Soc.* **97** 2497
- Abdelfattah M S, Kazufumi T and Ishibashi M 2010 Structure revision of the antibiotic echinomycin *J. Nat. Prod.* **73** 1999
- Hirayama T, Yamasaki S, Ameku H, Ishi I T, Thiemann T and Mataka S 2005 Fluorescent solvatochromism of bi-polar N,N-diphenylaminoaryl-substituted hexaazatriphenylenes, tetraazaphenanthrene, and quinoxalines *Dyes Pigm.* **67** 105
- Justin Thomas K R, Velusamy M, Lin Jiann T, Chuen C H and Tao Y T 2005 Chromophore-labeled quinoxaline derivatives as efficient electroluminescent materials *Chem. Mater.* **17** 1860
- Dailey S, Feast W J, Peace R J, Sage I C, Till S and Wood E L 2001 Synthesis and device characterisation of side-chain polymer electron transport materials for organic semiconductor applications *J. Mater. Chem.* **11** 2238
- Sessler J L, Maeda H, Mizuno T, Lynch V M and Furuta H 2002 Quinoxaline-bridged porphyrinoids *J. Am. Chem. Soc.* **124** 13474
- Brown D J 2004 In *Quinoxalines: Supplement II. In The Chemistry of Heterocyclic Compounds* E C Taylor and P Wipf (Eds.) (New Jersey: John Wiley)
- Li Z, Zhu A and Yang J 2012 Eco-friendly synthesis of quinoxaline derivatives by grinding under solvent-free conditions *J. Heterocycl. Chem.* **49** 1458
- Zhao Z, Wisnoski D D, Wolkenberg S E, Leister W H, Wang Y and Lindsley C W 2004 General microwave-assisted protocols for the expedient synthesis of quinoxalines and heterocyclic pyrazines *Tetrahedron Lett.* **45** 4873
- Mirjalili B B F, Bamoniri A and Akbari A 2011 Nano-BF₃-SiO₂: A reusable and eco-friendly catalyst for synthesis of quinoxalines *Chem. Heterocycl. Compd.* **47** 487
- Kaupf G and Naimi-Jamal M R 2002 Quantitative cascade condensations between o-phenylenediamines and 1,2-dicarbonyl compounds without production of wastes *Eur. J. Org. Chem.* **2002** 1368
- Darabi H R, Mohandessi S, Aghapoor K and Mohsenzadeh F 2007 A recyclable and highly effective sulfamic acid/MeOH catalytic system for the synthesis of quinoxalines at room temperature *Catal. Commun.* **8** 389
- Heravi M M, Taheri S, Bakhtiari K and Oskooie H A 2007 On water: A practical and efficient synthesis of quinoxaline derivatives catalyzed by CuSO₄:5H₂O *Catal. Commun.* **8** 211
- Li Z, Li W, Sun Y, Huang H and Ouyang P 2008 Room temperature facile synthesis of quinoxalines catalyzed by amidosulfonic acid *J. Heterocycl. Chem.* **45** 285
- Srinivas C, Kumar C N S S P, Rao V J and Palaniappan S 2007 Efficient, convenient and reusable polyaniline-sulfate salt catalyst for the synthesis of quinoxaline derivatives *J. Mol. Catal. A: Chem.* **265** 227
- Da-Qing S and Guo-Lan D 2008 Efficient synthesis of quinoxaline derivatives catalyzed by p-toluenesulfonic acid under solvent-free conditions *Synth. Commun.* **38** 3329
- Potewar T M, Ingale S and Srinivasan K V 2008 Efficient synthesis of quinoxalines in the ionic liquid 1-n-butylimidazolium tetrafluoroborate ([Hbim]⁺BF₄⁻) at ambient temperature *Synth. Commun.* **38** 3601
- Sithambaram S, Ding Y, Li W, Shen X, Gaenzler F and Suib S L 2008 Manganese octahedral molecular sieves catalyzed tandem process for synthesis of quinoxalines *Green Chem.* **10** 1029
- Cai J J, Zou J P, Pan X Q and Zhang W 2008 Gallium(III) triflate-catalyzed synthesis of quinoxaline derivatives *Tetrahedron Lett.* **49** 7386
- Huang T, Wang R, Shi L and Lu X 2008 Montmorillonite K-10: An efficient and reusable catalyst for the synthesis of quinoxaline derivatives in water *Catal. Commun.* **9** 1143
- Huang T, Shi L, Wang R, Guo X and Lu X 2009 Keggin type heteropolyacids-catalyzed synthesis of quinoxaline derivatives in water *Chinese Chem. Lett.* **20** 161
- Liu J Y, Liu J, Wang J D, Jiao D Q and Liu H W 2010 Efficient, ecofriendly, and practical process for the synthesis of quinoxalines catalyzed by amberlyst-15 in aqueous media *Synth. Commun.* **40** 2047
- Shi D Q, Dou G L, Ni S N, Shi J W and Li X Y 2008 An efficient synthesis of quinoxaline derivatives mediated by stannous chloride *J. Heterocycl. Chem.* **45** 1797

34. Darabi H R, Aghapoor K, Mohsenzadeh F, Jalali M R, Talebian S, Ebadi Nia L, Khatamifar E and Aghaee A 2011 Heterogeneous $\text{SnCl}_2/\text{SiO}_2$ versus homogeneous SnCl_2 acid catalysis in the benzo[N,N]-heterocyclic condensation *Bull. Korean Chem. Soc.* **32** 213
35. Hasaninejad A, Zare A, Zolfigol M A and Shekouhy M 2009 Zirconium tetrakis(dodecyl sulfate) $[\text{Zr}(\text{DS})_4]$ as an efficient lewis acid–surfactant combined catalyst for the synthesis of quinoxaline derivatives in aqueous media *Synth. Commun.* **39** 569
36. Ajaikumar S and Pandurangan A 2009 Efficient synthesis of quinoxaline derivatives over $\text{ZrO}_2/\text{MxO}_y$ (M = Al, Ga, In and La) mixed metal oxides supported on MCM-41 mesoporous molecular sieves *Appl. Catal. A Gen.* **357** 184
37. Bhosale R S, Sarda S R, Ardhpure S S, Jadhav W N, Bhusare S R and Pawar R P 2005 An efficient protocol for the synthesis of quinoxaline derivatives at room temperature using molecular iodine as the catalyst *Tetrahedron Lett.* **46** 7183
38. Niknam K, Saberi D and Mohagheghnejad M 2009 Silica bonded S-Sulfonic acid: A recyclable catalyst for the synthesis of quinoxalines at room temperature *Molecules* **14** 1915
39. Darabi H R, Aghapoor K, Mohsenzadeh F, Taala F, Asadollahnejad N and Badieli A 2009 Silica-supported antimony(III) chloride as highly effective and reusable heterogeneous catalyst for the synthesis of quinoxalines *Catal. Lett.* **133** 84
40. Heravi M M, Tehrani M H, Bakhtiari K and Oskooie H A 2007 $\text{Zn}[(\text{L})\text{proline}]$: A powerful catalyst for the very fast synthesis of quinoxaline derivatives at room temperature *Catal. Commun.* **8** 1341
41. Nandi G C, Samai S, Kumar R and Singh M S 2011 Silica-gel–catalyzed efficient synthesis of quinoxaline derivatives under solvent-free conditions *Synth. Commun.* **41** 417
42. Jafarpour M, Rezaeifard A and Danehchin M 2011 Easy access to quinoxaline derivatives using alumina as an effective and reusable catalyst under solvent-free conditions *Appl. Catal. A Gen.* **394** 48
43. Raghuvveerachary P and Devanna N 2011 Samarium triflate catalyzed efficient synthesis of quinoxalines *Asian J. Chem.* **23** 1628
44. Oskooie H A, Heravi M M, Bakhtiari K and Taheri S 2007 An efficient and facile synthesis of quinoxaline derivatives catalyzed by KHSO_4 at room temperature *Monatsh. Chem.* **138** 875
45. Huang T, Jiang D, Chen J, Gao W, Ding J and Wu H 2011 Silica sulfuric acid (SSA)/polyethylene glycol (PEG) as a recyclable system for the synthesis of quinoxalines and pyrazines *Synth. Commun.* **41** 3334
46. Bachhav H M, Bhagat S B and Telvekar V N 2011 Efficient protocol for the synthesis of quinoxaline, benzoxazole and benzimidazole derivatives using glycerol as green solvent *Tetrahedron Lett.* **52** 5697
47. Narsaiah A V and Kumar J K 2012 Glycerin and $\text{CeCl}_3 \cdot 7\text{H}_2\text{O}$: A new and efficient recyclable reaction medium for the synthesis of quinoxalines *Synth. Commun.* **42** 883
48. Zhang C, Xu Z, Zhang L and Jiao N 2012 Et_3N -catalyzed oxidative dehydrogenative coupling of α -unsubstituted aldehydes and ketones with aryl diamines leading to quinoxalines using molecular oxygen as oxidant *Tetrahedron* **68** 5258
49. Song W, Liu P, Lei M, You H, Chen X, Chen H, Ma L and Hu L 2012 FeCl_3 and morpholine as efficient cocatalysts for the one-step synthesis of quinoxalines from α -hydroxyketones and 1,2-diamines *Synth. Commun.* **42** 236
50. Pan F, Chen T M, Cao J J, Zou J P and Zhang W 2012 $\text{Ga}(\text{ClO}_4)_3$ -catalyzed synthesis of quinoxalines by cycloaddition of α -hydroxyketones and o-phenylenediamines *Tetrahedron Lett.* **53** 2508
51. Kumbhar A, Kamble S, Barge M, Rashinkar G and Salunkhe R 2012 Brønsted acid hydrotrope combined catalyst for environmentally benign synthesis of quinoxalines and pyrido[2,3-b]pyrazines in aqueous medium *Tetrahedron Lett.* **53** 2756
52. Kadam H K, Khan S, Kunkalkar R A and Tilve S G 2013 Graphite catalyzed green synthesis of quinoxalines *Tetrahedron Lett.* **54** 1003
53. Krishnakumar B and Swaminathan M 2011 A Recyclable solid acid catalyst sulfated titania for easy synthesis of quinoxaline and dipyrindophenazine derivatives under microwave irradiation *Bull. Chem. Soc. Jpn.* **84** 1261
54. Zhang X Z, Wang J X, Sun Y J and Zhan H W 2010 Synthesis of quinoxaline derivatives catalyzed by PEG-400 *Chin. Chem. Lett.* **21** 395
55. Shahrissa A, Esmati S and Nazari M G 2012 Boric acid as a mild and efficient catalyst for one-pot synthesis of 1-amidoalkyl-2-naphthols under solvent-free conditions *J. Chem. Sci.* **124** 927
56. Arce G, Carrau G, Bellomo A and Gonzalez D 2015 Greener synthesis of an amide by direct reaction of an acid and amine under catalytic conditions *World J. Chem. Educ.* **3** 27
57. Zheng Y J, Zhang J C and Lu H C 2012 Synthesis of n-butyl salicylate catalyzed by boric Acid *Adv. Mater. Res.* **466** 319
58. Chandrasekhar S and Gopalaiah K 2002 Beckmann rearrangement of ketoximes on solid metaboric acid: A simple and effective procedure *Tetrahedron Lett.* **43** 2455
59. Sivrikaya O and Arol A 2010 Use of Boron Compounds as Binders in Iron Ore Pelletization *Open Miner. Process. J.* **3** 25
60. Khatri C K, Rekunge D S and Chaturbhuj G U 2016 Sulfated polyborate: A new and eco-friendly catalyst for one-pot multi-component synthesis of 3,4-dihydro pyrimidin-2(1H)-ones/thiones via Biginelli reaction *New J. Chem.* **40** 10412
61. Khatri C K, Satalkar V B and Chaturbhuj G U 2017 Sulfated polyborate catalyzed Kabachnik-Fields reaction: An efficient and eco-friendly protocol for synthesis of α -amino phosphonates *Tetrahedron Lett.* **58** 694
62. Go A, Lee G, Kim J, Bae S, Lee B M and Kim B H 2015 One-pot synthesis of quinoxalines from reductive coupling of 2-nitroanilines and 1,2-diketones using indium *Tetrahedron* **71** 1215
63. Urban S, Ortega N and Glorius F 2011 Ligand-controlled highly regioselective and asymmetric hydrogenation of quinoxalines catalyzed by ruthenium

- n-heterocyclic carbene complexes *Angew. Chem. Int. Ed.* **50** 3803
64. Mohammadi M, Bardajee G R and Pesyan N N 2015 Efficient solvent-free synthesis of pyridopyrazine and quinoxaline derivatives using copper-DiAmSar complex anchored on SBA-15 as a reusable catalyst *Chin. J. Catal.* **36** 1379
 65. Rtishchev N I and Selitrennikov A V 2004 Phototransformations of 6-X-5-nitroquinoxalines *Russ. J. Gen. Chem.* **74** 428
 66. Zhu W, Dai M, Xu Y and Qian X 2008 Novel nitroheterocyclic hypoxic markers for solid tumor: Synthesis and biological evaluation *Bioorg. Med. Chem.* **16** 3255
 67. Paul S and Basu B 2011 Synthesis of libraries of quinoxalines through eco-friendly tandem oxidation-condensation or condensation reactions *Tetrahedron Lett.* **52** 6597
 68. Ulrich H and Galen K 1980 Carbon-13 NMR Studies on some 5-Substituted Quinoxalines *Org. Magn. Resonance* **14** 300