

An overview of some recent advances in DOPO-derivatives: Chemistry and flame retardant applications



Khalifah A. Salmeia, Sabyasachi Gaan^{*}

Additives and Chemistry Group, Advanced Fibers, EMPA Swiss Federal Laboratories for Materials Science and Technology, Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland

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ABSTRACT

Owing to the toxicity and environmental concerns of halogen-containing flame retardants, phosphorus-containing flame retardants have attracted much attention as ecofriendly substitutes. Synthesis of organophosphorus compounds based on 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide (DOPO) and its application as flame retardant have created much attention in the flame retardant community. Various chemical reactions and synthetic approaches are followed to develop numerous derivatives of DOPO. This review focuses on the recent advances in DOPO chemistry, classifying its derivatives based on the chemical reactions and functional groups. The reaction mechanisms of each specific reaction for DOPO derivatization are discussed in detail. Additionally some characteristic applications of these DOPO-derivatives with important flammability performance are also reported in this short review.

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1. Introduction

In 1972, Sanko Chemical Co., Ltd. patented a new class of cyclic organophosphorus compounds and their method of manufacturing [1]. In general, the new organophosphorus compounds were obtained by heat-condensation of the orthophenylphenol derivatives and PCl_3 in presence of a catalyst. Accordingly, 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide (DOPO) was designed and synthesized by reacting of orthophenylphenol in stoichiometric amount with PCl_3 in presence of Zinc(II) chloride or Aluminum trichloride at around 210 °C, affording 10-chloro-9,10-dihydro-9-oxa-10-phosphaphenanthrene (DOP-Cl) which was then hydrolyzed to DOPO compound (**1**) (Scheme 1).

In the past few decades, DOP-Cl and DOPO have been used as starting materials for synthesis of various organophosphorus compounds for different applications (mainly as flame retardants) [2–16]. These DOPO-derivatives are used as flame retardants mainly in epoxy resins [3,5,11–13,15], for applications in adhesives, composites, printed wiring boards and others [17]. As some halogenated flame retardants have been found to be toxic, the research

on halogen-free flame retardants is gaining more and more importance [18]. DOPO-derivatives are considered as suitable alternative to halogenated flame retardants because of their versatile flame extinguishing behavior in gas phase and condensed phase [17].

Despite a growing interest in DOPO-derivatives as flame retardants [4,19] there exist no comprehensive review on their synthesis and application. In this review we have summarized the chemistry and application of DOPO compounds published mostly in the past two years. This review is presented according to the type of the chemical reactions used in the synthesis of DOPO-derivatives and their reaction mechanisms.

2. Reactivity of DOPO

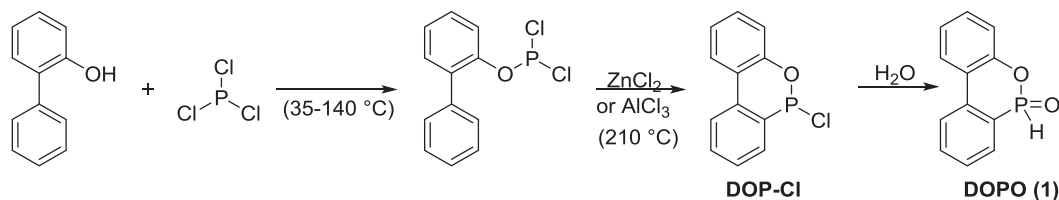
DOPO is a *H*-Phosphinate compound ($\text{HPR}(\text{O})(\text{OR})$, $\text{R} = \text{aryl}$) that can tautomerize to its $\text{P}-\text{OH}$ form in a solution (Scheme 2) [20].

Owing to tautomeric equilibrium between the species **1a** and **1b**, the phosphorus atom in DOPO can be reactive toward nucleophiles and electrophiles [21]. *H*-Phosphinates compared to phosphines are stable toward oxygen owing to the presence of the phosphoryl group ($\text{P}=\text{O}$). Accordingly, the form **1a** in a solution is considered to be the dominant species and it is predicted that **1a** species determines the overall reactivity. This equilibrium

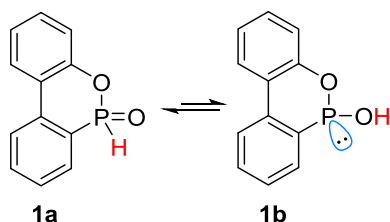
^{*} Corresponding author. Tel.: +41 71 2747 611; fax: +41 71 2747 862.

E-mail address: sabyasachi.gaan@empa.ch (S. Gaan).

URL: <http://www.empa.ch>



Scheme 1. Synthetic approach of DOPO compound (1).



Scheme 2. The tautomeric equilibrium of DOPO.

is also affected by the electronic properties of the substituents around the phosphorus atom, which may shift the equilibrium to the right [20]. Due this property, DOPO-derivatives and its analogs can be prepared via different synthetic approaches categorized below.

2.1. P–C bond formation

The phosphinate derivatives of DOPO are a product of P–H bond substitution with P–C bond. These P–C bond derivatives can be prepared by two main approaches, namely nucleophilic addition/substitution and via molecular rearrangement.

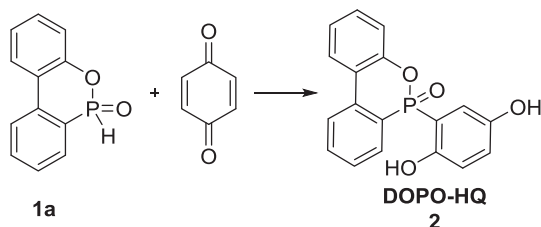
2.1.1. Michael-type addition

In 1985 a Japanese company (Sanko Kaihatsu Kagaku Kenkyusho), patented synthesis of 10-(2,5-dihydroxyphenyl)-10H-9-oxa-10-phosphaphenanthrene-10-oxide (DOPO-HQ) (2). The product was synthesized by reacting DOPO with *p*-benzoquinone via Michael-type addition (Scheme 3) using 2-ethoxyethanol as solvent at temperature range from 70 °C to 130 °C.

The reaction mechanism is proposed by addition of 1a to *p*-benzoquinone to produce monosubstituted hydroquinone, which subsequently tautomerizes to give 2 (Scheme 4) [22].

Nowadays, compound 2 and its synthetic approach are an important building block for miscellaneous DOPO-compounds. Compound 2 is always the only monosubstituted *p*-benzoquinone product for this reaction [23,24].

Döring and coworkers have recently published a disubstituted derivative of *p*-hydroquinone [25]. The reaction took place by oxidation of 2 using activated MnO₂ followed by the reaction with DOPO, affording 3 (Scheme 5) as two diastereomers. In both cases, it

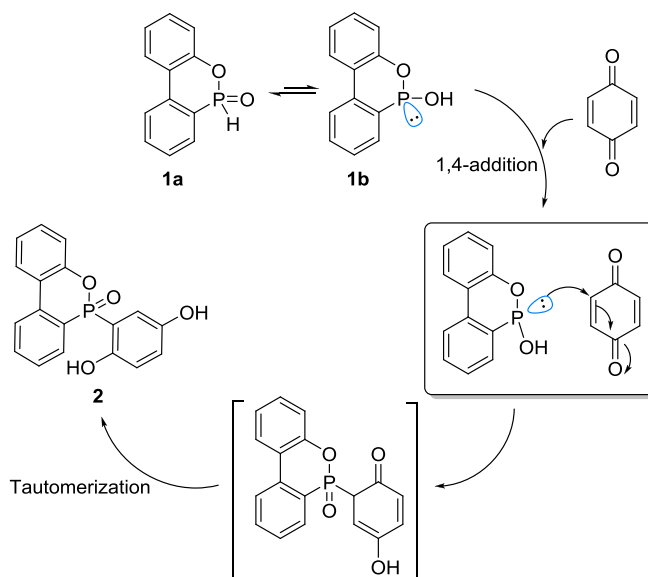


Scheme 3. Synthesis of DOPO-HQ (2).

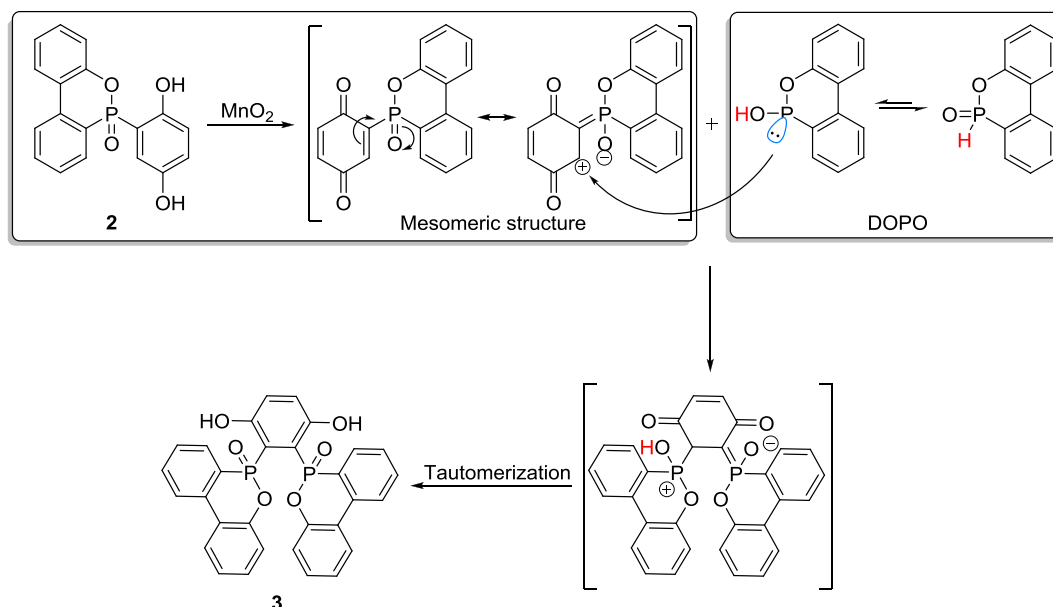
was found that the DOPO-substituents are in ortho position which is attributed to the distribution of the local charges in the meso-meric structure. Following the same approach, Döring and co-workers could prepare tri- and tetra-substituted *p*-hydroquinone [26].

Compound 2 is a reactive monomer, Owing to the diol functionality. Therefore, it could be incorporated into the molecular backbone of polymers for flame retardant application. Scheme 6 summarizes some recent examples for these syntheses.

Compound 3 was used as flame retardant in epoxy resin for aerospace and automotive purposes [27]. It was prepolymerized by heating with a diacid and the resulting ester was then admixed with polymers such as polyesters, bis-maleimides, polyimides, polyurethane and epoxies. Compound 4 was synthesized as a reactive monomer to be copolymerized via radical initiation reaction in different concentrations with unsaturated polyester resin (UPR) [28]. LOI was used to evaluate the flammability of the developed polymers. It was found that a LOI of 28% can be achieved with an addition 20 wt% of 4. On the other hand, 5 is liquid and designed to avoid the disadvantages of the solid DOPO derivatives that are used for UV-curing coating [29]. Compound 5 was used in epoxy acrylate and was incorporated via UV-curing process. It was found that, the peak heat release rate (pHRR) decreases with increased concentration of 5 in the resin. At 30 wt% of 5, the pHRR reduces by 50%. 6 was incorporated in polyimide films by the polymerization with 4,4'-oxydianiline (ODA-6) or 2,2-bis-[4-(4-aminophenoxy)phenyl]propane (BAPP-6) [30]. The UL-94 and LOI results for ODA-6 were V0 and 41% respectively. On the contrary, BAPP-6 couldn't be rated in UL-94 test but had a LOI of 36.5%.



Scheme 4. Generally proposed mechanism for synthesis of 2, involving 1,4-addition and tautomerization.



Scheme 5. Proposed mechanism for synthesis of disubstituted *p*-hydroquinone.

Additionally, **6** was investigated as curing agent for epoxy resin with various phosphorus content [31]. It was found that the UL-94 V0 rating can be obtained with a phosphorus content of 1.75 wt% and the LOI values were increased up to 30.6% with a phosphorus content of 2.25 wt%. Compound **7** was designed and tested for application in lithium-ion battery [32]. Compound **7** exhibited good thermal and electrochemistry stability and ionic conductivity as well.

Similar to the syntheses and applications of compound **2**, many research groups have also developed various other DOPO derivatives based on Michael-type addition (Scheme 7).

Compound **8** is a liquid and represents organic/inorganic hybrid material. It was developed and synthesized to overcome the problems (incomplete reaction, poor compatibility and leaching) that appear from using nonreactive DOPO-derivatives as additives in polymer matrix. By employing the sol–gel and UV-curing methods, it could be incorporated in a modified epoxy acrylate (MEA) (Fig. 1) [33].

MEA-**8** was prepared by mixing **8** and MEA in different ratios. By varying the concentration (10 wt%, 20 wt% and 30 wt%) of **8** in the matrix, LOI values of 27.5%, 29.0% and 31.5%, respectively were obtained. The char yield increased from 0.3% to 21.3% at 700 °C, by increasing the organic/inorganic network. The same approach was also applied to introduce **8** into orthophthalic based unsaturated polyesters (UPR) [39]. The reaction occurs in two steps as shown in Scheme 8.

UPR-**8** showed an increase in the LOI from 21% to 27% when **8** content increased from 0 to 20 wt%, which are also consistent with the char residue [39]. It was also found that, UPR-**8** (with a 20 wt% of **8**) has a dual mode of flame retardant action. It produces phosphoric and polyphosphoric acid during the thermal decomposition process which acts as a heat-resistance barrier, as well has a flame inhibition characteristic in gas phase.

8 was also used in P–N–Si containing organic/inorganic flame retardant system, using isocyanurate as nitrogen based material to produce intumescent system [40]. When this system was used in epoxy resin, the formulation exhibited LOI values up to 29.5% and UL-94 V0 rating with a 10 wt% content of **8**. Compound **9** is a bifunctional acid and was also used as a building block in UPR [34].

At a P-content of 2.2 wt%, the LOI and UL-94 rating for the formulation were found to be 25.4% and V1 respectively. Further increased P-content resulted in an improved char formation. Compound **10a** can be obtained from reaction of DOPO with dicyandiamide [35]. It was found that, synthesis and yields of **10a** can be controlled by the reaction parameters such as time of reaction and the reactant ratio. By increasing the reactant ratios and/or reaction time other DOPO products can be formed (Fig. 2).

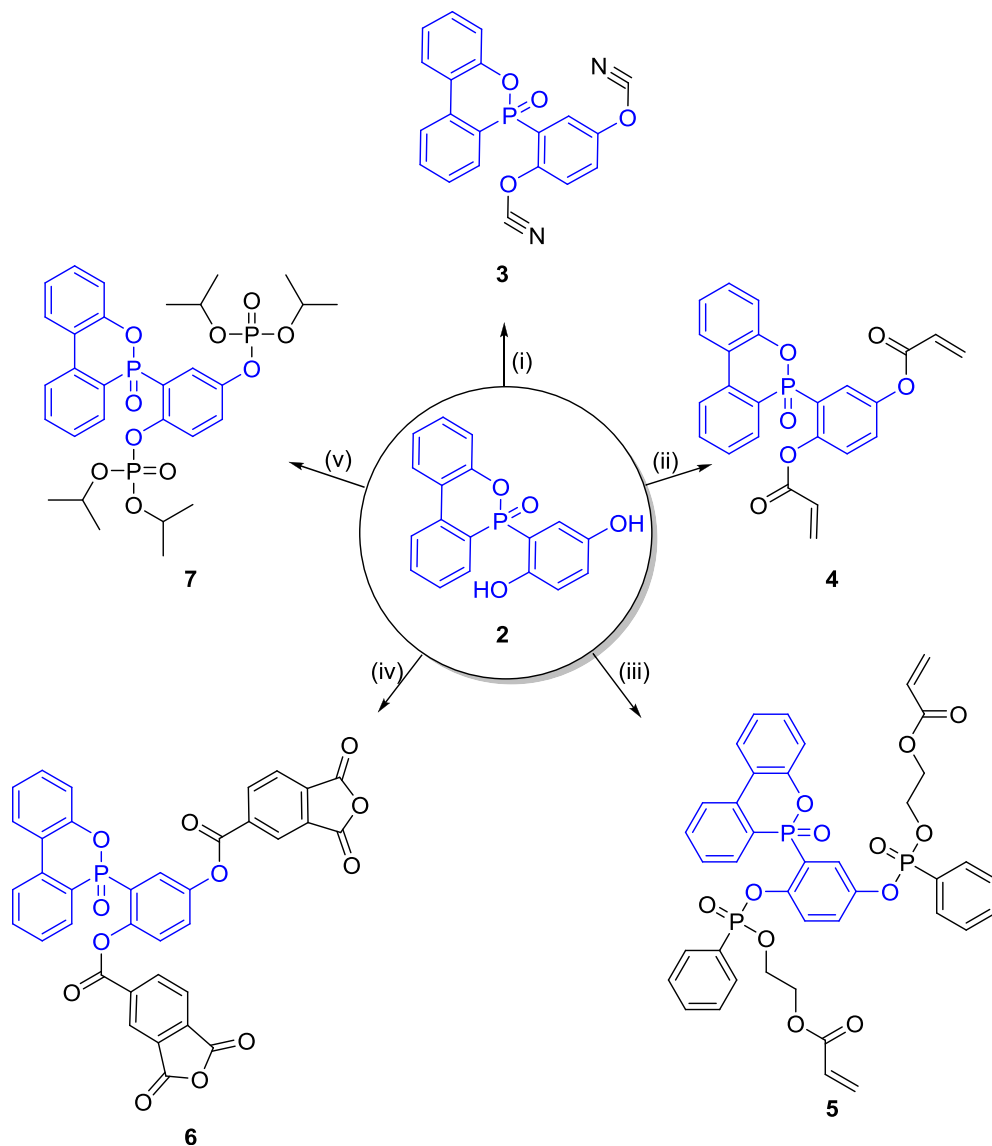
Compounds **10a–c** were investigated as flame retardants and hardener for epoxy resin based on bisphenol A, bisphenol A-Novolac, and o-cresol novolac. In UL-94 test, V0 rating was reported for most of the formulations. Compound **11a** represents oligomer star-shaped DOPO-derivatives [11,41]. Based on the central linkage, two different types of DOPO-derivatives, **11a** (Scheme 7) and **11b** (Fig. 3) were tested as flame retardants in epoxy resin.

Derivatives **11a–b** were tested on commercial epoxy resins, the UL-94 tests for different formulations are summarized in Table 1:

Compound **12** was used as a flame retardant additive for poly(butylene terephthalate) [8]. The flame retardancy was evaluated by LOI and UL-94 tests. It was found that, with different wt% of **12** in the polymer matrix, namely 10, 15, 20 and 25%, the UL-94 test results was V2, V1, V0 and V0, respectively with LOI range of 25.6–25.8 %. **12** was also tested as flame retardant for acrylated epoxidized soybean oil (AESO) [36]. It was found that, the physical properties as well as the flame retardancy of the AESO were improved.

Compound **13a** was designed to be a building unit as a hardener and flame retardant for epoxy resin [37]. Owing to the positive effect of the aromatic group on the flame retardancy and thermal properties, **13b** was also designed as an example of DOPO-derivative with higher content of aromatic groups (Fig. 4) [37].

13a–b were used as curing agent for o-cresol formaldehyde novolac epoxy (CNE) resin meant for application in electronic devices. **13b** was shown to have much better flame retardancy than **13a**, which is attributed to the increased content of aromatic group. LOI values for the resin formulation containing **13a** (2.9% P) and **13b** (3.0% P) were 22 and 27, respectively [37]. Compound **14** was designed to be used in electrical applications, because of its reactivity, high melting point and its heat resistance [38].



Scheme 6. Synthetic routes for some derivatives of **2**; (i) cyanogen bromide, Et_3N (-30 to -50 °C) [27]. (ii) a) Acryloyl chloride, Et_3N (THF; -5 °C, 4 h); Ambient temperature (12 h) [28]. (iii) a) Phenyl dichlorophosphate (THF; 0 °C); b) 2-Hydroxyethyl acrylate, Et_3N (0–5 °C, 6 h) [29]. (iv) a) Ac_2O ; b) 1,3-dioxo-2-benzofuran-5-carboxylic acid [30], or 1,3-Dioxo-2-benzofuran-5-carbonyl chloride [31]. (v) diisopropyl phosphoryl chloride; K_2CO_3 (CH_3CN , 12 h reflux) [32].

2.1.2. Michaelis–Arbuzov rearrangement

Döring and coworkers have published an efficient synthesis methodology of some trivalent DOPO analogs (9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide-methoxy (**15a**) and 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide-ethoxy (**15b**)) under acidic conditions (Scheme 9, Route a) [42]. Alternatively the same trivalent DOPO analogs can be obtained by reacting the corresponding alcohol with DOP-Cl in presence of amine under anaerobic system (Scheme 9, Route b) [43,44].

The mechanism of DOPO transformation into its phosphonite analogs was proposed based on the acid-catalyzed dehydration of the intermediate (Scheme 10) [42].

The chemical rearrangement for **15a** and **15b** was performed by using catalytic amount of *p*-toluenesulfonic acid methylester or dimethyl sulfone at elevated temperature (Scheme 11) [2,6,45].

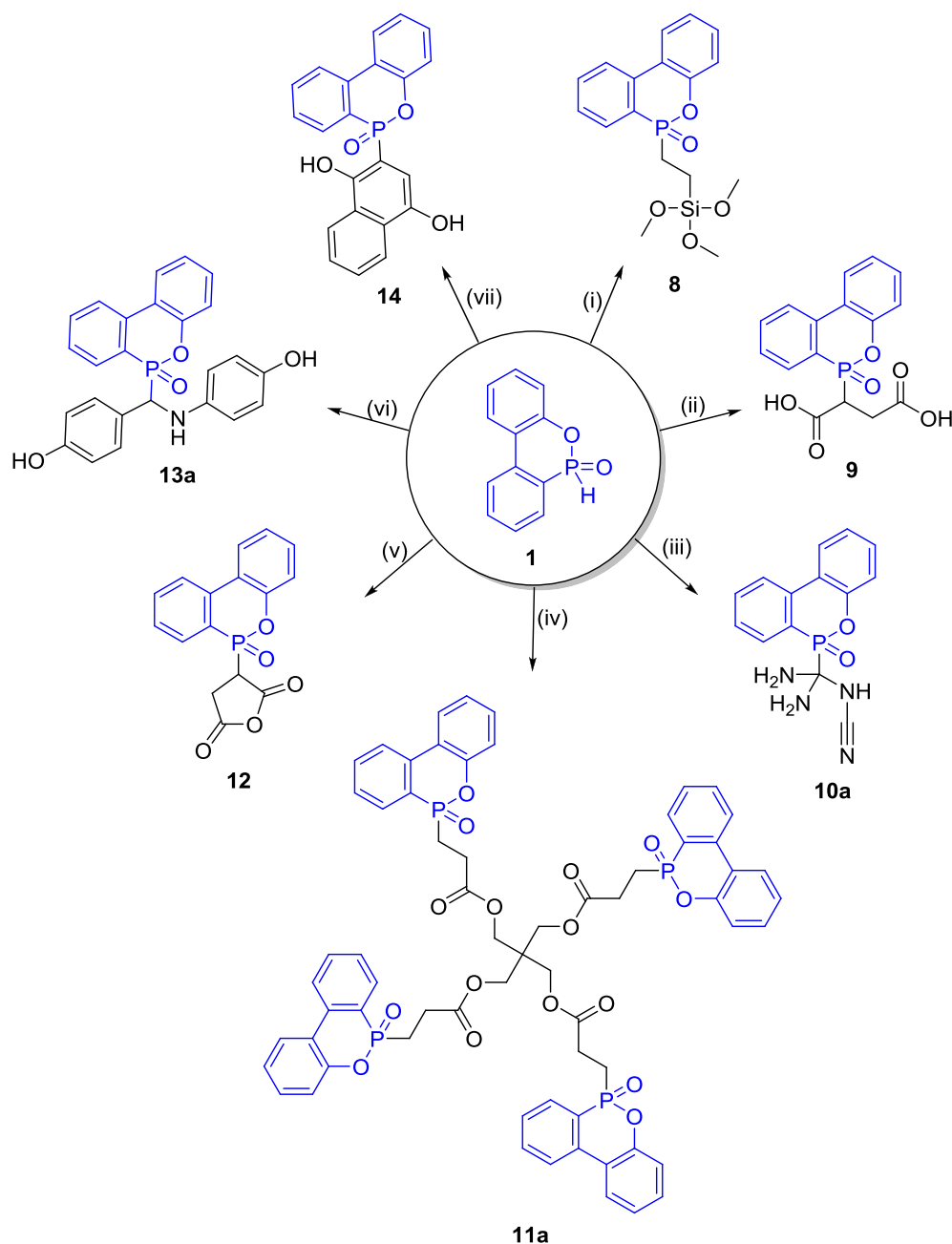
This synthetic approach was also followed by the same group to synthesis isocyanurate star-shaped DOPO derivative (**17**) using *p*-toluenesulfonic acid methylester as a catalyst (Fig. 5) [46].

DOPO-derivatives **16b** and **17** were investigated as flame retardant additives for epoxy resin (Table 2) [10,46].

Owing to the importance of P–C bond-formation in organic synthesis, many researches have been conducted to study the reaction mechanism of Michaelis–Arbuzov rearrangement. Mioskowski and coworkers [47] have proposed the bimolecular process mechanism using oxophilic lewis acids, such as $\text{BF}_2\cdot\text{OEt}_2$ or TMSOTf (Scheme 12a). Shum and coworkers also studied the rearrangement mechanism of some phosphites to phosphonate using triethylaluminum as a catalyst [48]. The reaction mechanism was followed by using NMR spectroscopy and proposed as shown in Scheme 12b.

2.1.3. Nucleophilic addition/substitution

Owing to the tautomeric equilibrium of DOPO and the electronic influence of aromatic group, it is expected that DOPO can undergo nucleophilic reactions [20]. For example, DOPO reacts with 4,4'-diaminobenzophenone (**DABP**) by nucleophilic addition on the carbonyl carbon, affording **18** (Scheme 13) [13,49,50].



Scheme 7. Some derivatives of DOPO (1), synthesized via Michael-type addition: (i) a) Vinyltrimethoxysilane (benzene, 80 °C); b) AIBN (benzene, 80 °C; 12 h) [33], (ii) Maleic acid (xylene:THF (1:1), 80 °C; 20 h) [34], (iii) dicyandiamide (130 °C) [35], (iv) a) Toluene (s) (100 °C); b) Tetra-[(acryloyl-oxy)ethyl] pentaerythrit (toluene, 100 °C; 2 h); c) 200 °C (10 mbar; 6 h) [11], (v) Maleic anhydride (THF; reflux) [8], or using xylene (80 °C; 24 h) [36], (vi) a) 4-aminophenol, 4-hydroxybenzaldehyde (MeOH, 50 °C; 5 h), b) the product from (a) was then used for the next step (THF, 60 °C; 12 h) [37], (vii) 1,4-naphthoquinone (inert solvent, dielectric constant ≤ 10) [38].

The amine moiety of **18** was then reacted with epichlorohydrin, followed by ring-closure in basic media to obtain high functionality epoxy resin. The obtained resin was then cured with different hardeners for aerospace and high performance applications [13]. Another example is reported by Dai and co-workers [51]. In their reported work, they reacted DOPO with 4-hydroxybenzaldehyde (**4-HBA**) to produce P–C bond, followed by the reaction with aniline using *p*-toluenesulfonic acid (***p*-TSA**) as catalyst to afford the reactive DOPO-derivative 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-yl-(phenylimino)-(4-hydroxyphenyl)-methane (**19**) (Scheme 14) [51].

Owing to the stereochemistry of the phosphorus and its adjacent methine carbon, compound **19** has two chiral centers and each stereocenter can have either *R* or *S* configuration. Accordingly, four stereoisomers can be obtained which can exist in two sets of diastereomers (*SR* + *RS* and *RR* + *SS*). Even though, only one set of diastereomers were found according to ^{31}P NMR spectra. Additionally compound **19** was investigated as active flame retardant in combination with 4,4'-diaminodiphenylmethane (**DDM**) in E51 epoxy resin. With increasing wt% of P-content in the resin, both char yield and LOI values were increased. By varying of P-content increased from 0 to 1.7%, LOI values improved from 24.5 to 33.5%.

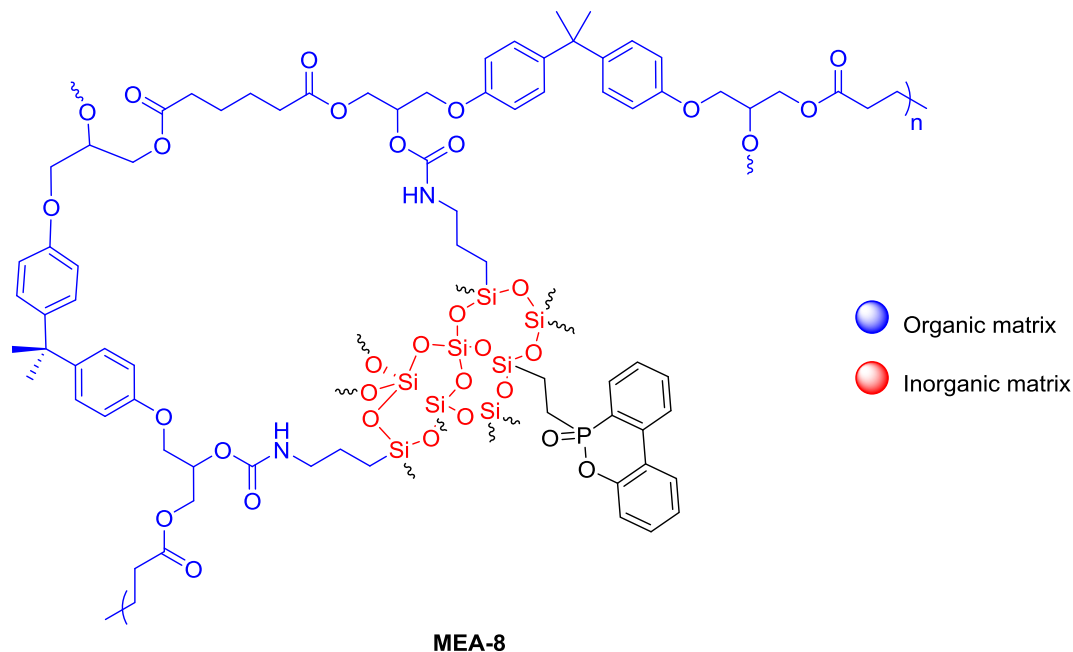
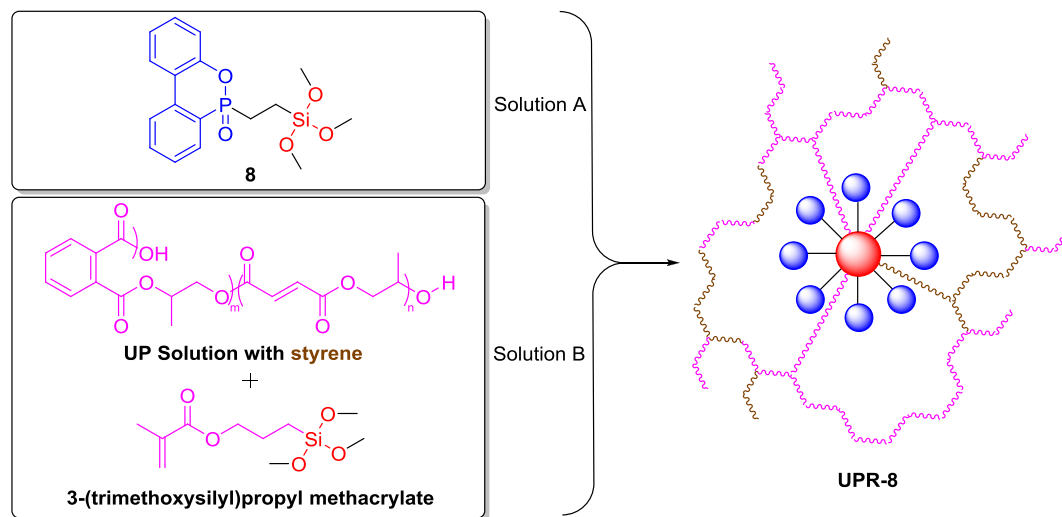


Fig. 1. Proposed substructure for the sol-gel and UV-curing reaction product of MEA and 8.



Scheme 8. Preparation process for UPR-8.

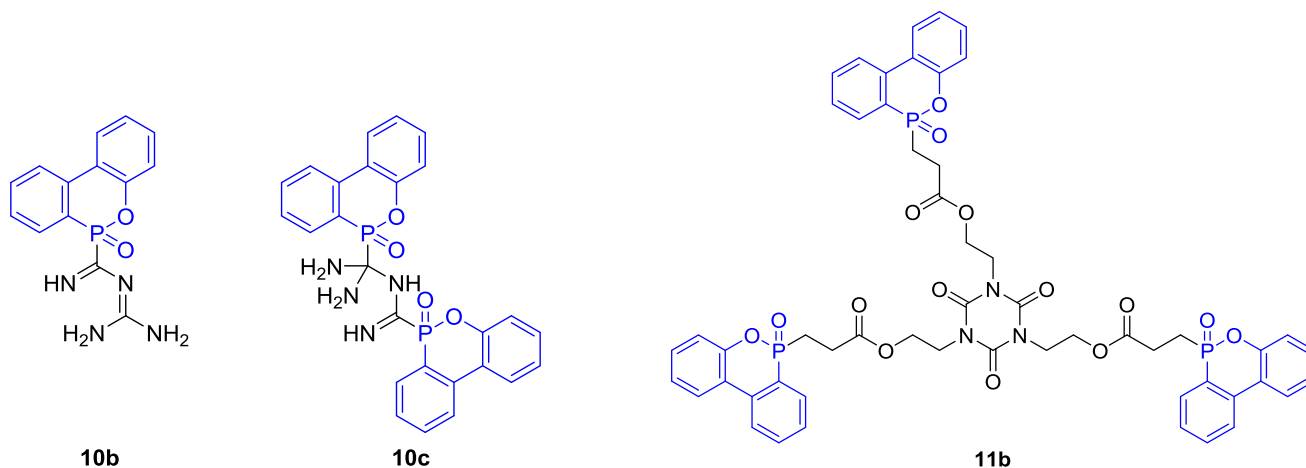


Fig. 2. By-products of the DOPO reaction with dicyandiamide [35].

Fig. 3. Chemical structure of star-shaped oligomer 11b.

Table 1
UL 94-V screening for epoxy resins using **11a–b** additives [41].

Additives	%P	Epoxy resin	
		RTM6	Epoxy novolac (DEN438) cured with DICY
11a	1.0	—	V0
	1.5	V1	V0
	2.0	V0	V0
11b	1.0	V1	V0
	1.5	V1	V0
	2.0	V0	V0

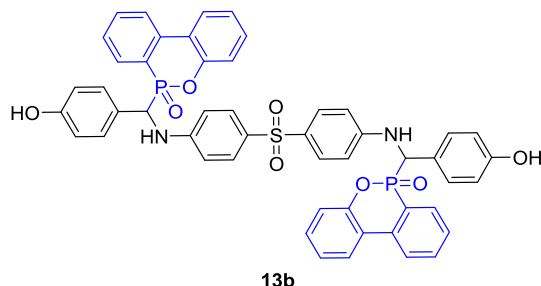
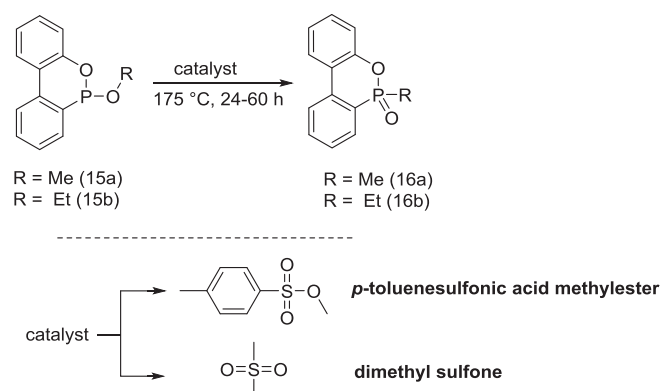


Fig. 4. Chemical structure of **13b**.

Additionally Dai and coworkers, proposed a mechanism for synthesis of compound **19** as illustrated in Scheme 15.

The accessibility of P–H bond to react with inorganic or organic bases enhances the ability of phosphorus atom to nucleophilic reactions. For example, bridged DOPO-derivatives were synthesized by reacting DOPO with *t*-BuOK in DMSO and disubstituted alkyl halides (Scheme 16) [15]. Side-chain phenol-functionalized poly(ether sulfone) with DOPO-pendant group was synthesized by Lin and coworkers following the above approach, using sulfuric acid as a catalyst [52]. Moreover, Lin and coworkers suggested the same proposed mechanism in Scheme 15. They used this polymer as curing agent for epoxy

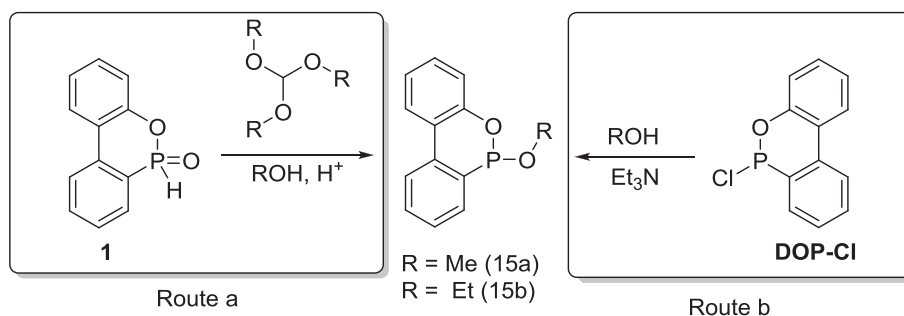


Scheme 11. Representative example of Michael–Arbuzov rearrangement of trivalent DOPO analogs.

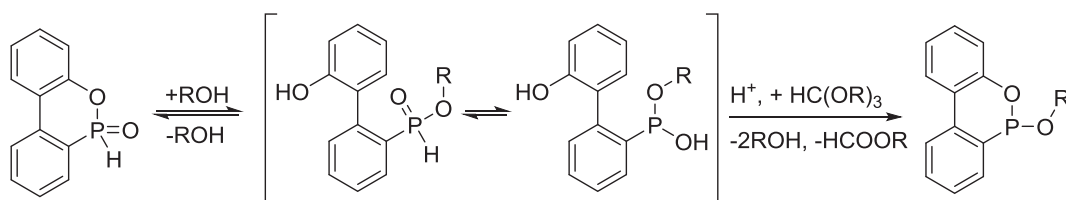
thermosets (GEBA and CNE). The produced epoxy resin showed enhanced thermal stability and flexibility. Recently, the similar approach was also followed by the same workers to synthesize DOPO-based acetoxybenzoic acid [53]. Compound **20a** was synthesized by nucleophilic addition of DOPO to 4-methylacetylphenone using *p*-TSA as a catalyst. It was then followed by electrophilic substitution of phenol to afford the corresponding product (Scheme 16), which was applied for synthesis of **18** [53]. Compound **20a** was acetylated, followed by oxidation of the resulting product to afford **20b** (Fig. 6) [53]. The authors tried to synthesis **20b** using the same approach in Scheme 16, using 4-acetylbenzoic acid as starting material via nucleophilic addition followed by reaction with phenol via the electrophilic substitution. They reported that, existence of the electron-withdrawing carboxylic acid group hinders this reaction.

Compound **20b** was then incorporated into poly(ethylene terephthalate) through acidolysis and polycondensation reaction at 280 °C in vacuum [53]. UL-94 results showed that 1.43 wt% of P-content in the polymer matrix is enough to achieve V0 rating.

Compounds **21a–c** were synthesized by nucleophilic substitution reaction of C_{sp3}–halogen bond with C_{sp3}–P bond (Scheme 17).



Scheme 9. Synthetic routes to trivalent phosphorus analogs of DOPO.



Scheme 10. Proposed mechanism for synthesis of trivalent analogs of DOPO.

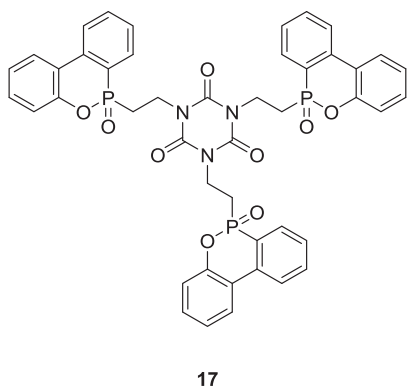


Fig. 5. Chemical structure of **17** [46].

Table 2

Some representative UL-94 and LOI test results of **16b** and **17** formulations in epoxy resins [10,46].

Additive	Epoxy system	Wt% P	UL-94	LOI
16b	DGEBA/DDS	1	V0	—
		2	V0	—
		3	V0	31
17	DGEBA/DDS	1	V1	—
		2	V0	—
		3	V0	32
	DGEBA/DICY/Fenuron	2.5	V2	—
	DEN 438/DICY/Fenuron	1.5	V0	—

DGEBA: bisphenol A diglycidyl ether, DDS: 4,4'-Diaminodiphenyl sulfone, DEN 438: epoxy novolac resin, DICY: dicyandiamide, Fenuron: 1,1-Dimethyl-3-phenylurea.

Compounds **21a–c** were investigated as flame retardant for epoxy resins for laminate application. In this study, DEN 438 novolac epoxy resin was used with Durite SD-1702 novolac curing agent [15]. V1 and V0 rating were obtained for formulations containing 3 wt% and 4 wt% P-content of compound **21a** in epoxy resin respectively. V0 ratings were also obtained for formulations of **21b–c** containing 4 wt% P.

It is noteworthy to mention that, the synthesis of bridged DOPO-derivatives leads to formation of diastereomers. For example, the stereoisomers of compound **21a** were produced and investigated recently (Scheme 18) [16].

These stereoisomers have different melting points as characterized by DSC and their ratio can be determined either by ^{13}P NMR or DSC data [16]. It was found that, the melting point of (*R,S*)-configuration is higher than the other stereoisomers. This observation is important for high temperature polymer application of these compounds. Chin and coworkers reported synthesis of phosphinated poly(2,6-dimethyl-1,4-phenylene oxide) [54]. The synthesis was performed via two steps, first brominating poly(2,6-dimethyl-1,4-phenylene oxide) and secondly nucleophilic substitution of DOPO. The flame retardancy of the resulting polymers was tested by UL-94 VTM test. VTM-o rating could be obtained for various formulations. Recently, Lin and coworkers extended their work on acid- or base-catalyzed fragmentation of bisphenol A to phenol and 4-isopropenylphenol and reported synthesis of other DOPO-derivatives via one-pot reaction of DOPO and bisphenol A analogs (Fig. 7) [55].

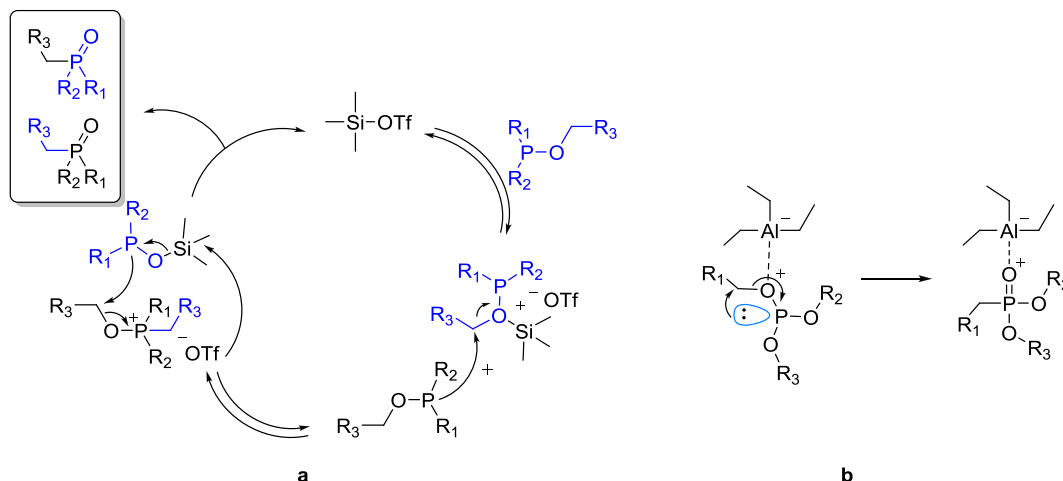
Lin and coworkers proposed carbocation addition mechanism where the protonated intermediate (protonated bisphenol A analogs) was fragmented to phenol and the carbocation species which is stabilized by electron-donating phenolic hydroxyl group, followed by attack of DOPO anion (Scheme 19) [55]. Compounds **22a–d** were further reacted with 1-chloro-2,4-dinitrobenzene via nucleophilic substitution form further DOPO derivatives. The corresponding diamino derivatives were then reduced to their corresponding diamines via hydrogenation over Pd/C catalyst to prepare co-polyimides.

2.2. P–heteroatom bond formation

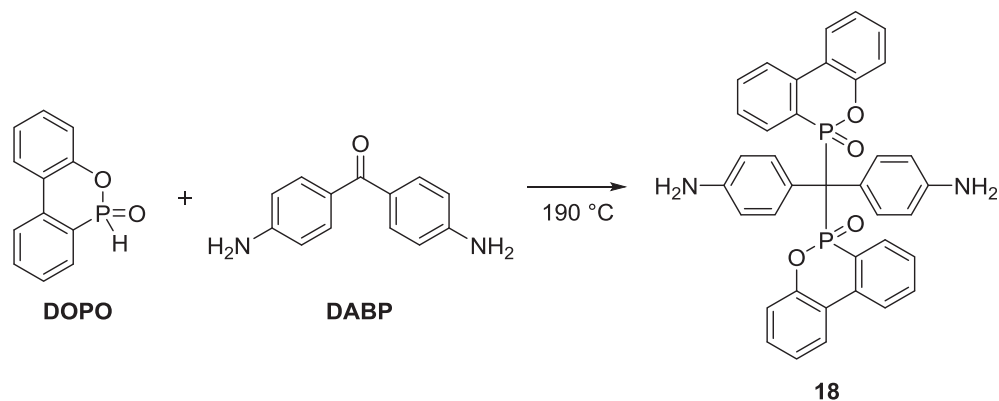
Two type of P–heteroatoms bond have been primarily investigated for DOPO-derivatives, namely P–O bond to prepare phosphonate type DOPO-derivatives or P–N bond to prepare phosphonamide type DOPO derivatives. In both cases, P–H bond activation of DOPO is intrinsic and crucial step to achieve P–N or P–O bond transformation. Two main reaction pathways are followed in the literature to prepare such DOPO-derivatives.

2.2.1. Atherton–Todd reaction

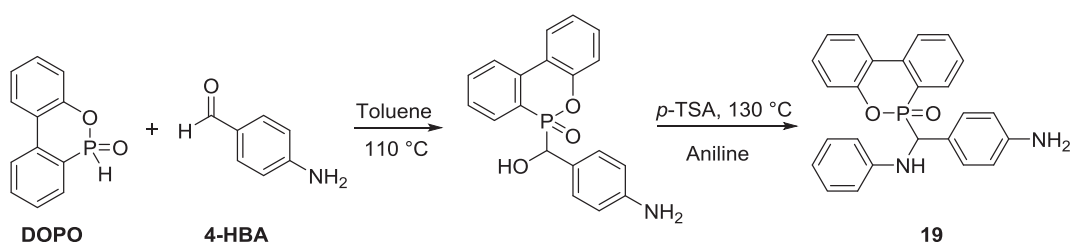
This reaction was first reported in 1945 by Atherton and Todd [56]. Atherton–Todd reaction is a transformation of P–H bond into P–Cl bond using carbon tetrachloride in presence of an organic base. In 1947, Atherton and Todd studied further the applicability of using polyhalogen compounds for this reaction [57]. The main



Scheme 12. Proposed mechanisms for Michaelis–Arbuzov rearrangement.



Scheme 13. Synthetic approach of 18.



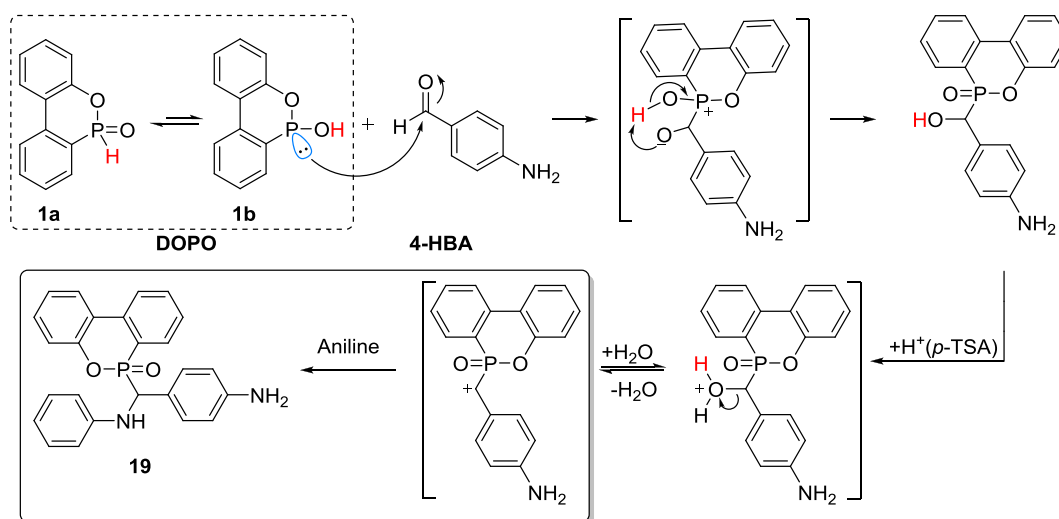
Scheme 14. Schematic two step synthesis of 19.

characteristic feature of this reaction is oxidation of P-atom which makes it eligible to be attacked by nucleophiles, namely oxygen and nitrogen [58]. This reaction is very effective and straightforward resulting in high yield of products. Despite numerous investigations to elucidate the Atherton–Todd reaction mechanism, the actual mechanism is not fully understood [59–63], especially the change in the oxidation state of P-atom. The reaction mechanism can be proposed as illustrated in Scheme 20.

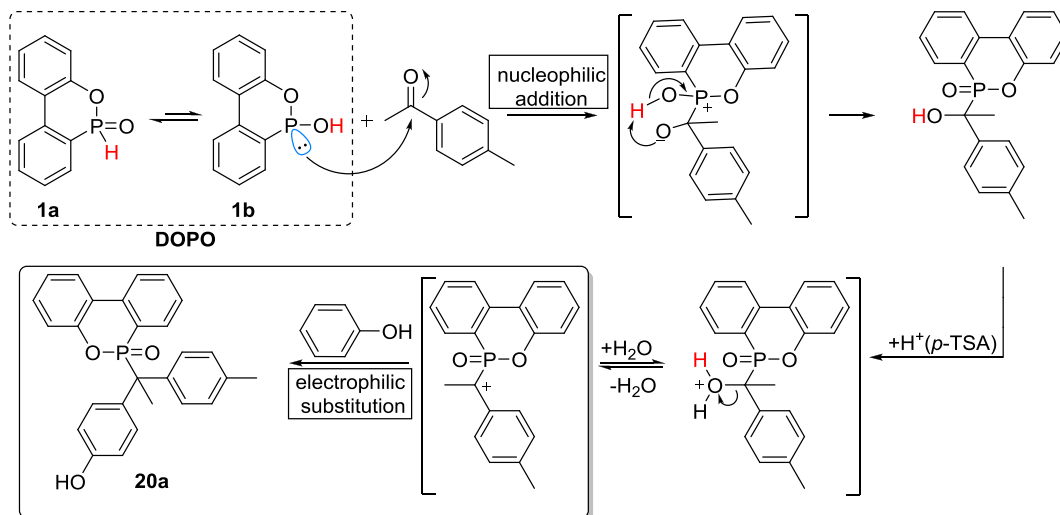
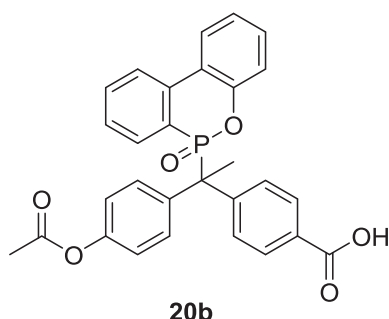
Abstraction of the proton from DOPO by the organic base initiates the chemical reaction which leads to formation of chemically active DOPO-Cl which is then used in situ without isolation. In a more detailed study on the stereo-structures of the

Atherton–Todd reaction products, Han and coworkers reported that this reaction is stereospecific [64]. Therefore, the reaction might proceed via P–Cl intermediate with S_N -type reaction, followed by S_N -type reaction at the phosphorus center to give the substitution products with inversion of configuration (Scheme 21) [65].

Despite the versatile nature of Atherton–Todd reaction and its wide application in phosphorus chemistry, it has not been exploited properly for P–Heteroatoms bond formation of DOPO compounds [4]. Recently, Gaan and coworkers used Atherton–Todd reaction to synthesize some novel bridged DOPO-derivatives with P–heteroatom bond (Scheme 22) [66,67].



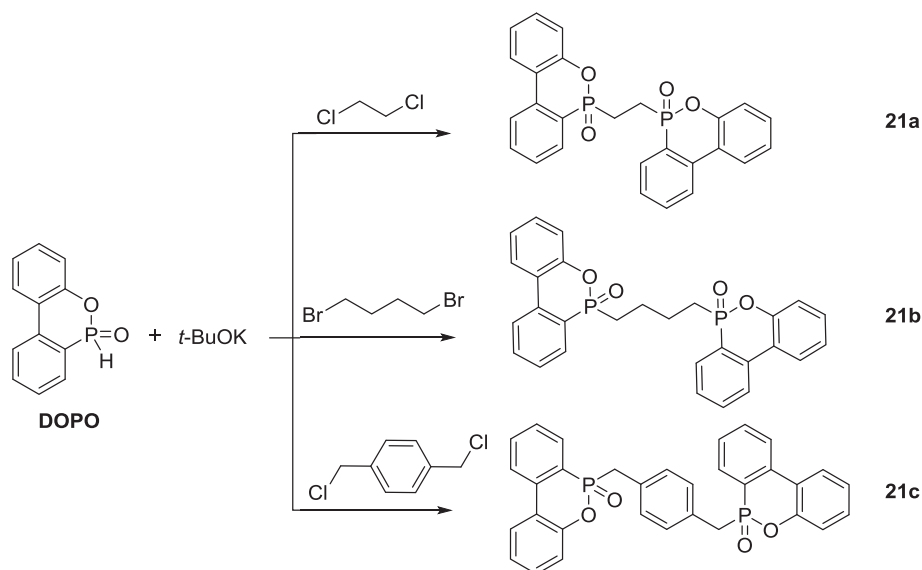
Scheme 15. Proposed mechanism for synthesis of 19.

Scheme 16. Synthetic approach and proposed mechanism of **20a**.Fig. 6. Chemical structure of **20b**.

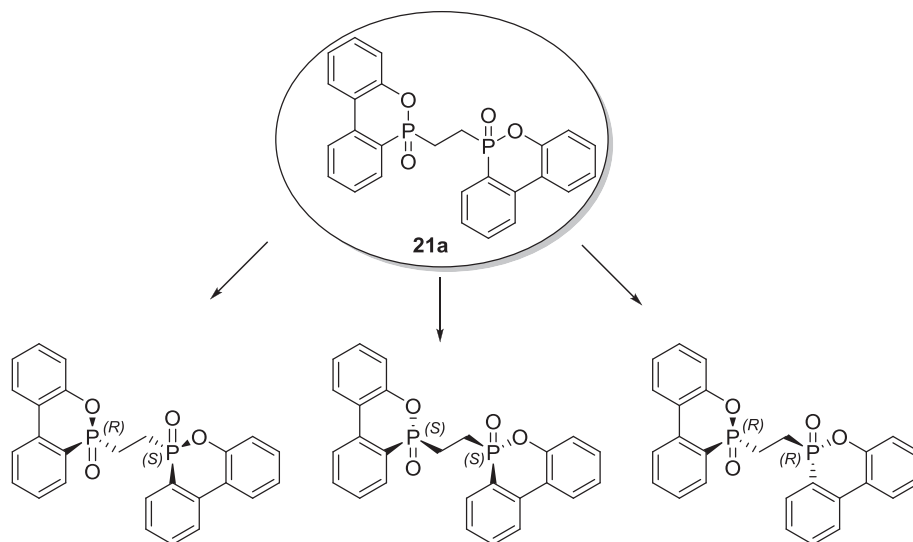
It is noteworthy to mention that owing to the exothermic nature of Atherton–Todd reaction, the reaction temperature should be maintained below 10 °C during addition of CCl_4 . The ^{31}P NMR spectrum of **23–26** exhibited two adjacent peaks, which

are attributed to presence of stereoisomers. However, compounds **23–26** showed high thermal stabilities, which make them potential compounds for high temperature processing applications. They have been reported as effective flame retardants for application in polyurethane foams and engineering plastics [66]. Döring and coworkers have also used Atherton–Todd reaction as versatile tool to synthesize some new DOPO-compounds (Fig. 8) [58]. Compounds **27–29** were prepared by reaction of the corresponding monofunctional nucleophiles with DOPO by dropwise addition of CCl_4 and Et_3N . These reactions were investigated by ^{31}P NMR spectroscopy to follow the reaction intermediate. It was found by NMR studies, that the reaction of the intermediate with the nucleophiles is the rate-limiting step [58]. Following the same route, Döring and coworkers synthesized compounds **30–32** and analyzed their microstructure using NMR spectroscopy [68].

In the same work, Döring and coworkers could synthesize the mixed anhydride DOPO-derivatives (**33**), using Atherton–Todd reaction as illustrated in Scheme 23 [58].



Scheme 17. Synthetic routes to synthesize bridged DOPO-derivatives with P–C bond formation.



Scheme 18. The stereoisomers of 21a.

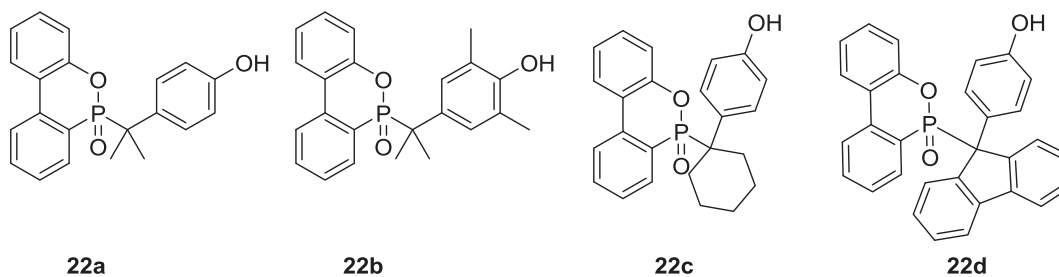
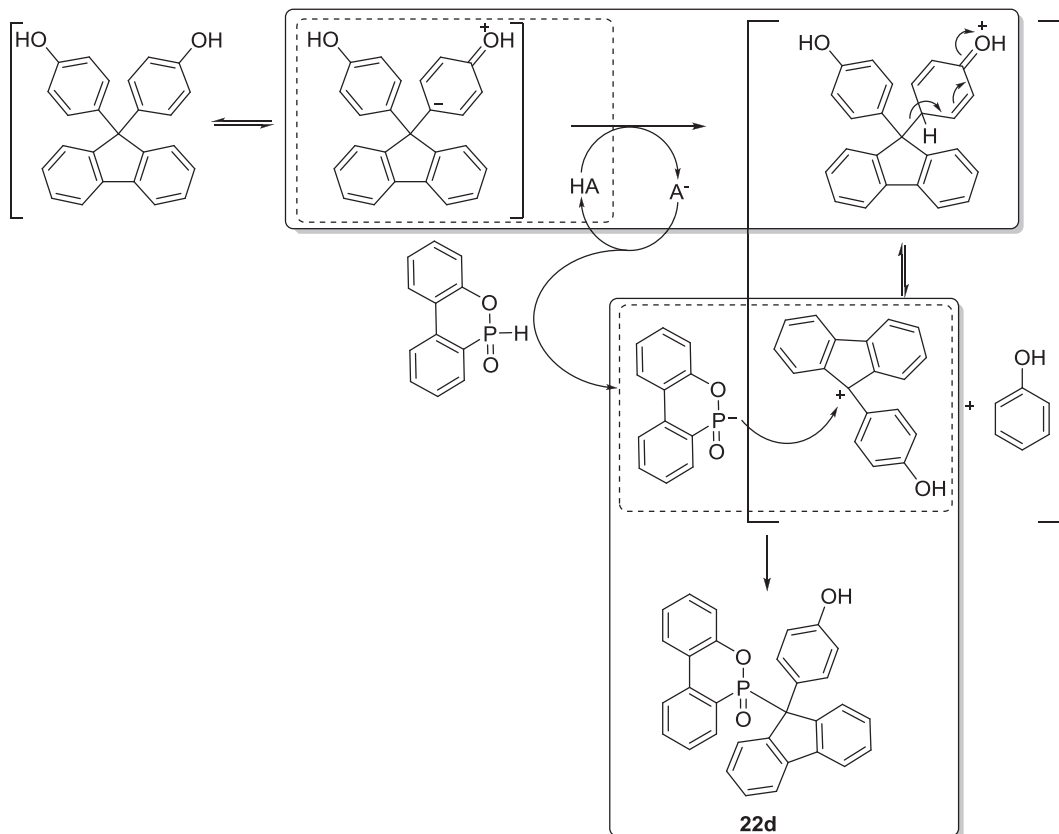
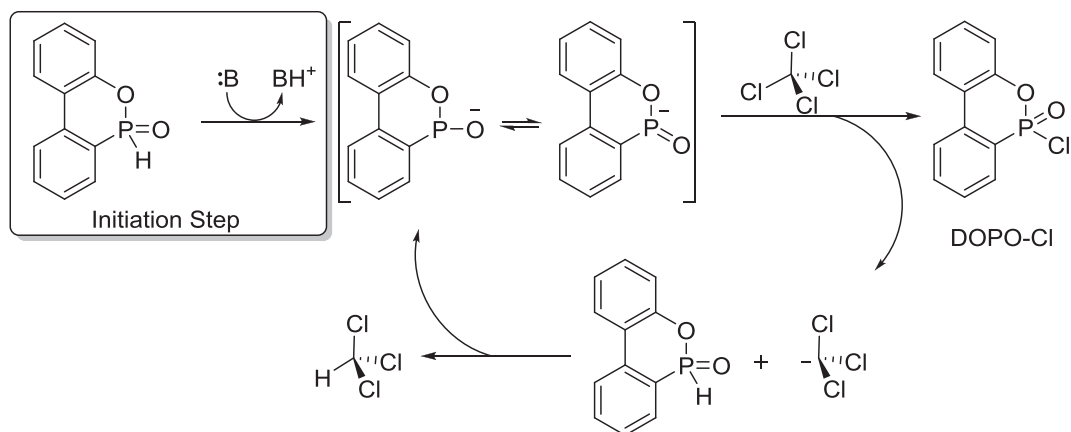


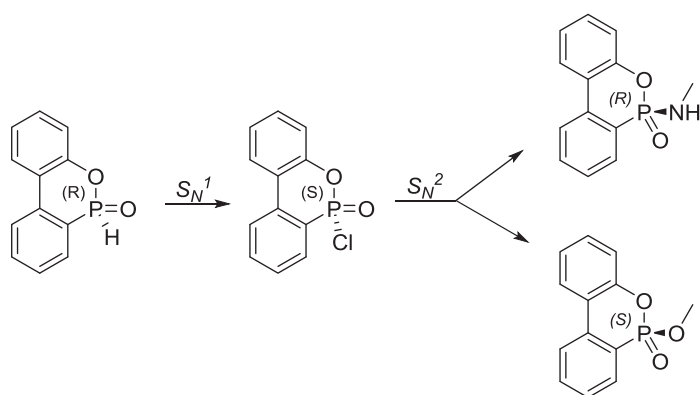
Fig. 7. Chemical structure of reaction product of DOPO and the corresponding bisphenol A.



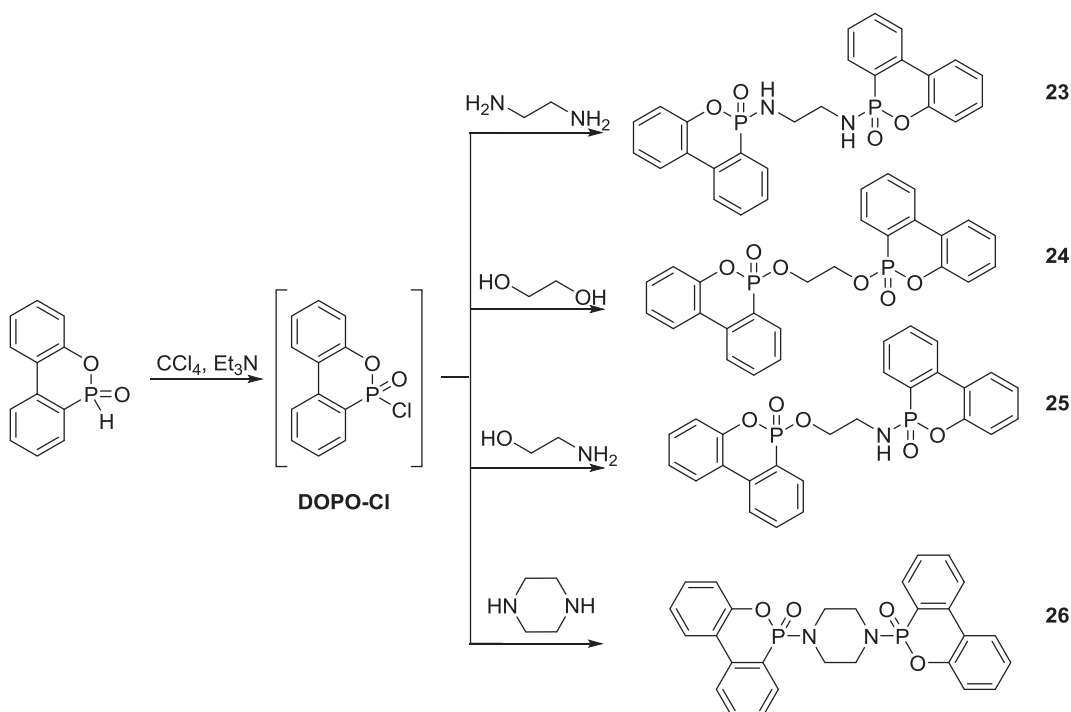
Scheme 19. Proposed reaction mechanism for synthesis of 22d.



Scheme 20. Proposed reaction mechanism of Atherton–Todd reaction.



Scheme 21. A plausible reaction mechanism for Atherton–Todd reaction of DOPO, with respect to stereochemistry.



Scheme 22. Schematic reaction path for synthesis of some bridged DOPO-derivatives with P–O and P–N bonds [66,67].

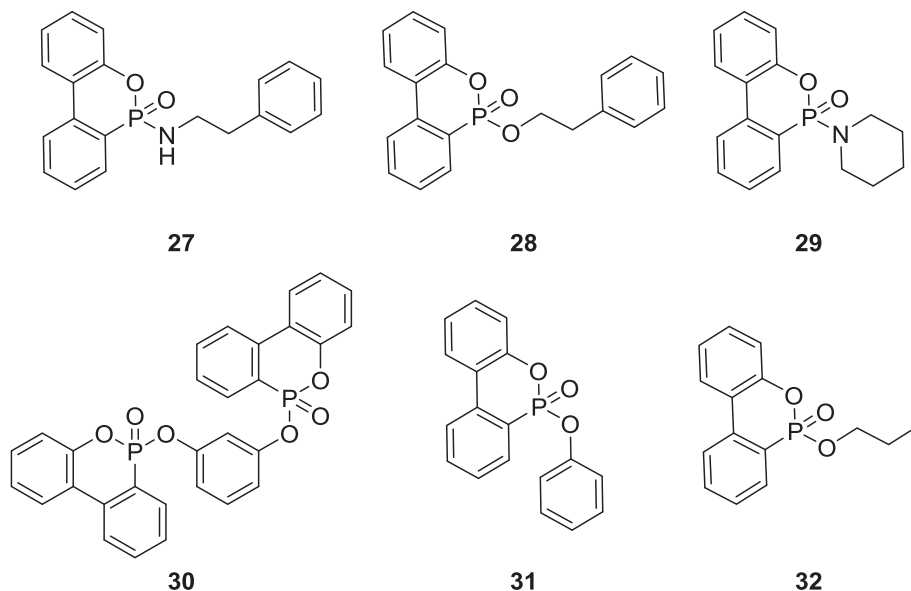
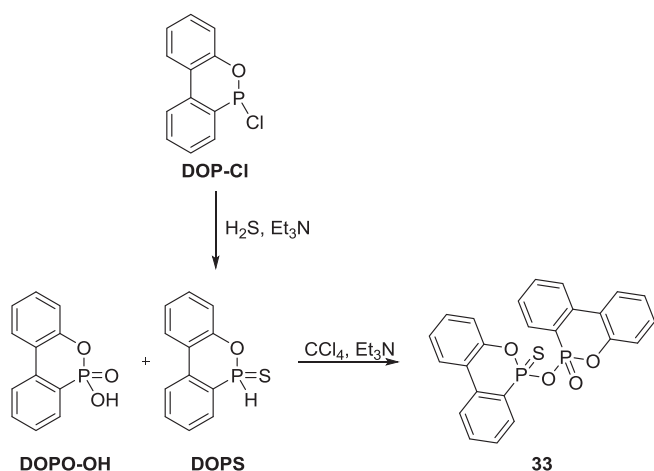


Fig. 8. Chemical structure of some DOPO-derivatives synthesized by Atherton–Todd reaction [58,68].



Scheme 23. Synthetic route of **31**, using Atherton–Todd reaction.

One can only find limited examples of P–heteroatoms bonds of DOPO-derivatives synthesized using Atherton–Todd reaction. The reason could be attributed to the carcinogenic nature of CCl₄ and its dangerous side effect on the ecosystem. For proper industrial exploitation, there is still a need to develop alternative synthetic routes to produce these DOPO-derivatives. Accordingly, Gaan and coworkers, tested some other synthetic approaches as potential alternative routes for Atherton–Todd reaction [9].

In their recent report, they investigated trichlorocyanuric acid (TCCA) and sulfonyl chloride as alternative chlorinating

agents [69,70]. Two new chlorinating agents were used to synthesize compounds **23** and **26** and five other DOPO derivatives (Fig. 9) [9].

Compared to Atherton–Todd reaction, TCCA as chlorinating agent is highly exothermic which hinders adaptation for industrial purpose. On the other hand, sulfonyl chloride evolves HCl and SO₂ as byproducts which need to be removed and disposed. However, sulfonyl chloride could be used as an alternative approach to replace Atherton–Todd reaction for upscaling of amino–DOPO derivatives in industrial scale. In future, more sustainable approaches to develop DOPO derivatives need to be developed.

2.2.2. Using DOP-Cl as starting material

DOP-Cl is an intermediate to synthesize DOPO which is already isolated and commercialized. Owing to its high reactivity, many researchers used DOP-Cl as reactant with nucleophiles for P–O or P–N bond formation. For example, 1,4-bis(6*H*-Dibenzo[*c,e*][1,2]oxaphosphinin-6-yl)-piperazine (**39**) was synthesized by reacting of DOP-Cl with piperazine in dry chloroform [71]. Afterward, **39** was oxidized by using H₂O₂ in ethyl acetate to afford **26**. If **39** is heated in presence of sulfur, 6,6'-(Piperazine-1,4-diyl)-bis(6*H*-dibenzo[*c,e*] [1,2]oxophosphinine-6-sulphide) (**40**) is produced (Scheme 24) [71].

The flame retardancy of **26** and **40** were tested in epoxy resin (DEN 438/DICY/Funoron). A UL 94 V0 rating for **26** and **40** were obtained at 9.79 and 16.48 parts per hundred part of resins, respectively [71].

Starting from DOP-Cl, BASF has reported novel bridged DOPO-derivatives as shown in Fig. 10 [72]. Compounds **41–46**, were investigated and tested as flame retardants.

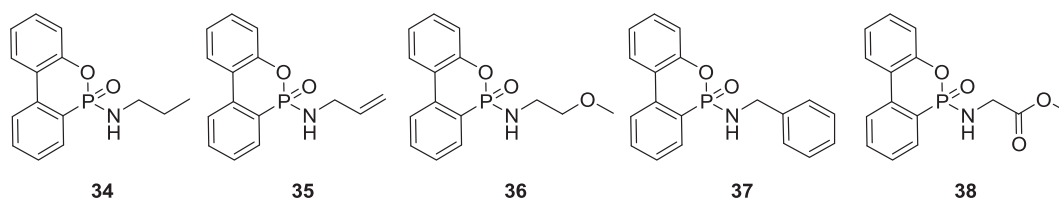
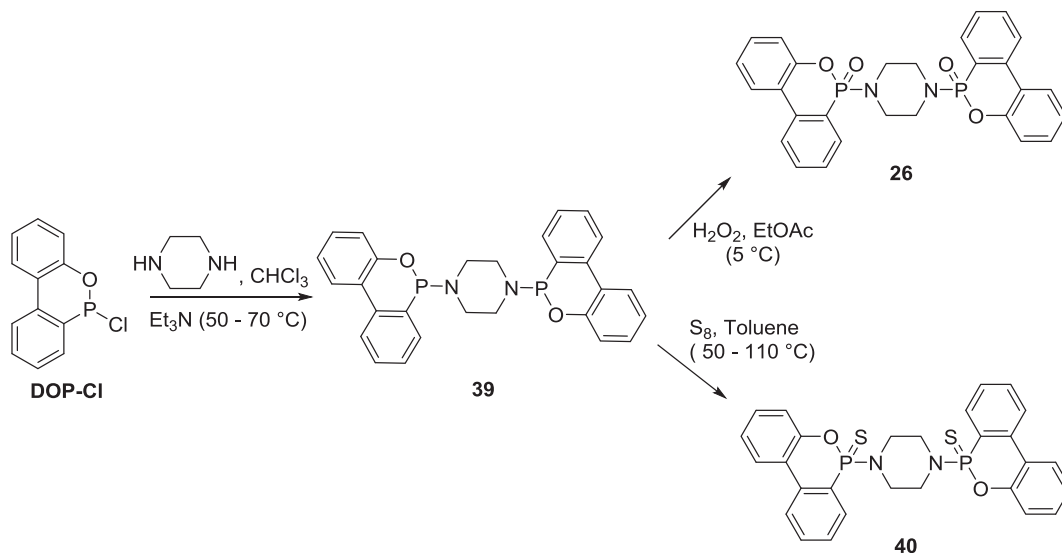


Fig. 9. Chemical structure of P–N bond of DOPO-derivatives, synthesized using different chlorinating agents as well as compounds **23** and **26** [9].



Scheme 24. Synthetic approach of **26** and **40** starting from DOP-Cl.

Recently, Krems Chemie Chemical Services AG has patented synthesis of some triazine-based DOPO-derivatives using DOP-Cl as starting materials. The DOPO-derivatives were then oxidized in ethyl acetate using H_2O_2 to afford the corresponding DOPO-derivatives with P–N bond formation (Fig. 11) [73].

3. Conclusion

Although DOPO was discovered in 1972, only recently it and its derivatives have attracted a lot of attention in flame retardant community. Economical ways of producing DOPO and need for developing halogen free flame retardants have definitely helped its recent commercial exploitation. Various chemistry of DOPO has been developed within the last decades affording various DOPO-derivatives with P–C, P–N and P–O bond functionality. A

majority of P–C bonded DOPO derivatives find application as flame retardants in epoxy resins as reactive and non-reactive system. Application of DOPO derivatives for developing inherently flame retardant polyester and polyamide fibers has also found commercial success. More recently P–N and P–O bonded DOPO derivatives have found application in polyurethane foams, epoxy resins and engineering plastics. The chemistry of DOPO-derivatives with P–C bond formation has been thoroughly studied and many chemical reactions investigated. On the other hand, synthesis of DOPO-derivatives with P–heteroatom bond formation is still relatively unknown. The reason may be attributed to unavailability of suitable economic and environmental friendly chlorination method for DOPO which serves as intermediate for further substitution with nucleophiles. For future commercial exploitation of DOPO derivatives, there is a need to investigate alternative methodologies to

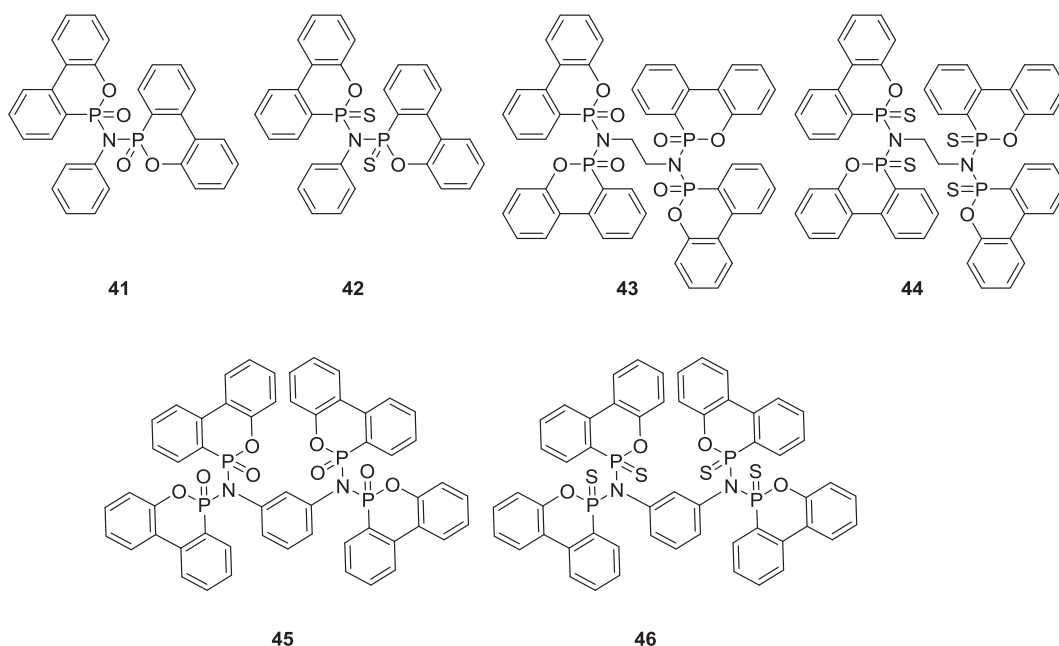


Fig. 10. Novel bridged DOPO-derivatives with P–N bond, synthesized from DOP-Cl as starting material [72].

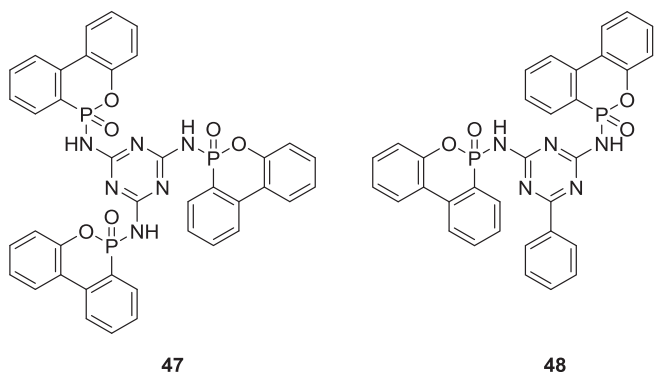


Fig. 11. Chemical structures of melamine- and benzoguanamine-based DOPO-derivatives, **47** and **48**, respectively [73].

activate the P–H bond of DOPO. Understanding the detailed reaction mechanism is the key to developing new DOPO based chemistry.

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