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o-BENZENEDISULFONIMIDE: AN ORGANIC REAGENT AND ORGANOCATALYST OF RENEWED INTEREST

M. Barbero,* S. Bazzi, S. Cadamuro, S. Dughera

Dipartimento di Chimica Generale e Chimica Organica dell’Università, Università di Torino, Via P. Giuria 7, I 10125 Torino, Italy.

Fax: +39 011 6707642

E-mail: margherita.barbero@unito.it
ABSTRACT:

Synthesized nearly one century ago as a saccharine-like sweetener compound, the \textit{o}-benzenedisulfonimide has received a discontinuous attention in the past. In the last century, various synthetic procedures have been reported, in confirmation of the interest in this intriguing compound. In recent years, it has been used as a leaving group in reactions of nucleophilic substitution of amines with alcohols or phenols to give the corresponding ethers. Its \textit{N}-fluoroderivative is a stable and efficient fluorinating agent, which has found applications in several asymmetric syntheses. In previous studies, its conjugated base has been extensively used as stabilizing counter-ion of arenediazonium salts; safely isolated and stored in a dry state, ready to use, they have been applied successfully in many dediazoniation reactions, with interesting mechanistic insights. More recently, due to its high acidity, the \textit{o}-benzenedisulfonimide has been used in catalytic amounts in some common acid-catalyzed organic reactions. Valuable aspects of this catalyst are its easy recovery from the reaction mixture and its reuse in other reactions, with clear economic and ecological advantages. Finally, the disulfonimide functional group has been proposed as a powerful chiral motif for strong Brønsted acids in asymmetric organocatalysis.

\textbf{Keywords:} \textit{o}-benzenedisulfonimide, organic synthesis, stabilizing anion, organocatalysis, recoverable catalyst, recyclable catalyst.
In this review, we report a survey of the literature concerning the synthetic applications and the useful potential of an organic reagent and organocatalyst of renewed interest, the \( o \)-benzenedisulfonimide (1), and its derivatives.

\[
\begin{align*}
\text{SO}_2 & \quad \text{NH} \\
\text{SO}_2 & \quad 1
\end{align*}
\]

Fig. (1).

Cyclic disulfonimides are strong Brønsted acids: their acidity is comparable to that of strong mineral acids, higher than acyclic analogues; the acid-strengthening effect of the sulfonyl groups is likely enhanced by the incorporation in the five-membered ring [1a]. Several such compounds are reported in literature: by varying the ring size from 4 to 9, a substructure search on CAS databases resulted in 495 substances (using SciFinder software client, updated on 06/29/2009), most of them perfluorinated. In this review, we will cover the literature concerning synthesis, reactivity, and applications of the title compound and derivatives, following the chronological development.

1. **SYNTHESIS OF \( o \)-BENZENEDISULFONIMIDE AND DERIVATIVES**

1.1 **SYNTHESIS OF \( o \)-BENZENEDISULFONIMIDE (1) AND RELATED STRUCTURES**

In general, cyclic disulfonimides have been prepared either by cyclization of disulfonyl halides (chlorides or fluorides) with ammonia and subsequent \( N \)-derivatization, or by cyclization of disulfonyl chlorides with ammonia derivatives. As a consequence, the key intermediate for the synthesis of the 1,3,2-benzodithiazole-1,1,3,3-tetraoxide (\( o \)-benzenedisulfonimide, 1) is the \( o \)-benzenedisulfonyl chloride (2). This, by reaction with ammonia or derivatives, gives always the imide derivatives as major products, along with very low amounts of the corresponding bisamides.
All syntheses of 1 differ only by the starting reagent to prepare 2, the intermediate reaction steps or the purification procedure. The only real difference in the cyclization of o-benzenedisulfonyl chloride is that with nitrous acid, followed by reduction of the intermediate N-hydroxy derivative.

Fig. (2).

o-Benzenedisulfonimide was synthesized for the first time by Holleman [2] and Hurtley and Smiles [3], nearly contemporarily, in 1921 and 1926. Both syntheses started from o-aminobenzenesulfonic acid (3) via a very troublesome multistage route, and were differing in the oxidation step (HNO₃ or KMnO₄) and in the conversion of the disulfonyl chloride 2 into disulfonimide 1, via acidification of the intermediate ammonium salt 8 [2] or via reduction of the N-hydroxy derivative 9 (Scheme 1) [3].

Scheme 1.

These procedures were successively modified by Hendrickson and co-workers [4], by using gaseous ammonia in benzene/ethanol for the cyclization step (quantitative yield of ammonium salt, “sweet taste”), and Dowex 50X8 ion-exchange resin for the purification of 1 (79% yield from 2).
They described the acid 1 as “fully ionized in (and not extractable from) water and ... possess acidity comparable to that of hydrochloric acid”. In 1993 Blaschette’s group [5] modified substantially the preparation of the disulfonyl chloride 2 from acid 3 [6], using then gaseous ammonia in toluene/ethanol for the cyclization step and Lewatit S 100 ion-exchange resin for the purification (Scheme 2).

![Scheme 2](image)

An improved synthesis of o-benzenedisulfonimide was proposed by Davis and co-workers [7], in a four-step process starting from Li-benzenesulfonate (10) (49% overall yield); the sole purification step was the final filtration on Dowex ion-exchange resin (Scheme 3).

![Scheme 3](image)

Finally, two procedures have been reported to prepare the disulfonyl chloride 2. In 1986, it was prepared starting from anthranilic acid (13), through its conversion into the intermediates 2-(3-methylbutoxy)-1,3-benzodithiole (14) or 1,3-benzodithiolium tetrafluoroborate (15), and treatment with chlorine/water; the overall yield of 2 from 13 was 46% via isolated 14 or 62–67% via isolated...
The product 2 was then converted into 1 in 83% yield by a slightly modified procedure (Scheme 4) [9].

![Chemical Reaction Diagram]

**Scheme 4.**

The second procedure was patented in 1996: amongst a number of aromatic and heteroaromatic sulfonyl halides prepared by oxidative chlorination or bromination of methyl sulfides or methyl sulfoxides, in the presence of water, 2 was obtained in 82% yield from o-bis(methylsulfanyl)benzene (16) [10].

![Structural Chemical Compound Image]

**Fig. (3).**

In conclusion, the key intermediate of the above syntheses is o-benzenedisulfonyl chloride (2), which accordingly can now be prepared starting from the commercially available o-benzenedisulfonic acid dipotassium salt [3,7], anthranilic acid [8], o-aminobenzenesulfonic acid [2–4,6,11], and from o-bis(methylsulfanyl)benzene [10]. In recent times, o-benzenedisulfonyl chloride has become commercially available, and now also o-benzenedisulfonimide is sold.

Structurally related to o-benzenedisulfonimide are compounds 17 [12], 18 [13], and 19 [14]; 17 and 18 were obtained from the corresponding disulfonyl chlorides and ammonia, and 19 by pyrolysis of the corresponding N-R derivatives (N-R derivatives were prepared from the disulfonic
anhydride and primary amines, then treated with P₂O₅; direct reaction with ammonia failed). No further studies were done after their synthesis.

Fig. (4).

In confirming the renewed interest in this class of compounds, while this manuscript was being reviewed, two studies regarding the cyclic disulfonimides 20 [15] and 21 [16] below have been published. The disulfonimide functional group has been introduced as new chiral motif in these strong Brønsted acids.

Fig. (5).

(R)-3,3’-Bis[3,5-bis(trifluoromethyl)phenyl]-1,1’-binaphthyl-2,2’-disulfonimide (20) and (R)-1,1’-binaphthyl-2,2’-disulfonimide (21) were synthesized from the optically pure 1,1’-binaphthyl-2,2’-diols 22 through the intermediate O,O’-diaryl bis(N,N-dimethylthiocarbamates) 23, then isomerized to the S,S’-diaryl bis(N,N-dimethylthiocarbamates) 24 by a Newman–Kwart rearrangement. The two synthetic procedures differ on the subsequent oxidation step and conversion to the disulfonfonyl chlorides 26, key intermediates of the target chiral imides (Scheme 5).
Scheme 5.

1.2 SYNTHESIS OF o-BENZENEDISULFONIMIDE DERIVATIVES

N-Hydroxy-o-benzenedisulfonimide (9):

N-Hydroxy-o-benzenedisulfonimide (9) was first prepared by Hurtley and Smiles in 88% yield through reduction of o-benzenedisulfonyl chloride (2) and then reaction with nitrous acid (Scheme 1) [3]. The same sequence was adopted by Hendrickson and co-workers giving 83% yield of 9 [4], and then improved by Kice and Liao in 1981 (92% yield of product) (Scheme 6) [17].

Scheme 6.
**N-Halogen-o-benzenedisulfonimides (27, 30):**

In Hendrickson’s fundamental work, several derivatives of o-benzenedisulfonimide were prepared as attractive synthetic tools, since the imide anion seemed to be a good leaving group, owing to the charge stabilization by the two sulfonyl moieties. Unfortunately, most of these compounds did not show the expected reactivity; only halides 27 (X = Cl, Br) were very active sources of halogen cations. Their synthesis was achieved by treating anhydrous silver o-benzenedisulfonimide 29 (from 1 and silver oxide) with chlorine or bromine in trifluoroacetic anhydride (Scheme 7) [4].

![Scheme 7.](image)

**N-Fluoro-o-benzenedisulfonimide (30):** was synthesized in high yield by Davis and co-workers about 30 years later, as a stable and easily prepared highly efficient source of “electrophilic” fluorine, and until now it has been used in a significant number of reactions (Scheme 8) [18].

![Scheme 8.](image)

**N-Aryl, N-Alkyl and N-dialkylaminoalkyl-o-benzenedisulfonimides (31):**

N-Aryl and N-arylalkyl o-benzenedisulfonimide 31 were prepared according to Hurtley and Smiles [3] from o-benzenedisulfonyl chloride and aniline in essentially quantitative yield, or with
primary arylalkyl amines in EtOH solution, in the presence of sodium acetate: in this case the bisamides were recovered in considerable amounts (Scheme 9) [4].

\[
\begin{align*}
\text{SO}_2 & \quad \text{N} & \quad \text{SO}_2 \\
\text{R} & \quad \text{SO}_2 & \quad \text{N} & \quad \text{R} \\
2 & \quad \text{R} & \quad \text{SO}_2 & \quad \text{N} & \quad \text{SO}_2 \\
31 & \quad \text{R} & \quad \text{SO}_2 & \quad \text{N} & \quad \text{SO}_2 \\
\end{align*}
\]

\[ R = \text{Ph (quant.)}, \text{PhCH}_2 (36\%), \text{PhCH}_2\text{CH}_2 (51\%) \]

Scheme 9.

\[ N\text{-Alkyl analogues 31 were unusually prepared in low yields by electrophilic alkylation, by refluxing sodium } o\text{-benzenedisulfonimide (32) with alkyl iodides or dialkylaminoalkyl chlorides in ethyleneglycol monoethyl ether-water mixtures (Scheme 10) [19].} \]

\[
\begin{align*}
\text{SO}_2 & \quad \text{N} & \quad \text{SO}_2 \\
\text{R} & \quad \text{RX} & \quad \text{SO}_2 & \quad \text{N} & \quad \text{SO}_2 \\
32 & \quad \text{R} & \quad \text{SO}_2 & \quad \text{N} & \quad \text{SO}_2 \\
31 & \quad \text{R} & \quad \text{SO}_2 & \quad \text{N} & \quad \text{SO}_2 \\
\end{align*}
\]

\[ R = \text{Me (37\%); Et (56\%); Pr (34\%); Bu (57\%); Et}_2\text{NCH}_2\text{CH}_2 (55\%); \text{Et}_2\text{NCH}_2\text{CH}_2\text{CH}_2 (26\%); \text{Bu}_2\text{NCH}_2\text{CH}_2 (62\%) \]

Scheme 10.

\[ N\text{-Methyl analogue (31; R = Me) was also prepared in quantitative yield from anhydrous silver } o\text{-benzenedisulfonimide (29) and methyl iodide in acetonitrile [20], whilst } N\text{-1-adamanthyl analogue was prepared from 29 and 1-bromoadamanthane in anhydrous benzene in 95\% yield [21]. Poor yields of } N\text{-phenyl-} o\text{-benzenedisulfonimide were obtained in transamidation reaction of sulfonimide 1 and aniline at 184–200 °C, whilst good yields were obtained starting from } N\text{-methyl-} o\text{-benzenedisulfonimide [22].} \]

\[ N\text{-Dialkylcarbamoyl-} o\text{-benzenedisulfonimides (32):} \]

Title compounds 32 were prepared treating silver } o\text{-benzenedisulfonimide (29) with diethyl or dimethylcarbamoyl chloride (Scheme 11) [23]; the molecular crystal structure was determined, the urea moiety showed a non-planar geometry.
Scheme 11.

\textit{N-Trialkylsilyl and N-trialkylstannyl-o-benzenedisulfonimides (33) (34)}:

Prepared by metathesis of silver 1,2-benzenedisulfonimide (29) with the appropriate trialkyl chlorosilane or chlorostannane, their crystal structures were determined [24]. Compounds 33 displayed unusually long bonds between the trigonal-planar \( N \) and the tetrahedrally coordinate \( \text{Si} \) atom [24b]; the solid state structures suggested that the N-Si bond lengthening in these disulfonylated aminosilanes is induced by the \( \pi \)-acceptor character of the sulfonyl groups.

\[ \text{29} \quad \overset{\text{MeCN}}{\longrightarrow} \quad \text{33: } M = \text{Si} \]

\[ \text{34: } M = \text{Sn} \]

Scheme 12.

\textbf{Miscellaneous \( N \)-derivatives:}

In order to check the activity of the conjugate base as good leaving group in electrophilic substitution reactions, several \( N \)-substituted derivatives were synthesized [4]. With the exception of the more promising compounds cited above (9,27,30), \( N \)-methoxy-o-benzenedisulfonimide was prepared by reaction with diazomethane but without synthetic developments, whilst other derivatives could not be prepared.
2. SYNTHETIC APPLICATIONS OF o-BENZENEDISULFONIMIDE AND DERIVATIVES

2.1 o-BENZENEDISULFONIMIDE DERIVATIVES

*N*-Hydroxy-o-benzenedisulfonimide (9):

Compound 9 was studied as a potential source of hydroxyl cations (as a peracid) both as Baeyer-Villiger reagent and oxidant agent of aldehydes to acids, but the results were negative [4]. Nearly 30 years later, the oxidizing properties of 9 were reconsidered and exploited by Degani and Fochi in the conversions of benzyl alcohols 35 to benzaldehydes 36, benzaldehydes 36 to benzoic acids 37, sulfides 38 to sulfoxides 39, and thiols 40 to disulfides 41 (Scheme 13) [25]. The reaction conditions were mild, highly selective regarding the oxidation of sulfides to sulfoxides, and chemoselective: 4-(methylsulfanyl)benzaldehyde gave excellent yield of the corresponding sulfoxide, leaving the formyl group unchanged.

Scheme 13.
**N-Fluoro-o-benzenedisulfonimide (30):**

Although inactivated aromatic compounds were efficiently halogenated by using N-chloro- and N-bromo-o-benzenedisulfonimide (27) [4], these reagents did not receive further studies. Only N-fluoro analogue is currently used as a halogenating agent.

As confirmed by the number of scientific publications, electrophilic fluorination has recently attracted considerable attention in organic synthesis, since fluorinated chemicals find applications in organic, agricultural, medicinal and material chemistry fields. Furthermore, several examples of asymmetric synthesis of fluorinated molecules have been successfully achieved. The topic is covered in many reports, and synthetic applications of compound 30 have been reviewed and compared with other fluorinating agents [26]. Without discussing all the examples, we will report on the most significant ones below.

*N*-Fluoro-o-benzenedisulfonimide (NFOBS, 30) was synthesized as above by Davis and co-workers (Scheme 8); they also performed the most significant work in the area of electrophilic fluorination of metal enolates (enolates, azaenolates, 1,3-dicarbonyl compounds, *ortho*-methalated aromatic compounds, silyl enol ethers [18b]), and highly diastereoselective electrophilic fluorination of chiral metal enolates (imide enolates [27]). *N*-Fluoro reagents with different reactivities have been developed to overcome the limitations of fluorinating procedures employing highly reactive, corrosive and toxic reagents. Amongst them, *N*-fluoro-o-benzenedisulfonimide (30) and *N*-fluorobenzenesulfonimide [(PhSO2)2NF, NFSI, 42] are particularly interesting because of their high reactivity, stability and ease of preparation. In the cited paper [18b], metal enolates, silyl enol ethers, and 1,3-dicarbonyl compounds gave α-fluorinated products in high yields. Good control of monofluorination *versus* difluorination was generally observed. Interestingly, difluorination was explained by the enolization, and hence the difluorination, induced by the acidity of the *o*-benzenedisulfonimide. NFOBS was sufficiently reactive to directly fluorinate activated aromatics, but not selectively. Regiospecific reaction was accomplished on aromatic organometallic compounds: Grignard reagent, phenyllithium, and *ortho*-lithiated aromatic substrates (generated
from directed metalation group aromatics, DMG, with alkyllithiums). Both 30 and 42 showed similar reactivity, but better yields were obtained with 30 in metal enolates, Grignard reagents and lithium reagents fluorination, whereas 42 gave better yields in the fluorination of lithiated arenes (Scheme 14). The difference has been related to the cyclic structure of 30 that makes the approach of the nucleophile more favourable for steric reasons and makes 1 a leaving group better than the acyclic benzenesulfonimide; the mechanism suggested is a $S_N2$-type.

Scheme 14.

Several examples of regiospecific synthesis of fluorinated aromatics using NFOBS and/or NFSI in the presence of DMG have also been reported [28] (Scheme 15).
In the diastereoselective fluorination of chiral imide enolates, Davis and co-workers used Evans’ oxazolidinones (55) [29] as chiral auxiliaries to prepare the α-fluoroacids 57 and the β-fluoroalcohols 58 with good de. Due to the enhanced acidity of the α-fluoro proton, some racemization occurred during the removal of the chiral auxiliary under basic conditions, whilst this was avoided by reducing with LiBH4. The efficiency of NFOBS (30, Scheme 16) [29] was compared with that of NFSI (42) [30] as fluorinating agent: compound 30 was proved to approach from the less hindered si-face of the imide enolate.

In one case, NFSI showed a better diastereoselectivity because of its greater steric bulk [31].

The procedure for asymmetric synthesis of fluoroorganic compounds has been applied to obtain 2-deoxy-2-fluoropentoses as final products from a non-carbohydrate precursor, and a fluorinated analogue of the side chain of the taxol [32].
N-Aryl, N-alkyl and N-dialkylaminoalkyl-o-benzenedisulfonimides (31):

Prepared in 1969 by Hendrickson [4] in order to study the feasibility of the C-N bond cleavage, these compounds appeared surprisingly inert, even by treatment with sodium cyanide or base or during sublimation at elevated temperatures: so the idea that o-benzenedisulfonimide anion would be a facile and useful leaving group was abandoned.

As in the case of compound 9, thirty years later, these products and naphthalene analogues received attention again. These derivatives were synthesized from the corresponding disulfonyl chlorides and primary amines (as major products along with traces of bisamides [34,35] by Carlsen and Fiksdahl, in the course of a wider study on nucleophilic substitution reactions of N,N-disulfonylimides; they were usefully converted with good stereoselective control of the reactions.

These imides were then used in benzylation of alcohols or phenols (Scheme 17) [33], in stereoselective nucleophilic substitution of the starting chiral amines [34,35], and finally in stereoselective synthesis of optically active aryl alkyl ethers from enantiopure amines or alcohols [36].

![Scheme 17](image)

Treatment of N-(4-methoxybenzyl)-1,2-benzenedisulfonimide with aqueous KOH in DMF yielded 4-methoxybenzyl alcohol, confirming that these reactions represented a mild procedure for the conversion of amines into the corresponding alcohols [33].

o-Benzenedisulfonyl chloride 2 or 1,2-naphthalenedisulfonyl chloride 60 and enantiopure primary amines 61 were reacted in dichloromethane in the presence of Et3N (Schemes 18 and 19) [33,34,35].
The enantiomerically pure derivatives 31 were easily converted into alcohols 62 or azides 63 by nucleophilic attack of KNO₂ and NaN₃ respectively, with inversion of configuration at the chiral centre; reduction of the azido group afforded the inverted amines 64 (Scheme 18). The nucleophilic substitution was easier on the benzylic substrate; higher stereoselectivity was obtained carrying out the reactions in DMSO (84–90 and 94–98.5% inversion for 62 and 63, respectively) and by decreasing the reaction temperature, as expected for a S_N2 mechanism.

Scheme 18.

The above conversions were then applied to the naphthalene derivatives 65; however in this case the observed stereoselectivity was lower (Scheme 19). The result was explained by a higher contribution from an ionic or ion pair mechanism, owing to a greater stability of the naphthalene leaving group relative to the benzene, and not to a better nucleophilicity of the former anion compared to the latter [35].

Scheme 19.
The same authors studied the stereoselective synthesis of chiral aryl ethers from an enantiopure amine, through the o-benzene- or the 1,2-naphthalenedisulfonimide intermediates (Scheme 20). The 1-phenylethyl phenyl (or 2-naphthyl) ethers 66 were formed in 39–44% (or 57–68%) yields and 83–87% (or 70–79%) inversion [36]. Alternative methods of preparation of 66 via benzyne or TFA ester showed higher selectivity.

![Scheme 20.](image)

Scheme 20.

### 2.2 o-BENZENEDISULFONIMIDE as STABILIZING COUNTER-ION of DRY ARENEDIAZONIUM SALTS

It is well-known that arenediazonium salts are quite unstable in the dry state, potentially explosive [37], but arenediazonium tetrafluoroborates, sulfonates, trifluoroacetates, nitrates or salts with complex anions have been proposed as exceptions to this behaviour.

Bearing in mind two brief notes described some arenediazonium salts stabilized by fluorinated disulfonimides [38], Degani first thought about the advantage of utilizing the anion of o-benzenedisulfonimide as stabilizing counter-ion of arenediazonium cations, even in the dry state, and then to revisit some synthetic applications of this versatile class of compounds. This resulted, in the last decade, in a significant number of papers by Degani’s research group.

Other studies were focused on selected arenediazonium o-benzenedisulfonimides, whose kinetics and azocoupling reactions were investigated for comparison with related tetrafluoroborates, confirming similar reactivity of both classes of diazonium salts, but greater stability and easier experimental procedures for dry salts 67 [39].
Dry arenediazonium o-benzenedisulfonimides (67):

Dry arenediazonium o-benzenedisulfonimides 67 were easily prepared by diazotization of aromatic amines 68 with isopentyl nitrite in the presence of 1 (1.2 equiv) in glacial acetic acid or in formic acid at 0–5 °C. The dry salts were always obtained in excellent yields and high purity, as proved by the conversion into the corresponding (2-hydroxy-1-naphthyl)aryl diazenes 69 (Scheme 21). The ionic nature of salts 67 was confirmed by the X-ray analysis of one of these salts [9,40]. They are soluble in water as well as in polar protic and aprotic solvents, but insoluble in apolar or slightly polar solvents, exceptionally stable, storable for long periods, and ready to be used.

\[
\text{Ar-NH}_2 + \text{H}_2\text{C}_2\text{ONO/} \text{AcOH or HCOOH} \xrightarrow{0-5 \, ^\circ\text{C}, \, 5 \, \text{min}} \text{ArN}_2^+ + \text{SO}_2\text{SO}_2\text{N-ar}\text{OH} \quad (\text{20 examples; 85–99\%})
\]

\[
\text{Ar} = \text{Ph; 2-, 3-, 4-MeC}_6\text{H}_4; \quad \text{2-, 3-, 4-MeOC}_6\text{H}_4; \quad \text{2-, 3-, 4-ClC}_6\text{H}_4; \quad \text{2-, 3-, 4-BrC}_6\text{H}_4; \quad \text{4-Me}_2\text{NC}_6\text{H}_4; \quad \text{2,6-Cl}_2\text{C}_6\text{H}_3; \quad \text{1-naphthyl}
\]

Scheme 21.

Since they have high, well-defined and reproducible decomposition points, decomposition of benzenediazonium o-benzenedisulfonimide (70, dp 110 °C) was studied in the presence and in the absence of toluene. In both cases, two products 71 and 72 were isolated, the former being predominant (71 : 72 = 79 : 14 or 66 : 18, respectively) (Scheme 22). The reaction carried out in solvent furnished also a mixture of three isomers of phenylation of toluene, with an isomeric ratio consistent with a heterolytic mechanism. This clue and the poor electron donor properties of the o-benzenedisulfonimide anion induced the authors to suggest a heterolytic decomposition mechanism.
Scheme 22.

Salts 67 have been successfully converted in several classes of compounds; dediazoniation reactions with O, S, N, and C nucleophiles, in aqueous or organic medium, gave isolated yields of pure products comparable or often higher than those reported with conventional methods. It has to be highlighted that a further valuable aspect of all procedures reported below is the easy recovery of o-benzenedisulfonimide (1). After workup of the reaction mixtures, 1 was recovered in good to high yield and so reusable for the preparation of other arenediazonium salts, with noticeable economic and ecological advantages.

For general literature references dealing with each dediazoniation reaction, we refer to the literature cited in each article.

Diaryldiazenes and aryl(tert-butyl)diazenes (73):

The first synthetic application of salts 67 was the synthesis of diaryldiazenes and aryl(tert-butyl)diazenes 73 by electrophilic C-coupling reactions of these salts with Grignard reagents (74) in equimolar amounts. The procedure was of general validity and gave high yields of products. In all the reactions, two isomeric products were observed, but complete isomerization of the Z into the E isomer was achieved by heating at 70 °C (Scheme 23) [41].

\[
\text{67} + (\text{Ar'})\text{RMgX} \xrightarrow{\text{THF, } -78 \degree C} \text{ArN=NR(Ar')} \quad \text{21 examples; 61–91%}
\]
\[
\text{74} \quad \text{3 examples; 45–52%}
\]

Scheme 23.

Aryl methanesulfonates (75):

Aryl methanesulfonates 75 (and three aryl trifluoromethanesulfonates) were easily prepared by thermal decomposition of some representative salts 67 in methanesulfonic acid (or trifluoromethanesulfonic acid), at a temperature between 60 and 120 °C, in reproducible good
yields (Scheme 24) [42]. The authors suggested that the reaction follows a D\textsubscript{N}+A\textsubscript{N} mechanism (Nucleofuge Detachment + Nucleophile Attachment) of dediazoniation. The failure of the reaction with ortho substituted arene diazonium salts and the decomposition reaction of benzenediazonium o-benzenedisulfonimide (70) in methanesulfonic acid in the presence of toluene or nitrobenzene confirmed the suggested mechanism. Small amounts of substituted biphenyls were detected and the ratio of the isomeric products was consistent with an electrophilic phenylation.

Scheme 24.

** Aryl chlorides, bromides, and iodides (76):**

Diazodediazoniation reactions of a wide range of dry arene diazonium o-benzenedisulfonimides 67 by using tetraalkylammonium halides 77 (2.5 equiv) were carried out in anhydrous acetonitrile at room temperature in the presence of copper catalyst, or at 60 °C (or room temperature) without catalyst. In 60 examples, yields were 61–94%, only in few cases were lower (8 examples, yields 51–55%) (Scheme 25) [43].

Scheme 25.

Normally halodediazoniation reactions follow a homolytic pathway: chloro and bromodediazoniation are catalyzed by metal ions or metals (acting as electron transfer agents to
arenediazonium ions), whilst in the iododediazoniation the iodide directly transfers one electron to the cation. Nevertheless, by using arenediazonium o-benzenedisulfonimide, at 60 °C in the absence of copper, all aryl bromides were obtained in slightly lower yields than those in the presence of catalyst (and at room temperature); on the contrary, only arenediazonium salts bearing strong electron-withdrawing groups in \textit{ortho} and/or \textit{para} positions on the aromatic ring, gave chlorodediazoniation products without catalyst at 60 °C. The explanation provided by the authors was that the anion of salt 67 could act as a primary electron donor reagent, giving rise to the outer-sphere (or not bonded) electron transfer complex 78. This would then easily react with the bromide, but not with the chloride (except for the above substituted salts), according to the redox potentials of the two halide anions.

\[
\text{ArN}_2^+ \overset{\text{SO}_2}{\rightleftharpoons} \text{ArN}_2^+ \text{SO}_2^-
\]

Fig. (6).

\textbf{Alkyl aryl and diaryl sulfides (79):}

It is well-known that alkyl and arylthiodediazoniation are dangerous reactions, due to the formation and accumulation of the highly explosive intermediate diazosulfides 81. By using arenediazonium \textit{o}-benzenedisulfonimides 67, the reactions of Stadler and Ziegler were slightly modified and transformed into an efficient and safe procedure, of general applicability [44]. Various unfunctionalized and functionalized alkyl aryl and diaryl sulphides (79) were prepared by reacting dry salts 67 with sodium thiolates 80 (1.1 equiv) in anhydrous methanol, at 0–5 °C for the alkylthiodediazoniation and room temperature for the arylthiodediazoniation (Scheme 26).
Scheme 26.

In 63 examples, the yields were generally high; lower yields were obtained from sterically hindered arenediazonium cations or thiols. The mechanism of these reactions proceeds through a homolytic pathway, as confirmed by the observed negligibility of the substituent electronic effects and also by a radical diagnostic test. Nonetheless, the authors proposed a $S_{RN2}$ mechanism, alternative to the $S_{RN1}$ suggested for arylthiodediazoniation of arenediazonium tetrafluoroborates [45]. A bimolecular $S_{RN2}$ homolytic chain process would better account for the reported observations and results: rate reaction increased by protic solvent, nearly equimolar amounts of reactants, considerable amounts of disulfides and arenes as by-products in the arylthiodediazoniation, halogen substitution never observed in halogen-substituted arenediazonium salts, and strong steric effects of bulky substituents on the ortho positions of either reactants.

Aryl thiocyanates (83):

Aryl thiocyanates are generally prepared by thiocyanodediazoniation of diazotized aromatic amines and metal thiocyanates in aqueous solutions, mostly under Sandmeyer-type reaction conditions. However, this synthetic route suffers some limitations, such as low yields, considerable by-product formation, nucleophilic substitution of other aromatic ring substituents. All these drawbacks were overcome by using arenediazonium $o$-benzenedisulfonimidates. Several aryl thiocyanates (83) were prepared in high yields and purity by reaction of dry 67 and sodium thiocyanate (1.1 equiv, in almost cases; 82) in anhydrous acetonitrile at room temperature in the
presence of copper powder or at 50 °C (or room temperature) in the absence of catalyst (Scheme 27) [46].

\[
\begin{align*}
67 & + \text{Na'SCN} & \text{(Cu)} & \rightarrow 82 \\
82 & \rightarrow \text{ArSCN} & \text{rt or 50 °C and Na'SCN} & \rightarrow 83: 22 \text{ examples; } 30–100\% \\
\text{Ar} & = \text{Ph; 2-, 3-, 4-MeC}_6\text{H}_4; 2-, 3-, 4-\text{MeOC}_6\text{H}_4; 2-, 4-\text{ClC}_6\text{H}_4; \\
& \quad 4-\text{IC}_6\text{H}_4; 2-, 3-, 4-\text{NO}_2\text{C}_6\text{H}_4; 2-, 4-\text{MeOOC}_6\text{H}_4; \\
& \quad 4-\text{CNC}_6\text{H}_4; 2,6-\text{Me}_{2}\text{C}_6\text{H}_3; 2,4-(\text{NO}_2)_{2}\text{C}_6\text{H}_3; \\
& \quad 2,6-\text{Br}_{2}\text{C}_6\text{H}_3; 2,5-\text{Cl}_{2}\text{C}_6\text{H}_3; 2-\text{PhSO}_2\text{C}_6\text{H}_4
\end{align*}
\]

Scheme 27.

As already reported for bromode diazoniation [43], the thiocyanodediazoniation is a homolytic process, also in the absence of copper: the anion of the o-benzenedisulfonimide behaves as an electron transfer reagent, giving rise to the electron transfer complex previously hypothesized. These considerations were supported by diagnostic tests and comparative reactions with arenediazonium tetrafluoroborates.

**1-Aryl-3,3-dialkyltriazenes (85) and conversion in aryl halides (76):**

Triazenes are a biologically interesting and synthetically useful class of compounds. Normally they are prepared by reaction of arenediazonium salts with secondary or cyclic amines, but there are several cases where their synthesis is particularly troublesome. Several 1-aryl-3,3-dialkyltriazenes 85 were prepared in high yields by reaction of dry salts 67 (also deriving from weakly basic aromatic amines) with dimethyl or diethylamine (1.1 equiv; 84) and NaOH (1 equiv), or with above amines (2.2 equiv) in aqueous solution at 0–5 °C (Scheme 28) [47].

\[
\begin{align*}
67 & + \text{R}_2\text{NH} & \text{H}_2\text{O (NaOH)} & \rightarrow 85: 12 \text{ examples; } 90–95\% \\
\text{Ar} & = 4-\text{MeOC}_6\text{H}_4; 4-\text{ClC}_6\text{H}_4; 4-\text{NO}_2\text{C}_6\text{H}_4; 2,6-\text{Br}_2\text{C}_6\text{H}_3; 2,6-\text{Cl}_2\text{C}_6\text{H}_3; 2,4-(\text{NO}_2)_{2}\text{C}_6\text{H}_3; \\
& \quad 2,4,6-\text{Cl}_3\text{C}_6\text{H}_2; 2,4,6-\text{Br}_3\text{C}_6\text{H}_2; 2-\text{Cl}_4-\text{NO}_2\text{C}_6\text{H}_3; 2,6-\text{Cl}_2-4-\text{NO}_2\text{C}_6\text{H}_3; 2,6-\text{Br}_2-4-\text{NO}_2\text{C}_6\text{H}_3; \\
\text{R} & = \text{Me, Et}
\end{align*}
\]

Scheme 28.
It is known the ability of triazenes to break down to release *in situ* diazonium ions, that directly reacted; the deprotection of the diazonium group is normally affected by acid and this can be a problem for the *in situ* subsequent reactions. The authors performed this break down by heating triazenes with *o*-benzenedisulfonimide (2.2 equiv, 1) in acetic acid or acetic acid-formic acid mixture: the dry salts 67 were separated from the dialkyl ammonium salt by cooling the reaction mixture at room temperature. This procedure is potentially very useful in organic synthesis, as it allows chemical modifications of both the intermediate triazene and the reconstituted arenediazonium salt.

Furthermore, aryltriazenes were converted into corresponding aryl iodides, bromides and chlorides, following two alternative procedures. The former used simply aqueous hydrogen halides (3 equiv) in acetonitrile at room temperature or 60 °C, sometimes in the presence of aqueous HBF₄ or copper powder (Scheme 29).

![Scheme 29.](image)

The presence of HBF₄ was necessary for iodo and chloroderiazonation of arenediazonium salts bearing strong electron-withdrawing substituents on the aromatic ring. The reason was that, in these cases, the triazene heterolytic dissociation, first step of the reaction, was slowed down, whilst the successive homolytic iododeriazonation was favoured. Finally, copper powder was needed in the conversion of the triazenes into aryl chlorides and bromides, except for bromides from triazene nitro substituted: in these cases, the substituent enabled the electron transfer to the arenediazonium group from the bromide anion.

The second procedure used anhydrous methanesulfonic acid and tetraalkylammonium halides 77 in anhydrous acetonitrile at temperatures ranging from room temperature to 80 °C, sometimes in the presence of copper powder, as mentioned above (Scheme 30).
N-Alkylanilines (89):

N-Monoalkylanilines 89 were selectively prepared from arenediazonium salts 67 with alkyllithiums (2.2 equiv; 88) [48], through synthesis and isolation of the corresponding intermediate (Z)-(tert-butyldisulfanyl)(aryl)diazenes 87 [44]. (Alkylsulfanyl or arylsulfanyl)(aryl) diazenes are highly unstable, decomposing in situ into the corresponding sulfides; exceptions are diazenes 87, that behave as a protected form of the diazonium functional group, like the better known triazenes.

Unexpectedly, treatment of 87 with an alkyllithium in anhydrous diethyl ether at 0 °C or at –78 °C led selectively to pure N-monoalkylation products (Scheme 31).

Scheme 30.

\[
\begin{align*}
Ar-N=N-NR_2 + Q^+X^- & \xrightarrow{\text{rt or 80 °C}} Ar-X \\
85 & \quad 77 & \quad 76 \\
\text{X = I; 6 examples; 65–85%} & \text{X = Br; 7 examples; 68–85%} & \text{X = Cl; 5 examples; 65–84%}
\end{align*}
\]

Scheme 30.

Besides the synthetic usefulness of the reaction, the authors proposed an interesting mechanism, on the basis of constant traces of hydrazines 92 as by-products and of suitable collateral proofs. Whilst the evidence of the intermediate 90 is almost certain, greater caution must be taken for the nitrene 91. It is worthwhile to highlight the umpolung of the amino nitrogen atom, in the diazene protected form, reacting as an electrophile towards carbanions (Scheme 32).
Scheme 32.

S-Aryl thiol esters (95):

An easy and safe procedure for the synthesis of S-aryl thiol esters 95 has been set up starting from arenediazonium \( o \)-benzenedisulfonimides 67 with sodium thioacetate or thiobenzoate (93) (2 equiv) in dry acetonitrile; the intermediate diazo thiol esters 94 were observed (Scheme 33) [49]. In all the considered examples, the yields were higher than those reported in literature, regardless of nature and position of the substituents on the aromatic ring.

\[
\begin{align*}
67 + \text{Na}^+ \text{SCOR} & \rightarrow [\text{Ar-N=N-S-COR}] & \rightarrow \text{Ar-S-COR} \\
93: R = \text{CH}_3, \text{C}_6\text{H}_5 & 94 & 95 \\
28 \text{ examples; } 81-100\% & & 
\end{align*}
\]

Scheme 33.

Hydrodediazoniation with hydrogen peroxide:

A wide range of variously substituted dry salts 67 were hydrodediazoniated by hydrogen peroxide (30 wt% in H\(_2\)O; 2 equiv, 96), in THF at reflux, yielding pure arenes 97 in high yields, in the presence of both electron-donating or electron-withdrawing substituents, and also of steric hindrance (Scheme 34). Collateral proofs in the presence of radical reaction inhibitors, or aryl radical trapping agents, led the authors to hypothesize a free radical mechanism [50].

\[
\begin{align*}
67 + \text{H}_2\text{O}_2 & \xrightarrow{\text{THF, reflux}} \text{Ar-H} \\
96 & 97: 18 \text{ examples; } 68-100\% & \\
\text{Ar} = 4-\text{MeC}_6\text{H}_4; 4-\text{BuC}_6\text{H}_4; 2-\text{PhC}_6\text{H}_4; 4-\text{MeOC}_6\text{H}_4; 4-\text{PhOC}_6\text{H}_4; 2-\text{MeSC}_6\text{H}_4; 4-\text{NO}_2\text{C}_6\text{H}_4; \\
4-\text{MeCOC}_6\text{H}_4; 4-\text{CNC}_6\text{H}_4; 2,6-\text{Me}_2\text{C}_6\text{H}_3; 2,6-\text{Br}_2\text{C}_6\text{H}_3; 2,4,6-\text{Me}_3\text{C}_6\text{H}_2; 2,4,6-\text{Br}_3\text{C}_6\text{H}_2; \\
2-\text{Me}-5-\text{NO}_2\text{C}_6\text{H}_3; 3,5-(\text{MeO})_2\text{C}_6\text{H}_3 & 
\end{align*}
\]

Scheme 34.
Heck-type arylation reactions:

Finally, the synthetic usefulness of dry arenediazonium o-benzenedisulfonimides 67 was tested in transition metal catalyzed cross-coupling reactions. They were first studied as electrophiles in Heck-type arylation reactions, arenediazonium salts (mainly tetrafluoroborates) being a valid alternative to conventional aryl halides and triflates [51]. Some common olefinic substrates used in this reaction were arylated by a wide range of arenediazonium salts 67 in the presence of Pd(OAc)$_2$ (1 mol% with respect to 67), in a suitable organic solvent. No ligands were necessary, complete stereoselectivity was observed and yields were excellent, regardless of the nature of the substituents (this finding being in contrast with the difficulties reported in literature for nitro substituted arenediazonium tetrafluoroborates [52]). Ethyl acrylate (98, 1.2 equiv), acrylic acid (99, 1.5 equiv), acroleyne (100, 1.5 equiv), and styrene (101, 1.2 equiv) gave high yields of arylated products 102–105, always in (E)-configuration; in the case of 99 and 100, a base (anhydrous CaCO$_3$, in equimolar amount to 99 or 100) and anhydrous conditions were needed (Scheme 35).

\[
67 + \text{Ar} \quad \xrightarrow{	ext{Pd(OAc)$_2$}} \quad \text{Ar} + 98, X = \text{COOEt} \quad 102, X = \text{COOEt}; 15 \text{ examples, 42–100\%}
\]

\[
99, X = \text{COOH} \quad 103, X = \text{COOH}; 4 \text{ examples, 55–96\%}
\]

\[
100, X = \text{CHO} \quad 104, X = \text{CHO}; 5 \text{ examples 83–95\%}
\]

\[
101, X = \text{Ph} \quad 105, X = \text{Ph}; 3 \text{ examples, 54–83\%}
\]

Ar = 2-, 4-MeC$_6$H$_4$; 2-, 3-, 4-MeOC$_6$H$_4$; 4-ClC$_6$H$_4$; 3-, 4-BrC$_6$H$_4$; 4-IC$_6$H$_4$; 2-, 4-NO$_2$C$_6$H$_4$;
2-HOOCC$_6$H$_4$; 2,4-(NO$_2$)$_2$C$_6$H$_3$; 2-MeOCO-3-thienyl

Scheme 35.

Heck-type arylation of cyclopentene (106, 1.2 equiv) gave 1-arylderivatives 107, with greater selectivity compared to corresponding reactions of tetrafluoroborates (Scheme 36).

\[
67 + \text{106} \quad \xrightarrow{} \quad \text{107}
\]

9 examples, 70–90\%

Scheme 36.
Dry arenediazonium \( o \)-benzenedisulfonimides were used in palladium-catalyzed arylation of allylic alcohols [53]. As known from literature, such reactions are generally poorly regiospecific and lead to mixtures of \( \beta \)- and \( \alpha \)-arylated both carbonyl compounds and allylic alcohols; selective procedures have been proposed, but only a few reports refer to arylation by arenediazonium salts. Various substituted salts 67 were reacted with a range of primary and secondary allylic alcohols, testing several reaction conditions (solvent, nature and equivalents of base and palladium catalyst). The synthetic goal were the \( \beta \)-arylated carbonyl compounds, useful intermediates for the synthesis of medicinal or natural products with biological properties. In optimized conditions, salts 67 and secondary allylic alcohols 108 (1.2 equiv) were reacted in aqueous 95% ethanol/\( \text{NaHCO}_3 \) (1.2 equiv) or acetonitrile/\( \text{NaOAc} \) (1.2 equiv), in the presence of \( \text{Pd(OAc)}_2 \) (1 mol%), at 60 °C; they gave \( \beta \)-arylated ketones 109 as major products, along with traces of \( \alpha \)-arylated ketones 110 and minor amounts of arylated allylic alcohols 111 (Scheme 37).

![Scheme 37](image)

Ar = Ph; 4-MeC\( _6 \)H\( _4 \); 2-, 4-MeOC\( _6 \)H\( _4 \); 4-BrC\( _6 \)H\( _4 \); 4-IC\( _6 \)H\( _4 \); 2,6-F\( _2 \)C\( _6 \)H\( _3 \); 2-, 3-, 4-NO\( _2 \)C\( _6 \)H\( _4 \)
R\( ^1 \) = H, Me
R\( ^2 \) = H, Me, \( n \)-C\( _5 \)H\( _11 \), Ph

According to literature, as electron-rich haloarenes disfavour Heck-type reactions, electron-rich arenediazonium salts gave lower product yields. Furthermore, from the reaction of these salts in ethanol, the corresponding 1-aryl-3-ethoxyalk-1-enes 112 were isolated and identified by GC-MS and \(^1\)H NMR spectra. Their formation was attributed by the authors to a nucleophilic attack of the alcoholic solvent on an intermediate \( \pi \)-allylpalladium complex (Tsuji–Trost reaction [54]), as confirmed by carrying out the reaction in methanol and isolating the corresponding 1-aryl-3-methoxyalk-1-enes.
Salts 67 and primary allylic alcohols 108 (R²=H; 1.2 equiv) in aqueous 95% ethanol/NaHCO₃ (1.2 equiv), in the presence of Pd(OAc)₂ (1 mol%) at 60 °C, led to mixtures of arylated aldehydes 113 and/or 114 with their diethyl acetals 115 and 116 (with the expected predominance of the former ones; Scheme 38).

Scheme 38.

**Palladium-catalyzed cross-coupling reactions with aryl and alkyl tin compounds, and with trialkylboranes:**

In order to broaden the synthetic potential of salts 67 as aryl electrophile components in transition metal catalyzed cross-coupling reactions, a wide range of dry arenediazonium o-benzenedisulfonimides were reacted with aryltin derivatives 117 (1.1 equiv) under Stille conditions to give asymmetric biaryls 118, fundamental building blocks in organic synthesis [55]. All the reactions were carried out in THF in the presence of Pd(OAc)₂ 5% as precatalyst, at room temperature or 40 °C for arenediazonium salts ortho monosubstituted; yields were always high (23 examples; average yield 80%), with the only exception of two ortho disubstituted salts (yields 22–23%). In these cases, more consistent amounts of symmetric biaryls 119 were isolated, otherwise present in traces (Scheme 39).
In contrast to numerous examples of cross-coupling reactions between arenediazonium salts and aromatic or alkenyl organometallic compounds, very few examples are reported with alkyl organometallic compounds. Salts 67 were successfully tested in such palladium-catalyzed alkylation [56]. By reaction with tetramethyl or tetrabutyltin 120 (1.1 equiv), in THF at room temperature or in acetonitrile at 40 °C, in the presence of Pd(OAc)$_2$ 2.5 mol%, chemoselective methylation and butylation products 121 and 122 were obtained in high and modest yields, respectively; the presence of arenes 123, formed by hydrodediazoniation, was nearly always observed and often made purifications difficult (Scheme 40).

Scheme 40.

In order to improve product yields and to avoid the use of toxic tin derivatives, reactions of salts 67 were investigated with triethyl or tributylborane 124 (1.1 equiv) under Suzuki protocol, in THF at room temperature, in the presence of different palladium catalysts, with good yields of products 125 and 122 (Scheme 41).

Scheme 41.
Palladium-catalyzed cross-coupling reactions with aryl and alkylindium compounds:

As a follow-up on our previous studies, dry arenediazonium $o$-benzenedisulfonimides $67$ were reacted with triorganoindium compounds $126$, and depending on the reaction conditions, it was possible to obtain biaryls $127$ or diaryldiazenes $128$ [57]. Before this paper, no reactions of arenediazonium salts with indium organometallics have been reported in literature. Triorganoindium compounds $126$ were prepared from indium(III) chloride with aryllithium or Grignard reagents.

As regards to the first synthetic application, in optimized conditions salts $67$ were reacted with compounds $126$ in a molar ratio 3:1, in THF at room temperature, in the presence of bis(triphenylphosphine)palladium (II) dichloride as precatalyst. Biaryls $127$ were obtained in high yields, chemoselectively, independently from electronic but not steric effects (Scheme 42).

$$
67 + Ar'_3In \xrightarrow{PdCl_2(PPh_3)_2} THF, rt \quad \xrightarrow{\text{Ar-Ar'}} 126 \quad \xrightarrow{127} \quad \frac{\text{Ar'}}{\text{N=N}} \quad \frac{\text{Ar'}}{\text{Ar'}} \quad 128 \quad 129
$$

16 examples; $127$: 70–94%; $128$: tr–4%;

$Ar = 4$-MeC$_6$H$_4$; 2-, 3-, 4-MeOC$_6$H$_4$; 3-, 4-BrC$_6$H$_4$; 4-IC$_6$H$_4$; 4-ClC$_6$H$_4$; 4-MeOCOC$_6$H$_4$; 2-, 3-, 4-NO$_2$C$_6$H$_4$; 2,6-F$_2$C$_6$H$_3$; 2,6-(NO$_2$)C$_6$H$_3$; 4-CNC$_6$H$_4$; 2,6-Me$_2$C$_6$H$_3$; $Ar' = \text{Ph, }$4-MeOC$_6$H$_4$; 4-ClC$_6$H$_4$; 4-MeC$_6$H$_4$; 2-thienyl

Scheme 42.

In order to favour the electrophilic C-coupling reaction and maximize the yields of $128$ derivatives, salts $67$ were reacted with triorganoindium $126$ without catalyst. In optimal conditions the molar ratio $67 : 126$ was 1 : 2, in THF at room temperature. Variously substituted aryldiazenes were obtained in good yields (except for sterically hindered arenediazonium cations), comparable to those previously obtained from the same arenediazonium salts (Scheme 43) [41].
Scheme 43.

The behaviour of salts 67 with indium triorganocompounds was investigated by reaction with other organometallic reagents, including organotin, boronic acid, Grignard and lithium compounds, in the presence or absence of Pd⁰ catalyst. Results were explained by different nucleophilicities of the tested organometallic reagents.

Next, reaction of salts 67 with aliphatic triorganoindium compounds (triethyl 130, tributyl 131 and trimethylindium 132; 2.5 equiv, in THF at room temperature) was investigated, but quite surprisingly, aqueous treatment of reaction mixtures gave N-ethyl- 133 and N-butyranilines 134 (uncontaminated by N,N-dialkylanilines) or formaldehyde (aryl)hydrazones 135, respectively [58]. Reactions were not influenced by electronic or steric effects, although hindered samples were obtained in moderate yields (Scheme 44).

$$67 + R_3\text{In} \rightarrow \text{Ar-NH-R} \text{ or } \text{Ar-N-N=CH}_2$$

<table>
<thead>
<tr>
<th>Scheme 44.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>130: R = Et</td>
<td>133: R = Et; 9 examples; 69–89%</td>
</tr>
<tr>
<td>131: R = Bu</td>
<td>134: R = Bu; 9 examples; 75–95%</td>
</tr>
<tr>
<td>132: R = Me</td>
<td>135: 9 examples; 61–89%</td>
</tr>
<tr>
<td>Ar = Ph; 4-MeC₆H₄; 4-MeOC₆H₄; 4-BrC₆H₄; 4-MeOCOC₆H₄; 2-, 3-, 4-NO₂C₆H₄; 2,6-Me₂C₆H₃</td>
<td></td>
</tr>
</tbody>
</table>

Scheme 45.

The mechanism previously proposed [44] was used in part also in this case: nucleophilic addition of 130 or 131 to the intermediate aryl(alkyl)diazene on the amino nitrogen atom and decomposition of this temporary adduct lead to the end products 133 or 134.
In the case of trimethylindium 132 only formaldehyde (aryl)hydrazones 135 were obtained. Experimental results were justified by the well-known tautomerism between diazenes (I) and hydrazones (II), the latter being unable to undergo nucleophilic addition (Fig. 8).

\[
\text{Ar-N=N-CH}_2\text{R} \quad \leftrightarrow \quad \text{Ar-NH-N=CHR}
\]

Fig. (8).

Basing our hypothesis on previously reported but not unequivocal data [59], a theoretical study was performed with detailed density functional (DFT) calculations; results confirmed the higher stability of hydrazone tautomers, shifted towards diazene tautomers by the catalytic effect of water added at the end of the reaction. The key step is the nucleophilic addition to the N=N double bond; by using three different reaction pathways, the anomalous behaviour of 132 was explained on the basis of stronger C–In bond in this organometallic reagent.

2.3 \textit{o-BENZENEDISULFONIMIDE as BRØNSTED ACID CATALYST}

The high acidity of the Brønsted acid 1 is well-known. Hendrickson [4] and co-workers described \textit{o-benzenedisulfonimide as “fully ionized in (and not extractable from) water”}; tabulated values for pK\textsubscript{a} are –4.1 (\(H_0\) at half-neutralization determined by UV spectra, at 20 °C in water [1b]), and –1.10 (calculated with the program ACD/pK\textsubscript{a} DB [60]). However, until our recent researches, to the best or our knowledge, no one has taken advantage of this finding.

Recently, during our investigations concerning the reactivity of dry salts 67 in metal-catalyzed cross-coupling reactions [53], along with the expected mixtures of \(\alpha\)- and \(\beta\)-arylated carbonyl compounds and of arylated allylic alcohols, some ethoxyderivatives 112 were isolated. Their formation was ascribed to a Pd catalyzed Tsuji–Trost reaction of ethanol on the intermediate arylated allylic alcohol. Unexpectedly, such derivatives derived from acid-catalyzed dehydration of the two cited alcohols: the strong Brønsted acid actively involved even in catalytic amounts was \textit{o-benzenedisulfonimide (1)}.\]
So far, several good results have been obtained using o-benzenedisulfonimide in catalytic amounts, as a safe, easy to handle, nonvolatile, non corrosive, and recyclable Brønsted acid. This organocatalyst presents many advantages: highly soluble in both organic solvents and water, efficiently catalyzes some of the most common acid-catalyzed organic reactions in homogeneous catalysis conditions, and thorough studies on other synthetic applications are in progress. As in the case of arenediazonium salts 67, a further valuable and not negligible aspect of this catalyst is its almost complete and easy recovery after workup of the reaction mixtures. Owing to the complete solubility in water, it can be recovered virtually pure, ready to be reused in catalytic amounts in other reactions, immediately or after a fast purification on cation-exchange resin, without loss of catalytic activity, with clear economic and ecological advantages.

**Dehydrative reactions:**

First, the synthetic usefulness of 1 as catalyst was tested in some acid-catalyzed reactions, selected on the basis of their synthetic significance and methodological simplicity: dehydrative etherification and esterification; acetics synthesis, cleavage and interconversion; pinacol rearrangement [61a,61b]. All the reactions were conducted in open air flasks, using analytical grade solvents, the only side product being water.

Protic acid catalyzed ether synthesis by alcohol dehydration is dependent on the choice of reactants and of Brønsted acid; generally, high acid concentration and high reaction temperatures are required. In order to prepare asymmetric allylic ethers 138, three different procedures have been set up by using o-benzenedisulfonimide, allylic alcohols 136 and aliphatic alcohols 137: in solution of alcohol 137, in THF as solvent, and under solvent-free conditions; in the last two procedures, aliphatic alcohols were used in stoichiometric ratio or in slight excess (Scheme 46).
Scheme 46.

All methods presented mild reaction conditions, short reaction times, good selectivity (only mixed ethers were formed, no side-products were isolated), good yields (in 8 examples: 70–88%; in 8 examples: 28–60%), and reduced load of catalyst (normally 5%). When the well-known allylic rearrangement of the reasonable intermediate carbocation was allowed, ethers 139 were isolated in mixture with the isomeric ones 138. As the reaction was an equilibrium, the conditions were optimized to lead to more stable derivatives. Furthermore, E-isomers always were the only isolated products. Unfortunately, $o$-benzenedisulfonimide did not play a role in such stereoselectivity: a collateral proof with sulphuric acid as catalyst gave the same results, although in lower yield.

Dehydrative esterification of carboxylic acids 140 and alcohols 137 was examined only in a few representative examples; reagents were used in nearly equimolar amounts, at 90 °C in toluene, in the presence of 1 (20–30 mol%). Our results agree with the known decreasing order reactivity of non-conjugated, conjugated and aromatic acids (Scheme 47).

Scheme 47.

Acetalization of aldehydes or ketones is one of the most useful methods used in protective groups chemistry. Drawbacks of the reaction are excess of alcohol, removal of water, use of a toxic or corrosive acid catalyst, sometimes needed in large amounts. In our conditions, dimethyl or ethylene acetics of a number of aldehydes and/or ketones were obtained in satisfactory yields by
reactions with methanol (also as solvent) or ethane-1,2-diol (3 equiv, in toluene), at room temperature or 90 °C respectively, in the presence of o-benzenedisulfonimide (0.5–1 mol%). In the presence of the same catalyst, some acetal cleavages and interconversions were achieved with good results (Scheme 48).

```
\begin{center}
\begin{tikzpicture}
  \node (A) at (0,0) {\textbf{142}};
  \node (B) at (2,0) {\textbf{143}};
  \node (C) at (1,1) {\textbf{144}};
  \node (D) at (1,-1) {\textbf{144}};
  \draw[<->] (A) -- (B) node[midway, above] {\textbf{MeOH, I}};
  \draw[<->] (A) -- (C) node[midway, left] {\textbf{HOCH\_2\_CH\_2\_OH, I cat}};
  \draw[<->] (B) -- (D) node[midway, right] {\textbf{MeOH, I}};
  \draw[<->] (C) -- (D) node[midway, below] {\textbf{HOCH\_2\_CH\_2\_OH, I cat}};
\end{tikzpicture}
\end{center}
```

\textbf{Scheme 48.}

Moreover, pinacol rearrangement of 1,1,2,2-tetraphenylethane-1,2-diol \textbf{145} was studied: depending on reaction conditions, benzopinacolone \textbf{146} or tetraphenyloxirane \textbf{147} were obtained, as in Scheme 49.

```
\begin{center}
\begin{tikzpicture}
  \node (A) at (0,0) {\textbf{145}};
  \node (B) at (2,0) {\textbf{146}};
  \node (C) at (1,1) {\textbf{147}};
  \draw[<->] (A) -- (B) node[midway, above] {\textbf{\text{Ph}_2\text{C(OH)-C(OH)Ph}_2 \rightarrow \text{Ph}_2\text{C-Ph}}};
  \draw[<->] (A) -- (C) node[midway, left] {\textbf{\text{I} (10\%)/\text{Tol} 90^\circ\text{C}, 1\ h}};
  \draw[<->] (B) -- (C) node[midway, right] {\textbf{\text{I} (20\%)/\text{Tol} 110^\circ\text{C}, 7\ h}};
\end{tikzpicture}
\end{center}
```

\textbf{Scheme 49.}

In further studies, o-benzenedisulfonimide was taken in consideration as Brønsted acid catalyst in acylation of alcohols, phenols, and thiols with acid anhydrides \cite{61c}. The number of recent methods reported in literature for this reaction is astonishing, and include the use of both homogeneous and heterogeneous conditions, in the presence of Brønsted or Lewis acids as
catalysts. This confirms the interest in new simple, low-cost, and environmental benign procedures, involving solvent- and/or metal-free recyclable catalytic systems.

To assess the general validity of the proposed procedure, scope and limitations of the use of 1 were investigated by reacting various aliphatic and aromatic alcohols and thiols 148 (20 and 4 examples, respectively) with various anhydrides 149 (3 examples) (Scheme 50).

\[
\text{(Ar)}R^1\text{-XH} + (R^2\text{CO})_2\text{O} \xrightarrow{\text{1}} \text{(Ar)}R^1\text{-X-COR}^2
\]

**Scheme 50.**

Under our optimized procedures, the conditions were very mild: nearly equimolar amounts of reagents (1 : 1.1), low and recyclable catalytic load (5 mol%), very short reaction times, room temperature (60 or 80 °C for benzylation only), complete conversion and high yields of acylated products 150, even in a preparation on large scale. The reaction worked well both with primary, secondary and tertiary alcohols, with stereoselectivity and without racemization of enantiomeric pure substrates; in very few cases the reaction failed, leading to a mixture of acid-catalyzed isomerization products, acylated or not.

**Ritter-type reactions**

The Ritter reaction is an efficient synthesis of amides from alkenes (or alcohols) and nitriles; many procedures have been achieved in the presence of Brønsted or Lewis acids, the main disadvantage being the use of toxic, corrosive, and/or expensive, and not recoverable catalysts.

By using o-benzenedisulfonimide as catalyst (1, 10 mol% for 151, 20% for 152), Ritter-type reaction of various benzylic alcohols 151 or t-butyl alcohol 152 with aliphatic or aromatic nitriles 153 (as solvent or in stoichiometric amount; in this case, only reaction rate was slowed down) gave amides 154 or 155 in good yields by heating at 100 °C or at reflux temperature (Scheme 51) [62a].

We highlight that catalyst 1 was recovered (as in all the above described procedures) and directly
reused in other two consecutive Ritter-type reactions, without purification steps: reaction times showed an increase, but yields of pure isolated product and recovery of \( I \) were always good.

\[
\begin{align*}
\text{Ar} & \quad \text{OH} \\
\text{R} & \quad \text{(or} \quad t\text{-BuOH}) \\
\end{align*}
\]

\[151; \text{R} = \text{Ar}', \text{Me} \]

\[152 \quad 153 \]

\[
\begin{align*}
\text{Ar} & \quad \text{OH} \\
\text{R} & \quad \text{(or} \quad t\text{-Bu}) \\
\end{align*}
\]

\[154 \quad 155 \]

\( \text{Ar} = \text{Ph, 4-FC}_6\text{H}_4, \text{4-MeOC}_6\text{H}_4, 2,4,6-\text{Me}_3\text{C}_6\text{H}_2 \)

\( \text{Ar}' = \text{Ph, 4-FC}_6\text{H}_4, 4-\text{MeOC}_6\text{H}_4, 4-\text{NO}_2\text{C}_6\text{H}_4, 2,4,6-\text{Me}_3\text{C}_6\text{H}_2 \)

\( \text{R}^1 = \text{Me, Ph, 2-, 3-, 4-MeC}_6\text{H}_4, 4-\text{MeCOC}_6\text{H}_4, \text{vinyl} \)

\( R = \text{Ar}' ; 15 \text{ examples} \)

\( R = \text{Me} ; 6 \text{ examples} \)

\( 5 \text{ examples} \)

**Scheme 51.**

The reactions were independent of electronic effects (13 examples: 73–99%), with regard to 153; in contrast, steric effects reduced drastically the yield (2 examples: 30–51%). As regard to 151, electronic effects were important and they were explained by considering the hypothesized mechanism of the reaction. By monitoring the reaction by GC-MS, formation of intermediate ethers 156 and their disappearance in favour of increase of final amides were always observed. Accordingly, the authors proposed the following catalytic cycle, where the conjugated base of catalyst 1 was omitted.

![Catalytic cycle](image)

**Fig. (9).**

When \( \text{Ar} \) and \( \text{R} \) were 4-methoxyphenyl, no traces of the corresponding 154 were detected: only bis(4-methoxyphenyl)methane (157) and 4,4’-dimethoxybenzophenone (158) were isolated in
42 and 58% yield respectively. Under catalytic acid conditions, diarylmethyl isopropyl ethers undergo disproportionation reaction with selective hydride transfer leading to diarylmethanes and acetone [63]; therefore, 157 and 158 formation was explained by the authors as disproportionation products of the intermediate ether 156.

![Fig. (10).](image)

When R was a methyl group, vinylbenzenes as side-products were detected; electronic effects of electron-donating and electron-withdrawing groups were observed.

Reactions of nitriles 153 with tert-butyl alcohol gave satisfactory yields, with the exception of the sterically hindered 2,6-dimethylbenzonitrile.

Finally, four primary benzylic alcohols were reacted with acetonitrile: larger amounts of catalyst (until 1 equiv) was needed to obtain moderate yields of 154 (35–64%), along with nearly the same amounts of N-benzyl-o-benzenedisulfonimides 159 (28–35%), despite the known poor nucleophilicity of 1 (Scheme 52).

![Scheme 52.](image)

Bearing in mind the disproportionation products observed in this study, the authors decided to investigate more in depth the reaction, both having the synthetic goal of diarylmethanes and a theoretical study confirmation. Therefore, various ethers 161 were synthesized in situ by reacting diarylmethanols or benzylic alcohols 151 with propan-2-ol (160), in the presence of 10 mol% of 1 as catalyst, and by heating at 80 °C until the complete conversion into diarylmethanes 162 and
acetone (163). Without electron-donating substituents on the aromatic ring the reaction did not occur, and it also failed with primary benzylic alcohols (Scheme 53).

\[
\text{Ar-CH}_2\text{-R} + \text{MeCOMe} \rightarrow \text{Ar-CH}_2\text{-R} + \text{MeCOMe}
\]

Scheme 53.

The theoretical study, performed within the Density Functional Theory (DFT), confirmed that the reaction proceeds through two steps: formation of a carbocation from the protonated ether followed by hydride transfer. Although the latter is the rate determining step, the whole reaction rate is determined by the stability of the carbocation: the more stable ion leads to the lower potential energy profile, the faster reaction and, therefore, the better yield of product [62b].

**Nazarov electrocyclization:**

The electrocyclization of divinyl ketones into cyclopentenones, the Nazarov reaction, is a versatile method for realizing cyclopentenone frameworks in more complex carbo- and heterocyclic molecules, possessing biological activities. The reaction requires acidic activation but, whilst Lewis acid catalysis is well assessed, protic acid catalysis has been less explored; in this context, the catalytic efficiency of \(o\)-benzenedisulfonimide was evaluated on a wide range of both activated and inactivated substrates [64]. It is well-known that the electrocyclization of dienones in cyclopentenones involves both a pentadienyl A and an hydroxyallyl cation B intermediate, as outlined in the catalytic cycle (Fig. 11).
After several preliminary proofs of cyclization on β-damascone (164), looking for the best conditions in terms of amounts of catalyst, solvent, and temperature, a series of various heterocyclic-derived dienones were successfully cyclized in the presence of 1 in catalytic amounts, with satisfactory results, comparable with those obtained under traditional Lewis or Brønsted acid catalysts (Scheme 54).

All the starting dienones 166, 167, 168, and 169 present one of the double bonds embedded in a heterocyclic framework; they were supposed to take advantage of the presence of the heteroatom in α-position of the dienone (Scheme 55). In the case of 167, isomerization of the terminal double bond must occur before the cyclization process takes place. Reaction conditions were optimized for each of the seven substrates (solvent, temperature, catalytic load 5–30 mol%), evidencing a strong solvent effect, as well solvent-free conditions.

Fig. (11).
With a suitable substrate (166, R = Me), a good diastereoselectivity was observed, with a 5 to 1 ratio in favour of the \textit{trans}-diastereoisomer, in accord to previously obtained data, both under Brønsted and Lewis acid catalysis.

Interestingly, \(o\)-benzenedisulfonimide proved to be an efficient electrocyclization catalyst, also in the case of dienone 169, where other catalysts failed. Furthermore, its recyclability was again demonstrated.

\[ \text{Scheme 55.} \]

### 2.4 ASYMMETRIC ORGANOCATALYSIS

The most recent and significant results concerning cyclic disulfonimides chemistry have been published in the last months.

The development of new organocatalysts is of crucial importance in asymmetric organic synthesis and many Lewis and Brønsted acids (and bases) have been proposed as useful organocatalysts in numerous organic transformations. In particular, very strong chiral Brønsted superacids have attracted the attention of chemists as promising catalysts because of their higher reactivity in the activation of substrates of low basicity, and the chiral environment induced by the corresponding chiral conjugated bases [65a] (concept also expressed as Asymmetric Counteranion Directed Catalysis, ACDC [65b]).

In this context, chiral disulfonimides 20 and 21 have been synthesized as new chiral strong Brønsted acids [15,16], and 20 has been shown to catalyze the asymmetric Mukaiyama aldol
reaction with high efficiency, high enantioselectivity and turnover numbers of up to 8800 [15]. \((R)-\)3,3'-Bis[3,5-bis(trifluoromethyl)phenyl]-1,1'-binaphthyl-2,2'-disulfonimide \((20)\) was used in catalytic amounts \((2–0.01\ \text{mol%})\) with good to excellent yields of aldol products \(173\) and high enantioselectivity \((8\ \text{examples})\). In the presence of 5 mol% of catalyst, also aliphatic aldehydes gave good yields of products and reasonably good enantioselectivity \((2\ \text{examples})\) (Scheme 56).

\[
\begin{array}{c}
R^1\text{CHO} + R^3\text{OSiR}_3\rightarrow 20 \ (0.05–5\ \text{mol%}) \\
171 \quad 172 \quad 173 \\
\end{array}
\]

\(R^1 = \text{Ar, styryl, alkyl} \quad R^2 = \text{H, Me} \quad R^3 = \text{Me, i-Pr} \quad 173: \ 8\ \text{examples} \ (20, \ 2\ \text{mol%}) \quad 78–98\% \ (86 : 14–97 : 3\% \ e.r.) \\
2\ \text{examples} \ (20, \ 5\ \text{mol%}) \quad 46–59\% \ (75 : 25–91 : 9\% \ e.r.)

Scheme 56.

Moreover, catalyst \(20\) resulted to be more active and efficient than other known chiral binaphthyl acidic derivatives in the catalysis of asymmetric Mukaiyama aldol reaction, thus opening new promising perspectives of applications in asymmetric organic transformations.

3. CRYSTAL STRUCTURE STUDIES ON \(o\)-BENZENEDISULFONIMIDE DERIVATIVES

Since molecules containing the sulfonimide \([(\text{SO}_2)_2\text{NH}]\) moiety are strong NH acids, they can form with base either onium salts or uncharged hydrogen-bonded complexes. In literature, there is a substantial number of papers, mainly by A. Blaschette and P. J. Jones, from 1993 [5], that report crystal structures of such derivatives with \(o\)-benzenedisulfonimide \((1)\), belonging to both classes of compounds, normally prepared by metathesis from silver(I) \(o\)-benzenedisulfonimide \((29)\) or by \(1\) directly. In Table 1, we reported a list of studied onium compounds or coordination complexes in a chronological order.

Table 1.
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>C₆H₄(SO₂)₂NAg·CH₃CN</td>
<td>[5]</td>
<td>Me₂[C₆H₄(SO₂)₂N]₂Sn(OPPh₃)₂ and [Me₂Sn(phen)]₂[C₆H₄(SO₂)₂N]₂· CH₃CN</td>
<td>[75]</td>
</tr>
<tr>
<td>C₆H₄(SO₂)₂NAg·H₂O</td>
<td>[66]</td>
<td>C₆H₄(SO₂)₂NH and C₆H₄(SO₂)₂NCs</td>
<td>[76]</td>
</tr>
<tr>
<td>[C₆H₄(SO₂)₂N]₂SnMe₂(H₂O)₄</td>
<td>[67]</td>
<td>C₆H₄(SO₂)₂NK·H₂O, C₆H₄(SO₂)₂NRb·H₂O, C₆H₄(SO₂)₂NNH₄·H₂O</td>
<td>[77]</td>
</tr>
<tr>
<td>{Me₂[C₆H₄(SO₂)₂N]Sn(µ-OH)}₂</td>
<td>[68]</td>
<td>C₆H₄(SO₂)₂NNa·H₂O</td>
<td>[78]</td>
</tr>
<tr>
<td>C₆H₄(SO₂)₂NAuPPh₃O</td>
<td>[69]</td>
<td>C₆H₄(SO₂)₂NLi(H₂O)₃</td>
<td>[79]</td>
</tr>
<tr>
<td>[C₆H₄(SO₂)₂N]₂Ca(H₂O)₇</td>
<td>[70]</td>
<td>[C₆H₄(SO₂)₂N]₂Cd₂(H₂O)₄ and [C₆H₄(SO₂)₂N]₂Cu(H₂O)₄</td>
<td>[80]</td>
</tr>
<tr>
<td>[C₆H₄(SO₂)₂N]₂NLi(12-crown-4)</td>
<td>[71]</td>
<td>[C₆H₄(SO₂)₂N]₂Mg(H₂O)₆ and [C₆H₄(SO₂)₂N]₂Be(H₂O)₄·2 H₂O</td>
<td>[81]</td>
</tr>
<tr>
<td>[C₆H₄(SO₂)₂NNa(15-crown-5)]</td>
<td>[72]</td>
<td>[C₆H₄(SO₂)₂N]₂Ba(H₂O)₂</td>
<td>[82]</td>
</tr>
<tr>
<td>C₆H₄(SO₂)₂NH·CH₃CN</td>
<td>[73]</td>
<td>C₆H₄(SO₂)₂NNH₄·H₂O and C₆H₄(SO₂)₂N[Ph₃PNPPh₃]</td>
<td>[60]</td>
</tr>
<tr>
<td>C₆H₄(SO₂)₂NAu(CyNH₂)₂</td>
<td>[74]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The crystal structure of o-benzenedisulfonimide itself was determined: the five membered 1,3,2-dithiazole ring has an envelope conformation, with the N atom lying outside the mean plane of the S–C–C–S moiety; in the crystal, the molecules are linked by N–H…O hydrogen bonds into chains.
and in a three-dimensional network [73,74]. The structure of the conjugated anion is described as an essentially planar bicyclic framework [67,72,73,74].

4. USES AND APPLICATIONS

Some of the uses below have only a historical interest. Prepared by Holleman as saccharine analogue, sweetener properties of the o-benzenedisulfonimide were tested: it “has at once a sweet and acid taste with a bitter after taste”[2]; however, the replacement of the imide hydrogen by an alkyl group led to practically tasteless compounds [83].

N-Alkyl and N-dialkylaminoalkylderivatives have been reported to have local anaesthetic activity, more effective intradermally than by topical application [19]. 2-Methyl-5-chloro-6-methylsulfamoylbenzo-1,3,2-dithiazole 1,1,3,3-tetraoxide showed diuretic activity [84]. A disulfonimide coumarin derivative is a bleach-resistant fluorescent whitener [85]. A N-aryl disulfonimide derivative has been copolymerized with acrylonitrile and methyl methacrylate to produce a useful fibre with permanent antistatic properties [86]. Heat-resistant polymers comprising poly(phenylene ethers), optionally styrene polymers and imides showed improved moldability [87].

5. CONCLUSIONS

o-Benzenedisulfonimide proved to be a useful reagent in organic synthesis. As outlined in the most recent studies, compared to strong liquid or solid Brønsted acids, extensively used from research laboratories to chemical manufacturing plants, the potential applications of 1 as safe, easy to handle, non corrosive, recoverable and recyclable organocatalyst are practically unlimited. Moreover, in the prospect of designing new chiral organocatalysts, investigations on new synthetic applications and structural modifications of 1 have gained the chemists attention and unprecedented results in asymmetric Mukaiyama aldol reaction have been recently reported.

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Moreover, thanks are due to the Ph. D students who contributed to the above-mentioned studies.
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break down to the starting dry salts and efficient conversions to aryl iodides, bromides and chlorides. *Synthesis, 2001*, 2180.


[54] see 49 (a) Chap.4, pp 431-469 and references therein.


