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- Chem. Eur. J -

- Full Paper -

**Supramolecular wiring of benzo-1,3-chalcogenazoles  
through programmed chalcogen-bonding interactions**

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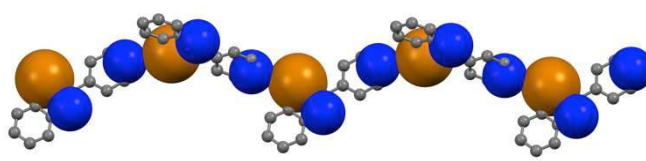
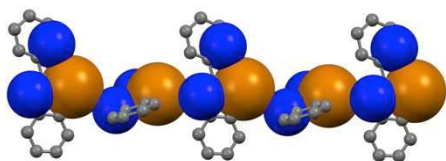
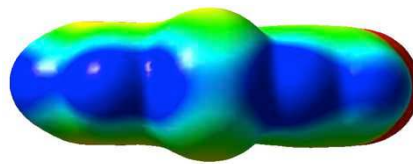
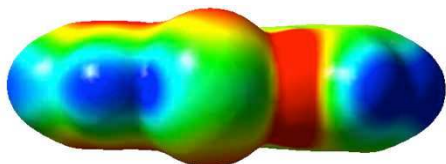
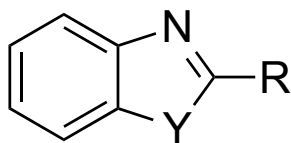
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**Keywords:** tellurazoles / selenazoles / SBIs / Te / Se / supramolecular chemistry / solid-state arrangement / supramolecular polymers / self-assembly

**Abstract:** The high-yielding synthesis of 2-substituted benzo-1,3-tellurazoles and benzo-1,3-selenazoles through a dehydrative cyclization reaction has been reported, giving access to a large variety of benzo-1,3-chalcogenazoles. Exceptionally, these aromatic heterocycles proved to be very stable and thus very handy to form controlled solid-state organizations in which wire-like polymeric structures are formed through secondary N···Y bonding interactions engaging the chalcogen (Y = Se or Te) and nitrogen atoms. In particular, it has been shown that the recognition properties of the chalcogen center at the solid state could be programmed by selectively barring one of its  $\sigma$ -holes through a combination of electronic and steric effects exerted by the substituent at the 2-position. As predicted by the electrostatic potential surfaces calculated by quantum chemical modeling, the pyridyl groups revealed to be the stronger chalcogen bonding acceptors, and thus the best ligand candidate for programming the molecular organization at the solid state. Vice-versa, the thiophenyl group is an unsuitable substituent for establishing SBIs in this molecular system as it gives rise to chalcogen-chalcogen repulsion. The weaker chalcogen donor properties of the Se-analogues trigger the formation of feeble N···Se

contacts, which are manifested in similar solid-state polymers featuring longer nitrogen-chalcogen distances.

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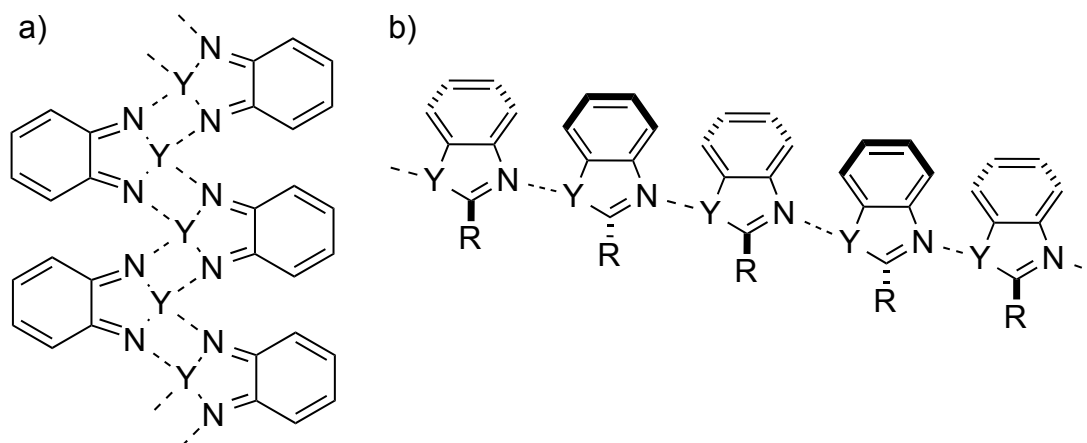


## Introduction

The concept of a secondary bonding interactions (SBIs) describes interactions resulting from interatomic contacts that are longer than the covalent single bonds, but shorter than the sum of van der Waals radii.<sup>[1, 2]</sup> Depending on the context, these interactions have been also called soft-soft, closed-shell, nonbonding, semi-bonding, non-covalent, weakly bonding, or  $\sigma$ -hole interactions.<sup>[3, 4]</sup> Formally, a secondary bond derives from a  $n^2(X) \rightarrow \sigma^*(Y\text{-EWG})$  donation, in which the lone pair of an electro-donating atom X interacts with an antibonding  $\sigma^*$  orbital of a Y-EWG bond, where Y and EWG stand for the polarizable atom and electron withdrawing group, respectively. Typically, this is described by a  $\sigma$ -hole, a region of positive electrostatic potential located on the Y atom at the opposite side of the Y-EWG bond. Descending the periodic table, the polarisability of atoms increases reducing the difference between the energy levels of the  $\sigma(Y\text{-EWG})$  and  $\sigma^*(Y\text{-EWG})$  molecular orbitals, thus favoring stronger SBIs. Halogen bonding is certainly the most investigated interactions of this class,<sup>[5-7]</sup> and its importance has been recently demonstrated in different domains, ranging from materials to biological applications.<sup>[8-16]</sup>

This type of interaction can be extended to all molecular structures, in which an electron-deficient polarizable atom is present. This includes electron-deficient chalcogen atoms, which are known to form  $X \cdots Y\text{-EWG}$  SBIs in the solid state<sup>[4, 17-20]</sup> and in solution.<sup>[21]</sup> Considering the experimental evidences and the theoretical studies<sup>[22-27]</sup>, strong SBIs can be expected when descending in the chalcogen group, with the Te-derived compounds establishing the strongest interactions.<sup>[21]</sup> Among the different chalcogenide derivatives, benzo-2,1,3-telluradiazoles have certainly attracted the greatest interest due to their unique ribbon-like self-organization at the solid state (Fig. 1a) formed through strong  $N \cdots Te$  SBIs (2.682(7)-

2.720(7) Å).<sup>[4, 28-31]</sup> Although of great potential, these molecular systems have remained confined to the fundamental research due to their thermal instability and aptitude to undergo hydrolysis under ambient conditions.



**Fig. 1.** Solid-state arrangements of a) benzo-2,1,3-telluradiazoles and b) benzo-1,3-tellurazole in tapes and wires, respectively.

On the other hands, 2-substituted benzo-1,3-tellurazoles have been only marginally studied for preparing self-organized functional materials although more chemically inert than their parent benzo-2,1,3-chalcogenadiazoles. It is only in the late eighties,<sup>[32]</sup> that the first and only X-Ray structure of a 2-substituted benzo-1,3-tellurazole was described. In the solid state, the molecule organizes into wires held by intermolecular N $\cdots$ Te contacts (Fig. 1b).<sup>[32]</sup> A similar wire-like organization was also recently reported by us with a phosphorescent 2-substituted ethynyl-benzotellurazole.<sup>[33]</sup> Given these premises and considering the ease of tuning their chemical and physical properties with simple chemical modifications of the benzo ring, 2-substituted benzo-1,3-chalcogenazoles can be privileged heterocyclic systems to engineer soft materials featuring wire-like arrangement at the molecular scale. To shed further light on the use of X $\cdots$ Y SBIs (Y = Se or Te) for mastering the supramolecular arrangement at the solid state, we have developed a versatile protocol to

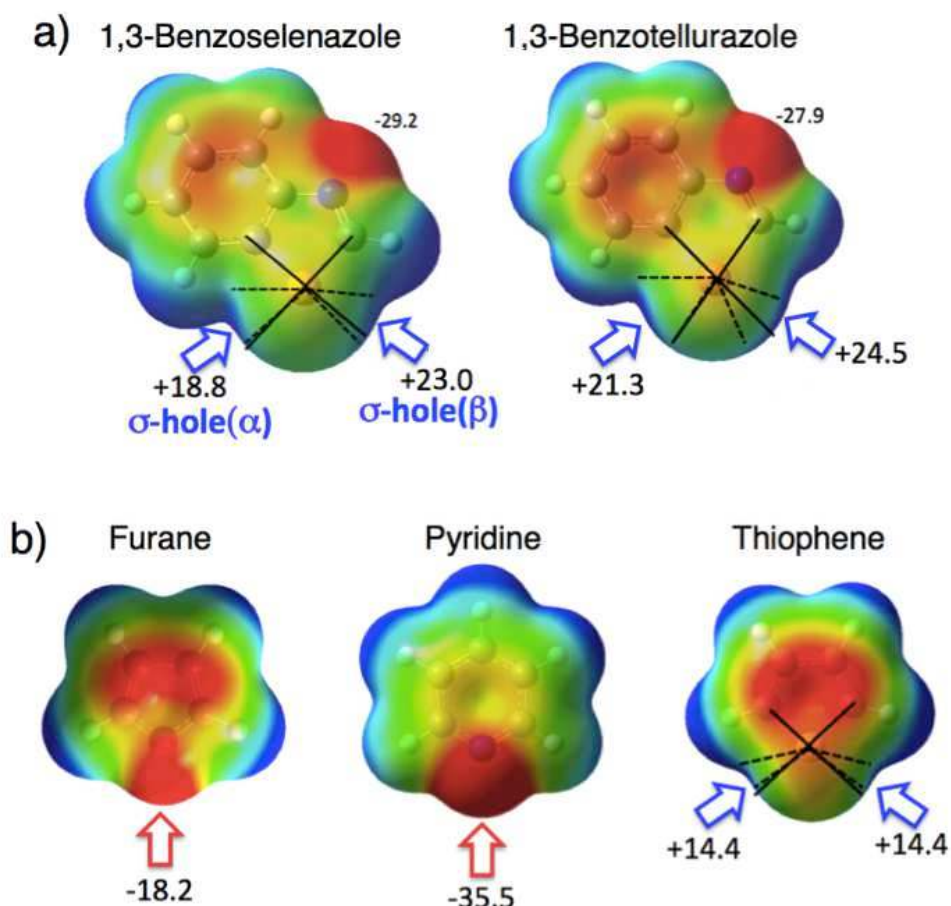
prepare 2-substituted benzo-1,3-selenazoles and benzo-1,3-tellurazoles bearing alkyl, alkenyl, aryl and heteroaryl groups in high yields. The solid-state arrangement shows that, depending on the electronic and geometrical properties of the substituent at the 2-position, one can control the wiring organization through two- (X···Y) or three-atoms (X···Y···X) SBIs.

## Results and discussion

**Programming the benzo-1,3-chalcogenazole synthones.** Provided that a sufficiently basic heteroatom (X) is present in the molecular structure of a substituted chalcogenazole, one can expect to control the organization at the solid state of functional molecular synthones *via* selected X···Y SBIs. In particular, programmed supramolecular wire-like polymers could be formed at the solid state exploiting SBIs other than those established through the chalcogenazole N atom. To appraise the possibility of programming the benzo-1,3-chalcogenazoles for controlling the solid-state arrangements through chalcogen SBIs, we used electrostatic surface potentials (ESP). As described recently by Taylor and co-workers,<sup>[21]</sup> it is well accepted that an estimation of the ability to make X···Y SBIs can be obtained considering the magnitude of  $V_{s,max}$  at X and Y atoms (*i.e.*, the value of the electrostatic potential at the point of the highest charge for both donor and acceptor atoms),<sup>[21-27]</sup> although the chalcogen bonding interactions cannot be considered as purely electrostatic interactions.<sup>[34-38]</sup> Calculations have been firstly performed on non-substituted benzo-1,3-chalcogenazoles using Gaussian 09 including the D01 revision, with the B97-D3/Def2-TZVP level of theory.<sup>[21]</sup> After geometry optimization, the ESPs were mapped on the van-der-Waals surface of each molecule up to an electron density of 0.001 electron·bohr<sup>-3</sup>.  $V_{s,max}$  were determined with a classical method.<sup>[39]</sup> As previously observed for benzo-2,1,3-chalcogenadiazoles,<sup>[21]</sup> two electron deficient regions ( $\sigma$ -holes)



centered at the chalcogen Y atom, each situated at the terminus of the C-Y bond, could be evidenced from the ESP surfaces. In contrast to benzo-2,1,3-telluradiazoles, both benzo-1,3-selenazole and benzo-1,3-tellurazole features  $\sigma$ -holes displaying different  $V_{s,max}$  values (Fig. 2a).



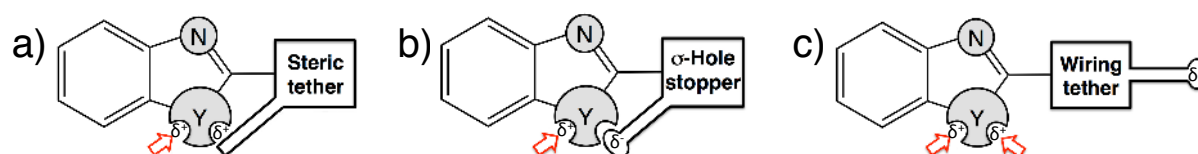
**Fig. 2.** ESP ( $\text{kCal mol}^{-1}$ , calculated using Gaussian 09 at B97-D3/def2-TZVP level of theory) for a) unsubstituted chalcogenazoles displaying the two  $\sigma$ -holes (labeled as  $\alpha$  and  $\beta$ , respectively) and b) furanyl, pyridyl and thiophenyl ligands. The red and blue indicate negative and positive charge densities.

To distinguish the  $\sigma$ -holes, the following terminology will be used throughout this manuscript:  $\sigma$ -hole( $\alpha$ ) and  $\sigma$ -hole( $\beta$ ) for describing positive electrostatic regions on the chalcogen atom exposed on the side of the 4- and 2-positions, respectively (Fig. 2a). The calculated  $V_{s,max}$  values for benzo-

1,3-selenazole are +18.8 and +23.0 kcal mol<sup>-1</sup> for the  $\alpha$  and  $\beta$   $\sigma$ -holes, respectively (Fig. 2). Similar values were also obtained for benzo-1,3-tellurazole, +21.3 and +24.5 kcal mol<sup>-1</sup> for the  $\alpha$  and  $\beta$   $\sigma$ -holes, respectively. This suggests that both benzo-1,3-chalcogenazoles are suitable molecular synthones to undergo SBI recognition. Although the differences in the  $V_{s,max}$  values between the two  $\sigma$ -holes are significantly small, the  $\sigma$ -hole( $\beta$ ) in non-substituted benzo-1,3-chalcogenazoles feature a slightly higher electrostatic values, possibly anticipating a selectivity in the recognition mode. Instead, the N atom of the chalcogenazole features the most negative  $V_{s,max}$  values (-29.2 and -27.9 kcal mol<sup>-1</sup>, for the Se and Te derivatives, respectively), making it the strongest basic site and thus a privileged acceptor atom for establishing a chalcogen bonding interaction. This behavior has been confirmed with 2-phenyl benzo-1,3-tellurazole at the solid state.<sup>[32]</sup> On the other hand, if one wants to control the supramolecular architecture with SBIs engaging a different atom than the N of the chalcogenazole, ligands featuring basic sites with higher negative  $V_{s,max}$  values have to be used. Among the different acceptors, we have focused our attention on the pyridyl, furanyl and thiophenyl aromatic rings. While the calculated  $V_{s,max}$  values are -18.2 and -35.0 kcal mol<sup>-1</sup> for the O and N atoms of the furane and pyridine structures respectively (Fig. 2b), the thiophenyl ring displays an ESP distribution on the S atom similar to that of the chalcogenazoles. Namely, two  $\sigma$ -hole electron-deficient regions centered on the S atom, each situated at the termini of the S-C bonds, are evident in the ESP (Fig. 2b). In particular, a calculated  $V_{s,max}$  value of +14.4 kcal mol<sup>-1</sup> has been obtained suggesting that the S atom does not present the favorable electrostatic properties for engaging the Se or Te atoms in a in-plane SBI. Therefore it is evident that the chalcogen bonding acceptor abilities that can be inferred from the calculated  $V_{s,max}$  designates the pyridyl

moiety as the best ligand, followed by the chalcogenazole and furanyl rings. Instead, the thiophenyl rings is expected to establish in-plane repulsive interactions.

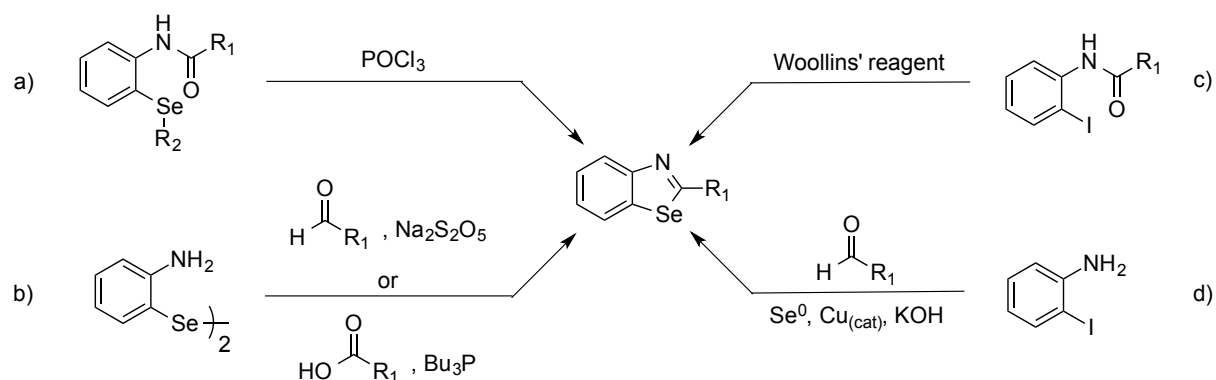
Indulging these computational results, programmed benzo-1,3-chalcogenazoles bearing different pyridyl, furanyl and thiophenyl moieties at the 2-position have been prepared to tailor the recognition properties of the chalcogen atom and to control the supramolecular organization at the solid state. Specifically, it is envisaged that the self-assembly behavior of benzo-1,3-chalcogenazoles can be mastered by programming the 2-position with suitable functional groups through *i*) steric hindrance (Fig. 3a), *ii*) electrostatic stopping (Fig. 3b), or *iii*) intermolecular tethering (Fig. 3c). This can result in either tuning the recognition properties of the chalcogen atom (*i* and *ii*) or governing the formation of different supramolecular arrangements (*iii*). As anticipated above, particular attention will be given to the introduction of substituents at the 2-position with suitable electronic and geometrical requirements to master the formation of supramolecular wires featured through two- ( $X\cdots Y$ ) or three-atoms ( $X\cdots Y\cdots X$ ) SBIs.



**Fig. 3.** Programming the recognition properties of benzo-1,3-chalcogenazoles through a) hindering, b) stopping or c) tethering the  $\sigma$ -holes.

**Synthesis.** Only a limited number of reports are described in the literature about the preparation of 2-functionalized benzoselenazole derivatives bearing in 2-position an alkyl, aryl or heteroaryl substituent (Scheme 1). A first approach is the dehydrative cyclization of 2-selenoanilides reported in the eighties by Christiaens and co-workers, who prepared a few

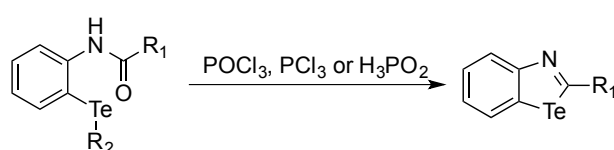
benzoselenazoles and tellurazoles derivatives by cyclization of 2-chalcogenoanilides with  $\text{POCl}_3$  (Route a).<sup>[40]</sup>



**Scheme 1.** The different synthetic approaches toward the preparation of 2-functionalized benzoselenazole derivatives starting from: a) 2-selenoanilides ( $R_1 = \text{Me}$  or aryl;  $R_2 = \text{Me}$  or Et),<sup>[40]</sup> b) bis(2-aminophenyl)diselenide ( $R_1 = \text{alkyl}$  or aryl),<sup>[44, 45]</sup> c) 2-iodoanilides ( $R_1 = \text{alkyl}$ , aryl or heteroaryl) and <sup>[47]</sup> d) 2-iodoaniline ( $R_1 = \text{aryl}$  or heteroaryl).<sup>[48]</sup>

Nevertheless, the extremely low yield (~1%, over the four steps synthesis), the use of extremely evil-smelling and toxic reagents (e.g.,  $\text{Et}_2\text{Te}_2$ ), the low chemical versatility, and contradictory reports about reproducibility issues,<sup>[41]</sup> limited the scope of the original protocol. Following reports by *Minkin* and co-workers, they showed that 2-methyl and 2-phenyl substituted benzotellurazoles could be obtained by cyclization of 2-telluroanilides in neat  $\text{POCl}_3$  with improved yields.<sup>[42, 43]</sup> However, the harsh acidic conditions severely narrow the compatibility of the protocol to a limited family of substrates. Recently, two new synthetic routes toward the preparation of alkyl-, aryl- and heteroaryl-substituted derivatives have been developed: routes b) and d). In route b,<sup>[44-46]</sup> bis(2-aminophenyl)diselenide is reacted with a carbonyl derivative in the presence of a reducing agent, while the second approach exploits Woollins' reagent and 2-iodoanilides (Route c).<sup>[47]</sup> Finally, a copper-catalyzed three-component one-pot synthesis, limited to the case of aryl and heteroaryl derivatives, has been described very recently (Route d).<sup>[48]</sup> In

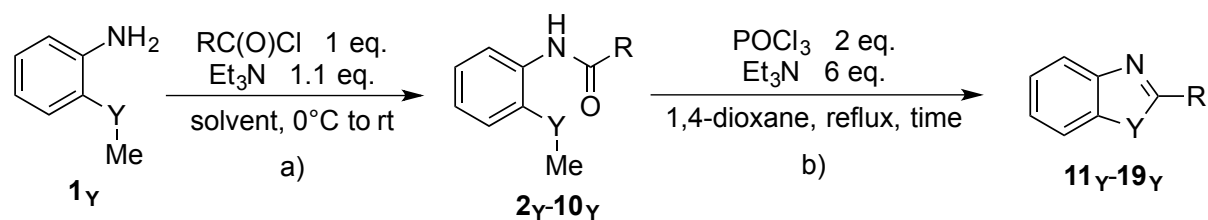
the case of the benzotellurazoles analogues, the synthetic protocols are scarcer.<sup>[40-43, 49-51]</sup> To the best of our knowledge, the developed methods to date (Scheme 2) are limited to the preparation of 2-substituted alkyl and aryl derivatives. This exploits the dehydrative cyclization of 2-telluroanilides with either phosphorus oxychloride,<sup>[40, 42, 43, 49]</sup> phosphorus trichloride<sup>[41]</sup> or hypophosphorus acid,<sup>[50, 51]</sup> with the latter conditions only compatible for the synthesis of alkyl and aryl 2-substituted derivatives.



**Scheme 2.** Synthetic approach for the preparation of 2-functionalized benzotellurazole derivatives ( $R_1$  = alkyl or aryl).<sup>[40-43, 49-51]</sup>

Inspired by the synthetic route developed by *Christiaens* and co-workers,<sup>[40]</sup> we focus our attention on the dehydrative cyclization reaction to prepare the targeted 2-substituted chalcogenazole derivatives. Starting from *o*-methylseleno- **1<sub>se</sub>** and *o*-methyltelluro-aniline **1<sub>te</sub>**, prepared in two steps from 2-bromoaniline,<sup>[33]</sup> we have synthesized a series of selenoanilides (**2<sub>se</sub>**-**10<sub>se</sub>**) and telluroanilides (**2<sub>te</sub>**-**10<sub>te</sub>**) with very good yields (Table 1, first step) upon reaction with the appropriate acyl chloride. Adapting the protocol by Minkin<sup>[42, 43]</sup> to milder reaction conditions, anilides **2<sub>y</sub>**-**10<sub>y</sub>** could be converted into targeted benzoselenazoles and tellurazoles **11<sub>y</sub>**-**19<sub>y</sub>** in very good to excellent yields in less than three hours (Table 1, second step, entries 1-14 and 17-18) using two equivalents of POCl<sub>3</sub> in the presence of Et<sub>3</sub>N under reflux in 1,4-dioxane.<sup>[42, 43]</sup> The only exception was restricted to the cases of picolinamide derivatives **9<sub>y</sub>**, which were transformed into the 2-(pyridin-2-yl)benzochalcogenazole derivatives, **18<sub>se</sub>** and **18<sub>te</sub>**, in modest yields (Table 1, entries 15-16).

**Table 1.** Two-steps synthesis for preparing 2-substituted chalogenazoles from 2-chalcogenoanilides by dehydrative cyclization. Y = Se or Te.



Entry	R	Y	a)		b)		
			Product	Yield(%) <sup>a</sup>	Time(h)	Product	Yield(%) <sup>a</sup>
1	<i>i</i> -Bu	Se	<b>2<sub>Se</sub></b>	90	3	<b>11<sub>Se</sub></b>	77
2		Te	<b>2<sub>Te</sub></b>	87	3	<b>11<sub>Te</sub></b>	84
3	Ph	Se	<b>3<sub>Se</sub></b>	95	3	<b>12<sub>Se</sub></b>	88
4		Te	<b>3<sub>Te</sub></b>	94	3	<b>12<sub>Te</sub></b>	83
5		Se	<b>4<sub>Se</sub></b>	64	3	<b>13<sub>Se</sub></b>	90
6		Te	<b>4<sub>Te</sub></b>	70	3	<b>13<sub>Te</sub></b>	86
7		Se	<b>5<sub>Se</sub></b>	84	3	<b>14<sub>Se</sub></b>	88
8		Te	<b>5<sub>Te</sub></b>	75	3	<b>14<sub>Te</sub></b>	96
9		Se	<b>6<sub>Se</sub></b>	90	3	<b>15<sub>Se</sub></b>	87
10		Te	<b>6<sub>Te</sub></b>	94	3	<b>15<sub>Te</sub></b>	91
11		Se	<b>7<sub>Se</sub></b>	88	3	<b>16<sub>Se</sub></b>	87
12		Te	<b>7<sub>Te</sub></b>	66	1.5	<b>16<sub>Te</sub></b>	88
13		Se	<b>8<sub>Se</sub></b>	98	2	<b>17<sub>Se</sub></b>	66
14		Te	<b>8<sub>Te</sub></b>	93	1.5	<b>17<sub>Te</sub></b>	80
15		Se	<b>9<sub>Se</sub></b>	98	8 <sup>b</sup>	<b>18<sub>Se</sub></b>	39 <sup>b</sup>
16		Te	<b>9<sub>Te</sub></b>	90	6 <sup>c</sup>	<b>18<sub>Te</sub></b>	67 <sup>c</sup>
17		Se	<b>10<sub>Se</sub></b>	55	3	<b>19<sub>Se</sub></b>	81
18		Te	<b>10<sub>Te</sub></b>	59	3	<b>19<sub>Te</sub></b>	81

<sup>a</sup>Yield of the isolated product; <sup>b</sup>83% and <sup>c</sup>92% of conversion.

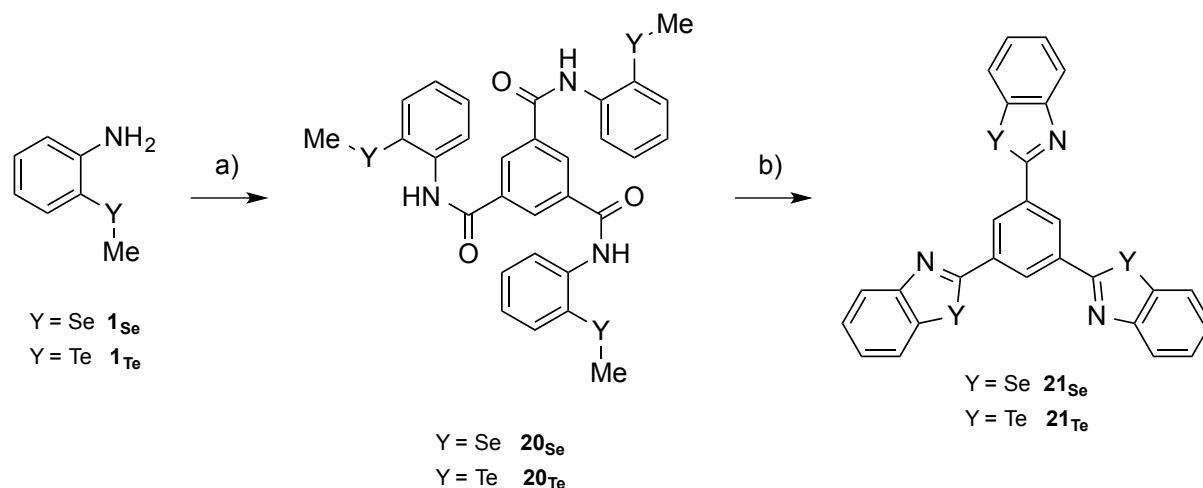
As anticipated above, the protocol is compatible with a wide range of substituents in the 2-position. Indeed, alkyl (Table 1, entries 1 and 2) and alkenyl (Table 1, entries 5 and 6) moieties were successfully inserted, as well as aromatic (Table 1, entries 3 and 4) and heterocyclic substituents, like furanyl, thiophenyl, pyridyl and ferrocenyl moieties (Table 1, entries 7-18). All structures were fully characterized by  $^1\text{H}$ - and  $^{13}\text{C}$ -NMR spectroscopy and HR-Mass spectrometry. Complementary  $^{125}\text{Te}$ -NMR analyses were also performed on the tellurazoles. All spectra display a singlet with similar chemical shifts in the spectral region between 852 and 892 ppm, with the 2-phenyl and 2-*i*-butyl tellurazoles exhibiting the two limiting values, respectively (Table 2). Due to the presence of the N atom in the 3-position, the  $^{125}\text{Te}$  chemical shifts are significantly deshielded with respect to reference  $\text{Ph}_2\text{Te}_2$ , in agreement with the literature reports.<sup>[41, 50, 52, 53]</sup> Considering that the coordination of a Te atom can result in upfield shifts as big as 200 ppm,<sup>[52, 53]</sup> the  $^{125}\text{Te}$ -NMR measurements are not conclusive to support the existence of any inter- or intramolecular SBIs in solution.

**Table 2.**  $^{125}\text{Te}$  NMR chemical shifts in  $\text{CDCl}_3$  solution at 293 K (reference taken with  $\text{Ph}_2\text{Te}_2$ ).

Compounds	<b>11<sub>Te</sub></b>	<b>12<sub>Te</sub></b>	<b>14<sub>Te</sub></b>	<b>15<sub>Te</sub></b>	<b>16<sub>Te</sub></b>	<b>17<sub>Te</sub></b>	<b>18<sub>Te</sub></b>
$\delta$ ( $^{125}\text{Te}$ , $\text{CDCl}_3$ , ppm)	892	852	884	877	884	870	874

Recently, the same protocol allowed us to prepare 2-ethynyl benzo-1,3-chalcogenazoles and bisbenzo-1,3-chalcogenazoles.<sup>[33]</sup> To further show the synthetic versatility of the approach, the preparation of trisbenzo-1,3-selenazole **21<sub>se</sub>** and -1,3-tellurazole **21<sub>te</sub>** was also attempted (Scheme 3). Reaction of anilines **1<sub>y</sub>** with 1,3,5-benzenetricarbonyl trichloride in the presence of  $\text{Et}_3\text{N}$  gave trisanilides **20<sub>y</sub>**. Subsequent cyclization of **20<sub>y</sub>**, using six equivalents of  $\text{POCl}_3$  in the presence of  $\text{Et}_3\text{N}$  under reflux in 1,4-dioxane, afforded

targeted trisbenzo-1,3-chalcogenazoles **21<sub>y</sub>** in very good yields. Both Se and Te trisbenzo-1,3-chalcogenazoles were characterized by mass spectrometric data (see SI), <sup>1</sup>H-NMR, and IR spectra. Due to the poor solubility, only the <sup>13</sup>C-NMR spectrum of **21<sub>Te</sub>** could be obtained. All attempts to obtain suitable crystals for X-ray analysis revealed to be fruitless.



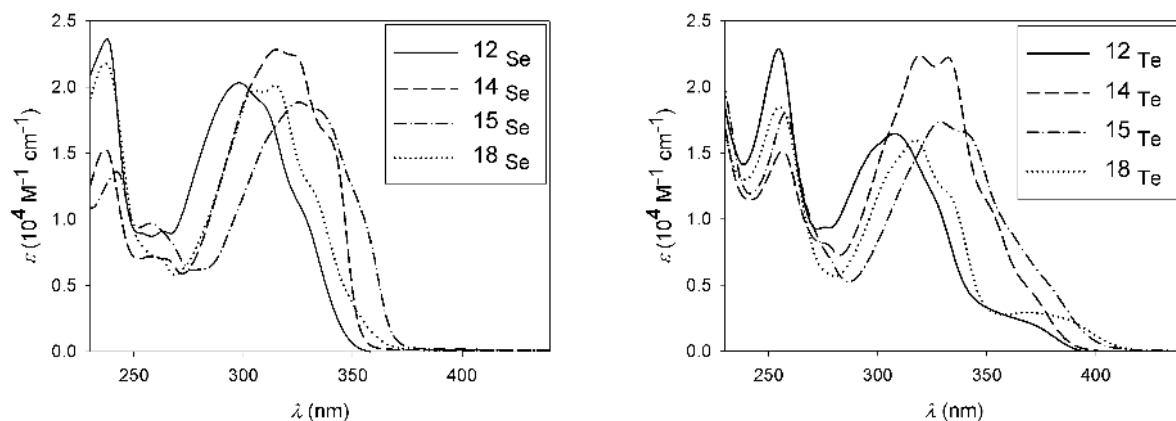
**Scheme 3.** Synthesis of trisbenzochalcogenazoles **21<sub>se</sub>** and **21<sub>te</sub>**. Reagents and conditions: a) 1,3,5-benzenetricarbonyl trichloride, Et<sub>3</sub>N, CH<sub>2</sub>Cl<sub>2</sub>, 24h, rt, Se: 82% of **20<sub>se</sub>**, Te: 57% of **20<sub>te</sub>**; b) POCl<sub>3</sub>, Et<sub>3</sub>N, 1,4-dioxane, time, rt to 102 °C; Se from **20<sub>se</sub>**: 3h, 72% of **21<sub>se</sub>**, Te from **20<sub>te</sub>**: 3h, 75% of **21<sub>te</sub>**.

**Steady-state UV-vis absorption and emission studies in solution.** Comparative absorption spectra of compounds **11<sub>y</sub>-19<sub>y</sub>** in CH<sub>2</sub>Cl<sub>2</sub> are shown in Figures 4-6 (see also SI), with the key absorption data resumed in Table 3. In general, absorption spectra for compounds **11<sub>se</sub>-18<sub>se</sub>** display a combination of two main bands in the UV region, while in the case of the tellurazole analogues (**11<sub>te</sub>-18<sub>te</sub>**) an additional electronic transition develops in the visible wavelengths.<sup>[33]</sup> Differently, **19<sub>se</sub>** and its analogue **19<sub>te</sub>** show a broad and low intense absorption band in the visible region, a typical electronic transition fingerprinting the ferrocene unit (Fig. 6). For both benzochalcogenazoles, a narrow band is recorded with  $\epsilon$  values between 15000 and 23000 M<sup>-1</sup>cm<sup>-1</sup> at higher  $\lambda$  (comprised between 235 and 265 nm), likely corresponding to the electronic transition centered on the phenyl unit. In the presence of an aryl substituent, this transition is slightly

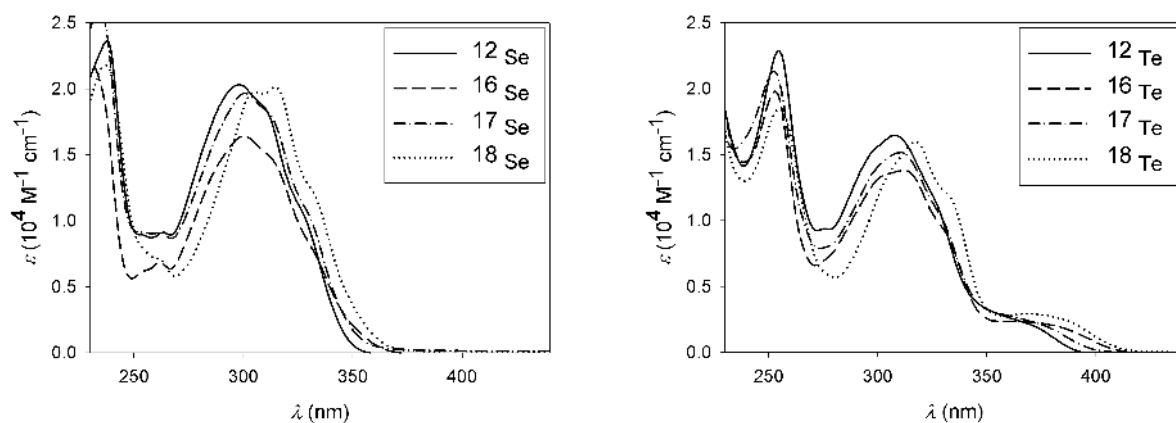


red-shifted (Fig. 4). In the region between 270 nm and 350 nm a broader band is detected for the aryl-substituted benzoselenazoles and benzotellurazoles, showing a vibrational structure only in the case of derivatives **14<sub>Te</sub>** and **15<sub>Te</sub>**. Again, this band results red-shifted within the progression of the aryl substituents (phenyl > pyridyl > furanyl > thiophenyl) in both chalcogenazole derivatives (Fig. 4). Notably, among the pyridyl-substituted chalcogenazoles, only the UV-vis profiles of **18<sub>se</sub>** and **18<sub>Te</sub>** are significantly red-shifted with respect to the phenyl analogues, probably because of the intramolecular N<sup>...</sup>Te interaction that planarizes the two heterocyclic moieties (see X-ray structure in Fig. 10). Most likely, the planar conformation significantly increases the  $\pi$ -conjugation between the two aromatic cycles, thus favoring a bathochromic shift of the electronic transitions. Finally, one can easily notice that the spectra of the benzotellurazole derivatives show a low-intensity (between 2500 and 5500 M<sup>-1</sup> cm<sup>-1</sup>) unstructured band (except for **13<sub>Te</sub>**-**15<sub>Te</sub>**, where it appears as a shoulder) that is absent in the absorption profiles of the congener benzoselenazoles.<sup>[33]</sup> This can be attributed to the presence of the Te atom, that most likely promotes additional  $^1n \rightarrow \pi^*$  electronic transition.<sup>[54-56]</sup>

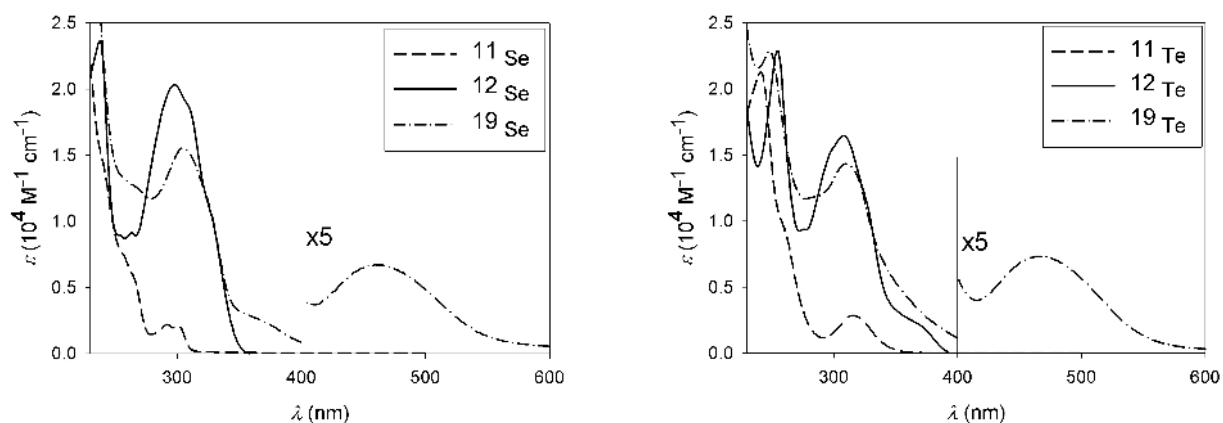
Luminescence studies of air-equilibrated solutions of benzotellurazoles **11<sub>Te</sub>**-**19<sub>Te</sub>** in CH<sub>2</sub>Cl<sub>2</sub> at room temperature showed negligible or very low intense ( $\Phi < 10^{-3}$ ) emission profiles, showing no relevant enhancement of the  $\Phi$  values in de-aerated solutions (after bubbling Ar in the medium for 25 minutes). On the other hand, 2-pyridyl tellurazole **18<sub>Te</sub>** displays appreciable phosphorus emission only as a powder, with an unstructured band centered at 535 nm (see SI). Emission lifetime analysis at 535 nm results in a  $\mu$ s timescale decay ( $\tau = 11 \mu$ s), which is compatible with a spin forbidden triplet-singlet deactivation pathway typical of this kind of system, as also recently observed by us with 2-ethynyl benzo-1,3-chalcogenazole derivatives.<sup>[33]</sup>



**Fig. 4.** UV-vis absorption spectra of 2-substituted phenyl (**12<sub>v</sub>**), furanyl (**14<sub>v</sub>**), thiophenyl (**15<sub>v</sub>**) and pyridyl (**18<sub>v</sub>**) benzoselenazoles (left) and benzotellurazoles (right) in  $\text{CH}_2\text{Cl}_2$  at 298 K.



**Fig. 5.** Comparison of the UV-vis absorption spectra of 2-substituted phenyl (**12<sub>v</sub>**) and the pyridyl (**16<sub>v</sub>**-**18<sub>v</sub>**) benzoselenazoles (left) and benzotellurazoles (right) in  $\text{CH}_2\text{Cl}_2$  at 298 K.



**Fig. 6.** UV-vis absorption spectra of 2-substituted alkyl- (**11<sub>v</sub>**), phenyl (**12<sub>v</sub>**) and ferrocenyl (**19<sub>v</sub>**) benzoselenazoles (left) and benzotellurazoles (right) in  $\text{CH}_2\text{Cl}_2$  at 298 K.

**Table 3.** Absorption parameters of **11<sub>y</sub>-19<sub>y</sub>** in CH<sub>2</sub>Cl<sub>2</sub> at 298 K.

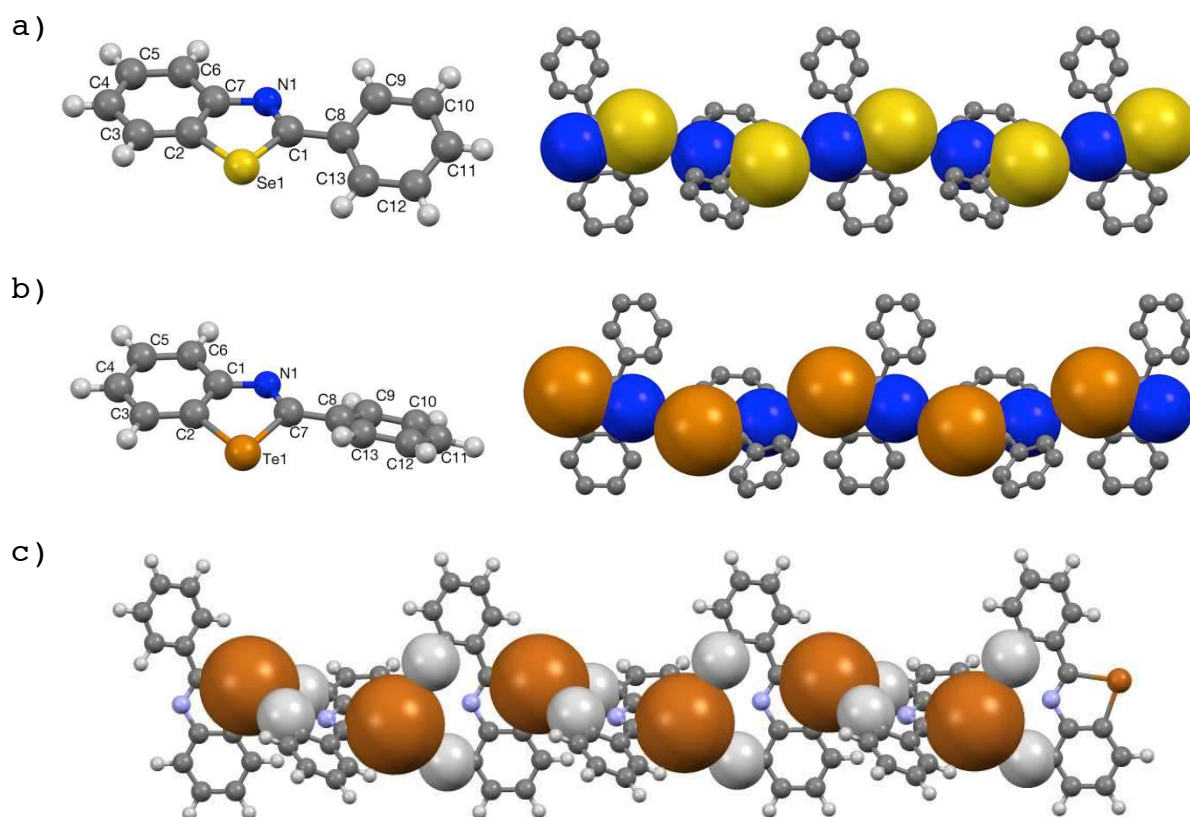
<b>M</b>	$\lambda_{\max}$ , nm ( $\epsilon_{\max}$ , 10 <sup>3</sup> M <sup>-1</sup> cm <sup>-1</sup> )	
	<b>Se</b>	<b>Te</b>
<b>11<sub>y</sub></b>	260 (6.8), 292 (2.2), 302 (2.1)	241 (21.3), 260 (9.5), 316 (2.8)
<b>12<sub>y</sub></b>	238 (23.7), 298 (20.3)	255 (22.9), 308 (16.5), 365 (2.4)
<b>13<sub>y</sub></b>	272 (7.5), 327 (28.9)	265 (19.0), 335 (29.3), 395 (4.7)
<b>14<sub>y</sub></b>	238 (15.1), 315 (22.8)	256 (15.2), 320 (22.4), 370 (4.6)
<b>15<sub>y</sub></b>	242 (13.5), 257 (9.7), 325 (18.9)	258 (17.6), 329 (17.2), 375 (5.5)
<b>16<sub>y</sub></b>	300 (16.4)	253 (19.8), 310 (13.8), 365 (2.3)
<b>17<sub>y</sub></b>	301 (19.7)	253 (21.3), 310 (15.2), 365 (2.6)
<b>18<sub>y</sub></b>	237 (21.8), 305 (19.7), 315 (20.1)	255 (18.5), 318 (16.0), 369 (2.9)
<b>19<sub>y</sub></b>	304 (15.5), 464 (1.3)	248 (22.9), 309 (14.3), 467 (1.5)

### **Programmed supramolecular organization at the solid state.**

In this section we will describe the solid-state arrangement of those benzo-1,3-chalcogenazoles that formed crystals suitable for X-ray diffraction (Fig. 7-12). In general, all the C-Se, C-Te and N-C bonds belonging to the 1,3-chalcogenazole cores do not significantly differ between the different molecules bearing the same chalcogen atom. This suggests that the crystal organization does not alter the covalent molecular skeleton. The recognition at the solid-state is discussed considering the molecular conformation (Table 4) and the calculated electrostatic surface potentials (ESP) displayed in the Supporting Information (Table S14). As general principle, one can be anticipated that the  $\sigma$ -hole displaying the highest positive  $V_{s,\max}$  value (Table 5) will be preferentially engaged in the SBI with the functional group bearing the most negative heteroatom.<sup>[21, 57, 58]</sup>

*Steric control of the  $\sigma$ -hole recognition.* As anticipated in the introductory section, this work was inspired by the solid-

state organization of 2-phenyl-benzotellurazole **12<sub>Te</sub>** (Fig. 7b),<sup>[32]</sup> in which supramolecular wires are formed through chalcogen bonding interactions ( $d_{N\dots Te} = 3.43 \text{ \AA}$ ).



**Fig. 7.** Ortep (left) and ball-stick/spacefill (right) representations of the crystal structure of a) **12<sub>se</sub>** and b) **12<sub>Te</sub>**, from which one can evidence the supramolecular wiring motif (the N...Y contacts are viewed with the space-filling model). Space groups:  $P2_1/c$  (**12<sub>se</sub>**) and  $P2_1/a$  (**12<sub>Te</sub>**). Atom colors: blue N, other Te, yellow Se, gray C.

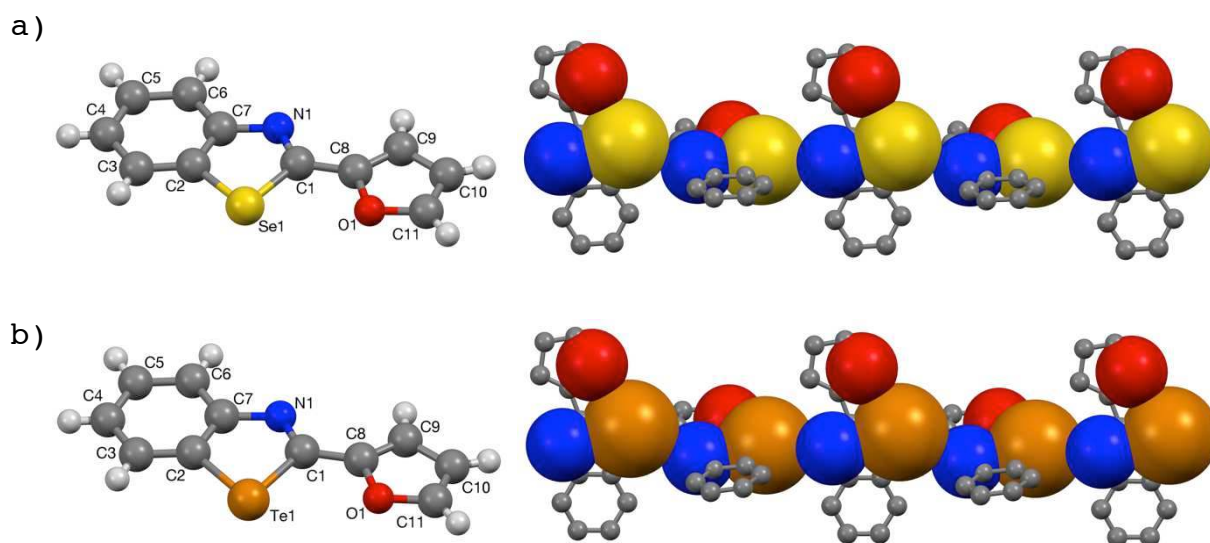
Colorless crystals of Se analogue **12<sub>se</sub>** could also be easily obtained from slow evaporation of a  $\text{CHCl}_3$  solution (Fig. 7a). As far as it concerns the chalcogenazole heterocycle, molecule **12<sub>se</sub>** displays significantly shorter Se-C bonds ( $\sim 1.90$  vs  $\sim 2.10 \text{ \AA}$ ) and C-N-C angle ( $112.8$  vs  $116.9^\circ$ ), but a larger C-Se-C angle ( $84.2$  and  $78.6^\circ$ ) than those of Te-containing molecule **12<sub>Te</sub>**. These structural characteristics are similar in all the analyzed benzo-1,3-chalcogenazoles. As it was observed for the Te derivative, also molecule **12<sub>se</sub>** arranges as rod-like polymers in which the benzo-1,3-chalcogenazole units are connected to each other through N...Se interactions (intermolecular  $d_{N\dots se} = 3.36 \text{ \AA}$ ), involving the chalcogen  $\sigma\text{-hole}(\alpha)$  and the

chalcogenazole N atom. In both cases, the 2-Ph substituent adopts a out-of-plane conformation (conformation A, Table 4) with respect to the benzo-1,3-chalcogenazole, featuring interplanar angles of about 25° and 31° for the Se and Te derivatives, respectively. To shed further light on the structural properties of molecules **12<sub>y</sub>**, we compared the molecular conformation in the crystal with that deriving from DFT minimization in the vacuum (Table 4). As one can clearly evidence, in all cases the theoretical optimization feature a planar conformation as the most stable, thus rejecting the initial hypothesis for which an electrostatic repulsion could exist between the nearest phenyl C-H and the  $\sigma$ -hole( $\beta$ ). However, a closer analysis of the crystal structure suggests that the non-planar conformation likely originates from the presence of double C-H $\cdots$ Y interactions (see Fig. 7c for the Te case:  $d_{\text{C-H}\cdots\text{Y}} = 2.959$  and  $3.072$  Å), which clamps the chalcogen atoms along the supramolecular wiring direction. The C-H $\cdots$ Y interactions are established between positively charged hydrogen atoms and the negative region of the electrostatic surface potential encircling the chalcogen atom. These interactions are more evident with the Te atom. Substitution of the phenyl ring with an alkyl moiety like did not alter the recognition properties of the benzo-1,3-chalcogenazole ring. In fact, X-ray analysis of a crystal of 2-*iso*-butyl-substituted benzotellurazole **11<sub>Te</sub>** (see Figure S4 in SI) displays the polymeric arrangement held by N $\cdots$ Te contacts ( $d_{\text{n}\cdots\text{Te}} = 3.23$  Å) through the  $\sigma$ -hole( $\alpha$ ).

It is clear that for this molecular series, the adopted conformation (conformation A, Table 4) brings a C-H bond in close proximity to the chalcogen atom hindering the access to the  $\sigma$ -hole( $\beta$ ). Thus, being the C-H bond on the  $\alpha$  side more distant from the chalcogen atom than that on  $\beta$  (DFT values:  $d_1 = 3.192$  and  $3.187$  Å and  $d_2 = 3.033$  and  $2.753$  Å for **11<sub>Te</sub>** and **12<sub>Te</sub>**,

respectively, Table 4), the chalcogen recognition preferentially occurs at the  $\sigma$ -hole( $\alpha$ ).

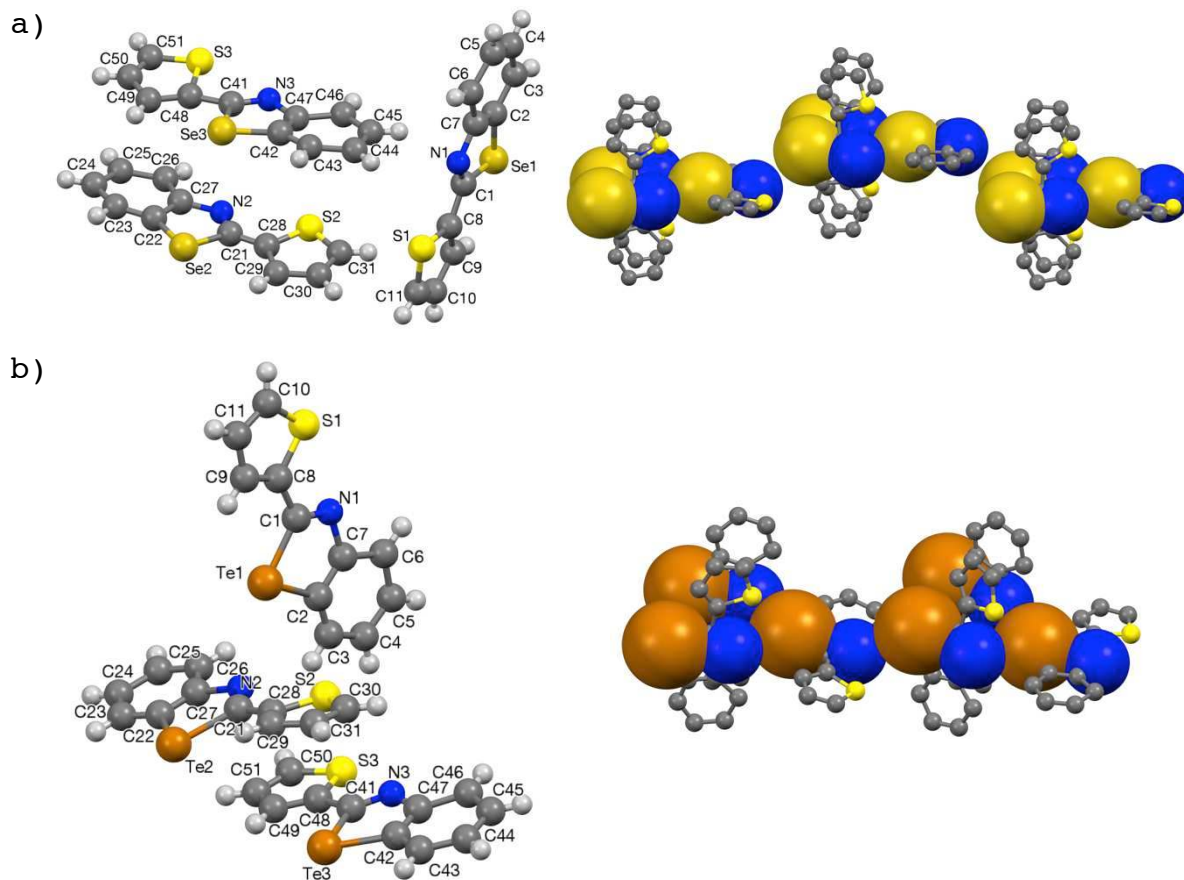
*Barring the  $\sigma$ -hole through intramolecular SBIs: the  $\sigma$ -hole stopper.* Colorless and beige crystals suitable for X-Ray analysis were instead obtained for 2-furanyl benzo-1,3-chalcogenazole **14<sub>Se</sub>** and **14<sub>Te</sub>** by slow evaporation of a CHCl<sub>3</sub> solution (Fig. 8).



**Fig. 8.** Ortep (left) and ball-stick/spacefill (right) representations of the crystal structure of a) **14<sub>Se</sub>** and b) **14<sub>Te</sub>** evidencing the supramolecular wiring motif (the N...Y contacts are viewed with the space-filling model). Space groups: P2<sub>1</sub>/c (**14<sub>Se</sub>**) and Pbcu (**14<sub>Te</sub>**). Atom colors: blue N, red O, other Te, yellow Se, gray C.

In both cases the molecule adopts a planar conformation (conformation B, Table 4), in which the furanyl substituent is essentially coplanar (interplanar angles: 1.45 and 6.98° for **14<sub>Se</sub>** and **14<sub>Te</sub>**, respectively) with the bicyclic benzo-1,3-chalcogenazole. Detailed analysis of the crystal structure showed that short intramolecular O...Y contacts are established ( $d_{O...Te} = 3.03$  and  $3.15$  Å for **14<sub>Se</sub>** and **14<sub>Te</sub>**, respectively, Table 5) between the furanyl O atom and the chalcogen  $\sigma$ -hole( $\beta$ ). As visualized in Table S14 (see SI), this causes a complete (**14<sub>Se</sub>**,  $V_{s,max} \approx 0$ ) or partial (**14<sub>Te</sub>**,  $V_{s,max} = +10.3$  kcal mol<sup>-1</sup>) occlusion of the  $\sigma$ -hole( $\beta$ ). As a result, molecules **14<sub>Se</sub>** and **14<sub>Te</sub>** feature only

one electron deficient  $\sigma$ -hole region on the  $\alpha$  side ( $V_{s,\max} = +16.4$  and  $+19.4$  kcal mol $^{-1}$ , respectively, see Table 5).

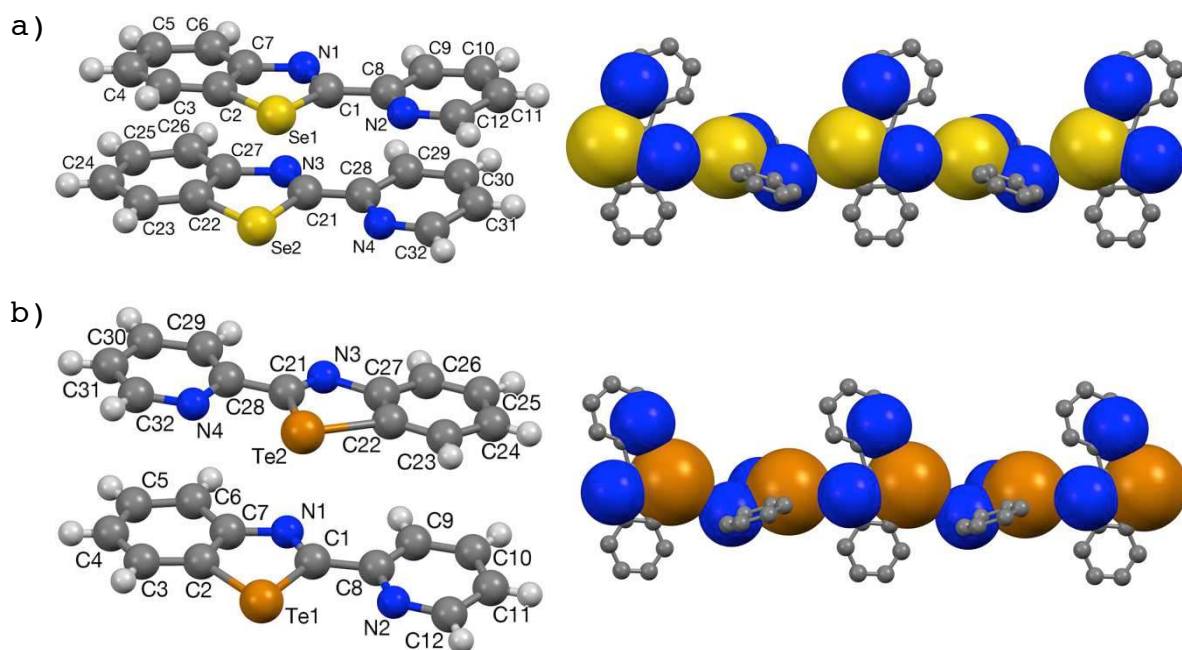


**Fig. 9.** Ortep (left) and ball-stick (right) representations of the crystal structure of a) **15<sub>Se</sub>** and b) **15<sub>Te</sub>**. While for **15<sub>Se</sub>** disconnected trimeric clusters are formed at the solid state, molecule **15<sub>Te</sub>** organizes into supramolecular polymers, alternating N $\cdots$ Te and N $\cdots$ Te $\cdots$ N contacts (the N $\cdots$ Y contacts are viewed with the space-filling model). Space groups: P $_2$ /c for both structures. Atom colors: blue N, bright yellow S, other Te, yellow Se, gray C. Three crystallographically independent molecules are found the unit cell for both benzochalcogenazoles.

It is thus through this  $\sigma$ -hole( $\alpha$ ) that molecules **14<sub>y</sub>** can develop into supramolecular wires by N $\cdots$ Y SBIs ( $d_{N\cdots Y} = 3.25$  and  $3.17$  Å, for the Se and Te derivatives, respectively). Crystals suitable for X-ray analysis were also obtained for 2-thiophenyl-benzochalcogenazole analogues **15<sub>y</sub>** (Fig. 9). Although the resolutions of the X-ray structures is slightly inferior if compared to those of other derivatives, the data clearly display that both molecules adopt a flat conformation A (Table 4), in which the two chalcogen atoms are facing opposite sides, likely governed by N $\cdots$ S contacts ( $d_{N\cdots S} = 2.99 - 3.02$  for

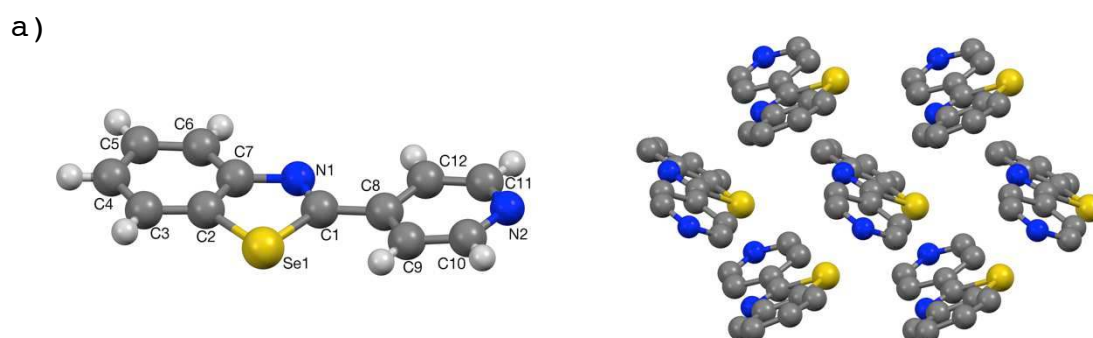
**15<sub>se</sub>** and 2.92 - 3.01 for **15<sub>te</sub>**). The crystals of molecule **15<sub>se</sub>** only display the presence of discrete trimeric clusters held together by double N $\cdots$ Se interactions that, sandwiching the Se atom ( $d_{N\dots Se} = 3.22$  and  $3.43$  Å) through its two  $\sigma$ -holes, form a three-atom chalcogen bonding motif (e.g., N $\cdots$ ( $\alpha$ )Se( $\beta$ ) $\cdots$ N). Although the Te analogue (**15<sub>te</sub>**) also forms three-atom chalcogen bonding motifs (N $\cdots$ ( $\alpha$ )Te( $\beta$ ) $\cdots$ N,  $d_{N\dots Te} = 3.11$  and  $3.37$  Å, respectively), the clusters are bridged by an additional N $\cdots$ Te contact ( $d_{N\dots Te} = 3.42$  Å), ultimately forming a supramolecular wire at the solid state. Notably, due to the larger angles of the five-member rings at the 2-position, the  $\sigma$ -hole( $\beta$ ) is not barred by the furanyl C-H bonds ( $d_{C-H\dots Te} = 3.072$  Å) and thus it results available for establishing a SBI (Table 4). 2-Pyrid-2'-yl benzo-1,3-chalcogenazoles **18<sub>x</sub>** display similar conformational properties (Fig. 10) as those of the furanyl derivatives, namely a co-planarity (conformation B, Table 4) between the pyridyl and the bicyclic benzo-1,3-chalcogenazole moiety (interplanar angles for the two crystallographically independent molecules:  $3.2$  and  $5.5^\circ$  for **18<sub>se</sub>** and  $4.4$  and  $5.0^\circ$  for **18<sub>te</sub>**). As one can clearly discern from the X-ray crystal structure, an intramolecular N $\cdots$ Y contact established between the N atom of the pyridyl ring and the chalcogen  $\sigma$ -hole( $\beta$ ) is observed in both derivatives ( $d_{N\dots Te} = 2.93$  and  $3.02$  Å for **18<sub>se</sub>** and  $2.86$  and  $3.09$  Å for **18<sub>te</sub>**), causing the complete occlusion of the relevant  $\sigma$ -hole ( $V_{s,max} = 0$ , Table 5 and Table S14 of SI). As results, only the chalcogen  $\sigma$ -hole( $\alpha$ ) can engage intermolecular N $\cdots$ Y SBIs with the N atom ( $d_{N\dots Te} = 3.33$  and  $3.23$  Å, for the Se and Te derivatives, respectively) to form the characteristic wire-like organization.



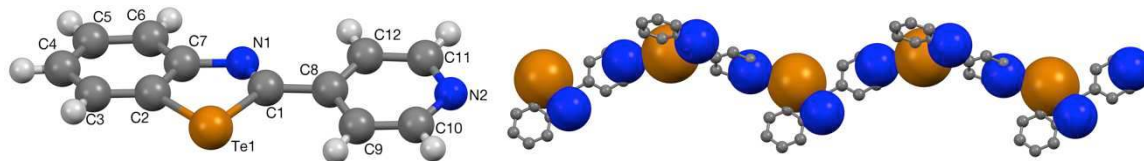


**Fig. 10.** Ortep (left) and ball-stick/spacefill (right) representations of the crystal structure of a) **18<sub>se</sub>** and b) **18<sub>te</sub>**. Both crystals evidence the wire-like organization and the conformational properties as exerted by the N···Y SBIs (the N···Y contacts are viewed with the space-filling model). Space groups:  $Pca_2_1$  for both structures. Atom colors: blue N, other Te, yellow Se, gray C. Two crystallographically independent molecules are found the unit cell for both benzochalcogenazoles.

*Triggering the wiring motif with a tethering moiety: overcoming the chalcogenazole nitrogen atom.* In all the cases discussed in the previous sections, the polymeric structures are triggered by intermolecular N···Y SBIs established through the N atom of the chalcogenazoles. However, when 2-pyrid-4'-yl benzotellurazole **16<sub>te</sub>** was crystallized, supramolecular wires featuring N···Te interactions (Figure 11) involving the pyridyl N atom and the Te *s*-hole(a) are formed ( $d_{N\dots Te} = 3.29 \text{ \AA}$ ).

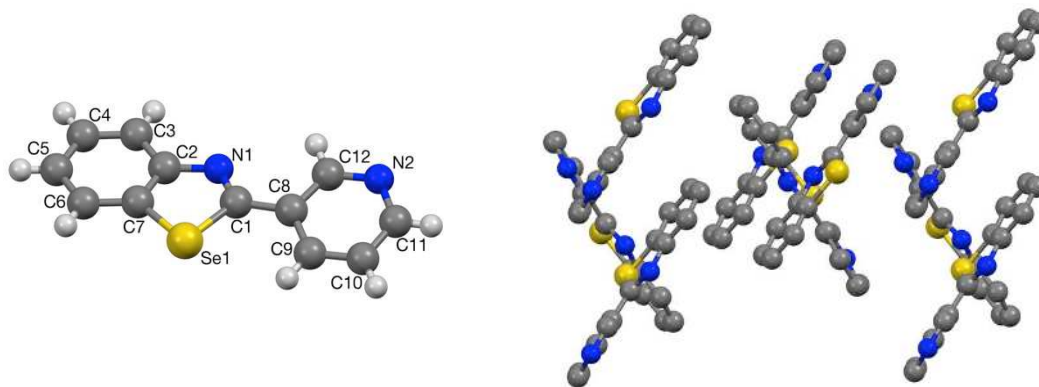


b)

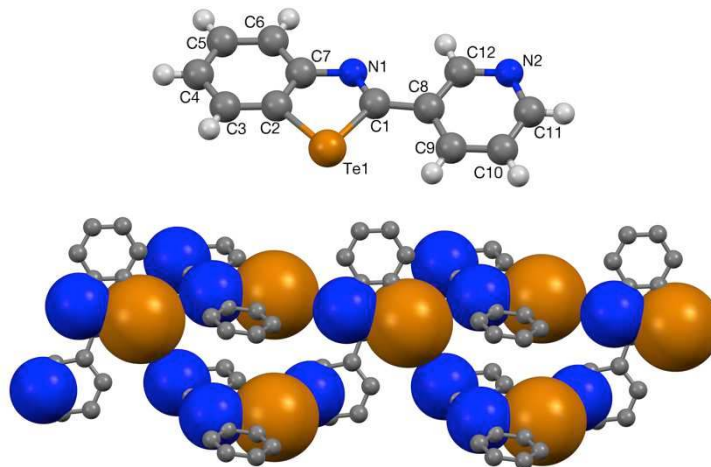


**Fig. 11.** Ortep (left) and ball-stick/spacefill (right) representation of the crystal structure of a) **16<sub>se</sub>** and b) **16<sub>Te</sub>**. Only molecule **16<sub>Te</sub>** forms supramolecular wires, this time tethered the pyridyl ring. Space groups:  $P2_1$  (**16<sub>se</sub>**) and  $Cc$  (**16<sub>Te</sub>**). Atom colors: blue N, other Te, yellow Se, gray C.

a)



b)



**Fig. 12.** Ortep and ball-stick/spacefill representations of the crystal structure of a) **17<sub>se</sub>** and b) **17<sub>Te</sub>** (the  $N\cdots Y$  contacts are viewed with the space-filling model only for **17<sub>Te</sub>**). Space group:  $P2_1/c$  for both structures. Atom colors: blue N, other Te, yellow Se, gray C.

Again, no contacts through the *s*-hole(a) have been observed, most likely due to the steric hindrance exerted by the neighboring C-H function of the pyridyl ring (conformation A, Table 4,  $d_{C-H\cdots Te} = 2.915 \text{ \AA}$ ). Interestingly, no  $N\cdots Se$  contacts have been observed in the solid state for Se analogue **16<sub>se</sub>**. Rather, only  $C-H\cdots p$  and  $p-p$  interactions seem to rule the crystal organization of this molecule (Fig. 11). The X-ray

structure of tellurazole **17<sub>Te</sub>** shows the formation of supramolecular polymers, in which the Te atoms are engaged in three-atom N $\cdots$ ( $\alpha$ )Te( $\beta$ ) $\cdots$ N bonding motifs (Fig. 12b) with the pyridyl and tellurazole moieties at the *s*-hole(a) and *s*-hole(b) sites, respectively ( $d_{\text{N}\cdots\text{Te}} = 3.51$  and  $3.42$  Å). Again, no N $\cdots$ Se contacts at have been found for Se analogue **17<sub>Se</sub>** (Fig. 12a).

**Table 4.** Experimental and theoretical conformational (A and B) properties of the 2-substituted benzo-1,3-tellurazoles. The theoretical and experimental (from X-ray) distances  $d_{1-3}$  between the Te atom and the nearest neighboring atom of the 2-substituent is reported.

		Conformation A		Conformation B		
Derivatives R	Distance (Å)					
	$d_1$		$d_2$		$d_3$	
	Exp.	Theor.	Exp.	Theor.	Exp.	Theor.
<b>11<sub>Te</sub></b> <i>i</i> -Bu	3.278	3.192	3.033	3.072	/	/
<b>12<sub>Te</sub></b> Ph	3.307	3.187	2.945	2.753	/	/
<b>14<sub>Te</sub></b> Furanyl	3.272	3.342	/	/	3.149 (X = O)	3.250 (X = O)
<b>15<sub>Te</sub></b> Thiophenyl	3.266	3.341	3.072	3.145	/	/
<b>16<sub>Te</sub></b> 4-Pyridyl	3.261	3.341	2.936	2.915	/	/
<b>17<sub>Te</sub></b> 3-Pyridyl	3.263	3.338	2.904	2.917	/	/
<b>18<sub>Te</sub></b> 2-Pyridyl	3.378	3.354	/	/	2.976 (X = N)	3.126 (X = N)

**Table 5.** ESP values for the benzo-1,3-chalcogenazoles derivatives. Y = Se or Te; X = O, N or S (heteroatom stopper).

Molecule	R	Y	$V_{S,max}$ (kCal mol <sup>-1</sup> )			
			$\sigma$ -hole( $\alpha$ )	N	$\sigma$ -hole( $\beta$ )	X
/	H	Se	+18.8	-29.2	+23.0	---
/		Te	+21.3	-27.9	+24.5	---

<b>11<sub>Se</sub></b>	<i>i</i> -Bu	Se	+14.1	-28.9	+16.6	---
<b>11<sub>Te</sub></b>		Te	+17.2	-20.3	+20.2	---
<b>12<sub>Se</sub></b>	Ph	Se	+15.7	-22.7	+14.4	---
<b>12<sub>Te</sub></b>		Te	+19.0	-21.0	+19.8	---
<b>14<sub>Se</sub></b>	Furanyl	Se	+16.4	-25.8	---	-9.4
<b>14<sub>Te</sub></b>		Te	+19.4	-24.5	+10.3	-7.5
<b>15<sub>Se</sub></b>	Thiophenyl	Se	+17.2	-27.0	+15.7	-15.7
<b>15<sub>Te</sub></b>		Te	+20.4	-25.1	+22.0	-15.7
<b>16<sub>Se</sub></b>	4-Pyridyl	Se	+20.5	-18.5	+18.2	-33.9
<b>16<sub>Te</sub></b>		Te	+23.5	-16.9	+24.1	-33.9
<b>17<sub>Se</sub></b>	3-Pyridyl	Se	+19.1	-21.1	+18.9	-33.9
<b>17<sub>Te</sub></b>		Te	+21.6	-19.8	+22.6	-33.9
<b>18<sub>Se</sub></b>	2-Pyridyl	Se	+14.1	-22.3	---	-23.2
<b>18<sub>Te</sub></b>		Te	+16.6	-21.6	---	-18.2

## Conclusion

In conclusion, we have developed a versatile four-step synthesis of 2-substituted benzo-1,3-selenazoles and tellurazoles starting from 2-bromoaniline. The mild reaction conditions, simple procedure and high yields make this methodology a valuable approach for preparing benzo-1,3-chalcogenazoles bearing a large variety of different substituents (e.g., alkyl, alkenyl, phenyl, furanyl, thiophenyl, pyridyl and ferrocenyl groups) at the 2-position. The principle of exploiting the benzo-1,3-chalcogenazole as self-assembling units to produce controlled organic networks at the solid-state through SBIs has been demonstrated with a large number of examples. In particular, programming the

recognition properties of the chalcogen  $\sigma$ -hole sites and of the basic chalcogen-bonding acceptor atom through the selection of suitable 2-substituents, we gain control of the wiring arrangement of the benzo-1,3-chalcogenazoles at the solid state. With such building units, when the overall assembly process is symmetry-conserved, the final supramolecular framework depends upon the type of the chalcogen bonding donor and the symmetry of its recognition  $\sigma$ -hole sites. With this simple governing principle and the large library of stable benzochalcogenazole modules that could be envisaged, it will be possible to engineer a great variety of materials featuring a series of tunable organizations with tremendous variations in the optoelectronic properties and thus device application.

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