catalysts

MDPI

Article

Efficient Regioselective Synthesis of Novel Ensembles of Organylselanyl-Functionalized Divinyl Sulfides and 1,3-Thiaselenoles under Phase Transfer Catalysis Conditions

Andrey S. Filippov, Svetlana V. Amosova, Nataliya A. Makhaeva, Alexander I. Albanov * and Vladimir A. Potapov

A. E. Favorsky Irkutsk Institute of Chemistry, Siberian Division of the Russian Academy of Sciences, 1 Favorsky Str., Irkutsk 664033, Russia; filippov@irioch.irk.ru (A.S.F.); amosova@irioch.irk.ru (S.V.A.); ggm@irioch.irk.ru (N.A.M.); v.a.potapov@mail.ru (V.A.P.)

* Correspondence: albanov@irioch.irk.ru

Abstract: Efficient regioselective synthesis of novel ensembles of organylselanyl-functionalized 1,3-thiaselenoles and divinyl sulfides in high yields under phase transfer catalysis conditions was developed. The methodology is based on the generation of sodium [(*Z*)-2-(vinylsulfanyl)ethenyl]selenolate and 1,3-thiaselenol-2-ylmethylselenolate, which were involved in a nucleophilic addition reaction with activated alkenes such as acrylonitrile, acrylamide, methyl vinyl ketone, methyl, and ethyl acrylates. In the case of methyl vinyl ketone, the reaction was accompanied by the hydrogenation of the carbonyl group. Methylene chloride was involved in the nucleophilic substitution reaction with sodium [(*Z*)-2-(vinylsulfanyl)ethenyl]selenolate and 1,3-thiaselenol-2-ylmethylselenolate to afford new polyunsaturated compounds with several sulfur and selenium atoms.

Keywords: 2-bromomethyl-1,3-thiaselenole; divinyl sulfide derivatives; 1,3-thiaselenole derivatives; heterocyclic compounds; nucleophilic reactions

Citation: Filippov, A.S.; Amosova, S.V.; Makhaeva, N.A.; Albanov, A.I.; Potapov, V.A. Efficient Regioselective Synthesis of Novel Ensembles of Organylselanyl-Functionalized Divinyl Sulfides and 1,3-Thiaselenoles under Phase Transfer Catalysis Conditions. *Catalysts* **2023**, *13*, 1227. https://doi.org/10.3390/catal13081227

Academic Editor: Loredana Maiuolo

Received: 1 July 2023
Revised: 9 August 2023
Accepted: 18 August 2023
Published: 21 August 2023

1. Introduction

Selenium had previously been considered a poison for many years until Schwartz and Foltz found that this element is an important micronutrient for humans and animals [1]. Since then, interest in the chemistry of organoselenium compounds has sharply increased, and multifaceted studies of these compounds gave impetus to the development of bioorganic chemistry, enzymology, and medicine [2–7].

To date, many classes of organoselenium compounds have been studied, and promising products, especially selenium heterocycles, have been found that exhibit various kinds of biological activities [8–23] including antiviral [13,14], antibacterial [11,12], antitumor [8–11], and glutathione peroxidase-like properties [15–17].

Ebselen (2-phenyl-1,2-benzoselenazol-3(2*H*)-one) is a well-known selenium-containing heterocyclic compound, an anti-inflammatory drug with neuroprotective and glutathione peroxidase-like properties [23–25]. Ebselen can be used for the prevention and treatment of cardiovascular diseases including ischemic stroke and reperfusion injury. It is worth noting that ebselen was found to inhibit SARS-CoV2 viral replication [24,25]. Recently, this compound has been undergoing evaluation as a therapeutic agent in clinical trials in the treatment of COVID-19, Meniere's disease, hearing loss, and bipolar disorder [23].

Other important classes of selenium heterocycles are 1,3-diselenoles and 1,3-thiaselenoles derivatives. The structures of 1,3-diselenole or 1,3-thiaselenole scaffolds are included in diselenafulvenes, thiaselenafulvenes, tetraselenafulvalenes, and dithiadiselenafulvalenes. Tetraselenafulvalenes and dithiadiselenafulvalenes are used as electron donors for the preparation of various conducting materials such as semiconductors, organic metals, superconductors, ferromagnets, and organic Dirac materials [26–36]. These materials can

find augmenting applications in various areas. The synthesis of tetraselenafulvalenes and dithiadiselenafulvalenes is usually based on 1,3-diselenole and 1,3-thiaselenole derivatives [32–37].

A number of 1,3-thiaselenole derivatives, dithiadiselenafulvalenes, are found to be promising electron donors for the preparation of conducting materials (Figure 1) [38–41]. For example, a charge transfer complex of 1,4,5-triselena-8-thiafulvalene with tetracyanoquinodimethane exhibited high anisotropic conductivity in the polycrystalline sample [38].

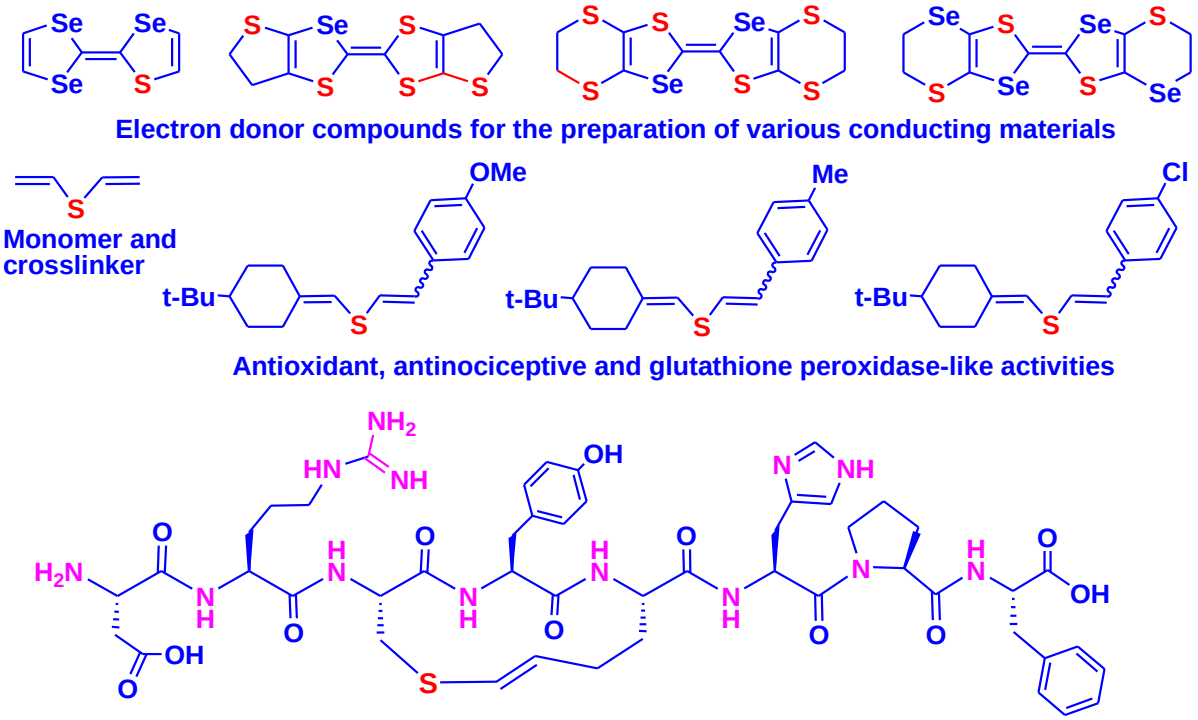


Figure 1. Examples of practical usage of 1,3-thiaselenole and vinyl sulfide derivatives.

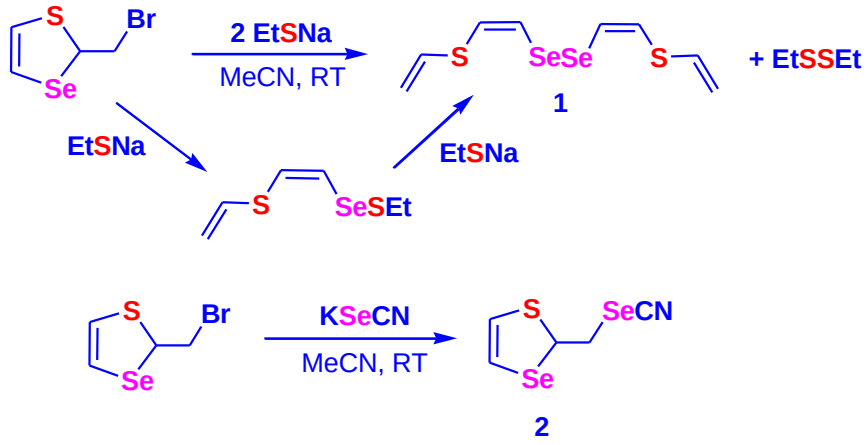
Organylselanyl-functionalized divinyl sulfides are very rare compounds. However, divinyl sulfides, and especially the first representative of this series, unsubstituted divinyl sulfide, are promising starting compounds for the synthesis of polyfunctional sulfides and heterocycles [42]. Divinyl sulfide exhibits very useful properties as a highly reactive monomer for the preparation of various valuable polymeric materials by polymerization and copolymerization reactions, as well as an effective crosslinking agent (Figure 1) [42].

Functionalized divinyl sulfides and (4-tert-butylcyclohexylidene)methyl styryl sulfides, show antioxidant, antinociceptive, and glutathione peroxidase-like properties (Figure 1) [43,44]. The potential of vinyl sulfides with respect to biological activity can be demonstrated by the example of a cyclic peptide with the vinyl sulfide group (Figure 1), which is an angiotensin II analog, exhibiting high affinity and agonist activity at the AT1 receptor [45].

Earlier, we developed the efficient one-pot synthesis of 2-bromomethyl-1,3-thiaselenole in high yield from selenium dibromide with divinyl sulfide [46]. 2-Bromomethyl-1,3-thiaselenole is a unique reagent for organic synthesis, which exhibits unusual behavior in nucleophilic substitution reactions [46–48]. The bromine atom in 2-bromomethyl-1,3-thiaselenole is highly activated by the strong anchimeric assistance effect of the selenium atom [49]. Quantum chemical calculations show that this reagent exists in equilibrium with corresponding three-membered seleniranium cation and nucleophilic reactions that proceed at three different centers of the seleniranium intermediate [46].

New promising reagents, namely, 1,2-bis[(*Z*)-2-(vinylsulfanyl)ethenyl] diselenide (**1**) and 1,3-thiaselenol-2-ylmethyl selenocyanate (**2**), were obtained based on 2-bromomethyl-

1,3-thiaselenole. The reaction of 2-(bromomethyl)-1,3-thiaselenole with sodium ethanethiolate in acetonitrile at room temperature afforded diselenide **1** in 82% yield (Scheme 1) [47].



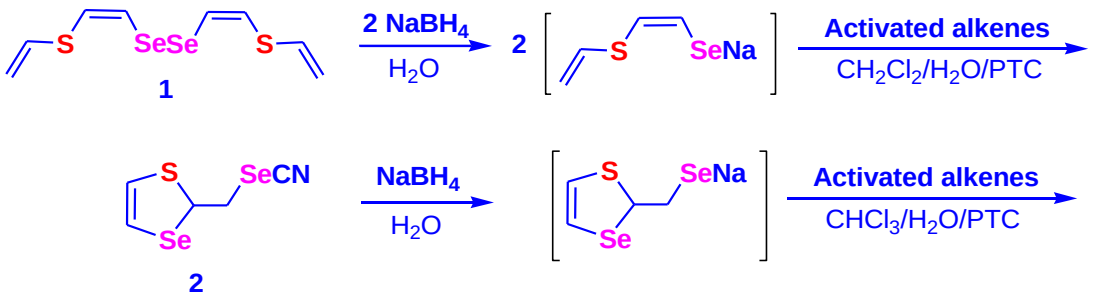
Scheme 1. The efficient synthesis of compounds **1** and **2** from 2-bromomethyl-1,3-thiaselenole.

The reaction of 2-bromomethyl-1,3-thiaselenole with potassium selenocyanate proceeded very smoothly (acetonitrile, room temperature, 5 min) giving selenocyanate **2** in a quantitative yield (Scheme 1) [48].

Compounds **1** and **2** were used as starting materials for the development of efficient synthetic methods for the preparation of novel ensembles of unsaturated sulfur/selenium products.

2. Results and Discussion

A goal of this work is to develop efficient regioselective syntheses of novel families of organylselanyl-functionalized 1,3-thiaselenoles and divinyl sulfides based on addition reactions of sodium [(*Z*)-2-(vinylsulfanyl)ethenyl]selenolate and 1,3-thiaselenol-2-ylmethylselenolate, generated from compounds **1** and **2**, to activated alkenes (Scheme 2).

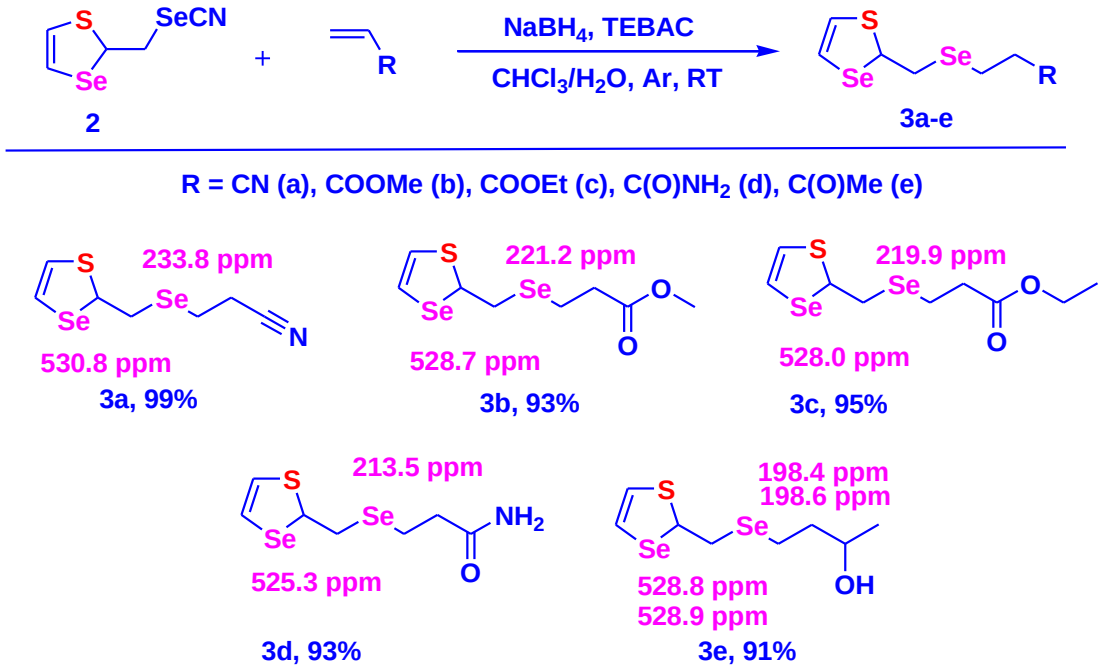


Scheme 2. The generation of sodium [(*Z*)-2-(vinylsulfanyl)ethenyl]selenolate and 1,3-thiaselenol-2-ylmethylselenolate from compounds **1** and **2**.

The treatment of compounds **1** and **2** with sodium borohydride ($NaBH_4$) led to the generation of corresponding sodium selenolates, which were involved in the nucleophilic addition reaction with activated alkenes such as acrylonitrile, methyl and ethyl acrylates, acrylamide, and methyl vinyl ketone.

We found that phase transfer catalysis conditions using triethylbenzylammonium chloride (TEBAC) as a phase transfer catalyst made it possible to realize this addition reaction in a chemo- and regioselective fashion and obtain the target products in high yields. The reactions were carried out by adding an aqueous solution of $NaBH_4$ to a solution of compounds **1** or **2** in methylene chloride or chloroform under argon followed by stirring for 1–3 h at room temperature.

The reaction of selenocyanate **2** with activated alkenes (acrylonitrile, methyl and ethyl acrylates, acrylamide, and methyl vinyl ketone) was carried out in the two-phase system $NaBH_4/H_2O$/TEBAC/chloroform under argon with stirring at room temperature for 3 h (Scheme 3).



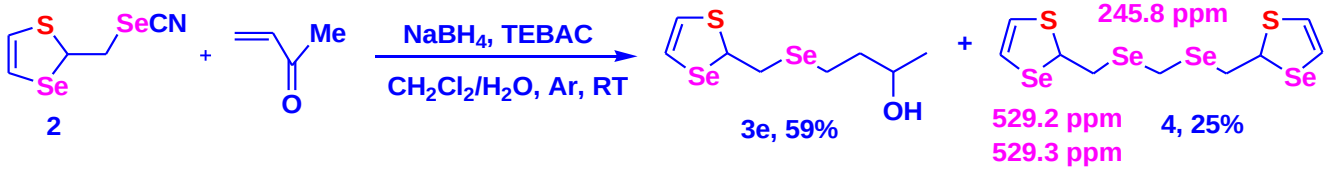
Scheme 3. The efficient synthesis of compounds **3a**–**e** from selenocyanate **2** and activated alkenes (the ^{77}Se NMR data are included).

3-[(1,3-Thiaselenol-2-ylmethyl)selanyl]propanenitrile (**3a**) was obtained in 99% yield and did not require additional purification (Scheme 3).

Methyl and ethyl acrylates and acrylamide were involved in the reaction with compound **2** affording the corresponding addition products **3b**,**c**,**d** in 93%, 95%, and 93% yields, respectively (Scheme 3).

When methyl vinyl ketone was used as an activated alkene in the reaction with compound **2** in the two-phase system $NaBH_4/H_2O$/TEBAC/chloroform, the suggested product was not obtained. In this case, the reaction was accompanied by hydrogenation of the carbonyl group affording 3-[(1,3-thiaselenol-2-ylmethyl)selanyl]butan-2-ol (**3e**) in 91% yield (Scheme 3).

In order to find out whether the hydrogenation would occur in another solvent, chloroform was replaced with methylene chloride. The reaction of compound **2** with methyl vinyl ketone under similar conditions in methylene chloride gave, along with hydrogenated product **3e** (yield 59%), a very interesting compound **4**, containing four selenium atoms, in 25% yield (Scheme 4).



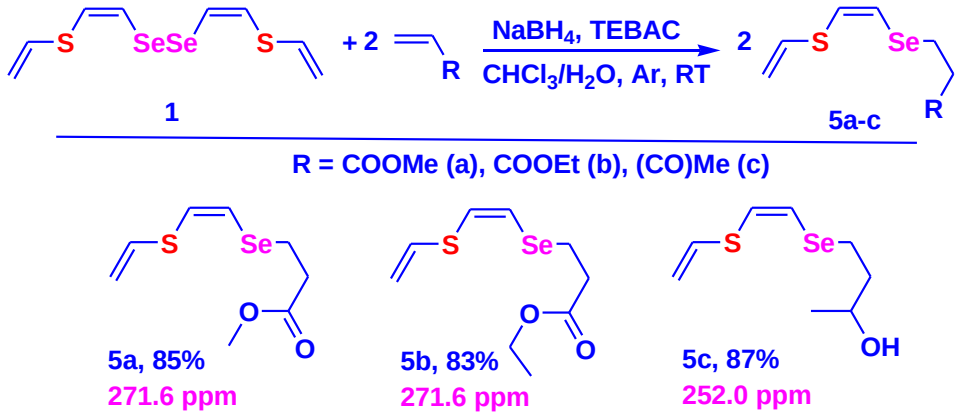
Scheme 4. The reaction of compound **2** with methyl vinyl ketone in methylene chloride (the ^{77}Se NMR data are included).

Compound **4** is formed by the nucleophilic substitution of two chlorine atoms in methylene chloride with sodium 1,3-thiaselenol-2-ylmethylselenolate. The formation of

the nucleophilic substitution products with chloroform was not observed in the system $NaBH_4/H_2O$/TEBAC/chloroform (Scheme 3). The ease of product formation by the nucleophilic substitution of two chlorine atoms in methylene chloride with selenium-centered nucleophiles was noted in the literature [50].

Compound **4** is a symmetrical molecule, which has two asymmetric carbon centers in the cycles. It consists of two diastereomers, which manifest themselves in the NMR spectra. For example, two signals of the selenium atom in the ring were observed in the ^{77}Se NMR spectrum of this compound (Scheme 4).

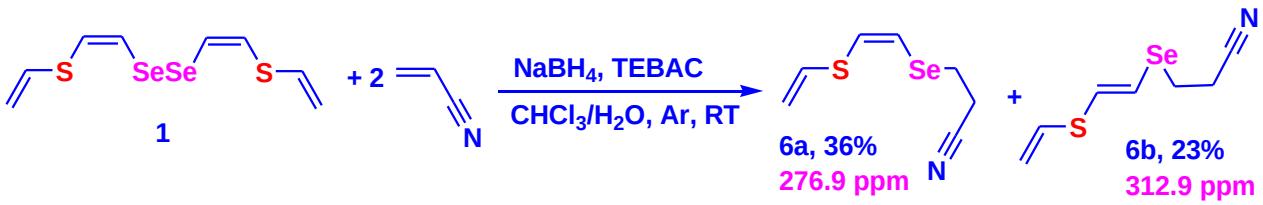
The reaction of polyunsaturated diselenide **1** with activated alkenes in the system $NaBH_4/H_2O$/TEBAC/chloroform was studied. The reaction of diselenide **1** with methyl and ethyl acrylates and acrylamide afforded the addition of products **5a**,**b** in 83–85% yields taking into account that one molecule of diselenide **1** gives two molecules of the target products (Scheme 5).



Scheme 5. The efficient synthesis of compounds **5a–c** from diselenide **1** and activated alkenes (the ^{77}Se NMR data are included).

In the case of using methyl vinyl ketone as an activated alkene in the reaction with diselenide **1**, the suggested addition product was not obtained. As in the reaction with compound **2** (Scheme 3), the process was accompanied by hydrogenation of the carbonyl group of methyl vinyl ketone, leading to 4-{[(*Z*)-2-(vinylsulfanyl)ethenyl]selanyl}-2-butanol (**5c**) in 87% yield (Scheme 5).

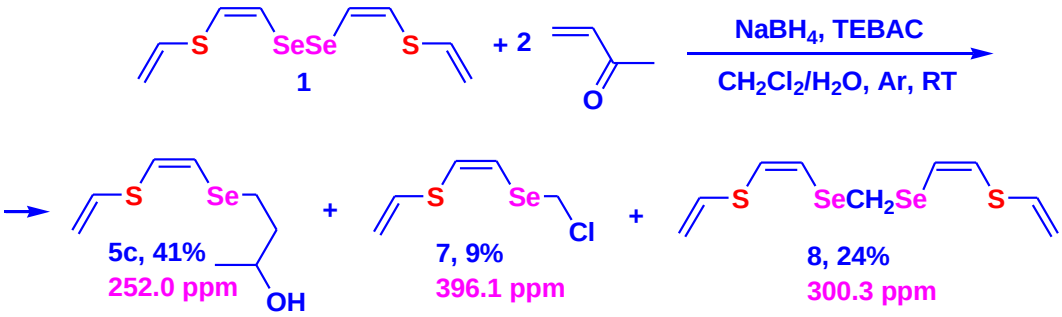
Acrylonitrile was involved in the reaction with diselenide **1**, giving two isomers, (*Z*)- and (*E*)-3-{[2-(vinylsulfanyl)ethenyl]selanyl}propanenitriles **6a**,**b** in 36% and 23% yields, respectively (Scheme 6).



Scheme 6. The reaction of compound **1** with acrylonitrile (the ^{77}Se NMR data are included).

Under the same conditions, the reaction of sodium [(*Z*)-2-(vinylsulfanyl)ethenyl]-selenolate and 1,3-thiaselenol-2-ylmethylselenolate with divinyl sulfone led to a complex mixture containing ethyl vinyl sulfone as the major product. The possibility of the hydrogenation reaction of divinyl sulfone to ethyl vinyl sulfone under the action of $NaBH_4$ under phase transfer catalysis conditions was confirmed by an additional experiment.

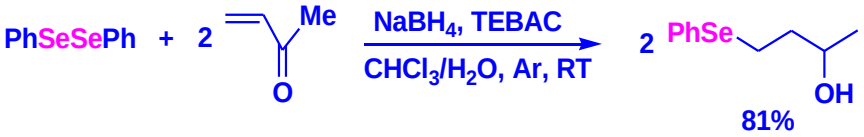
When methylene chloride was used instead of chloroform in the reaction of diselenide **1** with methyl vinyl ketone under similar conditions, three compounds **5c**, **7**, and **8** were obtained in 41%, 9%, and 24% yields, respectively (Scheme 7).



Scheme 7. The reaction of compound **1** with methyl vinyl ketone in methylene chloride (the ^{77}Se NMR data are included).

The formation of compounds **7** and **8** can be considered as the result of nucleophilic substitution of one or two chlorine atoms in methylene chloride by sodium [(*Z*)-2-(vinylsulfanyl)-ethenyl]selenolate. Taking into account the formation of bis(selanyl)methane compounds **4** and **8** from methylene chloride, we suggest that this method can be used for the preparation of other bis(organylselanyl)methane derivatives by the reactions of organylselenolate anions with methylene chloride under phase transfer catalysis conditions.

We have shown the possibility of obtaining other 3-hydroxybutyl selenides from methyl vinyl ketone by this method using diphenyl diselenide as an example. When diphenyl diselenide was involved in the reaction with methyl vinyl ketone under the same conditions as the reaction of diselenide **1** (Scheme 5), 3-hydroxybutyl phenyl selenide was obtained with an 81% yield (Scheme 8).



Scheme 8. The reaction of diphenyl diselenide with methyl vinyl ketone and sodium borohydride under phase transfer catalysis conditions.

It should be noted that alkyl and aryl 3-hydroxybutyl selenides are rare compounds, and only butyl and phenyl 3-hydroxybutyl selenides have been previously obtained [51–54]. Butyl and phenyl 3-hydroxybutyl selenides were synthesized in three stages starting from poly-3-hydroxybutanoate in 37% and 42% overall yields, respectively [51]. The proposed method (Schemes 5 and 8) makes it possible to obtain the target product (e.g., 3-hydroxybutyl phenyl selenide) in higher yield by a single-stage procedure.

Hydroxyorganyl selenides are a very important family of organoselenium compounds, many of which exhibit glutathione peroxidase mimetic properties and also serve as intermediates for organic synthesis [55–58]. For example, a novel cyclic seleninate ester with high glutathione peroxidase-like activity was obtained from allyl 3-hydroxypropyl selenide [56].

It is worth noting that the nucleophilic addition reactions of sodium [(*Z*)-2-(vinylsulfanyl)ethenyl]selenolate and 1,3-thiaselenol-2-ylmethylselenolate to the activated alkenes acrylonitrile, acrylamide, methyl vinyl ketone, methyl, and ethyl acrylates proceed in a regioselective fashion exclusively at the terminal carbon atom of the double bond.

The structural assignment of the obtained compounds was carried out based on the NMR investigations and mass spectrometry data and confirmed by elemental analysis. Molecular ions were observed in the mass spectra of the obtained compounds.

3. Materials and Methods

3.1. General Information

The ^{1}H (400.1 MHz), ^{13}C (100.6 MHz), and ^{77}Se (76.3 MHz) NMR spectra (the spectra can be found in Supplementary Materials) were recorded on a Bruker DPX-400 spectrometer

(Bruker BioSpin GmbH, Rheinstetten, Germany) in $CDCl_3$ solutions and referred to the residual solvent peaks ($CDCl_3$, δ = 7.27 and 77.0 ppm for ^{1}H- and ^{13}C-NMR, respectively), and dimethyl selenide (^{77}Se).

Mass spectra were recorded on a Shimadzu GCMS-QP5050A (Shimadzu Corporation, Kyoto, Japan) with electron impact (EI) ionization (70 eV). The data of mass spectra are given in the experimental part regarding the maximum isotope of selenium (^{80}Se).

Elemental analysis was performed on a Thermo Scientific Flash 2000 Elemental Analyzer (Thermo Fisher Scientific Inc., Milan, Italy). Distilled organic solvents and degassed water were used in syntheses. The spectral characteristics of obtained 3-hydroxybutyl phenyl selenide correspond to the data of the known sample [51].

3.2. Synthesis of the Products

3-[(1,3-Thiaselenol-2-ylmethyl)selanyl]propanenitrile (**3a**). A solution of $NaBH_4$ (0.08 g (2.1 mmol) and TEBAC (0.005 g) in water (0.5 mL) was added to a solution of 1,3-thiaselenol-2-ylmethylselenocyanate (0.165 g, 0.61 mmol) and acrylonitrile (0.033 g (0.61 mmol) in chloroform (2 mL) under argon. The resulting mixture was stirred at room temperature for 3 h. Chloroform (5 mL) was added, and the mixture was stirred for 10 min. The organic layer was separated and dried over Na_2SO_4, and the solvent was removed under reduced pressure to give the product (0.18 g, 99% yield) as a light-yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): 2.78 (t, 2H, CH_2CN, ^3J 6.9 Hz), 2.91 (t, 2H, $C\underline{H}_2CH_2CN$, ^3J 6.9 Hz), 3.06 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 7.5 Hz, ^2J 13.0 Hz), 3.18 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 8.1 Hz, ^2J 13.0 Hz), 5.03 (t, 1H, SeCHS, ^3J 7.7 Hz, $^2J_{SeH}$ 23.8 Hz), 6.41 (d, 1H, =CHS, ^3J 6.2 Hz), 6.63 (d, 1H, =CHS, ^3J 6.2 Hz, $^2J_{SeH}$ 47.5 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 18.89 ($\underline{C}H_2SeCH_2CH_2$, $^1J_{SeC}$ 70.7 Hz), 19.84 ($\underline{C}H_2CN$), 34.46 ($CH_2Se\underline{C}H_2CH_2$, $^1J_{SeC}$ 66.6 Hz), 48.15 (SeCHS, $^1J_{SeC}$ 68.1 Hz), 113.36 (=CHSe, $^1J_{SeC}$ 106.5 Hz), 118.50 (CN), 119.36 (=CHS).

^{77}Se NMR (76 MHz, $CDCl_3$): 233.82, 530.76 (in cycle).

MS (EI), *m/z* (%): 299 (7) $[M]^+$, 165 (5), 151 (100), 107 (5), 85 (25).

Anal. Calcd for $C_7H_9NSSe_2$ (297.14): C 28.29; H 3.05; N 4.71; S 10.79; Se 53.16%. Found: C 28.21; H 3.12; S 10.98; Se 53.46%.

Methyl 3-[(1,3-thiaselenol-2-ylmethyl)selanyl]propanoate (**3b**)**.** Yield: 93%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3).

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.71 (t, 2H, $CH_2SeC\underline{H}_2CH_2$, ^3J 6.9 Hz), 2.85 (t, 2H, $CH_2C(O)$, ^3J 6.9 Hz), 2.95 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 7.7 Hz, ^2J 12.8 Hz), 3.06 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 7.7 Hz, ^2J 12.8 Hz), 3.67 (s, 3H, CH_3), 5.00 (dd, 1H, SeCHS, ^3J 7.7 Hz, ^3J 8.0 Hz, $^2J_{SeH}$ 20.0 Hz), 6.38 (d, 1H, =CHS, ^3J 6.2 Hz), 6.59 (d, 1H, =CHS, ^3J 6.2 Hz, $^2J_{SeH}$ 48.2 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 18.71 ($\underline{C}H_2SeCH_2CH_2$, $^1J_{SeC}$ 62.7 Hz), 34.10 ($CH_2Se\underline{C}H_2$-CH_2, $^1J_{SeC}$ 67.5 Hz), 35.46 ($\underline{C}H_2C(O)$), 48.22 (SeCHS, $^1J_{SeC}$ 65.5 Hz), 51.68 (CH_3), 113.16 (=CHSe, $^1J_{SeC}$ 106.5 Hz), 119.35 (=CHS), 172.25 ($CH_2\underline{C}(O)$).

^{77}Se NMR (76 MHz, $CDCl_3$): 221.24, 528.69 (in cycle).

MS (EI), *m/z* (%): 332 (6) $[M]^+$, 165 (28), 151 (100), 125 (31), 85 (52). Anal. Calcd for $C_8H_{12}O_2SSe_2$ (330.17): C 29.10; H 3.66; S 9.71; Se 47.83%. Found: C 29.31; H 3.64; S 10.01; Se 48.03%.

Ethyl 3-[(1,3-thiaselenol-2-ylmethyl)seleno]propanoate (**3c**). Yield: 95%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:4).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.27 (t, 3H, CH_3, ^3J 7.0 Hz), 2.65 (t, 2H, $CH_2SeC\underline{H}_2CH_2$, ^3J 6.9 Hz), 2.83 (t, 2H, $CH_2C(O)$, ^3J 6.9 Hz), 2.94 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 7.8 Hz, ^2J 12.8 Hz), 3.05 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 8.0 Hz, ^2J 12.8 Hz), 4.12 (q, 2H, $CH_2C(O)$, ^3J 7.0 Hz), 5.00 (dd, 1H, SeCHS, ^3J 7.7 Hz, ^3J 8.0 Hz, $^2J_{SeH}$ 20.4 Hz), 6.35 (d, 1H, =CHS, ^3J 5.9 Hz), 6.54 (d, 1H, =CHS, ^3J 5.9 Hz, $^2J_{SeH}$ 47.6 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 14.16 (CH_3), 18.86 ($\underline{C}H_2SeCH_2CH_2$, $^1J_{SeC}$ 64.5 Hz), 34.19 ($CH_2Se\underline{C}H_2CH_2$, $^1J_{SeC}$ 67.3 Hz), 35.81 ($\underline{C}H_2C(O)$), 48.32 (SeCHS, $^1J_{SeC}$ 65.5 Hz), 60.66 ($\underline{C}H_2CH_3$), 113.19 (=CHSe, $^1J_{SeC}$ 106.9 Hz), 119.45 (=CHS), 171.91 ($CH_2\underline{C}(O)$).

^{77}Se NMR (76 MHz, $CDCl_3$): 219.92, 528.02 (in cycle).

MS (EI), *m/z* (%): 346 (30) $[M]^+$, 165 (30), 151 (10), 125 (31), 85 (100).

Anal. Calcd for $C_9H_{14}O_2SSe_2$ (344.19): C 31.41; H 4.10; S 9.32; Se 45.88%. Found: C 31.28; H 3.98; S 9.61; Se 45.59%.

3-[(1,3-Thiaselenol-2-ylmethyl)selanyl]propanamide (**3d**). Yield: 93%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3).

^{1}H NMR (400 MHz, d_6-DMSO): δ 2.45 (t, 2H, $CH_2C(O)$, ^3J 7.0 Hz), 2.78 (t, 2H, $CH_2SeC\underline{H}_2CH_2$, ^3J 7.0 Hz), 2.90 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 7.4 Hz, ^2J 12.7 Hz), 2.99 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 8.0 Hz, ^2J 12.7 Hz), 5.18 (dd, 1H, SeCHS, ^3J 7.4 Hz, ^3J 8.0 Hz), 6.53 (d, 1H, =CHS, ^3J 6.2 Hz), 6.74 (d, 1H, =CHS, ^3J 6.2 Hz, $^2J_{SeH}$ 54.4 Hz), 6.80 (br s, 1H, NH_2), 7.30 (br s, 1H, NH_2).

^{13}C NMR (100 MHz, d_6-DMSO): δ 19.27 ($\underline{C}H_2SeCH_2CH_2$, $^1J_{SeC}$ 62.3 Hz), 33.66 ($^1J_{SeC}$ = 66.4, $CH_2Se\underline{C}H_2CH_2$), 36.51 ($\underline{C}H_2C(O)$), 47.98 (SeCHS, $^1J_{SeC}$ 67.1 Hz), 113.76 (=CHSe, $^1J_{SeC}$ 106.4 Hz), 119.32 (=CHS), 172.85 ($CH_2\underline{C}(O)$).

^{77}Se NMR (76 MHz, d_6-DMSO): 213.47, 525.27 (in cycle).

MS (EI), *m/z* (%): 317 (7) $[M]^+$, 165 (5), 151 (100), 107 (5), 85 (25). Anal. Calcd for $C_7H_{11}NOSSe_2$ (315.15): C 26.68; H 3.52; N 4.44; S 10.17; Se 50.11.%. Found: C 26.38; H 3.58; S 10.33; Se 50.15%.

4-[(1,3-Thiaselenol-2-ylmethyl)selanyl]butan-2-ol (**3e**). Yield: 91%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:2).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.21 (d, 3H, CH_3, ^3J 6.2 Hz), 1.76 (br s, 1H, OH), 1.80 (m, 2H, $C\underline{H}_2CH(O)$), 2.76 (dt, 2H, $CH_2SeC\underline{H}_2CH_2$, ^2J 11.9 Hz, ^3J 7.7 Hz), 2.96 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^2J 12.9 Hz, ^3J 8.0 Hz, ^5J 1.6 Hz), 3.07 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^2J 12.9 Hz, ^3J 8.0 Hz, ^5J 1.6 Hz), 3.90 (t. q, 1H, $C\underline{H}(OH)CH_3$, ^2J 6.5 Hz, ^2J 6.2 Hz), 5.04 (t, 1H, SCHSe, ^3J 8.0 Hz), 6.40 (d, 1H, =CHS, ^3J 6.3 Hz, ^5J 1.6 Hz), 6.61 (d, 1H, =CHSe, ^3J 6.3 Hz, ^5J 1.6 Hz, $^2J_{SeH}$ 48.4 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 21.36 (CH_3), 23.47 ($\underline{C}H_2SeCH_2CH_2$, $^1J_{SeC}$ 65.2 Hz), 33.86 ($CH_2Se\underline{C}H_2CH_2$, $^1J_{SeC}$ 67.2 Hz), 39.48 ($\underline{C}H_2C(OH)$), 48.38, (SeCHS, $^1J_{SeC}$ 65.5 Hz), 67.51 ($\underline{C}H(OH)CH_3$), 113.23 (=CHSe, $^1J_{SeC}$ 106.9 Hz), 119.49 (=CHS).

^{77}Se NMR (76 MHz, $CDCl_3$): 198.36, 198.60; 528.79, 528.84 (in cycle).

MS (EI), *m/z* (%): 318 (12) $[M]^+$, 165 (28), 151 (100), 125 (5), 85 (30).

Anal. Calcd for $C_8H_{14}OSSe_2$ (316.18): C 30.39; H 4.46; S 10.14; Se 49.95%. Found: C 30.51; H 4.64; S 10.04; Se 50.14%.

2,2′-[Methylenebis(selenomethylene)]bis-1,3-thiaselenole (**4**). A solution of $NaBH_4$ (0.085 g, 2.24 mmol) and TEBAC (0.003 g) in water (0.5 mL) was added to a solution of 1,3-thiaselenol-2-ylmethylselenocyanate (0.326 g, 1.21 mmol) and methyl vinyl ketone (0.085 g (1.21 mmol) in methylene chloride (1 mL) under argon. The resulting mixture was stirred at room temperature for 3 h. Methylene chloride (5 mL) was added, and the mixture was stirred for 10 min. The organic layer was separated and dried over Na_2SO_4, and the solvent was removed under reduced pressure. The residue was subjected to column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3) to give butanol **3e** (0.259 g, 59% yield) and the product **4** (0.075 g, 25% yield) as light-yellow oils.

^{1}H NMR (400 MHz, $CDCl_3$ 3.11 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 8.0 Hz, ^2J 12.8 Hz), 3.22 (dd, 1H, $C\underline{H}_2SeCH_2CH_2$, ^3J 8.0 Hz, ^2J 12.8 Hz), 3.90 (s, 2H, $CH_2SeC\underline{H}_2SeCH_2$), 5.13 (t, 1H, SeCHS, ^3J 8.0 Hz), 6.42 (d, 1H, =CHS, ^3J 6.4 Hz), 6.63 (d, 1H, =CHS, ^3J 6.4 Hz, $^2J_{SeH}$ 48.3 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 15.81 ($CH_2Se\underline{C}H_2SeCH_2$, $^1J_{SeC}$ 86.1 Hz), 35.61 ($\underline{C}H_2Se$-$CH_2Se\underline{C}H_2$, $^1J_{SeC}$ 67.8 Hz), 47.97 (SeCHS, $^1J_{SeC}$ 67.4 Hz), 113.36 (=CHSe, $^1J_{SeC}$ 106.3 Hz), 119.51 (=CHS).

^{77}Se NMR (76 MHz, $CDCl_3$): 245.83; 529.17, 529.25 (in cycle).

MS (EI), *m/z* (%): 502 (9) $[M]^+$, 257(4), 243(4), 200(3), 165 (60), 151 (72), 85 (100).

Anal. Calcd for $C_9H_{12}S_2Se_4$ (500.16): C 30.64; H 4.63; S 10.11; Se 63.28%. Found: C 30.81; H 4.33; S 10.03; Se 63.15%.

Methyl 3-{[(Z)-2-(vinylsulfanyl)ethenyl]selanylpropanoate (**5a**). A solution of $NaBH_4$ (0.031 g, 0.82 mmol) and TEBAC (0.003 g) in water (0.5 mL) was added to a solution of diselenide **1** (0.082 g, 0.25 mmol) and methylacrylate (0.046 g, 0.53 mmol) in chloroform (1 mL) under argon for 30 min. The resulting mixture was stirred at room temperature for 1 h. Chloroform (5 mL) was added, and the mixture was stirred for 10 min. The organic layer was separated and dried over Na_2SO_4, and the solvent was removed under reduced pressure. The residue was subjected to column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3) to give the product (0.106 g, 85% yield).

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.80 (t, 2H, $CH_2C(O)$, ^3J 7.2 Hz), 2.97 (t, 2H, $SeCH_2$, ^3J 7.2 Hz), 3.71 (s, 3H, CH_3), 5.26 (d, 1H, CH_2=, $^3J^{trans}$ 16.9 Hz), 5.32 (d, 1H, CH_2=, $^3J^{cis}$ 9.8 Hz), 6.41 (dd, 1H, C<u>H</u>=CH_2, $^3J^{trans}$ 16.8 Hz, $^3J^{cis}$ 9.8 Hz), 6.62 (d, 1H, SC<u>H</u>=CHSe, ^3J 8.3 Hz), 6.63 (d, 1H, SCH=C<u>H</u>Se, ^3J 8.3 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 20.81 (Se<u>C</u>H_2CH_2, $^1J_{SeC}$ 60.9 Hz), 35.63 ($SeCH_2$<u>C</u>H_2), 51.75 (CH_3), 113.50 (H_2<u>C</u>=CHS), 121.92 (SCH=<u>C</u>HSe, $^1J_{SeC}$ 108.5 Hz), 124.51 (S<u>C</u>H=CHSe, $^2J_{SeC}$ 11.2 Hz), 129.88 (H_2C=<u>C</u>HS), 172.24 (CH_2<u>C</u>(O)).

^{77}Se NMR (76 MHz, $CDCl_3$): δ 271.56.

MS (EI), *m/z* (%): 252 (15) $[M]^+$, 165 (48), 151 (2), 125 (31), 85 (100).

Anal. Calcd for $C_8H_{12}O_2SSe$ (251.21): C 38.25; H 4.81; S 12.76; Se 31.43%. Found: C 38.26; H 4.66; S 12.81; Se 31.31%.

Ethyl 3-{[(Z)-2-(vinylsulfanyl)ethenyl]selanylpropanoate (**5b**). Yield: 83%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.26 (t, 3H, C<u>H</u>$_3CH_2$, ^3J 6.5 Hz), 2.70 (t, 2H, $CH_2C(O)$, ^3J 8.1 Hz), 2.89 (t, 2H, $SeCH_2$, ^3J 8.1 Hz), 4.11 (q, 2H, CH_2<u>C</u>H_3, ^2J 7.3 Hz), 5.18 (d, 1H, CH_2=, $^3J^{trans}$ 17.0 Hz), 5.26 (d, 1H, CH_2=, $^3J^{cis}$ 10.0 Hz), 6.35 (dd, 1H, C<u>H</u>=CH_2, $^3J^{trans}$ 17.0 Hz, $^3J^{cis}$ 10.0 Hz), 6.53 (d, 1H, SC<u>H</u>=CHSe, ^3J 8.1 Hz), 6.60 (d, 1H, SCH=C<u>H</u>Se, ^3J 8.1 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 14.09 (CH_3), 20.86 (Se<u>C</u>H_2CH_2, $^1J_{SeC}$ 59.9 Hz), 35.84 ($SeCH_2$<u>C</u>H_2), 60.63 (<u>C</u>H_2CH_3), 113.40 (H_2<u>C</u>=CHS), 122.07 (SCH=<u>C</u>HSe, $^1J_{SeC}$ 108.2 Hz), 124.30 (S<u>C</u>H=CHSe, $^2J_{SeC}$ 12.0 Hz), 129.89 (H_2C=<u>C</u>HS), 171.73 (CH_2<u>C</u>(O)).

^{77}Se NMR (76 MHz, $CDCl_3$): δ 271.55.

MS (EI), *m/z* (%): 266 (35) $[M]^+$, 165 (35), 151 (10), 125 (31), 85 (100).

Anal. Calcd for $C_9H_{14}O_2Sse$ (265.23): C 40.76; H 5.32; S 12.09; Se 29.77%. Found: C 40.49; H 5.29; S 12.19; Se 29.64%.

4-{[(Z)-2-(Vinylsulfanyl)ethenyl]selanyl}-2-butanol (**5c**). Yield: 87%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:2).

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.24 (d, 3H, CH_3, ^2J 5.9 Hz), 1.55 (br. s, 1H, OH) 1.87 (m, 2H, CH_2<u>C</u>H(OH)), 2.87 (m, 2H, $SeCH_2$), 3.95 (m, 1H, C<u>H</u>(OH)CH_3, ^2J 6.3 Hz), 5.26 (d, 1H, CH_2=, $^3J^{trans}$ 16.6 Hz), 5.32 (d, 1H, CH_2=, $^3J^{cis}$ 9.8 Hz), 6.42 (dd, 1H, C<u>H</u>=CH_2, $^3J^{trans}$ 16.6 Hz, $^3J^{cis}$ 9.8 Hz), 6.60 (d, 1H, SC<u>H</u>=CHSe, ^3J 8.2 Hz), 6.65 (d, 1H, SCH=C<u>H</u>Se, ^3J 8.2 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 23.40 (Se<u>C</u>H_2CH_2, $^1J_{SeC}$ 57.4 Hz), 23.50 (CH_3), 39.73 ($SeCH_2$<u>C</u>H_2), 67.22 (<u>C</u>H(OH)CH_3), 113.36 (H_2<u>C</u>=CHS), 122.58 (SCH=<u>C</u>HSe, $^1J_{SeC}$ 108.7 Hz), 123.64 (SCH=<u>C</u>HSe, $^2J_{SeC}$ 11.4 Hz), 129.98 (H_2C=<u>C</u>HS).

^{77}Se NMR (76 MHz, $CDCl_3$): δ 252.02.

MS (EI), *m/z* (%): 238 (35) $[M]^+$, 165 (21), 151 (35), 133 (15), 85 (91), 45 (100).

Anal. Calcd for $C_8H_{14}OSSe$ (237.22): C 40.50; H 5.95; S 13.52; Se 33.29. Found: C 40.49; H 5.76; S 13.59; Se 33.38%.

3-{[(Z)-2-(Vinylsulfanyl)ethenyl]selanyl}propanenitrile (**6a**). Yield: 36%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3).

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.80 (t, 2H, CH_2CN, ^3J 7.4 Hz), 2.95 (t, 2H, $SeCH_2$, ^3J 7.4 Hz), 5.30 (d, 1H, CH_2=, $^3J^{trans}$ 16.8 Hz), 5.36 (d, 2H, CH_2=, $^3J^{cis}$ 10.0 Hz), 6.43 (dd 1H, C<u>H</u>=CH_2, $^3J^{trans}$ 16.8 Hz, $^3J^{cis}$ 10.0 Hz), 6.58 (d, 1H, SC<u>H</u>=CHSe, ^3J 8.1 Hz), 6.76 (d, 1H, SCH=C<u>H</u>Se, ^3J 8.1 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 19.77 (<u>C</u>H_2CN, $^2J_{SeC}$ 6.8 Hz), 20.41 ($SeCH_2$, $^1J_{SeC}$ 66.9 Hz), 114.24 (H_2<u>C</u>=CHS), 118.40 (CN), 118.95 (SCH=<u>C</u>HSe, $^1J_{SeC}$ 107.0 Hz), 127.76 (S<u>C</u>H=CHSe, $^2J_{SeC}$ 11.0 Hz), 129.51 (H_2C=<u>C</u>HS).

^{77}Se NMR (76 MHz, $CDCl_3$): δ 276.94.

MS (EI), *m/z* (%): 219 (20) $[M]^+$, 165 (21), 137 (2), 107 (6), 85 (100), 58 (52).

Anal. Calcd for C_7H_9NSSe (218.18): C 38.53; H 4.16; N 6.42; S 14,70; Se 36.19%. Found: C 38.36; H 4.35; N 6.49; S 14,81; Se 36.34%.

3-{[(E)-2-(Vinylsulfanyl)ethenyl]selanyl}propanenitrile (**6b**). Yield: 23%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3).

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.79 (t, 2H, CH_2CN, ^3J 7.1 Hz), 2.91 (t, 2H, $SeCH_2$, ^3J 7.1 Hz), 5.35 (d, 1H, CH_2=, $^3J^{trans}$ 16.7 Hz), 5.41 (d, 2H, CH_2=, $^3J^{cis}$ 9.7 Hz), 6.42 (dd 1H, C<u>H</u>=CH_2, $^3J^{trans}$ 16.7 Hz, $^3J^{cis}$ 9.7 Hz), 6.52 (d, 1H, SC<u>H</u>=CHSe, ^3J 15.1 Hz), 6.65 (d, 1H, SCH=C<u>H</u>Se, ^3J 15.1 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 19.31 (<u>C</u>H_2CN, $^2J_{SeC}$ 6.3 Hz), 20.49 ($SeCH_2$, $^1J_{SeC}$ 68.1 Hz), 114.57 (H_2<u>C</u>=CHS), 115.72 (SCH=<u>C</u>HSe, $^1J_{SeC}$ 109.1 Hz), 118.38 (CN), 129.13 (S<u>C</u>H=CHSe, $^2J_{SeC}$ 11.2 Hz), 129.25 (H_2C=<u>C</u>HS).

^{77}Se NMR (76 MHz, $CDCl_3$): δ 312.93.

MS (EI), *m/z* (%): 219 (16) $[M]^+$, 165 (34), 137 (5), 107 (8), 85 (100), 58 (45).

Anal. Calcd for C_7H_9NSSe (218.18): C 38.53; H 4.16; N 6.42; S 14,70; Se 36.19%. Found: C 38.72; H 4.08; N 6.52; S 14,63; Se 36.38%.

(Z)-1-[(Chloromethyl)selanyl]ethenyl vinyl sulfide (**7**)**.** A solution of $NaBH_4$ (0.061 g, 1.6 mmol) and TEBAC (0.005 g) in water (0.5 mL) was added to a solution of diselenide **1** (0.174 g, 0.53 mmol) and methyl vinyl ketone (0.085 g (1.21 mmol) in methylene chloride (1 mL) under argon. The resulting mixture was stirred at room temperature for 3 h. Methylene chloride (5 mL) was added, and the mixture was stirred for 10 min. The organic layer was separated and dried over Na_2SO_4, and the solvent was removed under reduced pressure. The residue was subjected to column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3) to give butanol **6c** (0.103 g, 41% yield) and products **7** (0.020 g, 9% yield) and **8** (0.043 g, 24% yield) as light-yellow oils.

^{1}H NMR (400 MHz, $CDCl_3$): δ 4.79 (s, 2H, CH_2Cl), 5.29 (d, 1H, CH_2=, $^3J^{trans}$ 16.6 Hz), 5.36 (d, 1H, CH_2=, $^3J^{cis}$ 9.8 Hz), 6.42 (dd, 1H, C<u>H</u>=CH_2, $^3J^{trans}$ 16.6 Hz, $^3J^{cis}$ 9.8 Hz), 6.76 (d, 1H, SC<u>H</u>=CHSe, ^3J 8.1 Hz), 6.81 (d, 1H, SCH=C<u>H</u>Se, ^3J 8.1 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 37.51 (CH_2Cl, $^1J_{Se\text{-}C}$ 94.0 Hz), 114.20 (H_2<u>C</u>=CHS), 120.68 (CH=<u>C</u>HSe, $^1J_{Se\text{-}C}$ 103.5 Hz), 126.33 (S<u>C</u>H=CHSe, $^2J_{Se\text{-}C}$ 11.9 Hz), 129.47 (H_2C=<u>C</u>HS).

^{77}Se NMR (76 MHz, $CDCl_3$): δ 396.12.

MS (EI), *m/z* (%): 214 (23) $[M]^+$, 165 (28), 85 (100) 58 (50), 45 (48).

Anal. Calcd for C_5H_7ClSSe (213.59): C 28.12; H 3.30; Cl 16.60; S 15.01; Se 36.97%. Found: C 28.34; H 3.36; Cl 16.36; S 15.12; Se 37.13%.

Bis[(Z)-2-(vinylsulfanyl)ethenylselanyl]methane (**8**). Yield: 24%, a light-yellow oil. The product was purified by column chromatography (silica gel 60, 70–230 mesh, eluent: hexane, then chloroform–hexane 1:3).

^{1}H NMR (400 MHz, $CDCl_3$): δ 3.95 (s, 2H, $SeCH_2Se$, $^2J_{Se\text{-}H}$ 15.5 Hz), 5.29 (d, 2H, CH_2=, $^3J^{trans}$ 16.5 Hz), 5.35 (d, 2H, CH_2=, $^3J^{cis}$ 9.7 Hz), 6.43 (dd, 2H, C<u>H</u>=CH_2, $^3J^{trans}$ 16.5 Hz, $^3J^{cis}$ 9.7 Hz, $^2J_{Se\text{-}H}$ 41.2 Hz), 6.70 (d, 2H, SC<u>H</u>=CHSe, ^3J 8.0 Hz), 6.76 (d, 2H, SCH=C<u>H</u>Se, ^3J 8.0 Hz).

^{13}C NMR (100 MHz, $CDCl_3$): δ 17.68 ($SeCH_2Se$, $^1J_{Se\text{-}C}$ 83.4 Hz), 113.89 (H_2<u>C</u>=CHS), 122.45 (CH=<u>C</u>HSe, $^1J_{Se\text{-}C}$ 106.6 Hz), 125.23 (S<u>C</u>H=CHSe, $^2J_{Se\text{-}C}$ 11.9 Hz), 129.76 (H_2C=<u>C</u>HS).

^{77}Se NMR (76 MHz, $CDCl_3$): 300.29.

MS (EI), *m/z* (%): 344 (12) $[M]^+$, 165 (28), 85 (100) 58 (50), 45 (48).

Anal. Calcd for $C_9H_{12}S_2Se_2$ (342.24): C 31.58; H 3.53; S 18.74; Se 46.14%. Found: C 31.87; H 3.62; S 18.83; Se 46.16%.

4. Conclusions

Divinyl sulfide and its derivatives are highly reactive cross-linking agents and monomers for the preparation of various valuable polymeric materials, as well as starting compounds for the synthesis of functionalized organosulfur products and heterocycles [42,43]. A number of 1,3-thiaselenole derivatives are promising electron donor compounds for the preparation of conducting materials (Figure 1) [38–41].

The efficient regioselective synthesis of new families of organylselanyl-functionalized 1,3-thiaselenoles **3a–e**, **4** and divinyl sulfides **5a–c**, **6a**, **b**, **7** and **8** in high yields under phase transfer catalysis conditions was developed based on the generation of sodium [(*Z*)-2-(vinylsulfanyl)ethenyl]selenolate and 1,3-thiaselenol-2-ylmethylselenolate. The nucleophilic addition of the sodium selenolates to the activated alkenes acrylonitrile, acrylamide, methyl vinyl ketone, methyl, and ethyl acrylates proceed in a regioselective fashion exclusively at the terminal carbon atom of the double bond.

Unexpected but promising products, functionalized 1,3-thiaselenols **3a–e**, **4**, and divinyl sulfides **5c**, **7**, and **8**, were obtained as a result of unusual reactions accompanied by nucleophilic substitution of the chlorine atom in methylene chloride and hydrogenation.

A single-stage method for the synthesis of 3-hydroxybutyl selenides from methyl vinyl ketone, organic diselenides, and sodium borohydride under phase transfer catalysis conditions was proposed.

The synthesized products are new promising starting materials for the preparation of polyfunctional organochalcogen compounds with possible biological activity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/catal13081227/s1: ^{1}H, ^{13}C and ^{77}Se NMR spectra of the obtained compounds.

Author Contributions: Methodology, S.V.A. and A.S.F.; investigation, A.S.F., N.A.M. and A.I.A.; data curation, A.S.F., S.V.A., N.A.M. and A.I.A.; writing—original draft preparation, V.A.P. and A.S.F.; writing—review and editing, V.A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank Baikal Analytical Center SB RAS for providing the instrumental equipment.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Schwarz, K.; Foltz, C.M. Selenium as an integral part of factor 3 against dietary necrotic liver degeneration. *J. Am. Chem. Soc.* **1957**, *79*, 3292–3293. [CrossRef]
2. Lenardao, E.J.; Santi, C.; Sancineto, L. *New Frontiers in Organoselenium Compounds*; Springer International Publishing AG: Cham, Switzerland, 2018; 189p.
3. Woollins, J.D.; Laitinen, R.S. (Eds.) Selenium and Tellurium Chemistry. In *From Small Molecules to Biomolecules and Materials*; Springer: Berlin/Heidelberg, Germany, 2011; 334p.
4. Santi, C. (Ed.) *Organoselenium Chemistry: Between Synthesis and Biochemistry*; Bentham Science Publishers: Sharjah, United Arab Emirates, 2014; 563p.
5. Longtin, R. A forgotten debate: Is selenocysteine the 21st amino acid? *J. Nat. Cancer Inst.* **2004**, *96*, 504–505. [CrossRef] [PubMed]
6. Iwaoka, M.; Arai, K. From sulfur to selenium. A new research arena in chemical biology and biological chemistry. *Curr. Chem. Biol.* **2013**, *7*, 2–24. [CrossRef]
7. Gandhil, U.H.; Nagaraja, T.P.; Prabhu, K.S. Selenoproteins and their role in oxidative stress and inflammation. *Curr. Chem. Biol.* **2013**, *7*, 65–73. [CrossRef]
8. Shaaban, S.; Ashmawy, A.M.; Negm, A.; Wessjohann, L.A. Synthesis and biochemical studies of novel organic selenides with increased selectivity for hepatocellular carcinoma and breast adenocarcinoma. *Eur. J. Med. Chem.* **2019**, *179*, 515–526. [CrossRef]

9. Ramos-Inza, S.; Encío, I.; Raza, A.; Sharma, A.K.; Sanmartín, C.; Plano, D. Design, synthesis and anticancer evaluation of novel Se-NSAID hybrid molecules: Identification of a Se-indomethacin analog as a potential therapeutic for breast cancer. *Eur. J. Med. Chem.* **2022**, *244*, 114839. [CrossRef]
10. Astrain-Redin, N.; Paoletti, N.; Plano, D.; Bonardi, A.; Gratteri, P.; Angeli, A.; Sanmartin, C.; Supuran, C.T. Selenium-analogs based on natural sources as cancer-associated carbonic anhydrase isoforms IX and XII inhibitors. *J. Enzyme Inhib. Med. Chem.* **2023**, *38*, 2191165. [CrossRef]
11. Gouda, M.; Abbas, Y.J.; Abd El-Lateef, H.M.; Khalaf, M.M.; Shaaban, S. Design, Synthesis, and Biological Evaluations of Novel Naphthalene-based Organoselenocyanates. *Biointerface Res. Appl. Chem.* **2023**, *13*, 219.
12. Di Leo, I.; Messina, F.; Nascimento, V.; Nacca, F.G.; Pietrella, D.; Lenardão, E.J.; Perin, G.; Sancineto, L. Synthetic Approaches to Organoselenium Derivatives with Antimicrobial and Anti-Biofilm Activity. *Mini-Rev. Org. Chem.* **2018**, *16*, 589–601. [CrossRef]
13. Sarturi, J.M.; Dornelles, L.; Segatto, N.V.; Collares, T.; Seixas, F.K.; Piccoli, B.C.; D'Avila da Silva, F.; Omage, F.B.; Rocha, J.B.T.; Balaguez, R.A.; et al. Chalcogenium-AZT Derivatives: A Plausible Strategy To Tackle The RT-Inhibitors-Related Oxidative Stress While Maintaining Their Anti- HIV Properties. *Curr. Med. Chem.* **2023**, *30*, 2449–2462. [CrossRef]
14. Omage, F.B.; Madabeni, A.; Tucci, A.R.; Nogara, P.A.; Bortoli, M.; dos Santos Rosa, A.; dos Santos Ferreira, V.N.; Rocha, J.B.T.; Miranda, M.D.; Orian, L. Diphenyl Diselenide and SARS-CoV-2: In silico Exploration of the Mechanisms of Inhibition of Main Protease (Mpro) and Papain-like Protease (PLpro). *J. Chem. Inf. Model.* **2023**, *63*, 2226–2239. [CrossRef] [PubMed]
15. Refaay, D.A.; Ahmed, D.M.; Mowafy, A.M.; Shaaban, S. Evaluation of novel multifunctional organoselenium compounds as potential cholinesterase inhibitors against Alzheimer's disease. *Med. Chem. Res.* **2022**, *31*, 894–904. [CrossRef]
16. Mamgain, R.; Kostic, M.; Singh, F.V. Synthesis and Antioxidant Properties of Organoselenium Compounds. *Curr. Med. Chem.* **2023**, *30*, 2421–2448. [PubMed]
17. Elsherbini, M.; Hamama, W.S.; Zoorob, H.H. Recent advances in the chemistry of selenium-containing heterocycles: Five-membered ring systems. *Coord. Chem. Rev.* **2016**, *312*, 149–177. [CrossRef]
18. Elsherbini, M.; Hamama, W.S.; Zoorob, H.H. Recent advances in the chemistry of selenium-containing heterocycles: Six-membered ring systems. *Coord. Chem. Rev.* **2017**, *330*, 110–126. [CrossRef]
19. Młochowski, J.; Kloc, K.; Lisiak, R.; Potaczek, P.; Wójtowicz, H. Developments in the chemistry of selenaheterocyclic compounds of practical importance in synthesis and medicinal biology. *Arkivoc* **2007**, *vi*, 14–46. [CrossRef]
20. Tiekink, E.R.T. Therapeutic potential of selenium and tellurium compounds: Opportunities yet unrealized. *Dalton Trans.* **2012**, *41*, 6390–6395. [CrossRef]
21. Banerjee, B.; Koketsu, M. Recent developments in the synthesis of biologically relevant selenium-containing scaffolds. *Coord. Chem. Rev.* **2017**, *339*, 104–127. [CrossRef]
22. Rafique, J.; Canto, R.F.S.; Saba, S.; Barbosa, F.A.R.; Braga, A.L. Recent Advances in the Synthesis of Biologically Relevant Selenium-containing 5-Membered Heterocycles. *Curr. Org. Chem.* **2016**, *20*, 166–188. [CrossRef]
23. Obieziurska-Fabisiak, M.; Pacuła-Miszewska, A.J.; Laskowska, A.; Ścianowski, J. Organoselenium compounds as antioxidants. *Arkivoc* **2023**, *v*, 69–92. [CrossRef]
24. Azad, G.K.; Tomar, R.S. Ebselen, A promising antioxidant drug: Mechanisms of action and targets of biological pathways. *Mol. Biol. Rep.* **2014**, *41*, 4865–4879. [CrossRef] [PubMed]
25. Jin, Z.; Du, X.; Xu, Y.; Deng, Y.; Liu, M.; Zhao, Y.; Zhang, B.; Li, X.; Zhang, L.; Peng, C.; et al. Structure of M^{pro} from SARS-CoV-2 and discovery of its inhibitors. *Nature* **2020**, *582*, 289–293. [CrossRef] [PubMed]
26. Mori, T. Organic conductors with unusual band fillings. *Chem.Rev.* **2004**, *104*, 4947–4969. [CrossRef]
27. Weglarz-Tomczak, E.; Tomczak, J.M.; Talma, M.; Burda-Grabowska, M.; Giurg, M.; Brul, S. Identification of ebselen and its analogues as potent covalent inhibitors of papain-like protease from SARS-CoV-2. *Sci. Rep.* **2021**, *11*, 3640. [CrossRef] [PubMed]
28. Ashizawa, M.; Akutsu, A.; Noda, B.; Nii, H.; Kawamoto, T.; Mori, T.; Nakayashiki, T.; Misaki, Y.; Tanaka, K.; Takimiya, K.; et al. Synthesis and structures of highly conducting charge-transfer salts of selenium containing TTM-TTP derivatives. *Bull. Chem. Soc. Jpn.* **2004**, *77*, 1449–1458. [CrossRef]
29. Ashizawa, M.; Nakao, A.; Yamamoto, H.M.; Kato, R. Development of the first methyl antimony bridged tetrachalcogenafulvalene systems. *J. Low Temp. Phys.* **2006**, *142*, 449–452. [CrossRef]
30. Yamada, J.-I.; Akutsu, H. New trends in the synthesis of π -electron donors for molecular conductors and superconductors. *Chem. Rev.* **2004**, *104*, 5057–5083. [CrossRef]
31. Ohki, D.; Yoshimi, K.; Kobayashi, A. Interaction-induced quantum spin Hall insulator in the organic Dirac electron system α-(BEDT-TSeF)$_2$I$_3$. *Phys. Rev. B* **2022**, *105*, 205123. [CrossRef]
32. Ashizawa, M.; Yamamoto, H.M.; Nakao, A.; Kato, R. The first methyl antimony linked dimeric tetrathiafulvalene and tetraselenafulvalenes. *Tetrahedron. Lett.* **2006**, *47*, 8937–8941. [CrossRef]
33. Imakubo, T.; Shirahata, T.; Kibune, M.; Yoshino, H. Hybrid organic/inorganic supramolecular conductors $D_2[Au(CN)_4]$ [D = Diiodo(ethylenedichalcogeno)tetrachalcogenofulvalene], including a new ambient pressure superconductor. *Eur. J. Inorg. Chem.* **2007**, *30*, 4727–4735. [CrossRef]
34. Fabre, J.M. Synthesis strategies and chemistry of nonsymmetrically substituted tetrachalcogenafulvalenes. *Chem. Rev.* **2004**, *104*, 5133–5150. [CrossRef] [PubMed]
35. Takimiya, K.; Takamori, A.; Aso, Y.; Otsubo, T.; Kawamoto, T.; Mori, T. Organic superconductors based on a new electron donor, methylenedithio-diselenadithiafulvalene (MDT-ST). *Chem. Mater.* **2003**, *15*, 1225–1227. [CrossRef]

36. Takimiya, K.; Kodani, M.; Niihara, N.; Aso, Y.; Otsubo, T.; Bando, Y.; Kawamoto, T.; Mori, T. Pressure-induced superconductivity in (MDT-TS)$(AuI_2)_{0.441}$ [MDT-TS) = 5*H*-2-(1,3-diselenol-2-ylidene)-1,3,4,6-tetrathiapentalene]: A new organic superconductor possessing an incommensurate anion lattice. *Chem. Mater.* **2004**, *16*, 5120–5123. [CrossRef]
37. Makhaeva, N.A.; Amosova, S.V.; Potapov, V.A. Recent advances in design and synthesis of diselenafulvenes, tetraselenafulvalenes, and their tellurium analogs and application for materials sciences. *Molecules* **2022**, *27*, 5613. [CrossRef] [PubMed]
38. Walwyn, R.J.; Chan, B.; Usov, P.M.; Solomon, M.B.; Duyker, S.G.; Koo, J.Y.; Kawano, M.; Turner, P.; Kepert, C.J.; D'Alessandro, D.M. Spectroscopic, electronic and computational properties of a mixed tetrachalcogenafulvalene and its charge transfer complex. *J. Mater. Chem. C* **2018**, *6*, 1092–1104. [CrossRef]
39. Kodani, M.; Murakami, S.; Jigami, T.; Takimiya, K.; Aso, Y.; Otsubo, T. Bis(ethylenethio)tetraselenafulvalene and related hybrid diselenadithiafulvalenes as novel electron donors forming highly conductive complexes with 7,7,8,8-tetracyanoquinodimethane. *Heterocycles* **2001**, *54*, 225–235. [CrossRef]
40. Takimiya, K.; Jigami, T.; Kawashima, M.; Kodani, M.; Aso, Y.; Otsubo, T. Synthetic procedure for various selenium-containing electron donors of the bis(ethylenedithio)tetrathiafulvalene (BEDT-TTF) type. *J. Org. Chem.* **2002**, *67*, 4218–4227. [CrossRef]
41. Mori, H.; Suzuki, H.; Okano, T.; Moriyama, H.; Nishio, Y.; Kajita, K.; Kodani, M.; Takimiya, K.; Otsubo, T. Positional order and disorder of symmetric and unsymmetric BEDT-STF salts. *J. Solid State Chem.* **2002**, *168*, 626–631. [CrossRef]
42. Trofimov, B.A.; Amosova, S.V. Divinyl sulfide: Synthesis, properties, and applications. *Sulfur Rep.* **1984**, *3*, 323–393. [CrossRef]
43. Ianiski, F.R.; Bassaco, M.M.; Vogt, A.G.; Reis, A.S.; Pinz, M.P.; Voss, G.T.; de Oliveira, R.L.; Silveira, C.C.; Wilhelm, E.A.; Luchese, C. Antinociceptive property of vinyl sulfides in spite of their weak antioxidant activity. *Med. Chem. Res.* **2018**, *27*, 46–51. [CrossRef]
44. Ianiski, F.R.; Alves, C.B.; Bassaco, M.M.; Silveira, C.C.; Luchese, C. Protective effect of ((4-tert-butylcyclohexylidene) methyl) (4-methoxystyryl) sulfide, a novel unsymmetrical divinyl sulfide, on an oxidative stress model induced by sodium nitroprusside in mouse brain: Involvement of glutathione peroxidase activity. *J. Pharm. Pharmacol.* **2014**, *66*, 1747–1754. [CrossRef]
45. Johannesson, P.; Lindeberg, G.; Johansson, A.; Nikiforovich, G.V.; Gogoll, A.; Synnergren, B.; Le Greves, M.; Nyberg, F.; Karlen, A.; Hallberg, A.J. Vinyl sulfide cyclized analogues of angiotensin II with high affinity and full agonist activity at the AT1 receptor. *J. Med. Chem.* **2002**, *45*, 1767–1777. [CrossRef]
46. Amosova, S.V.; Shagun, V.A.; Makhaeva, N.A.; Novokshonova, A.I.; Potapov, V.A. Quantum Chemical and Experimental Studies of an Unprecedented Reaction Pathway of Nucleophilic Substitution of 2-Bromomethyl-1,3-thiaselenole with 1,3-Benzothiazole-2-thiol Proceeding Stepwise at Three Different Centers of Seleniranium Intermediates. *Molecules* **2021**, *26*, 6685. [CrossRef]
47. Amosova, S.V.; Filippov, A.S.; Potapov, V.A.; Penzik, M.V.; Albanov, A.I. Unexpected Reaction of 2-Bromomethyl-1,3-thiaselenole with Formation of Bis[(*Z*)-2-(vinylsulfanyl)ethenyl] Diselenide. *Russ. J. Org. Chem.* **2017**, *53*, 1878–1880. [CrossRef]
48. Potapov, V.A.; Filippov, A.S.; Amosova, S.V. Selective Synthesis of 1,3-Thiaselenol-2-ylmethyl Selenocyanate. *Russ. J. Org. Chem.* **2018**, *54*, 957–958. [CrossRef]
49. Accurso, A.A.; Cho, S.-H.; Amin, A.; Potapov, V.A.; Amosova, S.V.; Finn, M.G. Thia-, aza-, and selena[3.3.1]bicyclononane dichlorides: Rates vs internal nucleophile in anchimeric assistance. *J. Org. Chem.* **2011**, *76*, 4392–4395. [CrossRef] [PubMed]
50. Mlochowski, J.; Syper, L. The Convenient Synthesis of Organoselenium Reagents. *Synthesis* **1984**, *1984*, 439–442.
51. Princival, J.L.; de Oliveira, M.S.C.; Dos Santos, A.A.; Comasseto, J.V. A large-scale synthesis of enantiomerically pure γ-hydroxy-organochalcogenides. *Tetrahedron Asymmetry* **2009**, *20*, 2699–2703. [CrossRef]
52. Haraguchi, K.; Tanaka, H.; Hayakawa, H.; Miyasaka, T. Cleavage of cyclic ethers including oxetane and oxolane with a highly nucleophilic species of phenyl selenide anion. *Chem. Lett.* **1988**, *6*, 931–934. [CrossRef]
53. Haraguchi, K.; Tanaka, H.; Miyasaka, T. Preparation of γ- and δ-phenylselenenyl alcohols via ring cleavage of oxetane and oxolane. *Synthesis* **1989**, *1989*, 434–436. [CrossRef]
54. Middleton, D.S.; Simpkins, N.S.; Begley, M.J.; Terrett, N.K. Synthesis of spiro ethers using radical cyclizations. *Tetrahedron* **1990**, *46*, 545–564. [CrossRef]
55. McNeil, N.M.R.; Press, D.J.; Mayder, D.M.; Garnica, P.; Doyle, L.M.; Back, T.G. Enhanced glutathione peroxidase activity of water-soluble and polyethylene glycol-supported selenides, related spirodioxyselenuranes, and pincer selenuranes. *J. Org. Chem.* **2016**, *81*, 7884–7897. [CrossRef] [PubMed]
56. Back, T.G.; Moussa, Z. Remarkable Activity of a Novel Cyclic Seleninate Ester as a Glutathione Peroxidase Mimetic and Its Facile in Situ Generation from Allyl 3-Hydroxypropyl Selenide. *J. Am. Chem. Soc.* **2002**, *124*, 12104–12105. [CrossRef] [PubMed]
57. Back, T.G.; Moussa, Z. Diselenides and Allyl Selenides as Glutathione Peroxidase Mimetics. Remarkable Activity of Cyclic Seleninates Produced in Situ by the Oxidation of Allyl ω-Hydroxyalkyl Selenides. *J. Am. Chem. Soc.* **2003**, *125*, 13455–13460. [CrossRef] [PubMed]
58. Kumakura, F.; Mishra, B.; Priyadarsini, K.I.; Iwaoka, M. A Water-Soluble Cyclic Selenide with Enhanced Glutathione Peroxidase-Like Catalytic Activities. *Eur. J. Org. Chem.* **2010**, *3*, 440–445. [CrossRef]