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REVIEW

Geminal dithiols

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The review gives exhaustive coverage over the period 1876 to 2002 of the syntheses and physical and chemical properties of *gem*-dithiols. *gem*-Dithiols, poorly understood until recently, are organic sulfur compounds that contain a $>C(SH)_2$ group.

Keywords: *gem*-Dithiols; Preparation; Properties; Reactions; Heterocycles

1. Introduction

The simplest organic sulfur compounds containing a thiol group, mercaptans or thiols of general formula R-SH (R – organic substituent), have been long known and studied in detail. They appear in fossil fuels and are essential for living organisms [1, 2]. Mercaptans are of importance in organic synthesis and take part in many industrial processes.

In contrast to the thiols containing only one SH group at the carbon atom, compounds having a $>C(SH)_2$ fragment, *gem*-dithiols, appeared in chemical laboratories only in the middle of the 20th century [3]. They are few in number and poorly discussed in the literature until the present time. Nevertheless, they are of certain synthetic and practical interest. Unlike their oxygen analogs, *gem*-diols, containing a $>C(OH)_2$ fragment [4], they are stable enough to serve in some cases as valuable synthons.

This review considers all the literature data on *gem*-dithiols starting from their appearance up to the middle of 2002.

2. Synthetic routes

2.1 *Syntheses from carbon disulfide*

The first known *gem*-dithiol, trithiocarbonic acid, was obtained from carbon disulfide in 1876 [5]. It was synthesized by the reaction of carbon disulfide with aqueous calcium hydrosulfide. The acid was obtained as a foul-smelling heavy red oil which solidified at a low temperature

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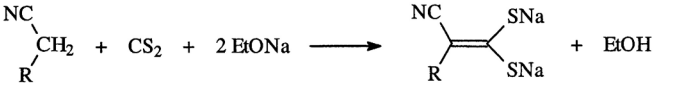
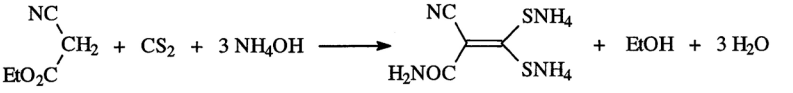
(−30 °C). The acid was very unstable and spontaneously decomposed to hydrogen sulfide and carbon disulfide. Decomposition of this kind also occurs during distillation of freshly prepared acid. The free acid is relatively stable in chloroform; however, in methanol its stability is much lower [6]. *gem*-Dithiols include some thiocarbonic acid derivatives such as oxomethanedithiol (dithiocarbonic acid) $O{=}C(SH)_2$, iminothiocarbonic acid $HN{=}C(SH)_2$ and methanetetrathiol (tetrathioorthocarbonic acid) $C{-}(SH)_4$. The latter two have not yet been isolated in the free state [5].

2-Substituted ethene-1,1-dithiolates of alkali metals or ammonium were prepared by the condensation of carbon disulfide with compounds containing reactive methylene groups in the presence of bases [7, 8].



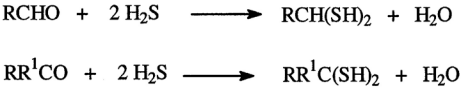
R = CN, CO_2Me, CO_2Et



SCHEME 1

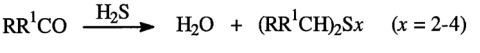
2.2 *Reaction of ketones with hydrogen sulfide*

Under pressure. The first aliphatic *gem*-dithiols were obtained in 1952 by the reactions of ketones or aldehydes with excess hydrogen sulfide under 35 to 8500 atm, preferably in the presence of acetic or *para*-toluenesulfonic acids [3].



SCHEME 2

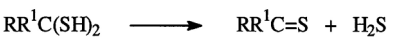
As a rule, under these conditions both internal and terminal *gem*-dithiols were surprisingly easily prepared in yields of up to 65%. In some cases, along with *gem*-dithiols, polysulfides were also formed.



SCHEME 3

In this way *gem*-dithiols were synthesized from formaldehyde, benzaldehyde, acetone, diethyl ketone and cyclohexanone. *gem*-Dithiols turned out to be prepared more readily from ketones than from aldehydes.

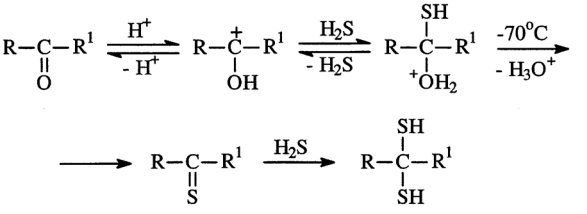
Under normal pressure without solvent. Liquid ketones react with hydrogen sulfide without solvent under normal pressure using amines (preferably primary ones) as catalysts [9]. The *gem*-dithiols formed release hydrogen sulfide, thus transforming into the corresponding thioketones.



SCHEME 4

The reaction mechanisms are not completely understood. It is only stated that the amines (ammonia, *n*-butylamine, morpholine and triethylamine) react with hydrogen sulfide as nucleophiles and this facilitates H_2S addition to the polarized thiocarbonyl group.

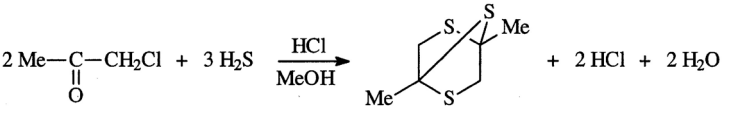
In a solvent medium. *gem*-Dithiols are often formed in attempts to transform ketones into thiones by treatment with hydrogen sulfide in an alcoholic hydrogen chloride solution [3, 9]. The first reaction stage involves oxygen atom protonation. The interaction of the intermediate carbocation with hydrogen sulfide leads to thioketone and *gem*-dithiol according to the scheme 5:



SCHEME 5

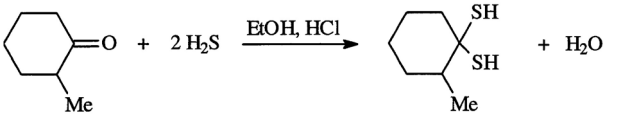
The result depends on reaction time, temperature and the nature of solvent. An essential role is played by the acidity of medium. A necessary reaction condition is an optimal degree of oxygen atom protonation since insufficient polarization of the >C=O bond impedes the addition of hydrogen sulfide. The acidity of medium may, in turn, reduce the amount of non-protonated (nucleophilic) molecules of hydrogen sulfide, thereby reducing the reaction rate [10].

The reaction of chloroacetone with hydrogen sulfide in methanolic hydrogen chloride solution was first performed by German chemists in 1942 [11]. Instead of the expected *gem*-dithiol, 2,5-dimethyl-2,5-endothio-1,4-dithiane (trithianorbornane) was the reaction product. Its structure was proven by X-ray diffraction in 1967 [12].



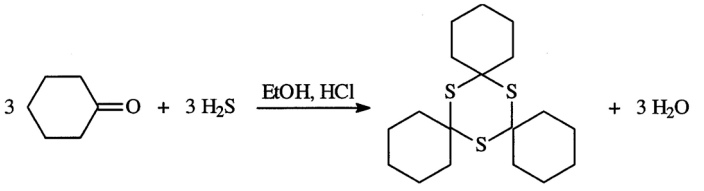
SCHEME 6

Later, the synthesis of aliphatic *gem*-dithiols was performed by the reaction of ketones in the H_2S/HCl system at −40 to −20 °C [11].



SCHEME 7

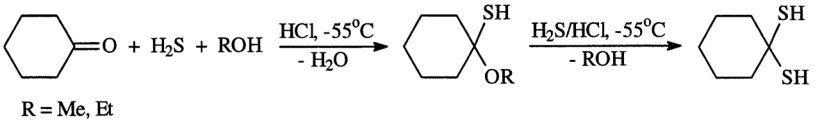
In 1927 E. Fromm pioneered the synthesis of 2-methylcyclohexane-1,1-dithiol [13].



SCHEME 8

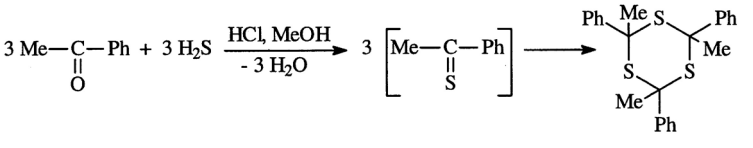
An analogous reaction of cyclohexanone afforded a cyclohexanethione cyclic trimer, a trithiane derivative.

It was only 40 years later that French chemists managed to prepare cyclohexane-1,1-dithiol by the reaction of cyclohexanone with hydrogen sulfide under the same conditions but at −55 °C [14]. With excess hydrogen sulfide, the reaction intermediate 1-alkoxycyclohexane-1-thiol, was readily transformed into *gem*-dithiol.



SCHEME 9

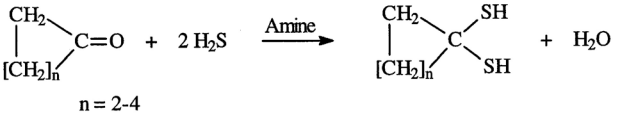
The first crystalline *gem*-dithiol, 1,3-diphenylpropane-2,2-dithiol, was prepared by the action of hydrogen sulfide and hydrogen chloride on dibenzyl ketone at 0–5 °C in methanol [15]. However, under the same conditions, an analogous reaction of acetophenone with hydrogen sulfide gave the corresponding trimer [16].



SCHEME 10

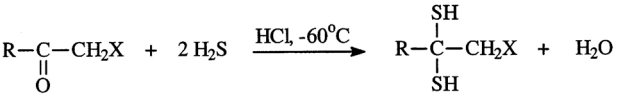
The intermediate formation of thioacetophenone was indicated by blue coloring of the reaction mixture in the initial state, which soon disappeared and colorless crystalline 2,4,6-trimethyl-2,4,6-triphenyl-1,3,5-trithiane precipitated.

German chemists established EtOH, DMF and DMSO to be the most appropriate solvents for the synthesis of *gem*-dithiols in the presence of amines [17]. In these solvents and the presence of amines (*n*-butylamine, morpholine, triethylamine) it was possible to obtain from cyclopentanone and cyclohexanone and hydrogen sulfide *gem*-dithiols in 70 and 80% yield, respectively. Four years later cyclobutane-1,1-dithiol was synthesized by a similar procedure [18].



SCHEME 11

The first representatives of α-halo-*gem*-dithiols, 1-halo-2-organylethane-2,2-dithiols, were synthesized in 1990 by hydrogen sulfide treatment of the corresponding α-haloketones in ethereal hydrogen chloride at $-60\,^{\circ}C$ [19].



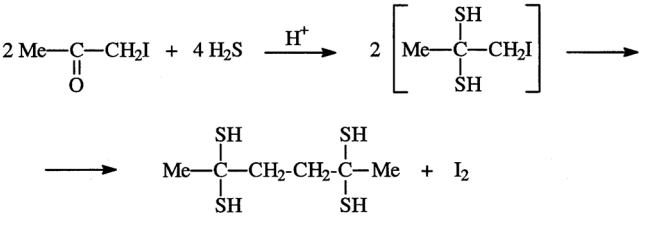
SCHEME 12

The reactions with fluoroacetophenone [20], as well as bromo- and fluoropinacoline [21], were carried out under analogous conditions.

Isolation of the *gem*-dithiols encounters some experimental difficulties. On attempted removal of hydrogen chloride from the reaction mixture by washing with ice water, the dithiols transform into the corresponding thioketones, which instantly undergo trimerization in an aqueous medium [22]. Therefore this procedure should be conducted at $0\,^{\circ}C$ as quickly as possible with removal of the solvent (ether) in vacuum.

The appearance of α-halothioketones as intermediates is confirmed by the fact that acid hydrothiolysis of chloro-, bromo- and fluoroacetones in ether leads to the corresponding geminal dithiols [19, 21].

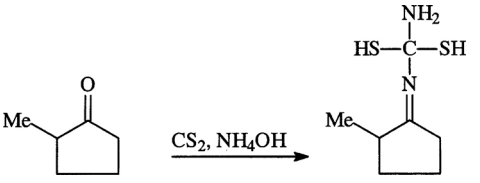
The hydrothiolysis of iodoacetone in ether unexpectedly proceeds with elimination of elemental iodine to form hexane-2,2,5,5-tetrathiol [23]. This reaction provides a new example of C−C bond formation. This tetrathiol is the first representative of compounds containing two $>C(SH)_2$ groups in the molecule.



SCHEME 13

2.3 *Reaction of ketones with carbon disulfide and ammonia*

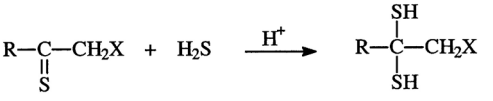
As found by Japanese chemists, in excess aqueous ammonia at below $0\,^{\circ}C$, 2-cyclopentanone reacts with carbon disulfide to give 2-methyl-*N*-[amino(dimercapto)methyl]cyclopentanimine [24].



SCHEME 14

2.4 *Formation from thioketones*

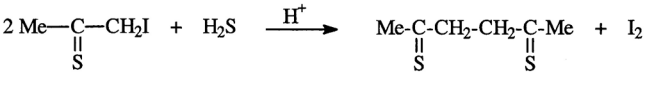
By analogy with the reaction of acid-catalyzed hydrothiylation of ketones, it was also possible to add hydrogen sulfide to aliphatic thioketones. However, this process requires special conditions due to the instability of many aliphatic thioketones. The stability of aliphatic thioketones increases when a halogen atom is introduced onto the α-position.



R = Me, Me_3C; X = F, Cl, Br

SCHEME 15

α-Halothioketones were synthesized by the reaction of hydrogen sulfide with chloro-, bromo- and fluoroacetone [19, 20, 25], as well as bromo- and fluoropinacoline [21] at $-70\,^{\circ}C$ in the presence of hydrogen chloride and in the absence of solvent. The hydrothiylation of α-halothioketones by an H_2S/HCl mixture in an appropriate solvent (Et_2O, MeCN, C_6H_{12}:C_6H_6 = 3:1) at $-60\,^{\circ}C$ allowed the preparation of the corresponding *gem*-dithiols in quantitative yield [26].

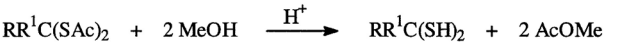


SCHEME 16

In an attempt to prepare, in the same manner, 1-iodopropane-2,2-dithiol from 1-iodopropane-thione a copious release of molecular iodine was observed, affording hexane-2,5-dithione as the reaction product [23].

2.5 *Formation from gem-bis(thiolacetates)*

A convenient synthetic route to aliphatic *gem*-dithiols based on acid-catalyzed methanolysis of *gem*-bis(thiolacetates) has been suggested [27]. The process is carried out according to the following scheme:



R = H, Me; R^1 = H, Me, Ph

SCHEME 17

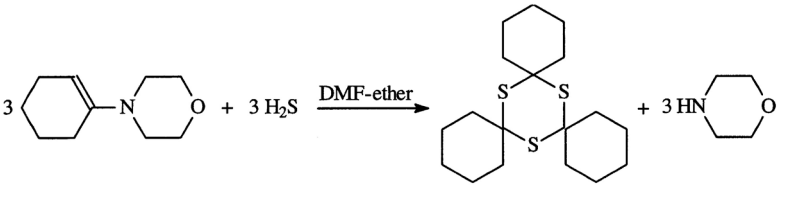
The initial *gem*-bis(thiolacetates) are formed in good yield in the reaction of the corresponding aldehyde or ketone with thiolacetic acid in acetic anhydride. The methanolysis reaction proceeds for a week at −15 °C. The yield of *gem*-dithiols approaches 65%. The low yields of some *gem*-dithiols are due to their polymerization in the isolation process.

2.6 *Formation from enamines*

Cycloalkane-1,1-dithiols are smoothly formed in the reaction of hydrogen sulfide with 1-(*N*-morpholino)cycloalkenes in DMF [28, 29].

SCHEME 18

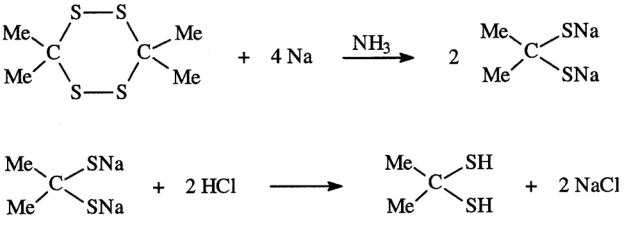
With a DMF–ether mixture as solvent, instead of cyclohexane-1,1-dithiol a trimer was isolated [30].



SCHEME 19

2.7 *Reduction of tetrathianes*

An interesting synthetic route to geminal dithiols has been suggested by B. Magnusson [31], who found that the reaction of 3,3,6,6-tetramethyl-1,2,4,5-tetrathiane with a sodium solution in liquid ammonia leads to sodium *gem*-dithiolate which, when treated with hydrochloric acid, gives propane-2,2-dithiol.

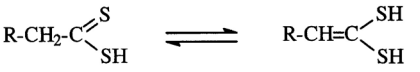


SCHEME 20

The corresponding *gem*-dithiols are formed on the reduction of tetrathianes by lithium alumohydride [32]. Moreover, the *gem*-dithiols are further partially reduced to the corresponding thiols.

2.8 *Preparation from dithiocarboxylic acids*

Dithiocarboxylic acids containing at least one hydrogen at the α-carbon atom are prone to formal 1,3-prototropic rearrangement (enethiolization).



SCHEME 21

Tautomeric equilibrium of this kind has not been proven for individual dithioacids; however, it is well established that dithiocarbonic acid in an aqueous solution exists as a mixture of the above two tautomers [33].

3. Physical properties

Terminal aliphatic *gem*-dithiols $R-CH(SH)_2$ (R = H, Me, Et) are malodorous liquids distilled under atmospheric pressure. In the dark they can be kept at room temperature for a year without decomposition [3]. However, propane-2,2-dithiol and phenylmethane-1,1-dithiol are less stable and undergo 50% decomposition within a month [3]. 1-Halo-2-organylethane-2,2-dithiols $R-C(SH)_2-CH_2X$ (X = Cl, Br) are even less stable. They can be kept at $-5\,^{\circ}C$ for 6 months [26]. Their analogs with X = F are more stable [20].

The smell of higher alkane-*gem*-dithiols is less unpleasant. They are sufficiently stable to be kept for a long time [3].

3.1 *Spectral properties*

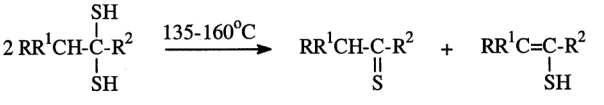
In the IR spectra of internal *gem*-dithiols the SH group gives rise to a strong absorption band in the 2500–2800 cm^{-1} region [1–4]. The lowest value of this band (2530–2545 cm^{-1}) is observed for cycloalkane-1,1-dithiols. Conversely, *N*-[amino(dimercapto)methyl]-2-methylcyclopentanimine containing a $>C{=}N-C(SH)_2-NH_2$ group has an unusually high value (2770 cm^{-1}) [10].

In the ^1H NMR spectra of *gem*-dithiols [9] the mercapto group proton signal (most often appearing as a doublet) is in the 1.9–3.5 ppm region. In 1-halo-2-organylethane-2,2-dithiols $R-C(SH)_2-CH_2X$ (X = F, Cl, Br) all the signals show a singlet shape and are observed in the 2.8–3.6 ppm region [26].

4. Chemical properties

4.1 *Thermal decomposition*

The *gem*-dithiols are thermally unstable. Their transformation into the corresponding thioketones and enethiols at 135–160 °C were first observed by S. Bleisch and R. Mayer on passage through a chromatographic column filled with a porous material [34].

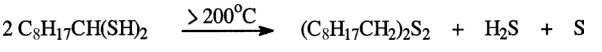


SCHEME 22

Thermal decomposition of *gem*-dithiols on quartz sand, activated charcoal or ceramics at 150–200 °C in an inert gas flow causes an abstraction of one hydrogen sulfide molecule to

form thioketones. A necessary condition for their preparation is immediate cooling of the condensate to approximately −50 °C.

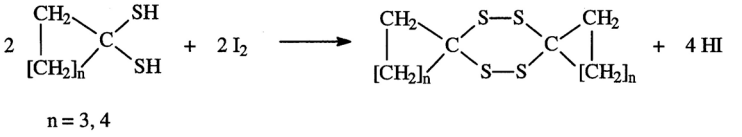
For thermolysis at 100 °C hydrogen sulfide is eliminated only negligibly. Above 200 °C *gem*-dithiols release not only hydrogen sulfide, but also elemental sulfur to generate the corresponding disulfides [3].



SCHEME 23

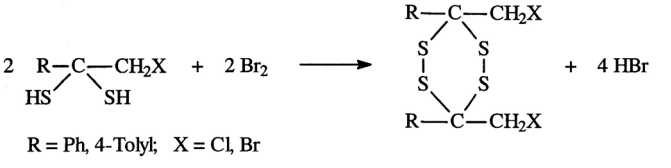
4.2 *Oxidation*

The oxidation of thiols, mainly leading to the corresponding sulfinic acids, sulfonic acids and disulfides, has been extensively studied [1, 2]. In contrast, few publications have been devoted to the oxidation of *gem*-dithiols. As early as 1962 Mayer found that the oxidation of cycloalkane-1,1-dithiols by iodine gave the corresponding 1,2,4,5-tetrathiane derivatives [17].



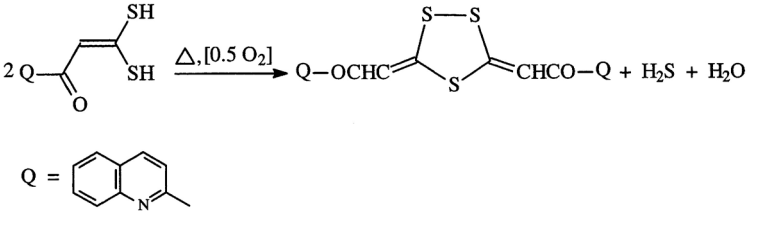
SCHEME 24

1-Halo-2-phenylethane-2,2-dithiols are oxidized with iodine or bromine in an analogous manner. Here, 1,4-diphenyl-1,4-bis(halomethyl)-1,2,4,5-tetrathianes are formed in 51% yield [35].



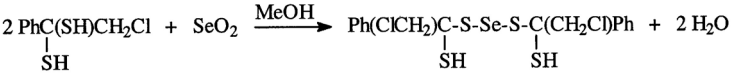
SCHEME 25

Boiling 2-quinaldinoylethene-1,1-dithiol in glacial acetic acid or benzene affords a trithiacyclopentane [36].



SCHEME 26

The oxidation of 1-chloro-2-phenylethane-2,2-dithiol with selenium dioxide in methanol proceeds in an unusual way to afford 1,5-diphenyl-1,5-bis(chloromethyl)-2,4-dithia-3-selenapentane-1,5-dithiol [35].



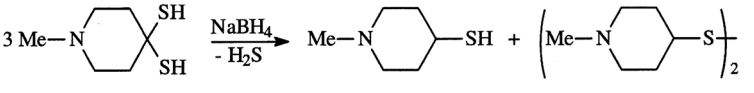
SCHEME 27

In an attempt to oxidize 3,5,5-trimethylhexane-1,1-dithiol with nitric acid only 3,5,5-trimethylhexanoic and 2,4,4-trimethylpentanoic acids were isolated [3].

SCHEME 28

4.3 *Reduction*

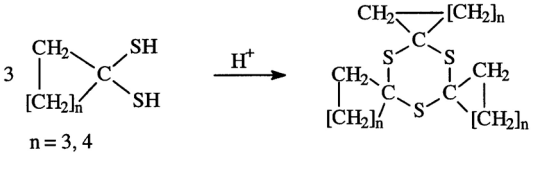
gem-Dithiols are readily reduced to the corresponding mercaptans under the action of lithium aluminium hydride [3] or sodium borohydride [37].



SCHEME 29

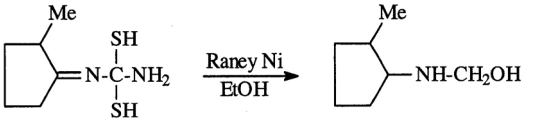
4.4 *Desulfurization*

gem-Dithiols readily release one molecule of hydrogen sulfide, and are thus transformed into the corresponding thiocarbonyl compounds, which then readily undergo trimerization. Thus, for instance, in 1962 Mayer found that, on heating with concentrated hydrochloric acid, cyclane-1,1-dithiols are transformed into trimers of the corresponding cycloalkanethiones [17].



SCHEME 30

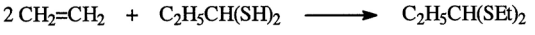
Desulfurization of 2-methyl-*N*-[amino(dimercapto)methyl]cyclopentanimine with Raney nickel follows scheme 31 [24].



SCHEME 31

4.5 *Hydrothiylation*

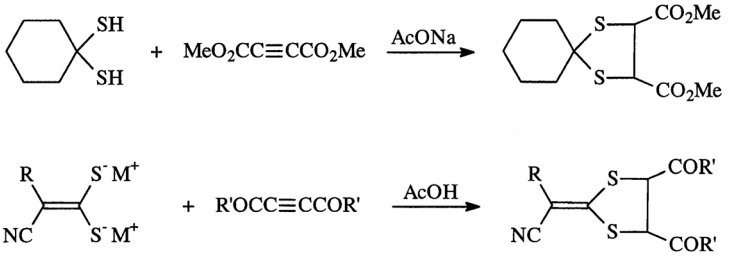
Two mercapto groups in *gem*-dithiols add to olefins in the presence of free-radical initiators. This reaction has been studied using as an example the addition of 1,1-propanedithiol and 3,5,5-trimethylhexane-1,1-dithiol to ethylene and that of propane-2,2-dithiol to propylene. In all the cases the yields of adducts are minor (7–32%) [3].



SCHEME 32

4.6 *Reactions with acetylene derivatives*

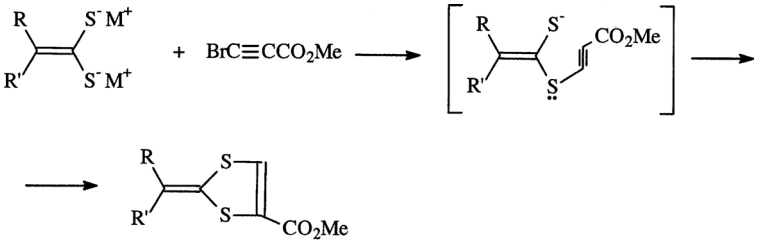
Cyclohexane-1,1,-dithiol and 2-substituted ethene-1,1-dithiolates of alkali metals or ammonium in buffer solutions react with the esters of acetylenedicarboxylic acid and dibenzoylacetylene to form the corresponding 1,3-dithiolanes [38].



M = Na, NH_4; R = CN, CO_2Et, $CONH_2$;
R' = OMe, OEt, Ph

SCHEME 33

However, in the reaction of *gem*-dithiols with activated haloacetylenes the attack of the second nucleophilic center is directed not to the β- but to the α-carbon atom to form isomeric five-membered 1,3-dithiols instead of the expected four-membered 1,1-dithiethanes. Thus, the reaction of vinylidene-1,1-dithiols with the methyl ether of bromopropiolic acid leads to 2-alkylidene-4-methoxycarbonyl-1,3-dithiols [39].

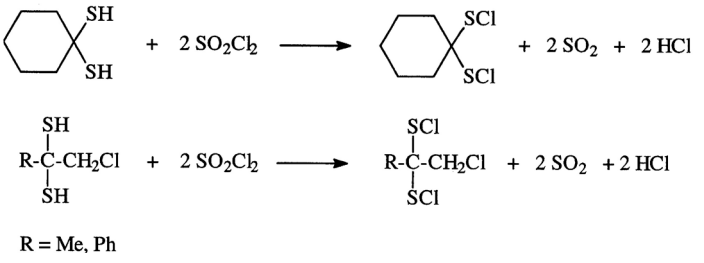


M = Na, K, NH_4; R = H, CN, CO_2Et;
R' = CN, NO_2, CO_2Et, $CONH_2$

SCHEME 34

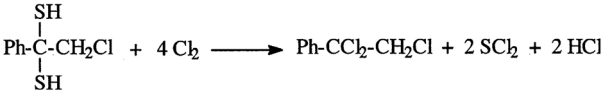
4.7 *Chlorination*

The chlorination of thiols leads to sulfenyl chlorides [40]. Compounds containing a $>C(SCl)_2$ group were first obtained, practically at the same time, by the reaction of cyclohexane-1,1-dithiol [40] and 1-chloro-2-organylethane-2,2-dithiols [41] with sulfuryl chloride.



SCHEME 35

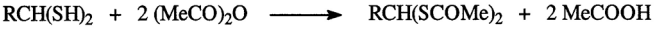
When gaseous chlorine was used instead of sulfuryl chloride, the chlorination of 1-chloro-2-phenylethane-2,2-dithiol gave 1-phenyl-1,1,2-trichloroethane, *i.e.* the product of chlorolysis of the two C—S bonds [41].



SCHEME 36

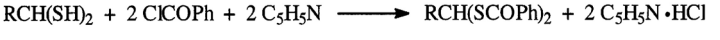
4.8 *Acylation*

gem-Dithiols are readily acylated with anhydrides of carboxylic acids and acid chlorides in the presence of pyridine. In all cases two acyl groups per molecule were introduced. Thus, the interaction of propane-1,1-dithiol, phenylmethane-1,1-dithiol, 3,5,5-trimethylhexane-1,1-dithiol with acetic anhydride leads to the corresponding *gem*-dithiolacetates [3].



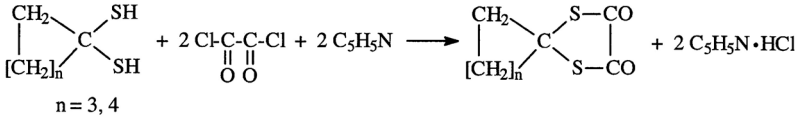
SCHEME 37

Analogous compounds are produced by the acylation of methanedithiol and phenylmethanedithiol with benzoyl chloride [17].



SCHEME 38

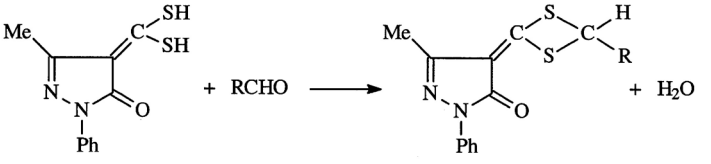
Acylation of cyclopentane- and cyclohexane-1,1-dithiols with oxalyl chloride affords 1,3-dithiolanediones [17].



SCHEME 39

4.9 *Reaction with aldehydes*

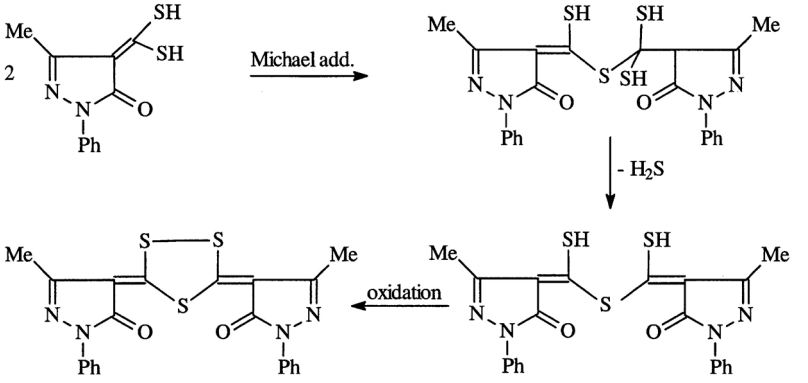
The reaction of 3-methyl-1-phenyl-4-dimercaptomethylene pyrazolidene-5-one with benzaldehyde and its derivatives in alcoholic hydrogen chloride gives the corresponding 1,3-dithiethane derivatives [42].



R = *o*-HOC_6H_4, *p*-$MeOC_6H_4$, *p*-HO-*m*-$MeOC_6H_3$, PhCH=CH

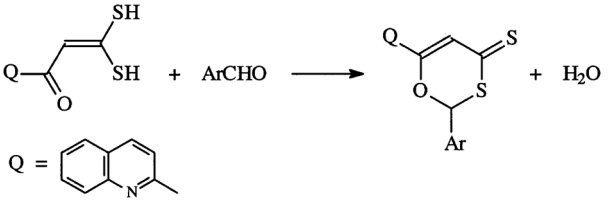
SCHEME 40

When carried out in acetic acid, this reaction fails to give dithiethane derivatives and the initial aldehyde remains unreacted [43]. In this case a 1,3,4-trithiacyclopentanedizaurine derivative is formed, which was also isolated *via* autocondensation of the initial *gem*-dithiol in boiling acetic acid (scheme 41).



SCHEME 41

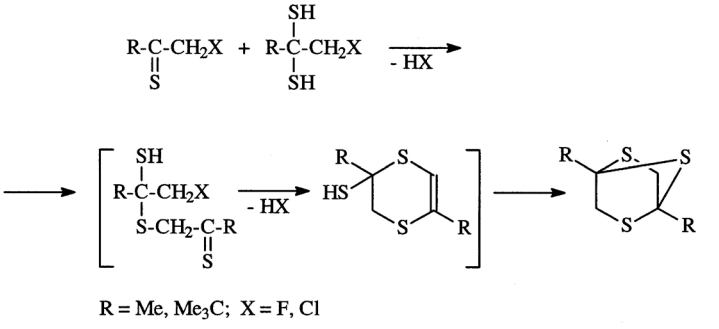
2-Quinaldinoylethene-1,1-dithiol reacts with aromatic aldehydes to give oxathiene derivatives [36].



SCHEME 42

4.10 *Reaction with thioketones*

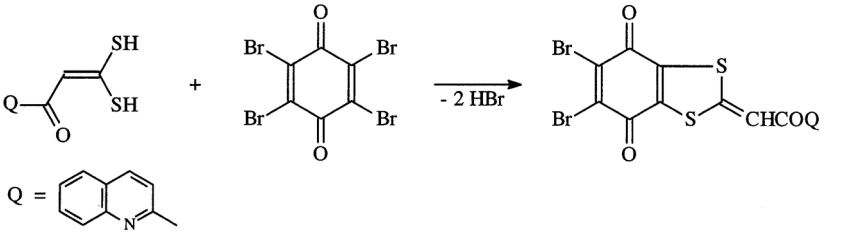
1-Chloro-2-organylethane-2,2-dithiols react readily with isostructural α-halothioketones to form 2,5,7-trithianorbornanes [21, 44].



SCHEME 43

4.11 *Reaction with organic halides*

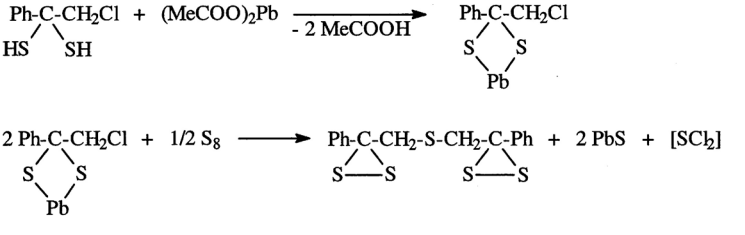
Reaction of 2-quinaldinoylethene-1,1-dithiol with haloquinones affords dithiolane derivatives [36].



SCHEME 44

4.12 *Reaction with divalent metal salts*

gem-Dithiol metal thiolates are little known. The reaction of 1-chloro-2-phenylethane-2,2-dithiol with divalent metal salts (M = Cu, Hg, Pb, Fe, Co, Ni) has been studied [45]. The reaction with lead acetate or mercury chloride afforded yellow cyclic four-membered lead and mercury 1-chloro-2-phenylethane-2,2-dithiolates. These dithiolates turned out to be convenient synthons which allowed, in particular, the preparation of the first compound containing two dithiirane cycles (scheme 45) [46].

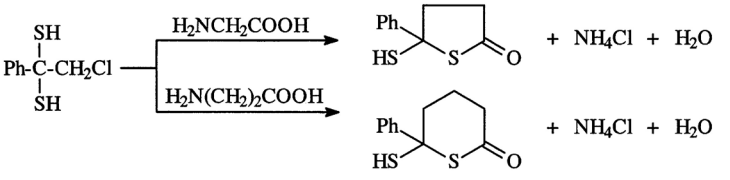


SCHEME 45

A similar reaction with copper, iron, cobalt and nickel salts unexpectedly led to the chlorine-free compounds $C_{16}H_{18}S_4M$. Evidently, these are polymers that are black paramagnetic powders, very soluble in chloroform and acetone. Their solutions form high quality films on glass and quartz, possessing some properties of organic semiconductors [46].

4.13 *Reaction with amino acids*

The authors have found that the reaction of 1-chloro-2-phenylethane-2,2-dithiol with amino acids leads to thiolactones [47]. During the reaction of this *gem*-dithiol with glycine in moist ether (1:1 molar ratio, 3 days, room temperature) 5-mercapto-5-phenylthiolan-2-one was isolated. An analogous reaction with β-alanine led to 6-mercapto-6-phenyltetrahydrothiopyran-2-one.



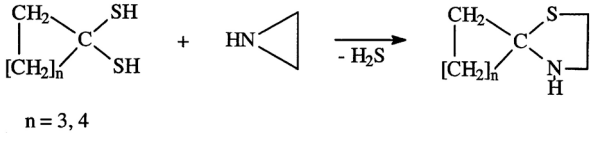
SCHEME 46

This reaction not only provides a new way of deamination of amino acids, but is also of considerable theoretical interest.

4.14 *Reaction with nitrogen-, oxygen- and phosphorus-containing organic compounds*

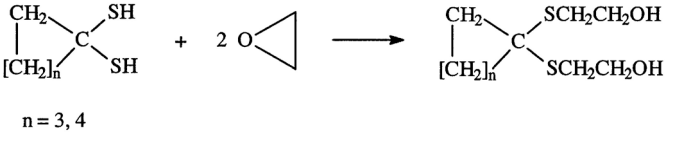
Reaction with three-membered heterocycles. R. Mayer's group has studied the reaction of *gem*-dithiols with three-membered heterocycles – aziridine and oxirane.

The reaction of cyclopentane- and cyclohexane-1,1-dithiols with aziridine in methanol gives the corresponding 1,3-thiazolidine derivatives [48].



SCHEME 47

Bis(2-hydroxyethyl)mercaptols are prepared from cyclic *gem*-dithiols and oxirane in the presence of an acidic (HCl) or basic (KOH or Et_3N) catalyst [49].

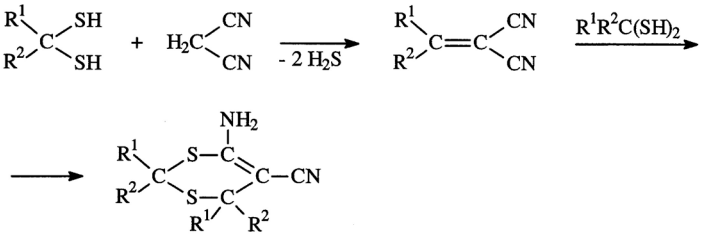


SCHEME 48

The compounds prepared are recommended for use in pharmaceuticals, photography, and insecticides.

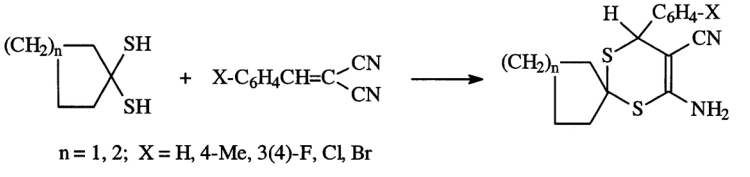
Reaction with malononitriles. In 1962 R. Mayer found that geminal alkanedithiols smoothly reacted with malonic acid dinitrile in the presence of a catalytic amount of base (alkali or amines) in MeOH or EtOH [50]. The reaction starts with the elimination of hydrogen sulfide and formation of the alkylidenemalononitrile. The addition to the latter of one more molecule

of *gem*-dithiol culminates in cyclization leading to 2,2,6,6-tetraalkyl-4-amino-5-cyano-1,3-dithiacyclohex-4-ene.



SCHEME 49

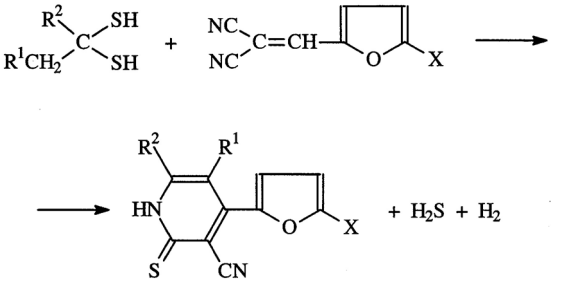
The reaction of benzylidenemalononitrile and *para*-substituted benzylidenemalononitriles with cycloalkane-2,2-dithiols proceeds in analogous fashion [51].



n = 1, 2; X = H, 4-Me, 3(4)-F, Cl, Br

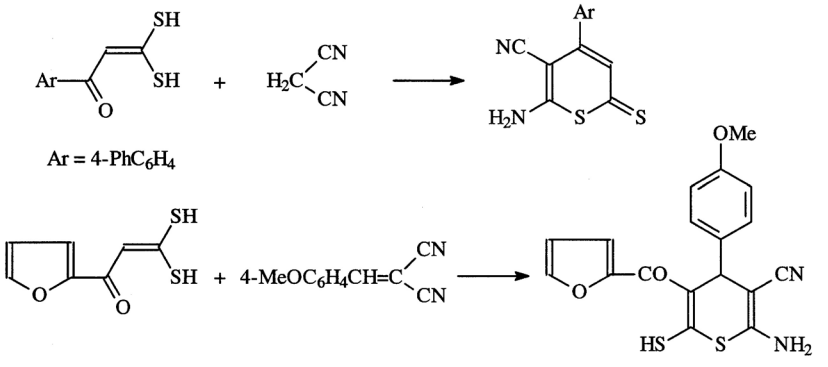
SCHEME 50

The reaction of alicyclic and cyclic *gem*-dithiols with 2-furfurylidenomalononitrile follows quite another direction, leading to 3-cyano-4-(2-furyl)-5-R^1-6-R^2-(1*H*)-pyridine-2-thiones [52].



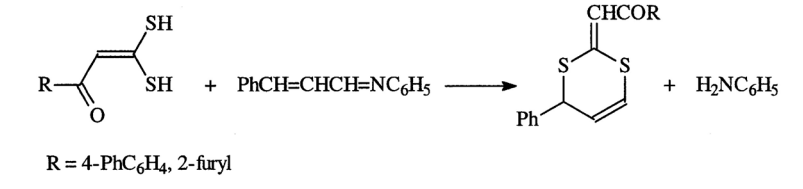
SCHEME 51

Thiopyran derivatives were prepared *via* reaction of 2-aroyl- and 2-furoylethene-1,1-dithiols with malonic acid dinitrile or 4-methoxybenzylidene malonodinitrile [53].



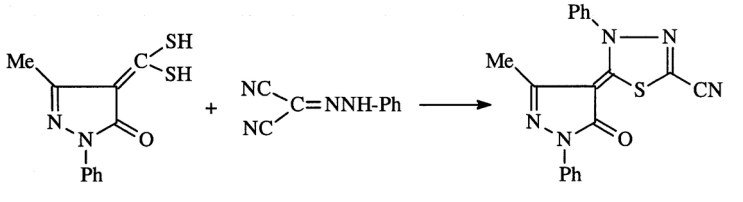
SCHEME 52

1,3-Dithienes can be obtained by reaction of the *gem*-dithiols mentioned above with cinnamaldehyde phenylimine [53].



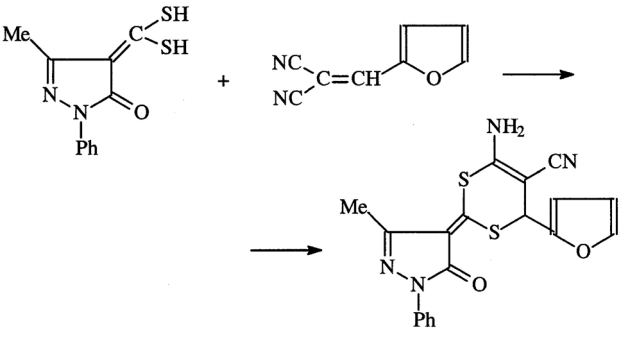
SCHEME 53

The reaction of 3-methyl-1-phenyl-4-dimercaptomethylene-pyrazolidene-5-one with phenylazomalononitrile in EtOH in the presence of a base results in 5-(3-methyl-5-oxo-1-phenyl-4-pyrazolidene)-2-cyano-4-phenyl-1,3,4-thiadiazole [43].



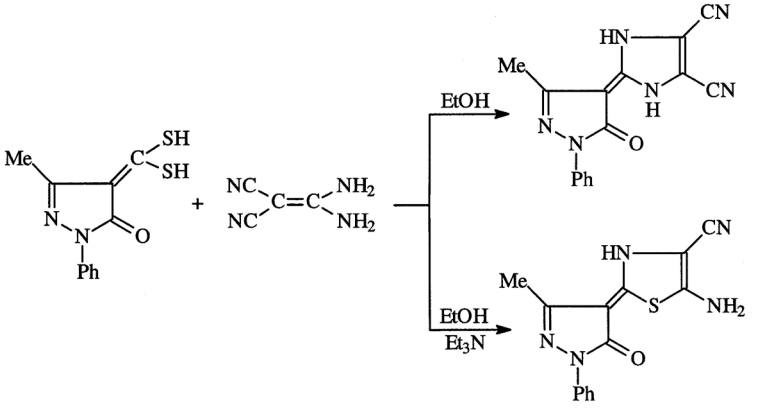
SCHEME 54

More recently it has been found that the reaction of 3-methyl-1-phenyl-4-dimercaptomethylene pyrazolidene-5-one with furfurylidenemalononitrile proceeds according to scheme 55 [43]. The formation of the final product is assumed to take place *via* Michael addition followed by addition of the second sulfhydryl to carbonitrile.



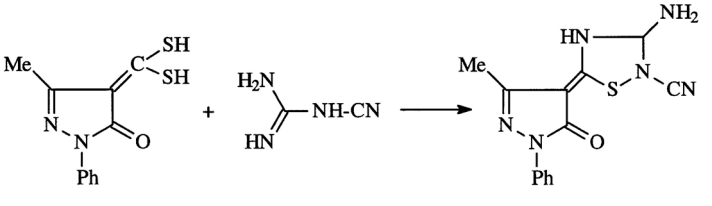
SCHEME 55

The reaction products of ketene *gem*-dithiol with diaminomalononitrile are 2-(3-methyl -5-oxo-1-phenyl-4-pyrazolidene)-4,5-dicyanoimidazole or 5-(3-methyl-5-oxo-1-phenyl-4-pyrazolidene)-2-amino-3-cyanothiazole, depending on the reaction conditions [43].



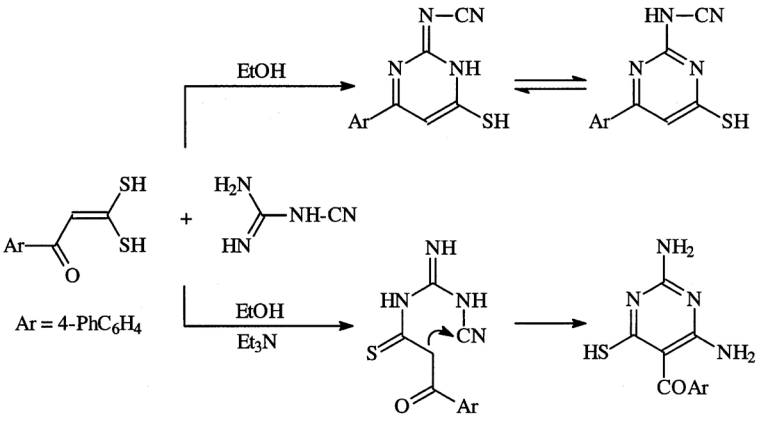
SCHEME 56

Finally, the reaction of 3-methyl-1-phenyl-4-dimercaptomethylene pyrazolidene-5-one with dicyanodiamide has opened up a new way to thiadiazole derivatives [43].



SCHEME 57

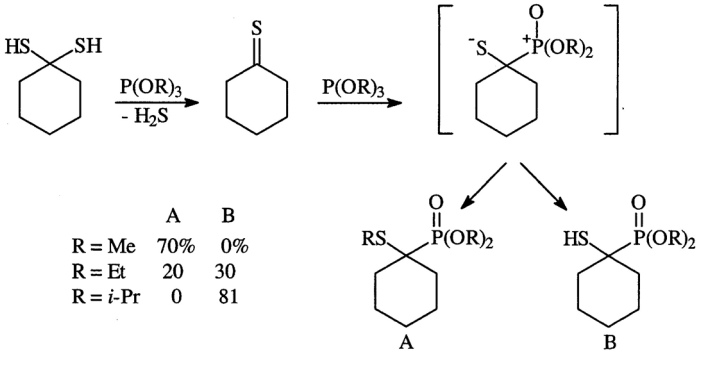
Treatment of equimolar quantities of α-oxoketene *gem*-dithiol and dicyanodiamide in boiling ethanol gave 2-cyanamino-4-mercapto-6-(4-biphenyl)pyrimidine, whereas the presence of triethylamine affords 2,4-diamino-5-(4-phenylbenzoyl)-6-mercaptopyrimidine [54].



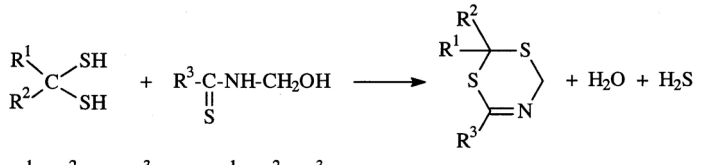
SCHEME 58

Reaction with trialkylphosphites. The reaction of cyclohexane-1,1-dithiol with trialkyl phosphites produces phosphonic acid ester derivatives A and B (scheme 59) [55]. These results are well accounted for by assuming a betaine intermediate. Firstly, the dithiol may be converted by trialkyl phosphite into thiocyclohexanone. Then the phosphite is thought to attack at the carbon atom of the thiocarbonyl group to afford the betaine intermediate. An alkyl group rearrangement in the intermediate yields the thioether-type product A, whereas a proton transfer from the alkyl group (R) produces the thiol-type product B.

Reaction with thioamides. In 1977 an original process for the preparation of a new class of heterocyclic compounds, *i.e.*, 1,3,5-dithiazine derivatives, was developed [56]. The method was based on the reaction of alkane-*gem*-dithiols with *N*-(hydroxymethyl)thioamides in ether at room temperature in the presence of the boron trifluoride etherate complex as a catalyst.

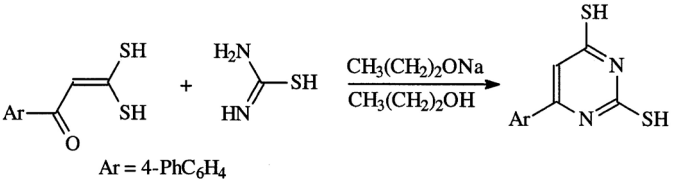


SCHEME 59



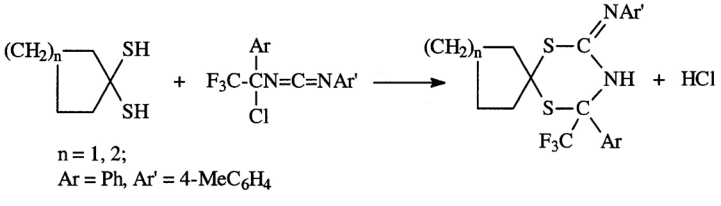
SCHEME 60

The reaction of α-oxoketene *gem*-dithiol with thiourea in the presence of $NaOC_3H_7$ gave 2,4-dimercapto-6-(4-biphenyl)pyrimidine [54].



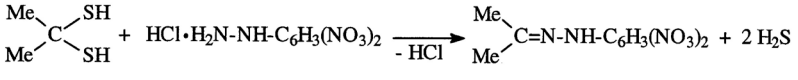
SCHEME 61

Reaction with carbodiimides. Cycloalkane-1,1-dithiols regioselectively react with 1-chloroalkylcarbodiimides in benzene in the presence of an organic base to form, in high yield, 4-imino-1,3,5-dithiazinane derivatives [57].



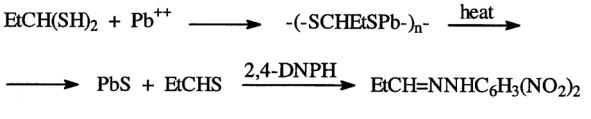
SCHEME 62

Reaction with 2,4-dinitrophenylhydrazine. Heating propane-2,2-dithiol with 2,4-dinitrophenylhydrazine hydrochloride in EtOH leads to the corresponding 2-(2,4-dinitrophenylhydrazo)propane in 37% yield [3].



SCHEME 63

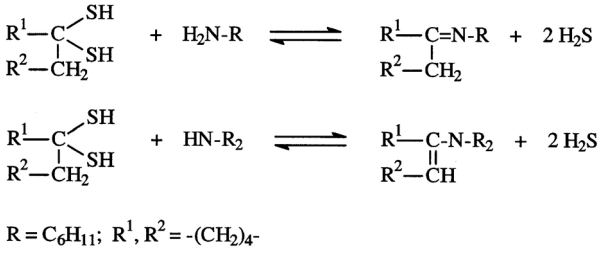
Under analogous conditions propane-1,1-dithiol fails to form dinitrophenylhydrazone [3]. However, it was obtained by the preliminary reaction of *gem*-dithiol with lead acetate.



SCHEME 64

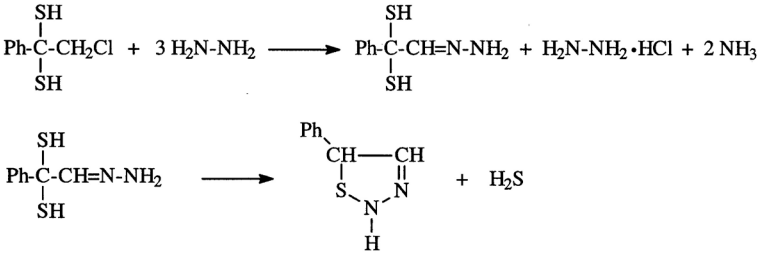
The authors suggested that the lead thiolate generated in this case was unstable and decomposed to form propanethial. As no intermediate lead derivative was isolated and analyzed, the above reported structure is considered unreliable. According to our data, *gem*-dithiols react with lead acetate to form cyclic four-membered lead dithiolates, 1,3-dithia-2-plumbocyclobutanes [46]. The reaction of analogous dithiolates with 2,4-dinitrophenylhydrazine and hydrogen chloride seems to be responsible for the formation of the corresponding hydrazones in Ref. [3].

Reaction with amines. The reaction of *gem*-dithiols with amines was first studied by Mayer in 1964 [58]. He found that with primary amines the corresponding ketimines were formed, whereas secondary amines gave enamines. These reactions are reversible processes as the forming ketimines and enamines react with hydrogen sulfide to generate the corresponding *gem*-dithiols.



SCHEME 65

The reaction of 1-chloro-2-phenylethane-2,2-dithiol with hydrazine proceeds in an unexpected manner [59]. The primary reaction product is represented by the corresponding hydrazone formed due to elimination of hydrogen chloride from the terminal $-CH_2Cl$ group and liberation of hydrazine hydrochloride and ammonia. While releasing hydrogen sulfide the above hydrazone further undergoes cyclization to 1,2-diazo-4-phenyl-5-thiacyclopent-2-ene.



SCHEME 66

Intermediate formation of hydrazone was fixed by IR spectroscopy. In this case the reaction mixture spectrum shows an absorption band at 1650 cm^{-1} corresponding to the C=N bond in the linear intermediate. The band disappears with time, with the concomitant growth of an absorption at 1630 cm^{-1}, which is attributable to the endocyclic C=N bond of the product.

5. Conclusion

We hope that this review devoted to the methods of synthesis, physical properties and chemical transformations of *gem*-dithiols will be of interest to the specialists involved in the chemistry of organic sulfur compounds and heterocyclic compounds. We anticipate that it will initiate further research into this field and extend the capabilities of *gem*-dithiols as reagents and synthons in organic synthesis.

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