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Alkylation of 5-Substituted Tetrazoles with Various Alcohols in 1,2-Dichloroethane in the Presence of $BF_3 \cdot Et_2O$

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Abstract—The alkylation of 1*H*-tetrazole, 5-methyl-1*H*-tetrazole, and 5-phenyl-1*H*-tetrazole with primary, secondary, and tertiary alcohols, including benzylic and allylic ones, have been studied in 1,2-dichloroethane in the presence of boron trifluoride–diethyl ether complex. Neither primary nor secondary saturated alcohols alkylated tetrazoles in the given system. Tertiary alcohols such *tert*-butyl alcohol and adamantan-1-ol reacted with unsubstituted and 5-substituted tetrazoles to give 70–85% of the corresponding 2-alkyl-5-R-tetrazoles with high regioselectivity. The alkylation of 1*H*-tetrazole with benzyl alcohol afforded 55% of 2-benzyl-2*H*-tetrazole as the only product. The alkylation of 1*H*-tetrazole with various allylic alcohols led to the formation of mixtures of 2-alkyl-2*H*-tetrazoles with isomeric alkyl substituents.

Keywords: tetrazole, boron trifuloride–diethyl ether complex, regioselective alkylation, alcohols

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Tetrazoles are important products of organic synthesis that are especially interesting due to their energetic and pharmacological properties originating from the high enthalpy of formation, high nitrogen content, and biological activity of tetrazole ring. In particular, tetrazole-containing compounds are used as primary [1, 2] and secondary explosives [3, 4], binders [5], and energy-rich additives [6] to gun powders and solid propellants.

Tetrazole-based pharmaceuticals exhibit antiviral [7], antifungal [8], antibacterial, and hypotensive activity [9, 10], and they can be used in the treatment of some skin diseases [11]. Some tetrazole derivatives were expected to display radioprotective and antitumor properties [12, 13]. Many other potential, as well as already confirmed, effects of various tetrazole compounds in the field of medicinal chemistry have been reported [14, 15].

In addition to the above listed application areas, tetrazoles are used to obtain ion-exchange membranes [16], coordination polymers [17], light-sensitive polymers [18], catalysts [19, 20], ionic liquids [21], corrosion inhibitors [22, 23], etc. On the basis of the aforesaid, we can conclude that extension of our knowledge of the tetrazole chemistry is an important problem.

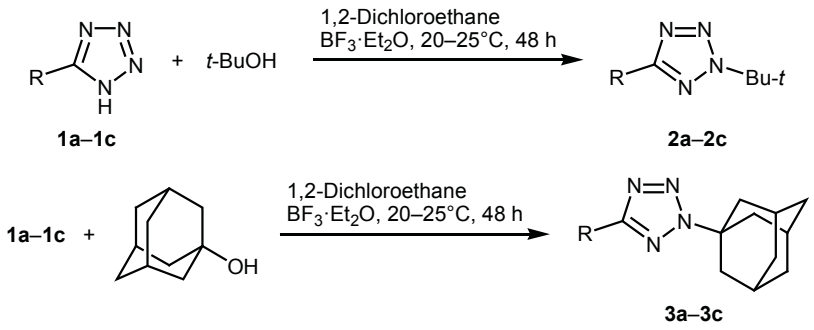
The alkylation of 5-R-tetrazoles with 3-chlorobut-2-en-1-ol in a mixture of $BF_3 \cdot Et_2O$ and 1,2-dichloroethane (DCE) was studied by us previously [24]. It was found that, as applied to the given alcohol, this system is considerably more efficient than protic acids such as phosphoric, trifluoroacetic, and sulfuric acids, which is achieved due to high acidity of the system in combination with softness of the acidic reagent.

We decided to continue study in this field with a view to extending the scope of application of the system DCE/$BF_3 \cdot Et_2O$, establishing general relations in the alkylation of tetrazoles with various alcohols, and elucidating the fact of the reaction of a primary alcohol, 3-chlorobut-2-en-1-ol, with tetrazoles.

The set of alcohols used in this study included primary, secondary, and tertiary alcohols, allylic alcohols, benzyl alcohol, and salicyl alcohol. Primary and secondary saturated alcohols, namely propan-1-ol, butan-1-ol, propan-2-ol, and butan-2-ol, failed to react with tetrazoles in DCE/$BF_3 \cdot Et_2O$ due to instability of carbocations derived therefrom.

Among saturated aliphatic alcohols, only *tert*-butyl alcohol and adamantan-1-ol reacted with tetrazoles **1a**–**1c** at room temperature to give the corresponding 2-substituted 2*H*-tetrazoles **2a**–**2c** and **3a**–**3c** in 70–80% yield (Scheme 1). No alkylation products were

Scheme 1.



R = H (**a**), Me (**b**), Ph (**c**).

obtained in the reactions of these alcohols with 5-aminotetrazole. A probable reason is that boron trifluoride reacts with the amino group, thus deactivating endocyclic nitrogen atoms. According the NMR data, the reaction mixtures contained no 1-alkyl isomers. The high reactivity of tertiary alcohols is related to the stability of tertiary carbocations.

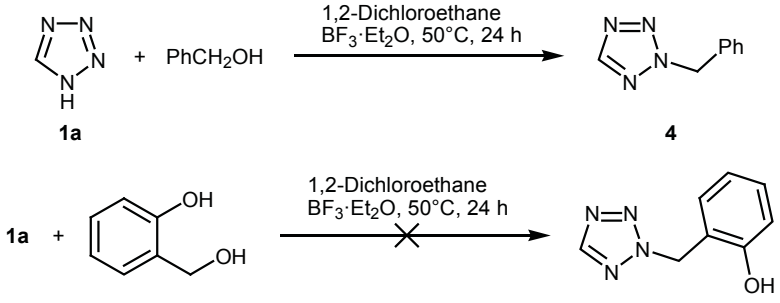
We also tried to alkylate unsubstituted 1*H*-tetrazole (**1a**) with benzyl and salicyl alcohols. Benzyl alcohol reacted with **1a** at 55°C (24 h) to give 46% of 2-benzyl-2*H*-tetrazole (**4**) (Scheme 2). When the reaction was carried out at room temperature, the yield of **4** reached 35% after 3 days. It should be noted that in the presence of protic acids benzyl alcohol either decomposed (sulfuric acid) or did not react with tetrazole (trifluoroacetic and phosphoric acids).

Unexpectedly, salicyl alcohol failed to react with 1*H*-tetrazole (**1a**) at room temperature or under reflux. After addition of salicyl alcohol to a solution of $BF_3 \cdot Et_2O$ in dichloroethane, a pink solid precipitated. Presumably, it is a complex of boron trifluoride with salicyl alcohol. No alkylation occurred when 1,2-dichloroethane was replaced by diethyl ether where the complex is soluble. Presumably, the phenolic hydroxy group deactivates the primary hydroxy group, thus preventing it from reacting with $BF_3 \cdot Et_2O$.

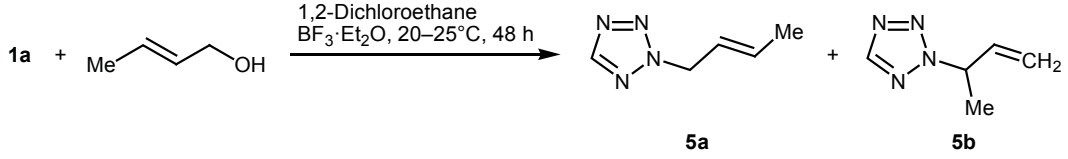
A large part of our study was concerned with allyl type alcohols. As we already noted, the alkylation of tetrazoles **1a**–**1c** with one representative of allylic alcohols, 3-chlorobut-2-en-1-ol, successfully afforded 75–85% of the corresponding 2,5-substituted tetrazoles with almost complete regioselectivity (>99%). Here, stabilization of intermediate carbocation due to conjugation with the double C=C bond seems obvious. Provided that this assumption is sufficient for a comprehensive explanation, any other allylic alcohols could be expected to react with tetrazoles in a similar way. However, this was not exactly the case. The series of examined allylic alcohols included proper allyl alcohol (prop-2-en-1-ol), but-2-ene-1,4-diol, 4-chlorobut-2-en-1-ol, 4-bromobut-2-en-1-ol, 2-chlorobut-2-ene-1,4-diol, 2-chloroprop-2-en-1-ol, and but-2-en-1-ol.

None of the alcohols listed above, except for but-2-en-1-ol (crotyl alcohol), reacted with 1*H*-tetrazole (**1a**) in DCE/$BF_3 \cdot Et_2O$ at room temperature. In some cases, raising the temperature resulted in the formation of traces of the target product which was contaminated with a large amount of impurities. Analysis of the structure of these alcohols in comparison to 3-chlorobut-2-en-1-ol showed that all unreacted alcohols lack a methyl group at the double bond. The only alcohol containing a methyl group at the double bond, but-2-

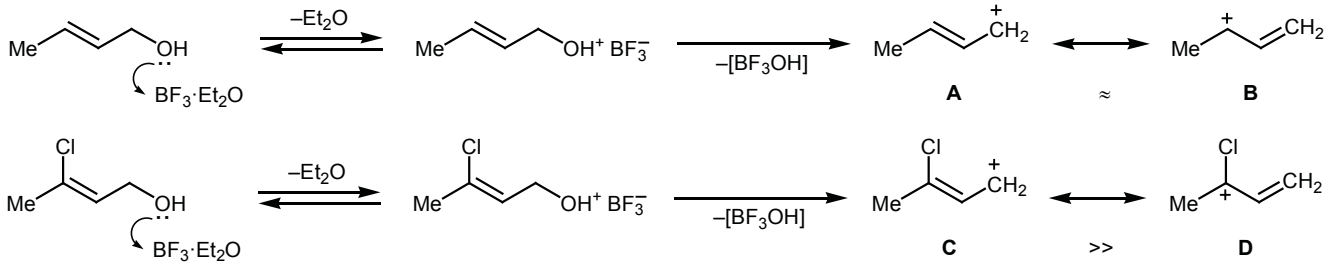
Scheme 2.



Scheme 3.



Scheme 4.



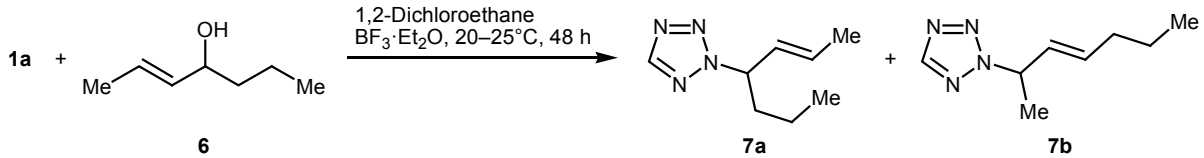
en-1-ol, reacted with 1*H*-tetrazole to give two isomeric 2-substituted 2*H*-tetrazoles **5a** and **5b** resulting from addition of the alcohol through C^1 and C^2, respectively, with double bond migration to the terminal position in the latter case (Scheme 3). Thus, we can speak about stabilizing effect of electron-donating methyl group at the double bond on the intermediate carbocation derived from the alcohol.

However, the alkylation of 1*H*-tetrazole with 3-chlorobut-2-en-1-ol afforded only one isomer, 2-(3-chloroprop-2-en-1-yl)-2*H*-tetrazole. Comparison of the results of alkylation of **1a** with 3-chlorobut-2-en-1-ol and but-2-en-1-ol led us to conclude that the presence of a chlorine atom at the double bond (in the γ-position with respect to the OH group) prevents addition of tetrazole to the γ-carbon atom. In the case of but-2-en-1-ol having no chlorine, two isomers are formed at a ratio close to equimolar.

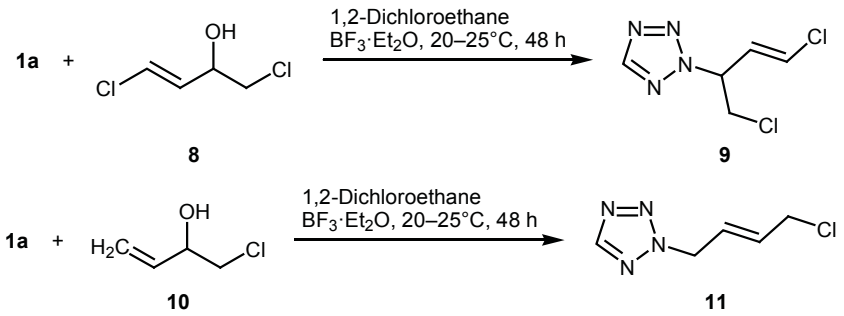
These findings can be rationalized as follows (Scheme 4). Carbocation generated from but-2-en-1-ol by the action of $BF_3 \cdot Et_2O$ may be represented as a resonance hybrid of two canonical structures **A** and **B** with approximately equal contributions. In the case of 3-chlorobut-2-en-1-ol, the contribution of canonical structure **D** to the resonance hybrid is significantly reduced due to the presence of chlorine atom at the cationic center, so that the attack on tetrazole nitrogen atom involves mainly carbocation **C** with the positive charge localized on the terminal carbon atom.

We then focused on the behavior of secondary allylic alcohols in order to find out whether they would give rise to a mixture of isomeric alkylation products as in the reaction with but-2-en-1-ol or only one isomer as in the reaction with 3-chlorobut-2-en-1-ol, depending on the presence or absence of chlorine at the double bond. Hept-2-en-4-ol (**6**) was selected as an example of chlorine-free secondary allylic alcohols. The reaction of 1*H*-tetrazole (**1a**) with alcohol **6**, as with but-2-en-ol, afforded a mixture of isomeric 2-substituted tetrazoles **7a** and **7b** at a ratio close to 1:1 with an overall yield of 41% (Scheme 5). As chlorine-containing alcohols we used 1,4-dichlorobut-3-en-2-ol (**8**) and 1-chlorobut-3-en-2-ol (**9**) (Scheme 6). In the reaction with alcohol **8** containing a chlorine atom at the double bond, tetrazole fragment added to the carbon atom formerly bearing the hydroxy group to give 2-(1,4-dichlorobut-3-en-2-yl)-2*H*-tetrazole (**9**). The alkylation of **1a** with alcohol **10** in which the chlorine atom is remote from the double bond lead to the formation of tetrazole addition product to the terminal position (compound **11**) and only traces of the product of direct substitution of the hydroxy group by tetrazole fragment. This may be due to repulsive effect of the terminal chlorine atom in **10**.

Scheme 5.



Scheme 6.



In summary, we have extended the knowledge of acid-catalyzed alkylation of tetrazoles with various alcohols and the scope of application of the system boron trifluoride–diethyl ether complex/1,2-dichloroethane for regioselective alkylation of tetrazoles. This system provides efficient and regioselective alkylation of 5-R-tetrazoles with tertiary alcohols. The alkylation of unsubstituted tetrazole with benzyl alcohol in up to 50% yield cannot be regarded as an excellent result, but it can be used in practice. Primary allylic alcohols containing a methyl group at the double bond, as well as secondary allylic alcohols, effectively alkylate 1*H*-tetrazole to give one 2-substituted 2*H*-tetrazole derivative if the alcohol contains a chlorine atom at the double bond or two 2-substituted 2*H*-tetrazole isomers in comparable amounts when the alcohol contains no chlorine atom; this is related to electron-withdrawing effect of the chlorine atom.

EXPERIMENTAL

The ^{1}H and ^{13}C NMR spectra were recorded on a Bruker Avance 400 spectrometer (Germany) at 400 and 100 MHz, respectively. The IR spectra were recorded on a Shimadzu IR Tracer-100 spectrometer (Japan) equipped with an ATR accessory. The progress of reactions was monitored by TLC on Sorbfil PTSKh-P-A-UF plates. Silica gel L (100–400 μm) was used for column chromatography. The elemental analyses were obtained with a LECO-932 CHNS analizer (UK).

General procedure for the alkylation of tetrazoles with alcohols in 1,2-dichloroethane in the presence of boron trifluoride–diethyl ether complex. Boron trifluoride–diethyl ether complex, 1 g, was dissolved in 2 mL of 1,2-dichloroethane, and 1.4 mmol of 5-R-tetrazole was added. When the mixture became homogeneous, the solution was added to 1.6 mmol of the corresponding alcohol at 20–25°C, and the mixture was stirred at 20–25°C for 48 h. The product was extracted with methylene chloride (3 × 5 mL), each time with vigorous stirring over a period of 5 min. The combined extracts were washed with a 2% aqueous solution of sodium carbonate and with water, dried over anhydrous sodium sulfate, and evaporated on a rotary evaportator. The residue was purified by column chromatography or recrystallization from ethanol.

2-(*tert*-Butyl)-2*H*-tetrazole (2a). The product was purified by column chromatography using *n*-hexane–ethyl acetate (80:20) as eluent. Yield 0.127 g (72%), colorless oily liquid. IR spectrum, ν, cm^{-1}: 2970, 2932, 2884, 1464, 1375, 1310, 1290, 1202, 1161, 1161, 1130, 1099, 1024, 951, 818, 702, 590. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm: 1.72 s (9H), 8.44 s (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 29.3, 63.9, 152.3. Found, %: C 47.64; H 7.91; N 44.45. $C_5H_{10}N_4$. Calculated, %: C 47.60; H 7.99; N 44.41.

2-(*tert*-Butyl)-5-methyl-2*H*-tetrazole (2b). The product was purified by column chromatography using *n*-hexane–ethyl acetate (80:20) as eluent. Yield 0.137 g (70%), colorless oily liquid. IR spectrum, ν, cm^{-1}: 2986, 2939, 2878, 1502, 1477, 1462, 1404, 1371, 1362, 1313, 1279, 1236, 1194, 1175, 1074, 1028, 985, 935, 825, 714, 577, 500, 465. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm: 1.72 s (9H), 2.52 s (3H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 10.9, 29.3, 63.3, 162.2. Found, %: C 51.43; H 8.58; N 39.99. $C_6H_{12}N_4$. Calculated %: C 51.41; H 8.63; N 39.97.

2-(*tert*-Butyl)-5-phenyl-2*H*-tetrazol (2c). The product was purified by column chromatography using *n*-hexane–ethyl acetate (80:20) as eluent. Yield 0.209 g (74%), colorless oily liquid IR spectrum, ν, cm^{-1}: 2954, 2112. 1531, 1450, 1369, 1315, 1267, 1236, 1201, 1072, 1026, 1006, 924, 823, 789, 733. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm: 1.79 s (9H), 7.44–7.50 m (3H), 8.17–8.19 m (2H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 29.4, 63.8, 126.8, 127.9, 128.8, 130.0, 164.3.

Found, %: C 65.41; H 6.86; N 27.73. $C_{11}H_{14}N_4$. Calculated, %: C 65.32; H 6.98; N 27.70.

2-(Adamantan-1-yl)-2*H*-tetrazole (3a). The product was recrystallized from ethanol. Yield 0.243 g (85%), white crystalline powder. IR spectrum, ν, cm^{-1}: 2905, 2851, 1456, 1352, 1346, 1304, 1254, 1205, 1115, 1078, 1055, 1033, 1022, 981, 927, 841, 816, 770, 694, 656, 551, 521, 466, 428. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 1.81 m (6H), 2.29 m (3H), 2.34 m (6H), 8.48 s (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 29.4, 35.8, 42.2, 64.0, 152.1. Found, %: C 64.70; H 7.92; N 27.38. $C_{11}H_{16}N_4$. Calculated, %: C 64.68; H 7.90; N 27.43.

2-(Adamantan-1-yl)-5-methyl-2*H*-tetrazole (3b). The product was recrystallized from ethanol. Yield 0.244 g (80%), white crystalline powder. IR spectrum, ν, cm^{-1}: 2916, 2850, 1499, 1452, 1356, 1315, 1188, 1167, 1103, 1088, 1053, 1022, 983, 970, 937, 847, 816, 771, 712, 669, 472. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 1.38 m (6H), 1.84 m (3H), 1.88 m (6H), 2.07 s (3H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 10.4, 29.0, 35.5, 41.8, 62.6, 161.2. Found, %: C 66.12; H 8.25; N 25.63. $C_{12}H_{18}N_4$. Calculated, %: C 66.02; H 8.31; N 25.67.

2-(Adamantan-1-yl)-5-phenyl-2*H*-tetrazole (3c). The product was recrystallized from ethanol. Yield 0.314 g (80%), white crystalline powder. IR spectrum, ν, cm^{-1}: 2912, 2853, 1528, 1463, 1447, 1358, 1346, 1306, 1186, 1168, 1107, 1049, 1030, 926, 843, 816, 789, 770, 729, 702, 692, 596, 525, 507, 474. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 1.77 m (6H), 2.25 m (3H), 2.36 m (6H), 7.41–7.44 m (3H), 8.13–8.15 m (2H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 34.0, 40.5, 46.9, 68.5, 158.8. Found, %: C 72.84; H 7.26; N 19.90. $C_{17}H_{20}N_4$. Calculated, %: C 72.83; H 7.19; N 19.98.

2-Benzyl-2*H*-tetrazole (4). The reaction mixture was heated at 55°C for 24 h, and the product was purified by column chromatography using *n*-hexane–ethyl acetate (80:20). Yield 0.103 g (46%), light yellow oily liquid. IR spectrum, ν, cm^{-1}: 2918, 2850, 2361, 1602, 1494, 1454, 1340, 1281, 1124, 1074, 1026, 881, 825, 694. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 5.79 s (2H), 7.39 s (5H), 8.52 s (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 56.7, 128.5, 129.1, 153.3. Found, %: C 60.06; H 5.08; N 34.86. $C_8H_8N_4$. Calculated, %: C 59.99; H 5.03; N 34.98.

2-(But-2-en-1-yl)-2*H*-tetrazole (5a) and 2-(but-3-en-2-yl)-2*H*-tetrazole (5b). The isomers were separated by column chromatography using *n*-hexane–butan-1-ol (95:5) as eluent. Overall yield 0.122 g (70%), ratio **5a**:**5b** 1.2:1, light yellow oily liquid.

2-(But-2-en-1-yl)-2*H*-tetrazole (5a). IR spectrum, ν, cm^{-1}: 3136, 2961, 2934, 2874, 1676, 1450, 1379, 1340, 1283, 1188, 1134, 1097, 1026, 1007, 966, 881, 793, 706, 683. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 1.72–1.73 m (3H), 5.15 d (2H, J = 6.8 Hz), 5.66–5.74 m (1H), 5.84–5.93 m (1H), 8.48 s (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 19.9, 54.9, 118.2, 133.3, 152.7. Found, %: C 48.50; H 6.51; N 44.99. $C_5H_8N_4$. Calculated, %: C 48.37; H 6.50; N 45.13.

2-(But-3-en-2-yl)-2*H*-tetrazole (5b). IR spectrum, ν, cm^{-1}: 3132, 2960, 2934, 2877, 1675, 1460, 1385, 1341, 1279, 1190, 1134, 1099, 1021, 1013, 969, 881, 793, 710, 686. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 1.75 d (3H, J = 10.0 Hz), 5.22–5.29 m (2H), 6.05–6.14 m (1H), 5.51 quint (1H, J = 6.7 Hz), 8.49 s (1H). ^{13}C NMR spectrum (100 MHz), δ_C, ppm: 17.7, 62.1, 122.6, 136.6, 152.9. Found, %: C 48.42; H 6.53; N 45.05. $C_5H_8N_4$. Calculated, %: C 48.37; H 6.50; N 45.13.

Hept-2-en-4-ol (6). A 250-mL three-necked flask was charged with 5.0 g (0.206 mol) of magnesium and a crystal of iodine. The flask was heated until violet iodine vapor appeared and cooled to room temperature, 100 mL of anhydrous diethyl ether was added, and about 2 g (0.016 mol) of 1-bromopropane was added dropwise with stirring. The mixture was carefully heated on a water bath to initiate a reaction (diethyl ether characteristically boiled up), and 24.3 g (0.198 mol) of 1-bromopropane was added dropwise. The mixture was then cooled to 0–5°C, 10 g (0.143 mol) of crotonaldehyde was added dropwise with stirring, maintaining the temperature at 0–5°C, and the mixture was stirred for 10 min at that temperature, poured into a mixture of 100 g of ice and 15 g of ammonium chloride, and extracted with chloroform (3×50 mL). The combined extracts were washed with water and dried over anhydrous sodium sulfate, the solvent was distilled off, and the residue was distilled. Yield 14.0 g (86%), colorless liquid. IR spectrum, ν, cm^{-1}: 3345, 2959, 2934, 2874, 1674, 1452, 1441, 1377, 1309, 1217, 1177, 1143, 1121, 1067, 1011, 964, 903, 847, 745, 507. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 0.81 t (3H), 1.27 m (2H), 1.43 m (2H), 1.59 m (3H), 3.90 m (1H), 5.33–5.54 m (2H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 13.8, 17.5, 18.6, 39.3, 72.5, 125.9, 134.5. Found, %: C 73.73; H 12.17. $C_7H_{14}O$. Calculated, %: C 73.63; H 12.36.

2-(Hept-2-en-4-yl)-2*H*-tetrazole (7a) and 2-(hept-3-en-2-yl)-2*H*-tetrazole (7b) were synthesized

according to the general procedure. The products were separated by column chromatography using *n*-hexane–butan-1-ol (90:10) as eluent. Overall yield 0.122 g (41%), ratio **7a**: **7b** 1.2:1, light yellow oily liquid.

2-(Hept-2-en-4-yl)-2*H*-tetrazole (7a). IR spectrum, ν, cm^{-1}: 3128, 2961, 2932, 2874, 1647, 1558, 1541, 1466, 1458, 1423, 1379, 1340, 1307, 1256, 1163, 1097, 1017, 966, 870, 679, 669, 660. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 0.87 m (3H), 1.39 m (2H), 1.71 m (3H), 2.10 m (2H), 5.03 q (1H, J = 22.5, 7.5 Hz), 5.69–5.60 m (1H), 5.75–5.84 m (1H), 8.60 s (1H). ^{13}C NMR spectrum (100 MHz, $CDCl_3$), δ, ppm: 13.5, 17.7, 21.8, 34.0, 62.1, 127.3, 131.9, 141.4. Found, %: C 57.88; H 8.53; N 33.59. $C_8H_{14}N_4$. Calculated, %: C 57.80; H 8.49; N 33.71.

2-(Hept-3-en-2-yl)-2*H*-tetrazole (7b). IR spectrum, ν, cm^{-1}: 3131, 2957, 2931, 2872, 1647, 1558, 1530, 1468, 1455, 1423, 1379, 1340, 1307, 1256, 1163, 1065, 1022, 966, 870, 681. ^1H NMR spectrum (400 MHz, $CDCl_3$), δ, ppm: 0.90 m (3H), 1.66 m (3H), 1.46 m (2H), 2.04 m (2H), 5.18 quint (1H, J = 6.5 Hz), 5.58–5.64 m (1H), 5.72–5.79 m (1H), 8.64 s (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 13.4, 18.9, 20.9, 36.9, 57.6, 127.6, 136.3, 141.1. Found, %: C 57.89; H 8.54; N 33.57. $C_8H_{14}N_4$. Calculated, %: C 57.80; H 8.49; N 33.71.

1,4-Dichlorobut-3-en-2-ol (8). Chloroacetyl chloride and 1,4-dichlorobut-3-en-2-one were synthesized preliminarily. Dimethylformamide, 8 g, was added with stirring at room temperature to 95 g (0.798 mol) of thionyl chloride, 50 g (0.575 mol) of chloroacetic acid was added with stirring at room temperature, and the mixture was kept for 24 h at room temperature. The product was isolated by vacuum distillation, a fraction boiling at 50–55°C (10 mm Hg) being collected. Yield 42 g (70%), colorless or light yellow liquid. ^1H NMR spectrum ($CDCl_3$): δ 4.54 ppm, s. ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 48.7, 167.5.

A 100-mL three-necked flask was charged with 30 mL of methylene chloride, 5 g (0.044 mol) of chloroacetyl chloride, and 6.2 g (0.047 mol) of anhydrous aluminum chloride. The mixture was cooled to –8°C, and acetylene was passed through the mixture over a period of 2 h (flow rate 0.1 L/min) at a temperature not exceeding 0°C The mixture was poured into 20 mL of an ice–water mixture and extracted with chloroform (3×10 mL). The combined extracts were washed with a 2% aqueous solution of sodium carbonate and with water, dried over anhydrous sodium sulfate for 4 h, and evaporated. Yield of 1,4-dichlorobut-3-en-2-one 4.0 g (64%), the product (black liquid) was used without further purification. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 4.17 s (2H), 6.70–6.74 m (1H), 7.40–7.43 m (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 47.3, 128.4, 139.4, 188.8.

A 100-mL three-necked flask was charged with 25 mL of etanol, 25 mL of water, and 5 g (0.036 mol) of 1,4-dichlorobut-3-en-2-one. The solution was cooled to 0°C in an ice–salt bath, and 0.8 g (0.021 mol) of sodium tetrahydridoborate was added in small portions with stirring, maintaining the temperature below 2°C. The mixture was then stirred at 0–5°C for 10 min and extracted with methylene chloride (2×20 mL), the combined extracts were washed with water and dried over anhydrous sodium sulfate, the solvent was distilled off, and the residue was distilled under reduced pressure using a water-jet pump. Yield of **8** 3.6 g (72%). IR spectrum, ν, cm^{-1}: 3366, 2959, 1640, 1626, 1429, 1286, 1256, 1192, 1084, 1051, 933, 887, 812, 736, 615, 517, 474. ^1H NMR spectrum ($CDCl_3$), δ, ppm: 3.18 s (OH), 3.49–3.63 m (2H), 4.36–4.40 q (1H, J = 4.7, 16.8 Hz), 5.94–5.99 m (1H), 6.37 d.d (1H, J = 12.4, 14.3 Hz). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 48.8, 70.6, 122.5, 131.6. Found, %: C 34.16; H 4.20; Cl 50.18. Calculated, %: C 34.08; H 4.29; Cl 50.29.

2-(1,4-Dichlorobut-3-en-2-yl)-2*H*-tetrazole (9) was synthesized according to the general procedure. The product was purified by column chromatography using *n*-hexane–ethyl acetate (80:20) as eluent. Yield 0.092 g (34%), light yellow oily liquid. IR spectrum, ν, cm^{-1}: 2959, 2920, 2850, 1738, 1628, 1429, 1285, 1242, 1091, 1053, 1026, 935, 743, 669, 609, 527, 476. ^1H NMR spectrum (400 MHz, $CDCl_3$), δ, ppm: 3.98–4.16 s (2H), 6.25–6.31 m (1H), 6.51 d (1H, J = 13.3 Hz), 5.67–5.72 m (1H), 8.59 s (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 44.3, 65.1, 126.3, 126.8, 153.2. Found, %: C 31.15; H 3.16; Cl 36.69; N 29.00. $C_5H_6Cl_2N_4$. Calculated, %: C 31.11; H 3.13; Cl 36.73; N 29.03.

1-Chlorobut-3-en-2-ol (10). A 250-mL three-necked flask was charged with 100 mL of water and 30 mL of glacial acetic acid, and the mixture was cooled to 0°C. Methylene chloride, 30 mL, was cooled to at least 0°C in a separate beaker, 10 g (0.185 mol) of freshly distilled buta-1,3-diene was added, and the resulting solution of buta-1,3-diene in methylene chloride was added to the flask containing aqueous acetic acid. *tert*-Butyl hypochlorite, 10 g (0.092 mol), was then added dropwise with vigorous stirring at

0–3°C over a period of 45 min, and the mixture was vigorously stirred for 1 h at a temperature not exceeding 5°C. The mixture was neutralized with potassium carbonate and filtered, the organic phase was separated, and the aqueous phase was extracted with chloroform (2×20 mL). The extracts were combined with the organic phase, washed with 20 mL of water, dried over anhydrous sodium sulfate, and evaporated on a rotary evaporator, and the residue was distilled under reduced pressure using a water-jet pump. Yield 3.1 g (32%). ^{1}H NMR spectrum ($CDCl_3$), δ, ppm: 3.43–3.59 m (2H), 4.36 m (1H), 5.26–5.42 d.d (2H, J = 10.4, 17.0 Hz), 5.83–5.91 m (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 49.1, 72.3, 117.3, 136.6.

2-(4-Chlorobut-2-en-2-yl)-2*H*-tetrazole (11). The product was purified by column chromatography using *n*-hexane–ethyl acetate (90:10 to 80:20) as eluent. Yield 0.067 g (30%), light yellow oily liquid. IR spectrum, ν, cm^{-1}: 3143, 2956, 2868, 2127, 1440, 1350, 1282, 1251, 1192, 1128, 1080, 1026, 1006, 968, 883, 742, 707, 682, 574. ^{1}H NMR spectrum ($CDCl_3$), δ, ppm: 4.06 m (2H), 5.27 m (2H), 6.25–6.31 m (2H), 8.53 s (1H). ^{13}C NMR spectrum ($CDCl_3$), δ_C, ppm: 43.2, 53.8, 125.4, 132.4, 153.0. Found, %: C 37.95; H 4.47; Cl 22.30; N 35.28. $C_5H_7ClN_4$. Calculated, %: C 37.87; H 4.45; Cl 22.35; N 35.33.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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