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Synthesis of Phenolic Antioxidants with Isobornyl and *tert*-Butyl Fragments

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Abstract—Hybrid antioxidants, phenols with a terpene and *tert*-butyl substituents, were synthesized by the alkylation of 2-*tert*-butyl-4-methylphenol with camphene and 2-isobornylphenol with *tert*-butyl chloride in the presence of acidic heterogeneous catalysts, montmorillonite KSF and FIBAN K-1. Antioxidant activity of the synthesized terpenophenols was evaluated using spectrophotometry.

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Terpenophenols exhibit a number of practically useful properties [1–3]. By their antioxidant activity, 2,6-diisobornyl-4-methylphenol exceeds the widely used in industry ionol-, 2,6-di-*tert*-butyl-4-methylphenol [4]. We have previously shown that ionol and 2,6-diisobornyl-4-methylphenol correspond to compounds with different type of mechanism of antiradical activity, which may be defined by the structure of substituents in the aromatic ring [5]. In order to identify the role of terpene fragment in the antioxidant activity, it was of interest to synthesize a phenol containing in its structure isobornyl and *tert*-butyl fragments. For the synthesis of this compound we used several approaches: alkylation of 2-*tert*-butyl-4-methylphenol, 2-*tert*-butylphenol and 2,6-di-*tert*-butylphenol with camphene, and alkylation of 2-isobornylphenol and 2-isobornyl-4-methylphenol with either *tert*-butyl alcohol, methyl *tert*-butyl ether, or *tert*-butyl chloride. As the catalysts heterogenous (KSF, FIBAN K-1) and homogeneous [$(PhO)_3Al$, $(i\text{-}PrO)_3Al$] ones were studied. The optimal reaction conditions were selected by varying temperature and the reactant ratio.

The direct alkylation of 2-*tert*-butylphenol (**I**) with camphene (**III**) in the presence of $(PhO)_3Al$ or $(i\text{-}PrO)_3Al$ failed. We attempted to perform transalkylation of 2,6-di-*tert*-butylphenol (**II**) with camphene (**III**) in the

Scheme 1.

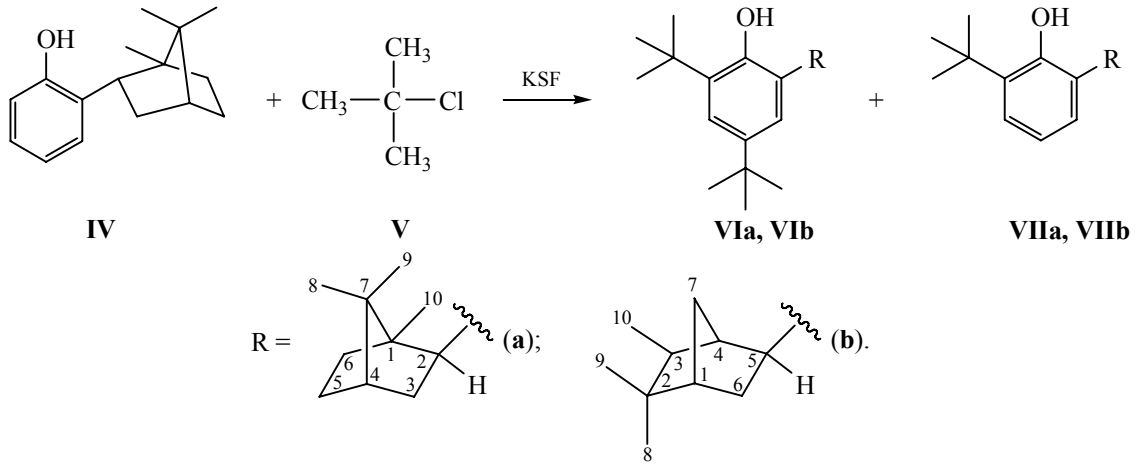


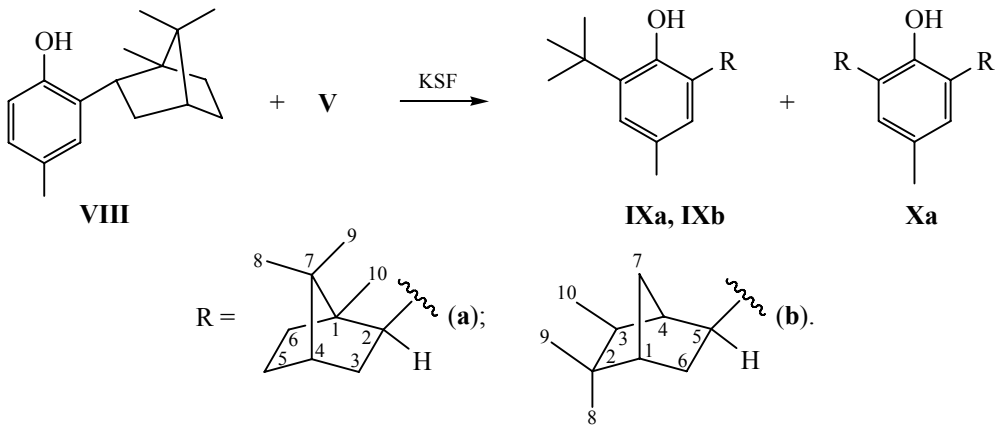
Table 1. *tert*-Butylphenol alkylation with camphene **III**: conditions and products

Initial phenol	Catalyst	Reaction conditions	Ratio of reaction products, %		
			ortho-	*ortho-,ortho-*	*ortho-, para*
2-*tert*-Butylphenol (**I**)	$(PhO)_3Al$	160°C, 32 h	13	74	13
	$(i\text{-}PrO)_3Al$	180–200°C, 46 h	5	57	38
2,6-Di-*tert*-butylphenol (**II**)	$(i\text{-}PrO)_3Al$	180–200°C, 26 h	–	–	–
	KSF	100°C, 40 h	43	–	57

presence of the same organoaluminum catalysts at 160°C and 180–200°C, as well as with acidic heterogeneous catalyst montmorillonite KSF in boiling heptane. The performed reactions resulted in the formation of a mixture of *ortho-/para-t*-Bu phenols. Under these conditions, *tert*-butyl fragment is easily detached from the original phenol and then, being more stable carbocation than the secondary carbocation based on the camphene, it alkylates phenol at *ortho-* or *para*-position affording a mixture of substituted phenols (Table 1).

The next approach was to introduce *tert*-butyl fragment in the molecule of 2-isobornylphenol **IV** in the reaction with either methyl *tert*-butyl ether, or *tert*-butyl alcohol, or *tert*-butyl chloride **V** (Scheme 1). The reactions with methyl-*tert*-butyl ether and *tert*-butyl alcohol were attempted in the presence of an organoaluminum catalyst, $(PhO)_3Al$ or $(i\text{-}PrO)_3Al$, at 180–200°C, as well as of KSF clay in boiling methyl *tert*-butyl ether or *tert*-butyl alcohol. According to GLC analysis, the reaction failed under all these conditions.

Scheme 2.

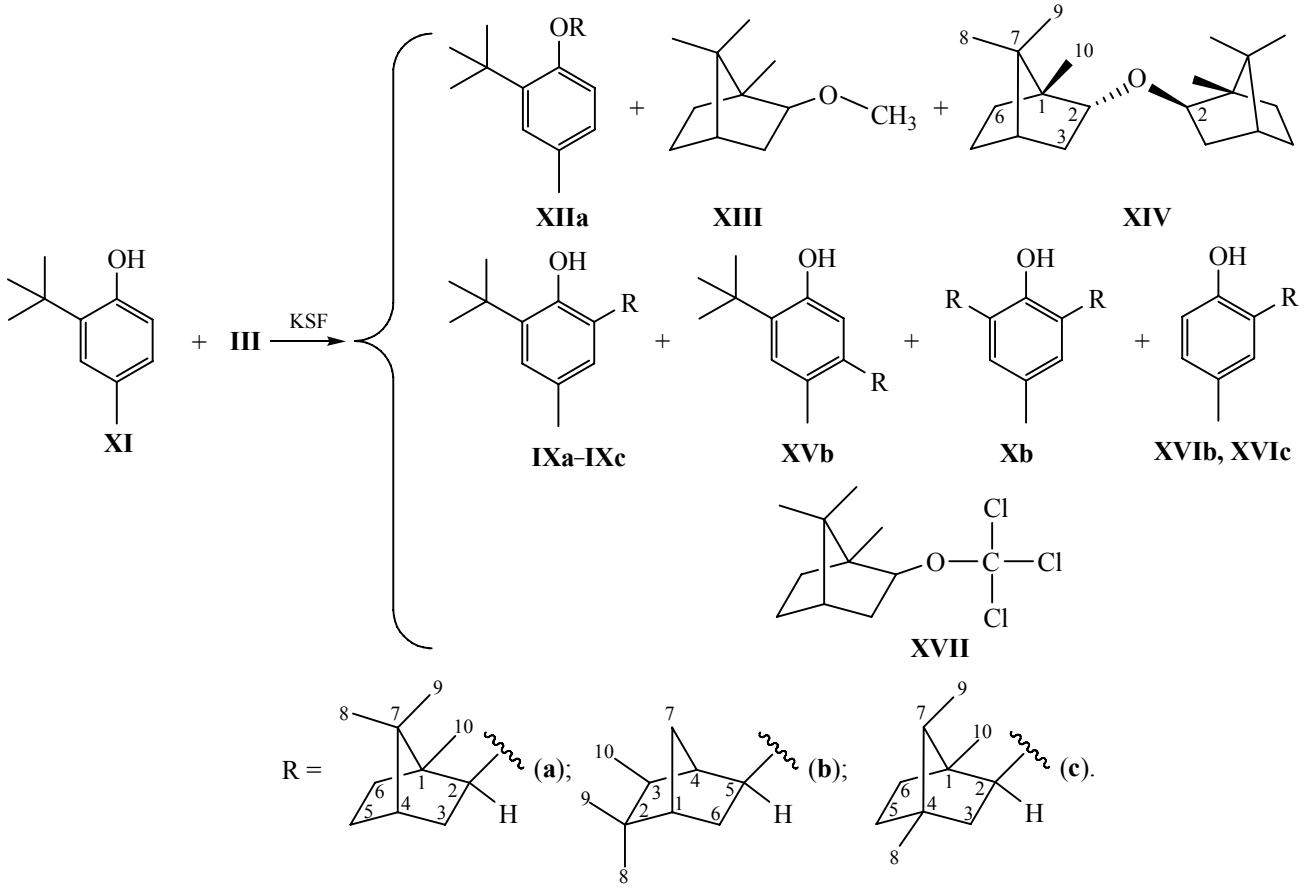


Reaction of 2-isobornylphenol **IV** with *tert*-butyl chloride **V** was performed in the presence of montmorillonite KSF in boiling CH_2Cl_2 (the ratio of **IV**:**V** = 1:1) or in boiling *tert*-butyl chloride. Boiling in CH_2Cl_2 promotes the formation of disubstituted phenols **VIIa** and **VIIb** with a total yield 59%, mainly a terpenephenol with isobornyl substituent (**VIIa**), yield 48%. The yield of trisubstituted phenol **VIa** was 32%. As by-products, we isolated phenols **I** and **II** (2% and 7% respectively). Boiling in *tert*-butyl chloride of phenol **IV** resulted in the selective formation of 2-isobornyl-4,6-di-*tert*-butyl-phenol **VIa** in 96% yield, and 2-isocamphyl-4,6-di-*tert*-butylphenol (**VIb**) was isolated in 4% yield. It should be noted that in these conditions isomerization of the isobornyl fragment (**a**) occurs to isocamphyl (**b**), with the formation of phenols **VIb** and **VIIb** due to the presence of HCl in the reaction mixture.

The alkylation of 2-isobornyl-4-methylphenol **VIII** with *tert*-butyl chloride **V** in the presence of montmorillonite KSF (Sceme 2) proceeds selectively

with the predominant formation of 2-isobornyl-4-methyl-6-*tert*-butylphenol **IXa** (74%), phenol (**IXb**) with isocamphyl structure of the terpene substituent (11%) also was isolated. The yield of disubstituted phenol **Xa** with isobornyl structure of the terpene substituent was 15%.

Scheme 3.



Alkylation of 2-*tert*-butyl-4-methylphenol **XI** with camphene **III** in the presence of heterogeneous catalysts also contributes to the formation of hybrid phenol (Scheme 3). As the source the phenol was used substituted in the *para*-position, to prevent the isomerization of 2-*tert*-butylphenol in 4-*tert*-butylphenol.

Scheme 4.

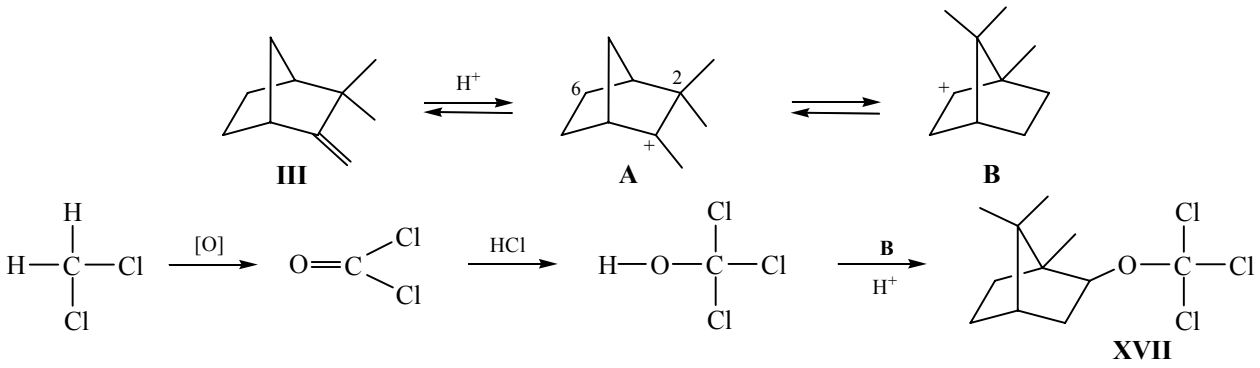


Table 2. 2-*tert*-Butyl-4-methylphenol alkylation with camphene **III**: conditions and products

Molar ratio **XI**:**III**	Reaction conditions	Conversion, %	Ratio of reaction products, %											
			IX			**X**	**XIIa**	**XIII**	**XIV**	**XVb**	**XVI**		**XVII**	Mixture[a]
			a	**b**	**c**						**b**	**c**		
FIBAN K-1														
1:1	10 h, CH_2Cl_2, boiling	40	8	18	–	–	–	10	26	–	–	–	38	–
	6 h, C_7H_{16}, boiling	81	9	30	19	–	–	–	–	2	7	5	–	28
Montmorillonite KSF														
1:1	10 h, CH_2Cl_2, boiling	72	50	9	2	–	13	–	–	1	–	–	6	19
	4.5 h, C_6H_{14}, boiling	85	30	50	–	–	7	–	–	7	–	–	–	6
	2 h, C_7H_{16}, boiling	84	24	43	–	9	–	–	–	7	7	–	–	10
1:2	4.5 h, CH_2Cl_2, boiling	71	20	15	9	–	8	11	34	–	–	–	3	–
2:1	4.5 h, CH_2Cl_2, boiling	98	31	19	–	–	16	–	25	–	–	–	9	–

[a] Complex mixture of products of alkylation and oxidation.

The results listed in Table 2 show that regardless of the catalyst (montmorillonite KSF, FIBAN K-1) a mixture of the products of O- and C-alkylation is formed. However, based on the conversion and the amount of target products **IXa–IXc**, we conclude that the optimal procedure consists in the use of the montmorillonite KSF: at boiling in CH_2Cl_2 and equimolar ratio of the initial reactants the products **XIIa–XIIc** are formed with a total yield 61%, at 70°C, 80%, and at 100°C, 67%.

We found that in the presence of sulfonic acid cation exchanger FIBAN K-1 (boiling in CH_2Cl_2) trichloromethoxy derivative **XVII** is formed in a significant amount (38%), which has not previously been observed in the alkylation of other phenols in similar conditions [6]. The formation of product **XVII** can be represented by Scheme 4.

The nature of the oxidant is currently unknown. Under the same conditions products **XIII** and **XIV** were obtained.

The reaction in heptane (100°C) using a sulfonic acid cation exchanger resulted in the conversion increase up to 81% and the overall yield of monoalkyl phenols **IXa–IXc**, mainly **IXb** (30%), to 58%. However, in this case up to 28% of the oxidation products is formed.

Thus, the optimal method of synthesis of the phenols containing in one molecule both isobornyl and *tert*-butyl substituents is alkylation of *ortho*-isobornylphenols with *tert*-butyl chloride in the presence of clay KSF.

Table 3. Antioxidant activity of compounds **IXa, IXb**, and **XVb**

Compound	DPPH-binding activity, %	Quantity of compound (μg) 50% discolorizing in 30 min 37.2 μg of DPPH
Trolox	0.014659	5.863587
IXb	0.028431	11.37231
IXa	0.029744	11.89772
Ionol	0.044662	17.86479
XVb	0.09481	37.9239

The evaluation of antioxidant activity of the synthesized hybrid terpenophenols by measuring their ability to bind the stable radical diphenylpicryl-hydrazyl (DPPH) using a spectrophotometric method showed that 2-isocamphyl-4-methyl-6-*tert*-butylphenol **IXb** and 2-isobornyl-4-methyl-6-*tert*-butylphenol **IXa** exhibit a higher antioxidant activity than ionol, but inferior to trolox (6-hydroxy-2,5,7,8-tetramethyl-chroman-2-carboxylic acid) (Table 3). For comparison, the level of antioxidant activity of 2-*tert*-butyl-4-methyl-5-isocamphylphenol **XVb** is significantly lower.

EXPERIMENTAL

The ^{1}H and ^{13}C NMR spectra of the obtained compounds were recorded on a Bruker Avance II 300 spectrometer (300 MHz and 75 MHz respectively), solvent $CDCl_3$, at room temperature. As the internal reference the signal of chloroform (δ_H 7.26 ppm, δ_C 76.90 ppm) was used. The assignment of signals was performed using ^{13}C NMR spectra recorded in JMOD mode and two-dimensional NMR spectroscopy (HSQC, COSY, NOESY). The IR spectra were recorded on a Shimadzu FT-IR spectrometer IR Prestige 21.

Purity of starting materials was checked and the analysis of reaction products was performed by GLC on a Shimadzu GC-2010AF instrument with the flame ionization detector (carrier gas helium), capillary column HP-1 (Agilent, 60 m × 0.25 mm × 0.25 μm, ramp 100–240°C, heating rate 6 deg min^{-1}). Melting points were determined on a Koeffler heating block.

The reactions course was monitored by TLC on Sorbfil plates, using the solvent system petroleum ether–diethyl ether with an increase in the proportion of the latter. The development was performed by treating the plate with a solution of $KMnO_4$ (25 g of $KMnO_4$, 300 ml of H_2O, and 0.5 ml of concn. H_2SO_4), and with a solution of vanillin (1 g of vanillin of 5 ml of conc. H_2SO_4 in 100 ml of 95% ethanol) followed by heating to 100–150°C. The separation of reaction products was performed by column chromato-graphy on a 70/230μ silica gel (from Alfa Aesar).

Camphene (racemate) used contained 5% of tricyclene. $(i\text{-PrO})_3Al$ (Alfa Aesar), $(PhO)_3Al$ (synthesized *in situ*), montmorillonite KSF (Acros Organics), and cationite FIBAN K-1 provided by the Institute of Physical Organic Chemistry, National Academy of Sciences of Belarus' were used as catalysts.

Alkylation of *tert*-butylphenols with camphene in the presence of aluminum-containing catalysts (by an example of 2-*tert*-butylphenol). To 0.1 g of a phenol heated to 160°C was added 0.01 g of aluminum shavings in small portions. After complete dissolution of aluminum in the phenol, the solution was cooled to 40°C and then 1 g (0.6 mmol) of 2-*tert*-butylphenol **I** and 1.82 g (13 mmol) of camphene **III** was added. The reaction was performed while maintaining the temperature at 160°C for 32 h (GLC monitoring). The reaction mixture was cooled, diluted with diethyl ether, treated with dilute hydrochloric acid to decompose the catalyst, and washed with water until neutral. The organic extract was dried over anhydrous Na_2SO_4, the solvent was evaporated. The reaction products were separated by column chromatography (Table 1).

When $(i\text{-PrO})_3Al$ was used as the catalyst, the reagents and catalyst were loaded simultaneously. The reaction was carried out for 46 h, maintaining the temperature at 180–200°C (Table 1).

Spectral characteristics of compounds obtained correspond to published data [8, 9].

Reaction of 2-isobornylphenol with *tert*-butyl chloride. A two-neck flask was charged with 2 g (0.87 mol) of 2-isobornylphenol **IV** and 0.8 g (0.87 mol) of *tert*-butyl chloride **V**. Montmorillonite KSF was taken in a weight ratio of 1:1 to the original 2-isobornylphenol **IV**. The reaction was carried out in CH_2Cl_2 for 5 h or in *tert*-butyl chloride for 1 h, at reflux.

After the reaction completing, the reaction mixture was dissolved in diethyl ether, filtered from the catalyst, and the separation of reaction products was performed by column chromatography.

2,4-Di-*tert*-butyl-6-(1,7,7-trimethylbicyclo[2.2.1]-hept-2-yl)phenol (VIa). Colorless powder, mp 119°C. IR spectrum (KBr, ν, cm^{-1}): 3641, 3604 (OH), 2953, 2874, 1462, 1388, 1363 (CH_3, CH_2), 1600 (C=C), 1186 (=C–O), 881 , 727 (=C–H). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 0.82 s (3H, CH_3^{10}), 0.88 s (3H, CH_3^{9}), 0.92 s (3H, CH_3^{8}), 1.44 s (9H, CH_3^{18}, CH_3^{19}, CH_3^{20}), 1.47 s (9H, CH_3^{22}, CH_3^{23}, CH_3^{24}), 1.69–1.73 m (2H, H^5, H^6), 1.89–1.91 m (1H, H^3, H^4, H^5, H^6), 2.58–2.32 m (1H, H^3), 2.92 m (1H, H^2, J 8.4 Hz), 4.80 s (1H, OH), 7.17 s (1H, H^{16}), 7.23 s (1H, H^{14}). ^{13}C NMR spectrum, δ_C, ppm: 12.48 (C^{10}), 20.17 (C^9), 21.47 (C^8), 27.67 (C^5), 29.96 (C^{18}, C^{19}, C^{20}), 30.43 (C^{21}), 31.67 (C^{22}, C^{23}, C^{24}), 34.62 (C^6), 40.57 (C^3), 45.52 (C^2), 46.53 (C^4), 48.27

(C^1), 49.41 (C^7), 121.15 (C^{14}), 127.73 (C^{16}), 127.85 (C^{11}), 134.51 (C^{13}), 140.98 (C^{15}), 150.95 (C^{12}).

2,4-Di-*tert*-butyl-6-(2,3,3-trimethylbicyclo[2.2.1]-hept-5-yl)phenol (VIb). Colorless oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 0.98 d (3H, CH_3^{10}, *J* 3.3 Hz), 1.12 s (6H, CH_3^8, CH_3^9), 1.44 s (9H, CH_3^{18}, CH_3^{19}, CH_3^{20}) 1.47 s (9H, CH_3^{22}, CH_3^{23}, CH_3^{24}), 1.69–1.73 m (3H, H^1, H^3, H^5), 1.89–1.91 m (1H, H^6, H^4), 2.76 t (1H, H^5, *J* 7.2 Hz), 4.80 s (1H, OH), 7.17 s (1H, H^{16}), 7.23 s (1H, H^{14}). ^{13}C NMR spectrum, δ_C, ppm: 16.28 (C^{10}), 24.47 (C^9), 27.49 (C^8), 27.67 (C^5), 29.96 (C^{18}, C^{19}, C^{20}), 30.43 (C^{21}), 31.67 (C^{22}, C^{23} , C^{24}), 32.72 (C^7), 33.58 (C^6), 45.52 (C^2), 46.53 (C^4), 49.57 (C^1), 48.27 (C^3), 121.15 (C^{14}), 127.73 (C^{16}), 127.85 (C^{11}), 134.51 (C^{13}), 140.98 (C^{15}), 150.95 (C^{12}).

2-*tert*-Butyl-6-(1,7,7-trimethylbicyclo[2.2.1]hept-2-yl)phenol (VIIa). Colorless oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 0.85 s (3H, CH_3^{10}), 0.90 s (3H, CH_3^9), 0.97 s (3H, CH_3^8), 1.46 s (9H, CH_3^{18}, CH_3^{19}, CH_3^{20}), 1.61–1.69 m (2H, H^5, H^6), 1.90–1.91 m (4H, H^3, H^4, H^5, H^6), 2.23–2.31 m (1H, 3H), 3.16 m (1H, H^2, *J* 8.4 Hz) 4.56 s (1H, OH), 7.07–7.13 m (1H, H^{15}), 7.33 d (1H, H^{14}, *J* 2.1 Hz), 7.39 d (1H, H^{16}, *J* 2.1 Hz). ^{13}C NMR spectrum, δ_C, ppm: 12.57 (C^{10}), 20.26 (C^9), 21.49 (C^8), 27.58 (C^5), 29.58 (C^{18}, C^{19}, C^{20}), 34.12 (C^{17}), 34.24 (C^6) 40.22 (C^3), 45.67 (C^2), 45.74 (C^4), 48.39 (C^1), 49.47 (C^7), 114.31 (C^{15}), 122.94 (C^{14}), 124.10 (C^{16}), 132.46 (C^{11}), 135.34 (C^{13}), 151.26 (C^{12}).

2-*tert*-Butyl-6-(2,3,3-trimethylbicyclo[2.2.1]hept-5-yl)phenol (VIIb). Colorless oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): d 0.98 (3H, CH_3^{10}, J 3.3 Hz), 1.12 s (6H, CH_3^8, CH_3^9), 1.49 s (9H, CH_3^{18}, CH_3^{19}, CH_3^{20}) 1.67–1.75 m (2H, H^1, H^7), 1.92–1.94 m (3H, H^3, H^6, H^7), 3.19 t (1H, H^5, *J* 7.2 Hz), 4.70 s (1H, OH), 7.11–7.16 m (1H, H^{15}), 7.37 d (1H, H^{14}, *J* 2.1 Hz), 7.43 d (1H, H^{16}, *J* 2.1 Hz). ^{13}C NMR spectrum, δ_C, ppm: 16.35 (C^{10}), 24.80 (C^9), 27.73 (C^8), 32.51 (C^{18}, C^{19}, C^{20}), 33.45 (C^7), 33.81 (C^{17}), 34.28 (C^3) 41.47 (C^1), 48.09 (C^2), 49.86 (C^5), 49.99 (C^6), 50.79 (C^4), 115.99 (C^{15}), 123.56 (C^{14}), 124.11 (C^{16}), 134.51 (C^{11}), 142.08 (C^{13}), 151.81 (C^{12}).

Reaction of 2-isobornyl-4-methylphenol with *tert*-butyl chloride. In a round-bottom flask was placed 0.2 g of 2-isobornyl-4-methylphenol **VIII** dissolved in 0.2 ml of *tert*-butyl chloride **V**. Montmorillonite KSF was taken in a weight ratio of 1:1 to the initial *ortho*-isobornylphenol. The reaction mixture was heated at reflux of *tert*-butyl chloride for 30 min. After the reaction completing, the reaction mixture was dissolved in diethyl ether, filtered from the catalyst, and the reaction products were separated by column chromatography.

2-*tert*-Butyl-4-methyl-6-(1,7,7-trimethylbicyclo-[2.2.1]hept-2-yl)phenol (Xa). Colorless powder, mp 112°C. IR spectrum (KBr, ν, cm^{-1}): 3603 (OH), 2954, 2920, 2876, 1442, 1386, 1361 (CH_3, CH_2), 1607 (C=C), 1166 (=C–O), 860 , 794, 765 (=C–H). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 0.84 s (3H, CH_3^{10}), 0.90 s (3H, CH_3^9), 0.93 s (3H, CH_3^8), 1.47 s (9H, CH_3^{19}, CH_3^{20}, CH_3^{21}), 1.68–1.74 m (6H, H^3, H^4, $2H^5$, $2H^6$), 1.93–1.99 m (1H, 3H), 2.33 s (3H, $CH_3$17), 2.93 t (1H, H^2, *J* 8.4 Hz), 4.82 s (1H, OH), 7.01 s (1H, H^{16}), 7.03 s (1H, H^{14}). ^{13}C NMR spectrum, δ_C, ppm: 12.25 (C^{10}), 20.23 (C^9), 21.46 (C^8), 21.35 (C^{17}), 27.65 (C^5), 29.90 (C^{19}, C^{20}, C^{21}), 34.28 (C^6) 34.40 (C^{18}), 40.35 (C^3), 45.44 (C^2), 46.29 (C^4), 48.39 (C^1), 49.47 (C^7), 125.07 (C^{16}), 126.14 (C^{14}), 127.93 (C^{11}), 128.46 (C^{15}), 135.34 (C^{13}), 151.26 (C^{12}).

2-*tert*-Butyl-4-methyl-6-(2,3,3-trimethylbicyclo-[2.2.1]hept-5-yl)phenol (Xb). Brown oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 0.99 d (3H, CH_3^{10}, *J* 3.3 Hz), 1.12 s (6H, CH_3^8, CH_3^9), 1.47 s (9H, CH_3^{19}, CH_3^{20}, CH_3^{21}) 1.85–2.09 m (7H, H^1, H^3, H^4, $2H^6$, $2H^7$), 2.33 s (3H, CH_3^{17}), 2.76 t (1H, H^5, *J* 7.2 Hz), 4.81 s (1H, OH), 6.90 s (1H , H^{16}), 7.00 s (1H, H^{14}). ^{13}C NMR spectrum, δ_C, ppm: 16.29 (C^{10}), 21.30 (C^{17}), 24.46 (C^9), 27.67 (C^8), 29.91 (C^{19}, C^{20}, C^{21}), 32.72 (C^7), 33.58 (C^6) 34.09 (C^{18}), 40.07 (C^2), 40.96 (C^1), 49.16 (C^3), 49.87 (C^4), 50.73 (C^5), 123.44 (C^{16}), 123.85 (C^{14}), 128.37 (C^{11}), 132.35 (C^{15}), 135.70 (C^{13}), 150.05 (C^{12}).

Alkylation of 2-*tert*-butyl-4-methylphenol camphene in the presence of acid catalysts. In the case of sulfonic acid cation exchanger FIBAN K-1 the catalyst was taken in amount 10% to the initial 2-*tert*-butyl-4-methylphenol, montmorillonite KSF was taken in a weight ratio of 1:1 to the original 2-*tert*-butyl-4-methylphenol. A mixture of 2-*tert*-butyl-4-methylphenol **XI**, camphene **III,** and the catalyst taken in the calculated amount was heated at a predetermined temperature in a two-neck flask equipped with thermometer and reflux condenser. The reaction was carried out in an organic solvent (methylene chloride, hexane, or heptane). The reaction conditions and results are listed in Table 2.

After the reaction completing, the reaction mixture was dissolved in diethyl ether, filtered from the catalyst, and the reaction products were separated by column chromatography.

Spectral characteristics of compounds **Xa, Xb**, and **XVIb, XVIc** correspond to published data [6, 7].

2-(2-*tert*-Butyl-4-methylphenoxy)-1,7,7-trimethylbicyclo[2.2.1]heptane (XIIa). Viscous oil of light brown color. IR spectrum (thin film, ν, cm^{-1}): 2953, 2874, 1492, 1454, 1388 (CH_3, CH_2), 1606 (C=C), 1220 (=C–O), 1189 (C–O), 802, 771 (=C–H). ^1H NMR spectrum, δ, ppm (*J*, Hz): 0.81 s (3H, CH_3^{10}), 0.88 s (3H, CH_3^9), 0.94 s (3H, CH_3^8), 1.45 s (9H, H^{19}, H^{20}, H^{21}), 1.69–2.02 m (7H, $2H^3$, H4, $2H^5$, $2H^6$), 2.34 s (3H, CH_3^{17}), 4.10–4.13 m (1H, H^2), 6.83 d (1H, H^{16}, *J* 8.1 Hz), 7.01 d (1H, H^{15}, *J* 8.1 Hz), 7.17 s (1H, H^{13}). ^{13}C NMR spectrum, δ_C, ppm: 12.83 (C^{10}), 20.35 (C^9), 20.67 (C^8), 21.3 (C^{17}), 27.41 (C^5), 34.68 (C^{18}), 35.05 (C^6), 40.91 (C^3) , 45.26 (C^2), 45.65 (C^4), 48.10 (C^1), 49.92 (C^7), 85.34 (C^2), 112.54 (C^{16}), 124.68 (C^{14}), 126.92 (C^{15}), 127.88 (C^{13}), 128.23 (C^{12}) , 154.32 (C^{11}).

2-Methoxy-1,7,7-trimethylbicyclo[2.2.1]heptane (XIII). Light yellow oil. IR spectrum (thin film, ν, cm^{-1}): 2949, 2874, 1452, 1365 (CH_3, CH_2), 1123, 1080 (C–O). ^1H NMR spectrum, δ, ppm (*J*, Hz) : 0.84 s (3H, CH_3^{10}), 0.93 s (3H, CH_3^9), 0.99 s (3H, CH_3^8), 1.44–1.49 m (5H, H^3, H^4, H^5, $2H^6$), 1.52–1.80 m (2H, 3H, $H^{5'}$), 3.13–3.17 m (1H, H^2), 3.27 s (3H, CH_3^{11}). ^{13}C NMR spectrum, δ_C, ppm: 11.80 (C^{10}), 20.15 (C^9), 20.24 (C^8), 27.34 (C^5), 34.64 (C^6), 37.91 (C^3), 45.05 (C^4), 47.02 (C^7) , 49.5 (C^1), 56.57 (C^{11}), 89.06 (C^2).

(1*S*,1'*R*,2*R*,4*R*,4'*S*,6'*R*)-2,6'-Oxybis(1,7,7-trimethylbicyclo[2.2.1] heptane) (XIV). Light yellow oil. ^1H NMR spectrum, δ, ppm (*J*, Hz): 0.82 s (6H, CH_3^9, $CH_3^{9'}$), 0.86 s (6H, CH_3^8, $CH_3^{8'}$), 1.00 (6H, CH_3^{10}, $CH_3^{10'}$), 1.09 –1.23 m (4H, $2H^6$, $2H^{6'}$), 1.50–1.76 m (10H, $2H^3$, $2H^{3'}$, 1H4, 1H4', $2H^5$, $2H^{5'}$), 3.20–3.24 m (2H, $1H^2$, $1H^{2'}$). ^{13}C NMR spectrum, δ_C, ppm: 12.45 (C^{10}, $C^{10'}$), 20.18 (C^9, $C^{9'}$), 20.71 (C^8, $C^{8'}$), 27.39 (C^5, $C^{5'}$), 34.45 (C^6, $C^{6'}$) , 38.46 ($C^{3'}$), 39.45 (C^3), 45.63 (C^4, $C^{4'}$), 47.08 (C^1, $C^{1'}$), 48.75 (C^1, $C^{1'}$), 84.42 ($C^{2'}$), 86.78 (C^2).

2-*tert*-Butyl-4-methyl-6-(1,4,7-trimethylbicyclo[2.2.1]hept-2-yl)phenol (IXc). Brown oil. ^1H NMR spectrum, δ, ppm (*J*, Hz): 0.71 s (6H, CH_3^8, CH_3^{10}), 0.76 d (3H, CH_3^9, *J* 6.9 Hz), 1.07–1.17 m (2H, H^5, H^6), 1.46 s (9H, CH_3^{19}, CH_3^{20}, CH_3^{21}), 1.58–1.62 m (2H, H^5, H^6), 1.84–1.87 m (2H, H^3, H^7), 2.08–2.10 m (1H, 3H), 2.33 s (3H , CH_3^{17}), 2.99–3.01 m (1H, H^2), 4.88 s (1H, OH), 6.90 s (1H, H^{16}), 7.04 m (1H, H^{14}). ^{13}C NMR spectrum, δ_C, ppm: 8.30 (C^9), 15.61 (C^{10}), 19.3 (C^8), 21.34 (C^{17}), 29.91 (C^{19}, C^{20}, C^{21}), 33.59 (C^{18}), 34.71 (C^6) 37.78 (C^5), 40.94 (C^4), 44.19 (C^2), 45.15 (C^3), 47.62 (C^7), 50.50 (C^1), 124.98 (C^{16}), 126.22 (C^{14}), 128.37 (C^{11}), 130.54 (C^{15}), 135.68 (C^{13}), 150.02 (C^{12}).

2-*tert*-Butyl-4-methyl-5-(2,3,3-trimethylbicyclo[2.2.1]hept-5-yl)phenol (XVb). Brown oil. ^1H NMR spectrum, δ, ppm (*J*, Hz): 0.94 d (3H, CH_3^{10}, *J* 3.2 Hz), 1.12 s (6H, CH_3^8, CH_3^9), 1.47 s (9H, CH_3^{19}, CH_3^{20}, CH_3^{21}) 1.59–1.81 m (7H, H^1, H^3, H^4, $2H^6$, $2H^7$), 2.27 s (3H, CH_3^{17}), 2.77 m (1H, H^5, *J* 7.5 Hz), 4.58 s (1H, OH), 6.58 s (1H , H^{12}), 7.04 s (1H, H^{15}). ^{13}C NMR spectrum, δ_C, ppm: 16.29 (C^{10}), 21.30 (C^{17}), 24.77 (C^9), 27.69 (C^8), 29.78 (C^{19}, C^{20}, C^{21}), 33.03 (C^7), 33.76 (C^6) 34.09 (C^{18}), 43.73 (C^1), 44.89 (C^2), 49.13 (C^3), 49.79 (C^4), 51.45 (C^5), 113.57 (C^{12}), 126.85 (C^{16}), 128.85 (C^{15}), 129.35 (C^{14}) 132.70 (C^{11}), 150.85 (C^{13}).

1,7,7–Trimethyl-2-(trichloromethoxy)bicyclo[2.2.1]heptane (XVII). Colorless oil. IR spectrum (thin film, ν, cm^{-1}): 2954, 2927, 2870, 1458, 1366 (CH_3, CH_2), 796 (C–Cl). ^1H NMR spectrum, δ, ppm (*J*, Hz): 0.86 s (3H, CH_3^9), 0.94 s (3H, CH_3^8), 1.05 s (3H, CH_3^{10}), 1.21–1.46 m (6H, $2H^3$, $2H^5$, $2H^6$), 1.75–1.77 m (1H, H^4), 3.64–3.67 m (1H, H^2). ^{13}C NMR spectrum, δ_C, ppm: 11.30 (C^{10}), 20.11 (C^9), 20.48 (C^8), 27.24 (C^5), 33.93 (C^6), 40.41 (C^3), 45.06 (C^4), 46.78 (C^7) , 48.52 (C^1), 79.95 (C^2), 115.40 (C^{11}).

Determination of antioxidant activity of the terpenophenols (spectrophotometric method). The antioxidant activity was determined by the ability of a terpenophenol to bind *in vitro* the stable radical DPPH (2,2-diphenyl-1-picrylhydrazyl) [10]. Each sample was studied thrice. As a control served a mixture containing all components except the analyte. To the 50 μl of 1, 0.1, 0.01 and 0.001% alcoholic solution of the preparation was added 150 μl of 0.6 mM solution of DPPH in ethanol. In parallel were carried out the reactions with an alcoholic solution of ionol and trolox at the same concentrations. The optical density was measured on a plate spectrophotometer PowerWave 200TM (Bio-Tek Instruments, USA) at λ = 517 nm, first immediately after adding DPPH and intensive mixing (t_0), then after 30 min of incubation in the dark under a polyethylene film (t_1) The antioxidant activity was calculated by the formula [11]:

$$AOA\ (\%) = (OD_{517blanc(0)} - OD_{517sample(1)})/OD_{517blanc(0)} \times 100,$$

where $OD_{517blanc(0)}$ is optical density of the blank measured immediately after adding DPPH, $OD_{517sample(1)}$ is optical density of the sample, measured after 30 min of incubation.

Then were drawn the plots of dependence of the antioxidant activity on the concentration of the analyte and the concentration of the substance was found required for the discoloration of DPPH by 50% ($DPPH_{50}$).

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