杨属植物化学成分及药理作用研究进展

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摘　要:杨属植物资源丰富,世界上共有天然杨树100余种,广泛分布于欧、亚、北美地区,因其具有生长速度快、繁殖容易、适应能力强等特点,被广泛应用于绿化造林、恢复植被、解决生态问题以及制浆、造纸原料等。该属植物化学成分多样,近15年来,国内外学者共从中发现了200多个化合物,包括酚苷、黄酮、酚酸、萜等类型。相关化合物在抗菌、抗炎、抗氧化、抗肿瘤、降血糖、神经保护等方面表现出一定的生物活性。笔者通过对近年来杨属植物的研究进行归纳总结,按酚苷类、黄酮类、有机酸类、挥发性成分及其它成分综述了其化学成分的研究情况,并对该属植物主要的药理作用研究进展进行了阐述,为该属植物药用活性成分及其作用机制的研究提供了参考依据,进一步促进杨属植物在医药保健等方面的合理开发利用。

关键词:杨属;化学成分;酚苷;黄酮;药理活性

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Research progress on chemical constituents and pharmacological activities of *Populus* plants

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Abstract: Plants of the genus *Populus* are abundant in resources,consisting more than 100 natural species throughout the world,distributed in Europe,Asia,and North America widely. Because of its fast growth,easy reproduction and strong adaptability,etc. ,the genus Populus is widely used in afforestation,restoring vegetation,solving ecosystem problem,raw materials for pulping and papermaking. There are several kinds of chemical components in the *Populus* plants. In nearly 15 years,nearly 200 compounds were identified from the *Populus* plants,consisting of phenolic glycosides,flavonoids,organic acids and terpenoids. Some of these compounds exhibited a broad array of the pharmacological activities,such as antibacterial,anti-inflammatory,anti-oxidant,anti-tumor,hypoglycemic and neuroprotective,etc. In the present paper,we summarize the research reports related with plants of the genus *Populus*,review the research progress of chemical components according to phenolic glycosides,flavonoids,organic acids,volatile components and other components,and describe pharmacological effects of this genus to provide references for the in-depth studies of medicinal active ingredients and their action mechanism on this genus,hoping to promote the further rational development and utilization of the *Populus* plants in medicine and health care.

Key words:*Populus*;chemical constituent;phenolic glycoside;flavonoid;pharmacological activity

杨属(*Populus*)为杨柳科(Salicacae)植物,通常所说的杨树是杨属植物所有树种的统称。杨属共分为五大派,即白杨派(Sect. *Leuce* Duby)、青杨派(Sect. *Tacamahaca* Spach)、黑杨派(Sect. *Aigeiros* Duby)、大叶杨派(Sect. *Leucoides* Spach)和胡杨派(Sect. *Turanga* Bge)[1]。世界上的杨树天然种类共有100余种,广泛分布在欧、亚、北美,资源极为丰富。中国处于世界杨树中心分布区,约有53种,五

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大派杨树在中国均有分布[1,2]。一直以来,杨树因具有生长快、适应性强、分布广、种类和品种多、易于杂交、易于改良遗传性状、易于进行无性繁殖等特点,被广泛应用于植树造林、植被恢复、解决生态问题等。同时,由于杨树木材的可加工利用率高,被广泛用作制浆、造纸原料和胶合板用原材料。

此外,杨树的皮、叶、花絮、芽脂兼可入药。在我国古代,杨属植物就常以胡桐泪、青杨、白杨树皮等名入药,有消炎、行瘀、化痰等功效。现代药理学研究证明,杨属植物中的多种化学物质具有抗肿瘤、抗菌、镇痛、抗炎、抗氧化、降血糖、调节神经系统等药理活性,如水杨苷(salicin,**1**)、特里杨苷(tremulacin,**2**)、柳皮苷(salicortin,**14**)和匍匐柳苷(salireposide,**28**)(见图1)等具有镇痛作用,**2** 具有抗炎作用,被广泛用作临床抗菌、抗炎和心血管药物[3]。目前,关于杨树的研究主要集中于病虫害防治[4-7]、品种选育[8-10]、造林[11-14]和木材改性[15,16]等方面。为了更好地开发杨属植物的药用价值,本文对近年来国内外有关杨属植物化学成分及药理作用的研究进展进行综述,以期为杨属植物进一步的开发利用提供参考。

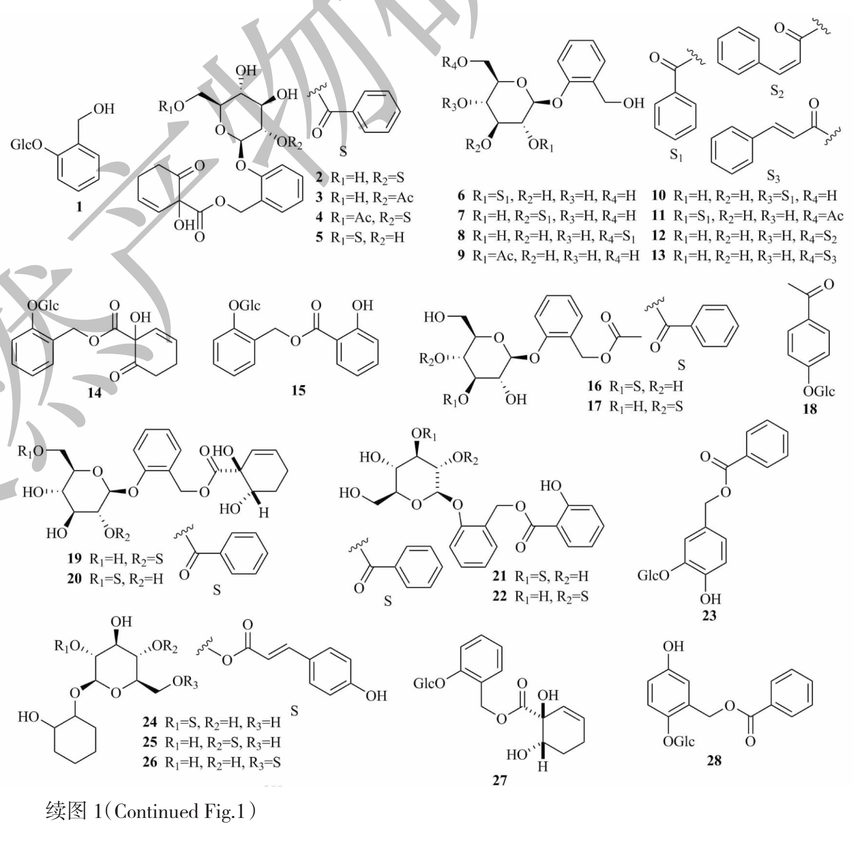
1 化学成分

杨属植物的化学成分研究始于1830年,Braconnot[17]首次从欧洲山杨(*P. tremula*)的树皮和叶中分离得到了水杨酸酯、酚苷、黄酮及酚酸等活性成分。随后国内外学者对杨属植物的树皮、叶芽、叶、木材、根、雄花序、花粉等不同部位进行了相关的化学研究。近15年来,共从杨属植物中分离鉴定得到了200多个化合物,主要包括酚苷、黄酮、有机酸、萜类等,其中酚苷类和黄酮类化合物是杨属植物的特征性成分。

1.1 酚苷类

酚苷是植物体内酚羟基与糖或糖的衍生物通过苷键结合形成的糖苷。它是杨柳科植物的特征性成分[18],广泛存在于杨柳科植物中。从欧洲山杨的树皮和叶中分离得到的 **1**[17] 是最早从杨属植物中分离出来的酚苷,随后 **2**、**14**、**28** 等多种酚苷类化合物从杨树的皮、叶、芽等部位被分离鉴定[19]。

近15年来,共从杨属植物中分离鉴定出了35个酚苷类化合物(**1**~**35**)(见图1、表1),其中有3种为新化合物,具体化合物名称见表1[20-31]。分离鉴定出的酚苷均是以水杨苷为基本结构单元的葡萄糖苷,水杨苷在杨属植物的皮、叶、花、芽中均有分布,其它酚苷根据杨属植物的种类及部位不同,分布也不同[32]。



续图1(Continued Fig.1)

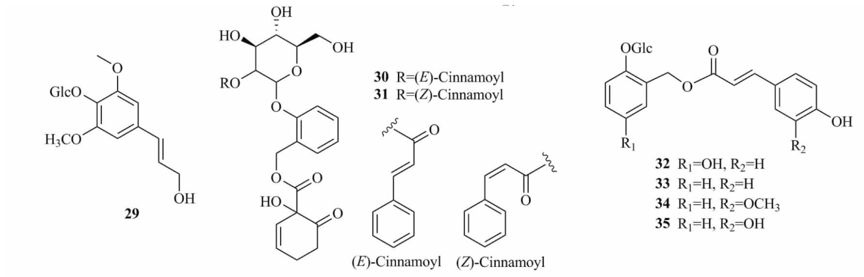


图 1　杨属植物中酚苷类化合物结构

Fig. 1　The structures of phenol glycoside compounds in *Populus* plants

表 1　杨属植物中酚苷类化合物

Table 1　Phenol glycoside compounds in *Populus* plants

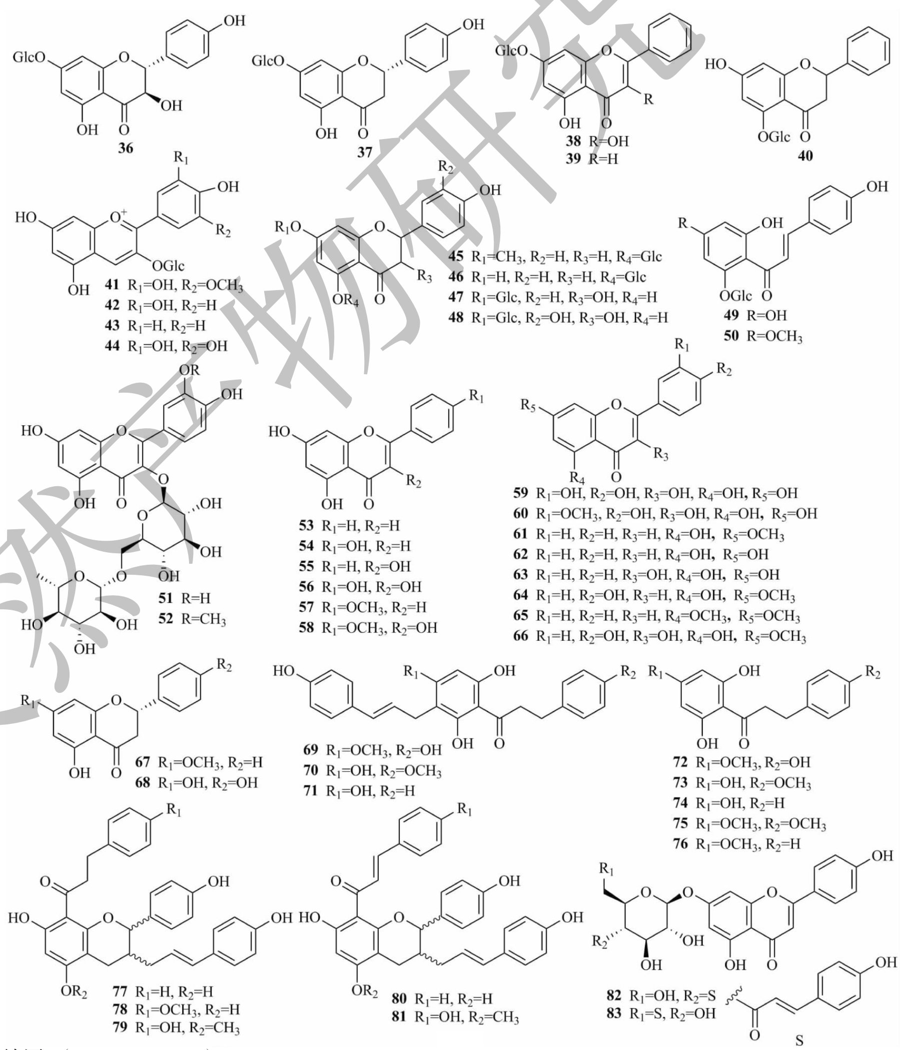
编号 No.	化合物 Compoud	文献 Ref.
1	水杨苷 Salicin	20-22
2	特里杨苷 Tremulacin	20,21
3	2′-*O*-乙酰基柳皮苷 2′-*O*-Acetyl-salicortin	21
4	6′-*O*-乙酰基特里杨苷 6′-*O*-Acetyl-tremulacin	21
5	柳皮苷-6′-苯甲酸酯 Salicortin-6′-benzoate	23
6	水杨苷-2′-苯甲酸酯 Salicin-2′-benzoate	20,21
7	3′-苯甲酰水杨苷 3′-Benzoylsalicin	20-22
8	6′-苯甲酰水杨苷 6′-Benzoylsalicin	20
9	2′-*O*-乙酰基水杨苷 2′-*O*-Acetyl-salicin	21
10	4′-苯甲酰水杨苷 4′-Benzoylsalicin	22
11	6′-*O*-乙酰基-2′-*O*-苯甲酰基水杨苷 6′-*O*-Acetyl-2′-*O*-benzoylsalicin	22
12	6′-*O*-顺式-肉桂酰水杨苷 6′-*O*-*cis*-Cinnamoylsalicin	24
13	6′-*O*-反式-肉桂酰水杨苷 6′-*O*-*trans*-Cinnamoylsalicin	24
14	柳皮苷 Salicortin	21-25
15	水杨酰基水杨苷 Salicyloylsalicin	21-22
16	7-*O*-乙酰基-3′-*O*-苯甲酰基水杨苷 7-*O*-Acetyl-3′-*O*-benzoylsalicin	22
17	7-*O*-乙酰基-4′-*O*-苯甲酰基水杨苷 7-*O*-Acetyl-4′-*O*-benzoylsalicin	22
18	云杉苷 Picein	25
19	Tremulacinol	22
20	6′-*O*-Benzoylsalicortinol	24
21	Salicyltomenside	26
22	邻羟苯基特里杨次苷 Salicyltremuloidin	26
23	Siebolside B	26
24	大齿杨苷 Grandidentatin	25
25	异大齿杨苷 A Isograndidentatin A	25
26	2-羟基环己基-6′-*O*-对香豆酰-*β*-*D*-葡萄吡喃糖苷 2-Hydroxy-cyclohexyl-6′-*O*-*p*-coumaroyl-*β*-*D*-glucopyranoside	27
27	Salicortinol	24
28	匍匐柳苷 Salireposide	24
29	紫丁香苷 Syringin	28

续表 2(Continued Tab. 2)

编号 No.	化合物 Compoud	文献 Ref.
30	2′-(*E*)-肉桂酰柳皮苷 2′-(*E*)-Cinnamoylsalicortin	29
31	2′-(*Z*)-肉桂酰柳皮苷 2′-(*Z*)-Cinnamoylsalicortin	29
32	白杨苷 Populoside	22
33	山杨苷 Davidianoside	30
34	白杨苷 B Populoside B	31
35	白杨苷 C Populoside C	31

1.2　黄酮类

黄酮类化合物,又称类黄酮,是一类广泛存在于植物中,以 2-苯基色原酮结构为基本母核的次生代谢产物,属于植物三大类次生代谢产物(酚类、萜类和含氮有机物)中的低分子量酚类物质[33]。该类化合物种类众多,根据化学结构对其进行分类,主要种类有黄酮醇、黄酮、黄烷酮、儿茶酸、花色素、异黄酮、二氢黄酮醇和查耳酮[34-36]。目前已发现的天然黄酮类化合物,多以游离态或与糖结合成苷的形式存在,是杨属植物主要的活性成分之一。近 15 年,从杨属植物中共发现 61 个黄酮化合物(见图 2),其中包括 17 个黄酮苷(**36**~**52**)和 44 个黄酮类化合物(**53**~**96**),化合物 **77**、**79** 和 **80** 为新的羟基肉桂酰二氢查耳酮,具体化合物名称见表 2[27,28,37-52]。



续图 2(Continued Fig.2)

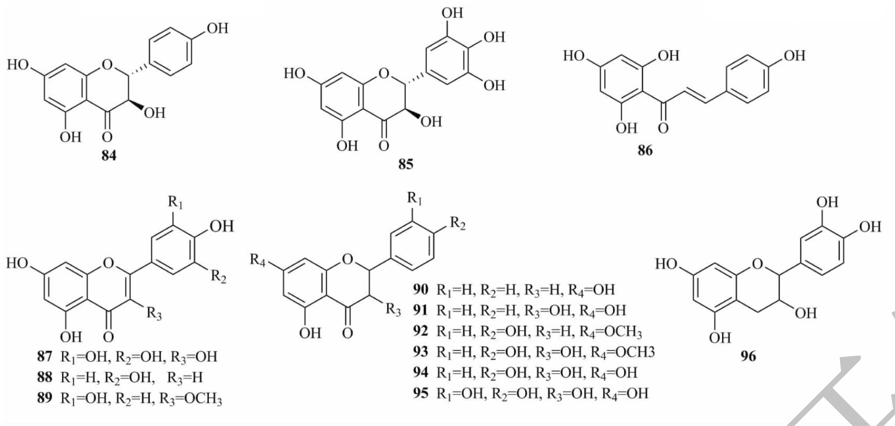


图 2 杨属植物中黄酮类化合物结构

Fig. 2 The structures of flavonoid compounds in *Populus* plants

表 2 杨属植物中黄酮类化合物

Table 2 Flavonoid compounds in *Populus* plants

编号 No.	化合物 Compoud	文献 Ref.
36	二氢山奈酚-7-*O*-*β*-葡萄糖苷 Dihydrokaempferol 7-*O*-*β*-glucoside	37,38
37	柚皮素-7-*O*-*β*-葡萄糖苷 Naringenin 7-*O*-*β*-glucoside	37,38
38	高良姜素-7-*O*-*β*-*D*-葡萄糖苷 Galangin 7-*O*-*β*-*D*-glucoside	39
39	白杨素-7-*O*-*β*-*D*-葡萄糖苷 Chrysin 7-*O*-*β*-*D*-glucoside	39
40	乔松素-5-*O*-*β*-*D*-葡萄糖苷 Pinocembrin 5-*O*-*β*-*D*-glucoside	39
41	矮牵牛素-3-*O*-葡萄糖苷 Petunidin 3-*O*-glucoside	40
42	矢车菊素-3-*O*-葡萄糖苷 Cyanidin 3-*O*-glucoside	40
43	天竺葵素-3-*O*-葡萄糖苷 Pelargonidin 3-*O*-glucoside	40
44	飞燕草素-3-*O*-葡萄糖苷 Delphinidin 3-*O*-glucoside	40
45	樱花苷 Sakuranin	41
46	杞柳苷 Salipurposide	42
47	香橙素 7-*O*-葡萄糖苷 Aromadendrin 7-*O*-glucoside	42
48	花旗松素 7-*O*-葡萄糖苷 Taxifolin 7-*O*-glucoside	42
49	异杞柳苷 Isosalipurposide	42
50	新野樱苷 Neosakuranin	42
51	芦丁 Rutin	43
52	水仙苷 Narcissin	43
53	白杨素 Chrysin	44
54	芹菜素 Apigenin	44,45
55	高良姜素 Galangin	44,46
56	山奈酚 Keampferol	44,46
57	刺槐黄素 Acacetin	47
58	山奈素 Kaempferide	47
59	槲皮素 Quercetin	45

续表 2(Continued Tab. 2)

编号 No.	化合物 Compoud	文献 Ref.
60	异鼠李素 Isorhamnetin	45
61	5-Hydroxy-7-methoxyflavone	48
62	5,7-Dihydoxyflavone	48
63	5,7-Dihydroxyflavonol	48
64	芫花素 Genkwanin	49
65	柯因二甲醚 Chrysin 5,7-dimethylether	49
66	鼠李柠檬素 Rhamnocitrin	47
67	乔松酮 Pnostrobin	49
68	柚皮素 Naringenin	49
69	Balsacones A	50
70	Balsacones B	50
71	Balsacones C	50
72	4,2′,6′-Trihydroxy-4′-methoxy-dihydrochalcone	50
73	2′,4′,6′-Trihydroxy-4-methoxydihydrochalcone	50
74	2′,4′,6′-Trihydroxydihydrochalcone	50
75	2′,6′-Dihydroxy-4,4′-dimethoxy-dihydro-chalcone	50
76	2′,6′-Dihydroxy-4′-methoxydihydrochalcone	50
77	(±)-Balsacone J	51
78	(±)-Iryantherin D	51
79	(±)-Balsacones K	51
80	(±)-Balsacones L	51
81	(±)-Balsacones M	51
82	Echinaticin	47
83	Echinacin	47
84	香橙素 Aromadendrin	47
85	白蔹素(+)-Ampelopsin	43
86	柚皮素查耳酮 2′,4,4′,6′-Tetrahydroxychalcone	52
87	杨梅素 Myricetin	49
88	木犀草素 Luteolin	27
89	3-*O*-甲基槲皮素 3-*O*-Methylquercetin	39
90	松属素 Pinocembrin	44,49
91	短叶松素 Pinobanksin	49
92	樱花素 Sakuranetin	41
93	7-甲氧基-2*R*,3*R*-二氢山奈酚 2*R*,3*R*-Dihydro-7-methoxykaempferol	27
94	二氢山奈酚 Dihydrokaempferol	37
95	黄杉素 Taxifolin	38
96	儿茶素 Catechin	38

1.3 有机酸类

有机酸类主要是指一些具有酸性的有机化合物,其酸性源于羧基(-COOH)、亚磺酸基(-SOOH)、磺酸基(-SO_3H)、硫羧酸基(-COSH)等。有机酸常以游离态或盐、酯的形式广泛存在于中草药的叶、根,特别是果实中。从目前的研究发现,杨属植物所含的有机酸中,咖啡酸(caffeic acid,**97**)及其衍生物、阿魏酸(ferulic acid,**99**)及其衍生物、香豆酸(coumaric acid,**106**)、苯甲酸(benzoic zcid,**114**)等的含量较高,其衍生物多以甲氧基、苯甲基、苯乙基、戊烯基、肉桂基等形式存在。近 15 年来,从杨属植物中分离得到的有机酸类化合物共有 18 种(**97** ~ **114**)(见图 3),具体化合物名称见表 3[39,53-55]。

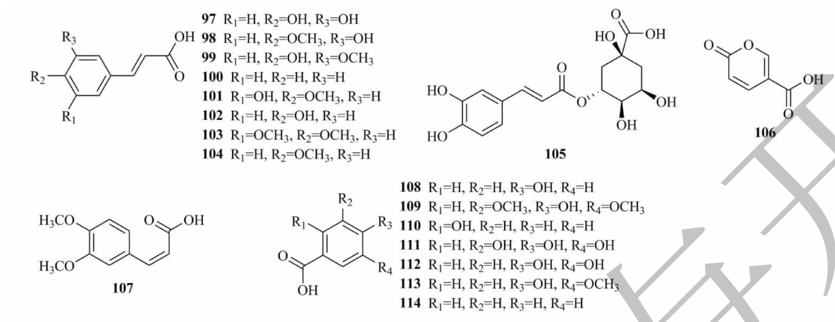


图 3 杨属植物中有机酸类化合物结构

Fig. 3 The structures of organic acid compounds in *Populus* plants

表 3 杨属植物中有机酸类化合物

Table 3 Organic acid compounds in *Populus* plants

编号 No.	化合物 Compoud	文献 Ref.
97	咖啡酸 Caffeic acid	39,53
98	异阿魏酸 Isoferulic acid	39
99	阿魏酸 Ferulic acid	53,54
100	肉桂酸 Cinnamic acid	53
101	(*E*)-异阿魏酸 (*E*)-Isoferulic acid	55
102	(*E*)-*p*-香豆酸 (*E*)-*p*-Coumaric acid	55
103	(*E*)-3,4-二甲氧基肉桂酸 (*E*)-3,4-Dimethoxycinnamic acid	55
104	(*E*)-*p*-甲氧基肉桂酸 (*E*)-*p*-Methoxycinnamic acid	55
105	绿原酸 Chlorogenic acid	53,54
106	香豆酸 Coumaric acid	53,54
107	(*Z*)-3,4-二甲氧基肉桂酸 (*Z*)-3,4-Dimethoxy cinnamic acid	55
108	对羟基苯甲酸 4-Hydroxybenzoic acid	54
109	丁香酸 Syringic acid	53,54
110	水杨酸 Salicylic acid	53,54
111	没食子酸 Gallic acid	53
112	原儿茶酸 3,4-Dihydroxybenzoic acid	53
113	香草酸 Vanillic acid	53
114	苯甲酸 Benzoic zcid	53

1.4 挥发性成分

植物挥发性化学成分,是一类具有一定挥发性的油状液态物质,可随水蒸气蒸出,又称挥发油、精油,是一种成分极其复杂的物质[46,56],在自然界分

布很广。植物挥发性物质的分子量大多在 100 ~ 200 之间,主要包括烃类、醇类、醛类、酮类、酯类、萜烯类、有机酸等物质[57-58]。杨属植物的挥发性成分主要存在于它的皮、叶、花和芽中,不同的杨属植物间所含的挥发性成分不尽相同。近 15 年来,从杨属植物中共鉴定出 65 种(**115 ~ 179**)主要的挥发性成分(见图 4),涉及醛、酯、醇、酮、酚、萜烯和烷烃等种类,萜烯类化合物和醇类化合物是其中最主要的成分。具体化合物名称见表 4[52,59-69]。

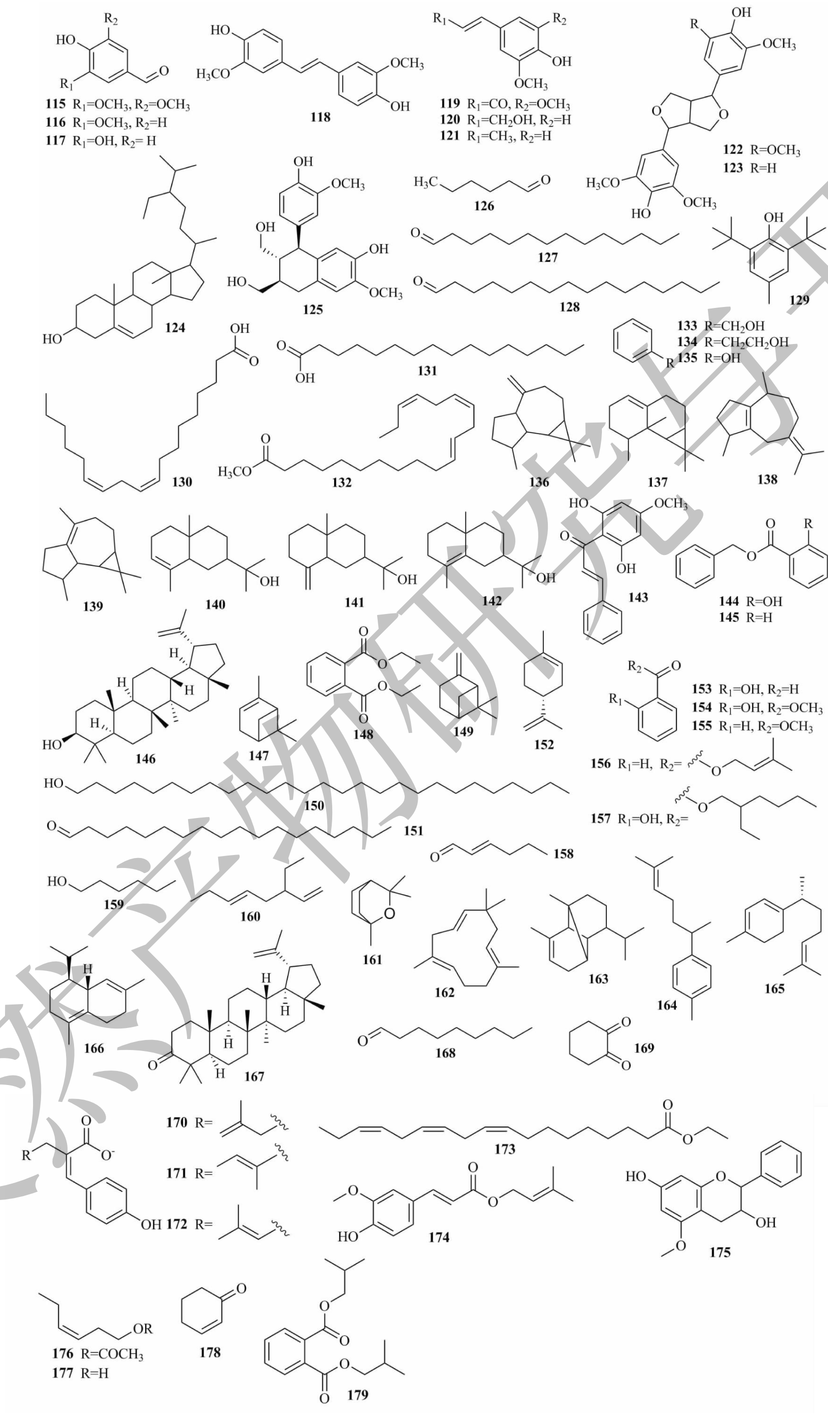


图 4 杨属植物中挥发性成分结构

Fig. 4 The structures of volatile compounds in *Populus* plants

表 4 杨属植物中挥发性成分

Table 4 Volatile compounds in *Populus* plants

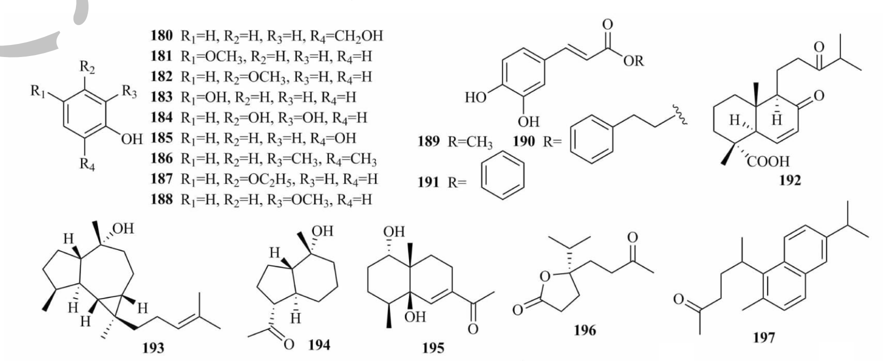
编号 No.	化合物 Compoud	文献 Ref.
115	丁香醛 Syringaldehyde	52
116	香兰素 Vanillin	52
117	3,4-二羟基苯甲醛 3,4-Dihydroxybenzaldehyde	52
118	4,4′-Dihyroxy-3,3′-dimethoxystilbene	52
119	3,5-二甲氧基-4-羟基肉桂醛 3,5-Dimethoxy-4-hydroxycinnamaldehyde	52
120	松柏醇 Coniferyl alcohol	52
121	丁香酚 Eugenol	59,60
122	丁香树脂酚 Syringaresinol	52
123	皮树脂醇 Medioresinol	52
124	谷甾醇 Sitosterol	52
125	异落叶松脂素 Isolariciresinol	52
126	己醛 Hexanal	59,61
127	十四醛 Tetradecanal	61
128	十六醛 Hexadecanal	61
129	2,6-二叔丁基-4-甲基苯酚 2,6-Ditertbuty-4-melthylphenol	61
130	亚油酸 Linoleic acid	61
131	十六酸 Hexadecanoic acid	61
132	11,14,17-二十碳三烯酸甲基酯 11,14,17-Eicosatrienoic acid metheylester	61
133	苯甲醇 Benzyl alcohol	59
134	苯乙醇 Phenylethyl alcohol	60
135	苯酚 Phenol	62
136	香橙烯 Aromadendrene	63
137	白菖烯 Allo-aromadendrene	63
138	δ-愈创木烯 δ-Guaiene	63
139	喇叭烯 Viridiflorene	63
140	α-桉叶醇 α-Selinene	64
141	β-桉叶醇 β-Selinene	64
142	γ-桉叶醇 γ-Selinene	64
143	球松素查耳酮 Pinostrobin chalcone	64
144	柳酸苄酯 Benzyl salicylate	64
145	苯甲酸苄酯 Benzyl benzoate	65
146	羽扇豆醇 Lupeol	66
147	α-蒎烯 α-Pinene	66
148	邻苯二甲酸二乙酯 Diethyl phthalate	66
149	β-蒎烯 β-Pinene	66
150	二十七烷醇 1-Heptacosanol	66
151	十八醛 Octadecanal	66
152	*d*-柠檬烯 *d*-Limonene	66

续表 4(Continued Tab. 4)

编号 No.	化合物 Compoud	文献 Ref.
153	邻羟基苯甲醛 Salicylaldehyde	60,61,65
154	水杨酸甲酯 Methyl salicylate	65
155	苯甲酸甲酯 Methyl benzoate	60
156	苯甲酸异戊二烯酯 Prenyl benzoate	67
157	水杨酸-2-乙基己基酯 2-Ethylhexyl 2-hydroxybenzoate	69
158	己烯醛 2-Hexenal	60
159	1-己醇 1-Hexanol	59
160	3-甲基-1,5-辛二烯 3-Ethyl-1,5-octadiene	60
161	桉树醇 Eucalyptol	60
162	α-律草烯 α-Caryo-phyllene	60
163	α-Copaene	60
164	芳-姜黄烯 Ar-curcumen	67
165	γ-姜黄烯 γ-Curcumen	67
166	δ-杜松烯 δ-Cadinene	67
167	羽扇烯酮 Lupenone	66
168	壬醛 Nonanal	60
169	1,2-环己二酮 1,2-Cyclohexanedione	62
170	3-Methyl-3-butenyl-p-coumarate	68
171	2-Methyl-2-butenyl-p-coumarate	68
172	3-Methyl-2-butenyl-p-coumarate	68
173	亚麻酸乙酯 Ethyl linolenate	68
174	3-Methyl-2-butenyl ferulate	68
175	Pinobanksin-5-methylether	68
176	顺-3-己烯酯 *cis*-3-*Hexenyl acetate*	69
177	顺-3-己烯醇 *cis*-3-Hexenol	69
178	环己烯 2-Cyclohexen-1-one	60
179	邻苯二甲酸二异丁酯 Diisobutyl phthalate	69

1.5 其他化学成分

除上述化合物外,研究者在杨属植物中还分离检测出了 32 种其它类型化合物(**180 ~ 211**)(见图 5),主要为酚类化合物和萜类化合物,具体化合物名称见表 5[20,23,24,39,50,51,70-73]。



续图 5(Continued Fig.5)

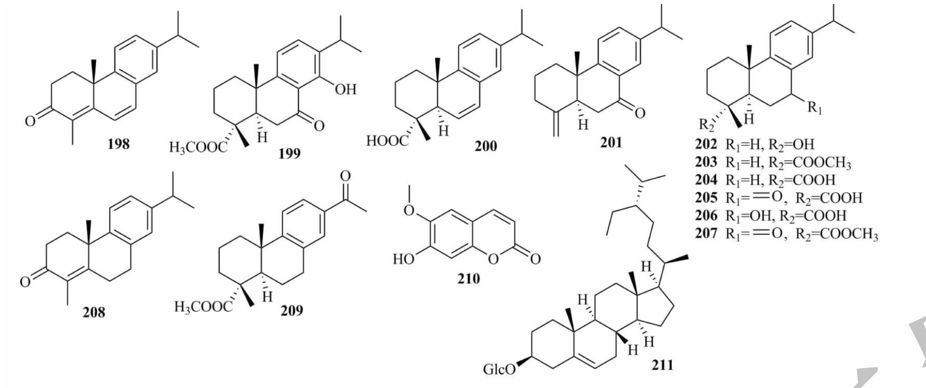


图 5 杨属植物中其它化学成分结构

Fig. 5 The structures of other compounds in *Populus* plants

表 5 杨属植物中其它化学成分

Table 5 Other compounds in *Populus* plants

编号 No.	化合物 Compoud	文献 Ref.
180	水杨醇 Salicortinol	24
181	对甲氧基苯酚 4-Methoxyphenol	39
182	间甲氧基苯酚 3-Methoxyphenol	39
183	对苯二酚 Hydroquinone	50
184	邻苯三酚 Pyrogallol	50
185	邻苯二酚 Pyrocatechol	51
186	2,6-二甲基苯酚 2,6-Dimethoxyphenol	70
187	3-乙氧基苯酚 3-Ethoxyphenol	70
188	愈创木酚 Guaiacol	70
189	咖啡酸甲酯 Caffeic acid methyl ester	71
190	咖啡酸苄酯 Caffeic acid benzyl ester	71
191	咖啡酸苯乙酯 Caffeic acid phenylethyl ester	71
192	Euphraticanoids E	72
193	Euphraticanoids F	72
194	Euphraticanoids G	72
195	Euphraticanoids H	72
196	Euphraticanoids I	72
197	5-(6-Isopropyl-2-methylnaphthalen-1-yl)pentan-2-one	73
198	19-Norabie-ta-4,6,8,11,13-penttaen-3-one	73
199	14-Hydroxy-7-oxo ester	73
200	6,8,11,13-Abit-eratrien-18-oic acid	73
201	19-*nor*-Abieta-4(18),8,11,13-tet-raen-7-one	73
202	18-Norabieta-8,11,13-4-ol	73
203	松香烷酯 Abietane ester	73
204	去氢松香酸 Dehydroabietic acid	73
205	7-Oxodehydroabietic acid	73
206	7α-Hydroxydehydroa-bietic acid	73
207	7-Oxoabieta-8,11,13-trien-18-oate	73
208	4,4a,9,10-Tetrahydro-1,4a-dimethyl-7-isopropyl-2(3*H*)-phenanthrone	73
209	Methyl-13-acetyl-podocarpa-8,11,13-trien-18-oate	73
210	东莨菪素 Scopoletin	20
211	胡萝卜苷 Daucosterol	23

2　药理作用

2.1　抗菌活性

Chu 等[70]将毛白杨边材在 160 ℃热处理过程中释放的挥发性成分收集冷凝，发现其中 **186**、**187** 和 **188** 等酚类化合物的相对含量最高，且对大肠杆菌、金黄色葡萄球菌、青霉菌和黑曲霉菌具有较好的抑菌活性。Simard 等[51]研究发现香脂杨叶芽乙醇提取物中的 4 对羟基肉桂酰二氢查耳酮（**77** ~ **80**）对映体对金黄色葡萄球菌具有良好的抑菌作用，且（-）-对映体的抑菌活性明显高于（+）-对映体。Nassima 等[74]采用扩散法研究了 2 种杨树芽的不同溶剂提取液对 11 种微生物的抑菌活性，结果表明提取液对所有微生物均有抑菌活性，其抑菌圈直径范围在 6.6 ~ 21.3 mm 之间，并进一步通过 HPLC 从不同溶剂提取液中检测到了 **56**、**102** 等多种具有生物活性的酚类化合物。上述研究表明，杨属植物的抗菌活性可能与其含有丰富的酚类化合物有关。

2.2　抗炎活性

近年来，杨属植物的抗炎活性研究主要集中于其化学成分对促炎因子表达的抑制作用。Pobłocka-Olech 等[75]通过建立体外模型，发现杨树叶芽提取物具有抑制 AgNPs 诱导人牙龈成纤维细胞分泌白细胞介素-6（IL-6）和白细胞介素-8（IL-8）的作用，并推测其抗炎作用是酚酸类与黄酮类化合物共同作用的结果。Wang 等[76]通过一系列的研究发现，加拿大杨树芽乙醇提取物在小鼠体内可以通过抑制特异性炎症细胞因子的产生发挥抗炎作用，抑制小鼠肺泡壁增厚、水肿、出血和炎性细胞浸润等肺部炎症。龚雪等[77]通过研究发现，胡杨树脂提取物能显著改善脂多糖（LPS）诱导小鼠单核巨噬白血病细胞 RAW264.7 的炎症反应，且具有较好的浓度依赖性。

2.3　抗氧化活性

酚苷类和黄酮类化合物是杨属植物中的特征性成分，其分子结构中的酚羟基可以与氧自由基反应，以中止自由基的链式反应，从而起到抗氧化的作用。Wang 等[76]采用 ABTS 法对加拿大杨树芽乙醇提取物的抗氧化性进行研究，其 IC_{50} 值为 55.63 ± 0.78 μg/mL，与 α-生育酚（56.43 ± 5.75 μg/mL）相当，说明加拿大杨树芽提取物具有显著的自由基清除能力。Si 等[23]研究发现 3 种从大青杨树皮乙酸乙酯提取物中分离得到的酚苷化合物在 ABTS 法实验中均表现出较好的抗氧化活性。Hamad 等[66]采用 DPPH 法、FRAP 法、金属离子螯和能力测定法等方法对杨树皮甲醇水（V/V，65∶35）提取液的抗氧化性进行测定，发现提取液具有较好的抗氧化作用，并推测可能与提取液中丰富的黄酮类成分杨梅素（**87**）有关。Dudonne 等[78]发现黑杨树芽水提物具有良好的抗氧化活性，其活性与提取物中丰富的酚类化合物有关，并证实咖啡酸（**97**）是提取物中抗氧化活性最强的化合物。同时，通过构建人皮肤成纤维细胞复制性衰老模型，发现黑杨树芽提取物能够显著调控皮肤抗氧化防御、炎症反应和细胞更新的相关基因转录，说明该提取物具有良好的抗皮肤衰老作用。

2.4　抗肿瘤活性

Wang 等[22]采用 MTT 法对水杨苷衍生物进行人胃癌 SGC-7901 细胞体外增殖的抑制活性实验，实验发现，特里杨苷类衍生物 **14**、**17**、**18** 和 **180** 对 SGC-7901 细胞体外增殖均显示一定抑制活性，IC_{50} 值分别为 257.8、71.0、212.7、122.5 mol/L。Cao 等[73]对从胡杨树脂中首次分离得到的 2 个松香烷二萜化合物进行体外细胞毒性测试，发现 2 种化合物对 5 种癌细胞—食管鳞癌细胞 Kyse30、肝癌细胞 HepG2、肺癌细胞 A549、胃癌细胞 BGC-823 和乳腺癌细胞 MDA-MB231 的增殖均有抑制作用，与单独使用的化疗药物 5-氟尿嘧啶（5-FU）相比，化合物 **198** 有更强的抑制性。Pichette 等[47]测试了从美洲山杨的叶芽中分离得到的 17 个化合物对肺癌细胞 A549 和大肠腺癌细胞 DLD-1 的细胞毒性，结果发现芫花素（**64**）对 2 种细胞均具有较强的细胞毒性，IC_{50} 值分别为 9.0 ± 3 μmol/L 和 9.2 ± 0.9 μmol/L。目前的研究表明，杨属植物中的生理活性成分主要是通过抑制肿瘤细胞的增殖来发挥抗肿瘤活性。

2.5　降血糖活性

Wei 等[45]采用 α-葡萄糖苷酶抑制剂筛选模型评价杨树胶脂不同极性组分的体外降血糖活性，通过链脲佐菌素（streptozocin）诱导的小鼠高血糖模型进行口服糖耐量实验，测定各分离组分体内抑制肠道内 α-葡萄糖苷酶的作用。结果发现，在体外实验中，50% 乙醇洗脱组分可以有效抑制 α-葡萄糖苷酶活性，IC_{50} 值为 28.28 ± 3.79 μg/mL。在小鼠高血糖模型口服糖耐量实验中，该组分对抑制糖尿病小鼠肠内 α-葡萄糖苷酶活性效果良好，可以显著降低糖尿病小鼠的餐后血糖水平，有利于血糖水平恢复和保持血糖稳定。Lee 等[79]研究发现从钻天杨（*P. nigraon*）树皮乙酸乙酯浸提液中分离得到的白杨苷（**32**）以浓度依赖的方式抑制醛糖还原酶的活性，IC_{50} 值为 18.55 μmol/L，同时 **32** 对红细胞中山梨醇

(Sorbitol)的累积也有抑制作用,说明其对糖尿病并发症的治疗具有一定的潜力。

2.6 其他活性

此外,杨属植物化学成分还具有较好的神经保护及抗肥胖活性。Bélanger 等[80]发现香脂杨树芽中的5种二氢查耳酮衍生物(**69**~**71**、**78**、**79**)可以通过减缓银屑病角质形成细胞的增殖及调控内披蛋白、兜甲蛋白、肿瘤细胞增殖因子 Ki67 的表达来抑制银屑病,具有良好的抗炎和抗氧化作用,有助于改善银屑病患者的临床症状。Liu 等[72]对从胡杨树脂中分离得到的化合物进行抗谷氨酸诱导神经母细胞瘤 SH-SY5Y 细胞株神经损伤活性测试,发现其中的化合物 euphraticanoid E(**192**)、euphraticanoid H(**195**)和 euphraticanoid I(**196**)具有显著减弱谷氨酸诱导的神经兴奋性毒性的作用,并呈现剂量依赖关系,具有较好的神经保护活性。Elsbaey 等[43]发现杨树木材提取液的乙酸乙酯部分具有良好的胰脂肪酶抑制活性,IC_{50}值为4.7 μg/mL,其中化合物(+)-二氢槲皮素(**95**)和(+)-白蔹素(**85**)抑制活性最高,表明杨树木材中的黄酮类和酚酸类化合物可望作为新型抗肥胖药物的潜在开发对象。Hage 等[81]通过研究发现杨树芽中的黄酮类化合物白杨素(**53**)对胆碱酯酶有一定的抑制作用,这为阿尔兹海默症等神经退行性疾病药物的研发提供了新的思路。

3 展望

杨属植物资源丰富,分布区域广,而且其中的化学成分具有抗菌、抗炎、抗肿瘤、抗氧化等多种药理活性。但目前对其研究主要集中于基础性药理研究,某些药理作用中具体的有效成分尚不明确,临床应用研究较少,药理活性的开发利用还比较薄弱。今后应进一步对杨属植物进行系统的化学成分分离和活性筛选,寻找活性强、疗效好的化学成分用于药物研发;结合分子生物学,深入研究并阐明杨属植物中有效成分的具体作用机制;对活性强的化合物进行临床研究,为杨属植物临床用药的安全性提供可靠的科学依据,进而促进杨属植物在医药保健等方面的综合开发利用。

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