ISSN 0253-2786
CN 31-1321/O6
http://sioc-journal.cn

有机化学

Chinese Journal of Organic Chemistry

金属有机化学专辑

第 39 卷 第6期 Vol. 39 No. 6 2019

ISSN 0253-2786

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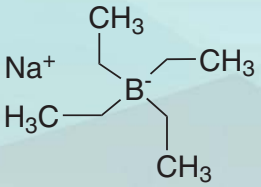

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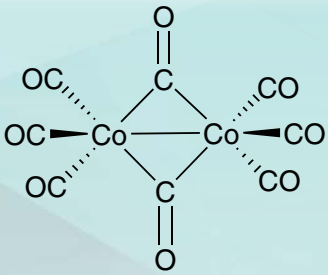

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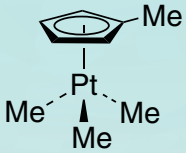

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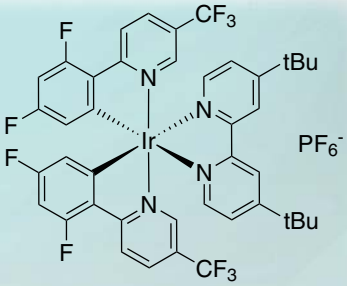

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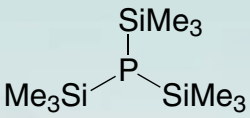

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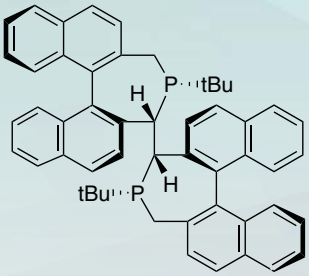

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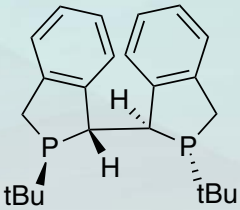

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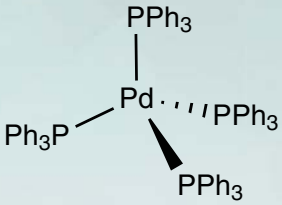

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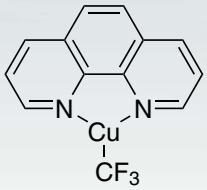

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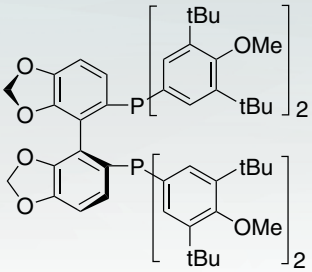

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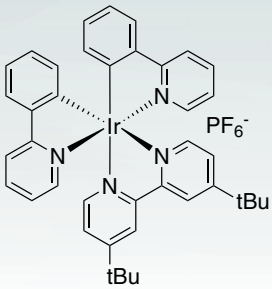

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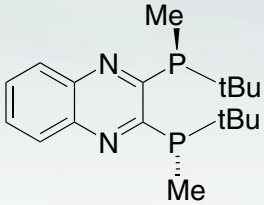

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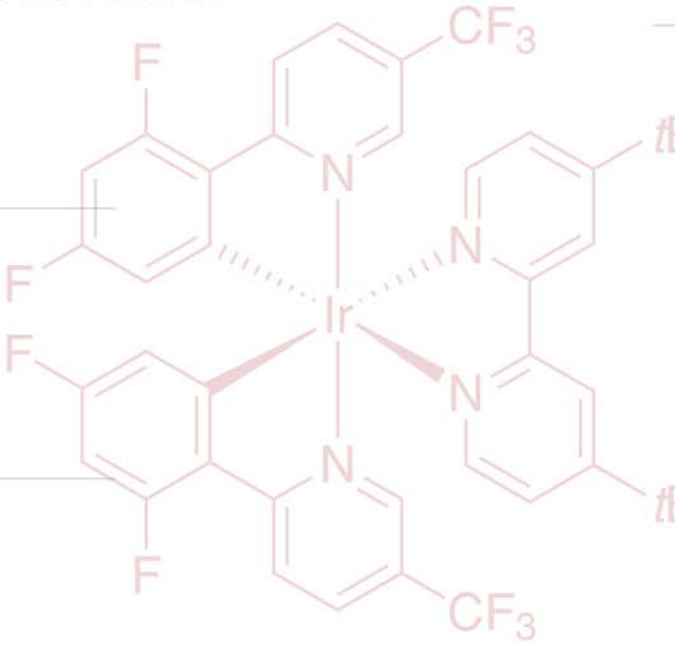

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P N O

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有机化学 DOI: 10.6023/cjoc201903003 研究论文
Chinese Journal of Organic Chemistry ARTICLE

氯化镍催化的过硫酸钠对芳烃苄位的氧化反应

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摘要 建立了一种实用的氧化芳烃侧链制备芳香族醛、酮的方法. 以过硫酸钠为氧化剂, 在氯化镍催化下, 甲苯类底物的苄位发生氧化反应, 得到芳香醛, 收率为 22%～79%. 乙苯类底物更容易发生反应得到芳香酮, 收率为 64%～84%. 苄基醇类底物的反应得到相应的羰基化合物, 并显示出更快的反应速度和更高的选择性和收率. 该反应条件温和, 无需贵金属参与和额外的促进剂, 选择性良好.

关键词 氧化; 芳烃; 苄醇; 氯化镍; 过硫酸钠

Nickel Chloride-Catalyzed Oxidation of Aromatic Hydrocarbon with Sodium Persulfate at the Benzylic Site

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([a] *College of Chemistry and Molecular Engineering, Nanjing Tech University, Nanjing 210036*)
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Abstract A practical method for the oxidation of aromatic side chains was established for the preparation of aromatic aldehydes and ketones. Using $NiCl_2$ as the catalyst, substituted toluenes were oxidized with $Na_2S_2O_8$ at the benzylic site for the synthesis of the corresponding aldehydes in the yield of 22%～79%. Ethylbenzene analogs were oxidized more easily to obtain the corresponding ketones with 64%～84% yields. The oxidation of benzyl alcohol analogs was completed to acquire the corresponding carbonyl compounds in shorter time with better selectivity and yields. The method has the advantages such as the mild reaction conditions, no requirement for precious metals or additional promoter, and good selectivity.

Keywords oxidation; aromatic hydrocarbon; benzyl alcohol; nickel chloride; sodium persulfate

芳香族羰基类化合物特别是芳香族醛酮, 作为基础中间体在医药、农药、染料等功能化学品的合成中都有着广泛的应用[1]. 工业上一般使用氯化苄基水解法与傅克酰基化反应生产醛、酮类化合物, 然而这两种工艺通常都伴随着卤化物的参与或生成, 对环境易造成严重的污染[2]. 传统的芳烃侧链氧化反应往往使用重金属氧化剂如重铬酸、高锰酸钾、二氧化锰等[3], 这些重金属氧化剂使用成本高, 收率一般, 三废严重, 难以在工业生产中获得应用.

近几十年来, 催化剂化学的发展, 尤其是基于金属催化的很多研究已到达分子水平, 低用量的金属催化体系可使很多传统的化学反应得到显著改进. 使用廉价氧源, 辅以合适的催化剂, 将来源丰富的碳氢化合物直接氧化成羰基化合物, 无疑是一种最简洁、最具原子经济性的途径. 因此, 芳烃侧链氧化合成芳香族醛、酮方法重新受到科学家的关注. 迄今为止, 许多氧源被报道应用于芳烃侧链的氧化反应. O_2 作为氧化剂具有廉价、易得、环境友好等特点, 近年来一直是芳烃侧链催化氧化的热点. 多种催化方法如过渡金属催化[4]、光催化[5]、仿生催化[6]、酶催化[7]等都已被开发, 但实际生产中, O_2 存在着对设备要求高、不易存储运输及有安全隐患等问题. O_3 虽然性质不稳定, 但相比 O_2 它的氧化能力更强, 在金属催化作用下也能较好地完成芳烃侧链氧化[8], 近些年关于它的文献也被报道. 如 Wang 等[8b]在 2009 年报道了在 Ti^{4+} 与 Ce^{4+} 的催化下利用 O_3 完成甲苯侧链氧化的反应. 除了 O_2 和 O_3 之外, 过氧化物是一类具有应用价值的氧源. 在金属催化、新型催化剂催化和(或)光促进条件下, 双氧水[9]、过氧化叔丁醇(TBHP)[10]、过硫酸

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Received March 2, 2019; revised April 18, 2019; published online April 26, 2019.

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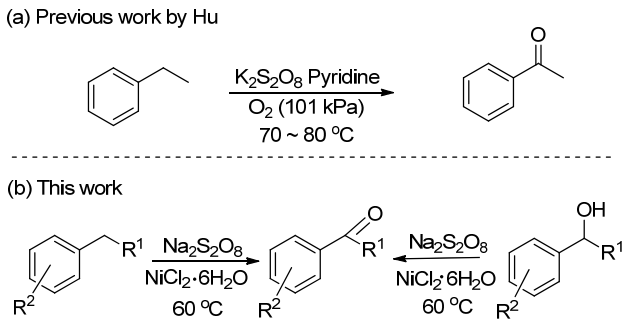
盐[11]等为代表的过氧化物对烷烃、烯烃或芳烃侧链具有良好的氧化选择性，也受到研究者的关注. 近期报道了非血红素锰[9c]、VO@g-C_3N_4[9d]、吡啶羧酸锰[9e]对双氧水氧化的促进作用；有机硒催化剂[10a]、氯化铜[10b]、锌钴金属有机骨架化合物(MOFs)材料[10c]、氮掺杂石墨烯材料[10d,10e]对 TBHP 氧化的促进作用；季鏻盐[11a]、吡啶[11b]、聚甲基氢硅氧烷[11c]对过硫酸盐氧化的促进作用. 相比其它氧化剂，过硫酸盐具有性质稳定及价格低廉等优点，此前的文献报道多以过硫酸钾为主，但相比过硫酸钾，过硫酸钠在水中有更好的溶解性[12]，无需相转移催化剂或其它促进剂. 本课题组在最近的甲苯胺羰基化反应基础上[13]，以过硫酸钠为氧化剂，研究了二价镍催化下芳香烃、苄醇类底物的侧链氧化反应，大多数底物具有较好的适应性，且选择性良好.



图式 1 芳烃与苄基醇的氧化

Scheme 1 Oxidation of aromatic hydrocarbons and benzyl alcohol

1 结果与讨论

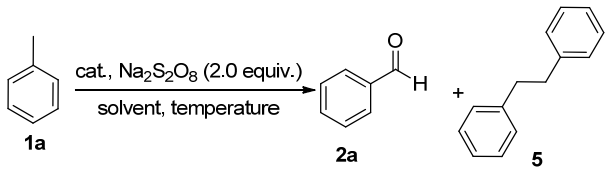
1.1 条件筛选

首先以甲苯为底物，乙腈-水混合液为溶剂，$Na_2S_2O_8$ 为氧化剂，固定甲苯(**1a**)/过硫酸钠投料比(物质的量比)为 1∶2，首先考察了在没有金属催化剂的条件下 **1a** 的氧化，反应 6 h 后 **1a** 也能生成 **2a** 但转化率较差(表 1, Entry 17). 接着考察了多种催化剂包括 $CuCl_2$, CuCl, $CoCl_2$, AgCl, $PdCl_2$, Ni_2SO_4, $NiCl_2 \cdot 6H_2O$, $Ni(acac)_2$ 对反应的影响(表 1, Entries 1～8). 从表中可以看出 $NiCl_2$ 的催化效果明显优于其它催化剂，**2a** 的分离收率达到 79%(表 1, Entry 8). 其它金属催化过程中，都发生不同程度的偶联反应，产生副产物联苄 **5**. 在很多苄位氧化反应中，联苄副产物能否得到控制是影响反应是否具有应用意义的关键性因素. 乙酰丙酮镍作为催化剂时，联苄副产最为严重(表 1, Entry 7). 硫酸镍与氯化镍相比，虽然产生联苄副产也较少，可能由于其在乙腈中的溶解及配位能力较差，催化活性较差 (表 1, Entry 6).

在确定催化剂后，对反应的其它条件进行了优化. 在乙腈或水单独作为溶剂时，都没有观察到 **2a** 的产生. 进一步考察了乙醇-水、*N*,*N*-二甲基甲酰胺-水、二氯乙烷-水等几种混合溶剂，发现都不利于 **2a** 的生成(表 1, Entries 9～13). 以上说明，**2a** 的生成与有机溶剂对金属的配位、溶解能力有关. 事实上，乙腈在许多金属催化的液相反应中充当良性溶剂，而在过硫酸盐的氧化反应中，水的必要性则来自于其对过硫酸盐的溶解能力. 降低反应温度，底物的转化速度慢；提高反应温度，底物的转化速度虽然提高，但选择性下降，**2a** 的产率降低(表 1, Entries 14～15). 对照试验表明，无金属催化时，虽然有 **2a** 产生，但底物转化率低(表 1, Entry 17).

表 1 甲苯氧化条件的优化 [a]

Table 1 Condition screening for the oxidation of toluene



Entry	Catalyst	Solvent	Temp./℃	Yield/%	
				2a[b]	**5**[c]
1	$CuCl_2$	MeCN-H_2O	60	23	32
2	CuCl	MeCN-H_2O	60	25	31
3	$CoCl_2$	MeCN-H_2O	60	37	27
4	AgCl	MeCN-H_2O	60	28	30
5	$PdCl_2$	MeCN-H_2O	60	36	29
6	Ni_2SO_4	MeCN-H_2O	60	54	Trace
7	$Ni(acac)_2$	MeCN-H_2O	60	13	42
8	$NiCl_2 \cdot 6H_2O$	MeCN-H_2O	60	79	Trace
9	$NiCl_2 \cdot 6H_2O$	H_2O	60	Trace	Trace
10	$NiCl_2 \cdot 6H_2O$	MeCN	60	Trace	Trace
11	$NiCl_2 \cdot 6H_2O$	EtOAc-H_2O	60	Trace	Trace
12	$NiCl_2 \cdot 6H_2O$	DMF-H_2O	60	Trace	Trace
13	$NiCl_2 \cdot 6H_2O$	DCE-H_2O	60	Trace	Trace
14	$NiCl_2 \cdot 6H_2O$	MeCN-H_2O	40	45	Trace
15	$NiCl_2 \cdot 6H_2O$	MeCN-H_2O	20	25	Trace
16	$NiCl_2 \cdot 6H_2O$	MeCN-H_2O	80	68	Trace
17	—	MeCN-H_2O	60	20	Trace

[a] **1a** (5.0 mmol), $Na_2S_2O_8$ (10.0 mmol), MeCN (5 mL), H_2O (5 mL), EtOAc (5 mL), DMF (5 mL), DCE (5 mL), catalyst (0.15 mmol); [b] Isolated yield of **2a**. [c] Isolated yield of **5**.

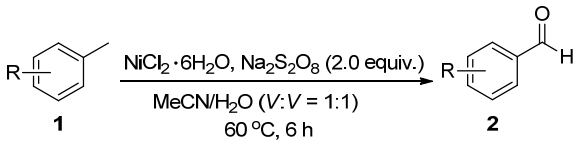
1.2 其它底物的反应

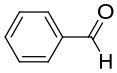
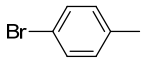
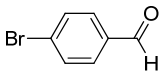
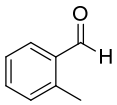
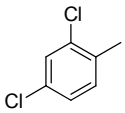
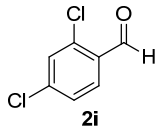
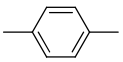
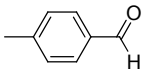
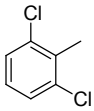
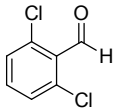
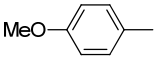
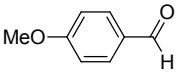
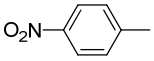
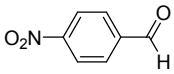
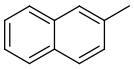
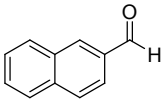
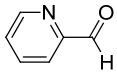
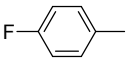
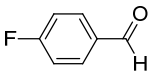
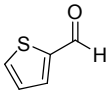
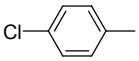
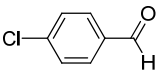
1.2.1 甲苯类化合物

在上述最优条件下(表 1, Entry 8)，考察了其它取代甲苯对该反应的适应性，反应结果见表 2. 当苯环上连有供电子基团化合物时，反应都在 6 h 内能完成，得到相应的芳香醛(表 2, Entries 1～5，产率 45%～79%)，其中邻二甲苯以及对二甲苯进行反应都未能检测到双氧化产物的产生，可能由于醛基的吸电子性抑制了邻对位甲基的反应活性. 卤素单取代甲苯底物反应也可以进行，获得中等收率产物(表 2, Entries 6～8，产率 53%～

表 2 甲苯类底物的氧化 [a]

Table 2 Oxidation of toluene analogs



Entry	1	2	Yield[b]/%	Entry	1	2	Yield[b]/%
1	**1a**	 **2a**	79	8	 **1h**	 **2h**	**67**
2	**1b**	 **2b**	72	9	 **1i**	 **2i**	34
3	 **1c**	 **2c**	68	10	 **1j**	 **2j**	**22**
4	 **1d**	 **2d**	62	11	 **1k**	 **2k**	30
5	 **1e**	 **2e**	45	12	**1l**	 **2l**	**37**
6	 **1f**	 **2f**	53	13	**1m**	 **2m**	39
7	 **1g**	 **2g**	53				

[a] Reaction conditions: **1** (5.0 mmol), $Na_2S_2O_8$ (10.0 mmol), MeCN (5 mL), H_2O (5 mL), $NiCl_2$•$6H_2O$ (0.15 mmol), 60 ℃ 6 h; [b] Isolated yield of **2**.

67%). 但当苯环上连有两个卤素尤其是存在于甲基邻位时, 反应收率显著下降(表 2, Entries 9～10, 产率 22%～34%). 当苯环上连有硝基时, 该氧化反应的产率也较低(表 2, Entry 11, 产率 30%). 此外, 甲基吡啶获得37%的收率(表2, Entry 12), 甲基噻吩获得了39%的收率(表 2, Entry 13).

1.2.2 其它芳香烃侧链的氧化

考察了乙苯、正丙苯等芳香烃侧链的氧化反应, 两者都产生相应的酮(表3), 而未发现联苄型副产. 有趣的是异丙苯在相同条件下则被氧化成苯乙酮(表 3, Entries 1～3, 产率 63%～84%), 相同的转化也曾被报道[14]. 无论乙苯的苯环连上何种类型的取代基都能以较高收率得到相应的苯乙酮(表 3, Entries 4～9, 产率 64%～78%). 相比于甲苯类底物, 苯环取代基电子效应对反应产生的影响较小, 这可能是因为亚甲基类底物的苄基游离基更为稳定, 也更容易生成. 这一点从底物**3d**的反应结果也得到证明(表 3, Entry 5): 仅得到对甲基苯乙酮产物(**4d**), 未发现有甲基氧化产物对乙基苯甲醛的产生.

1.2.3 苄醇类化合物反应

根据上述芳香烃氧化反应, 我们认为该氧化体系同样可应用于苄醇类物质的氧化. 减少一半过硫酸钠的用量, 以苄醇为底物的试验结果表明, 2 h 内苄醇转化率100%, 产物苯甲醛的分离收率可达到92%. 苯环上带有不同电子效应取代基的苄醇进行反应都可以完全转化,

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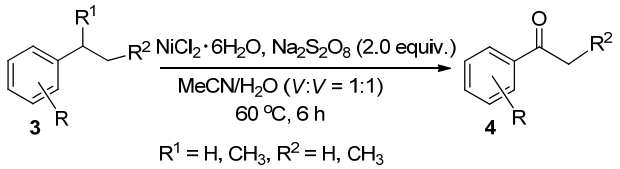
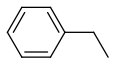
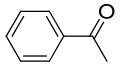
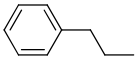
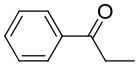
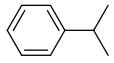
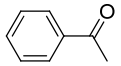
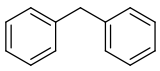
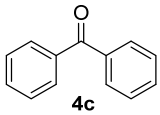
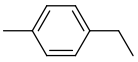
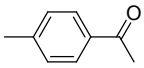
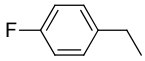
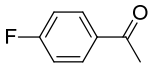
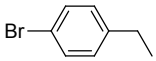
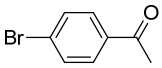
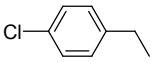
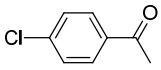
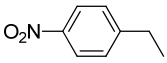
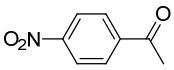
表 3 其它芳香烃的苄位氧化 [a]

Table 3 Oxidation of other arenes at the benzylic site



Entry	Structure **3**	Product **4**	Yield[b]/%
1	 **3a**	 **4a**	84
2	 **3b**	 **4b**	63
3	 **3c**	 **4a**	66
4	 **3d**	 **4c**	78
5	 **3e**	 **4d**	71
6	 **3f**	 **4e**	65
7	 **3g**	 **4f**	67
8	 **3h**	 **4g**	71
9	 **3i**	 **4h**	64

[a] Reaction conditions: **3** (5.0 mmol), $Na_2S_2O_8$ (10.0 mmol), MeCN (5 mL), H_2O (5 mL), $NiCl_2$•$6H_2O$ (0.15 mmol), 60 ℃, 6 h; [b] Isolated yield of **4**.

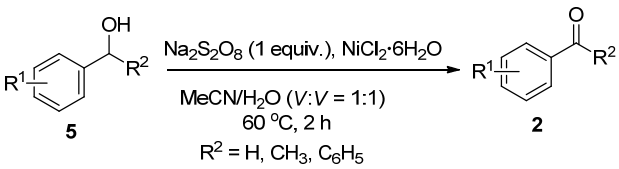
并以较高的产率得到相应的苯甲醛(表 4, Entries 1～6, 产率 75%～92%). 不同的仲式苄醇, 则得到相应的芳香酮(表 4, Entries 7～10, 产率 80%～92%). 该反应在未加催化剂的情况下, 也能完成反应, 但需要延长反应时间至 4 h. 说明金属对反应仍具有一定的促进作用.

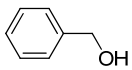
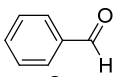
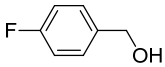
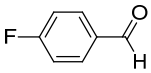
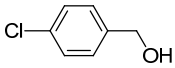
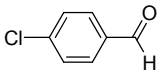
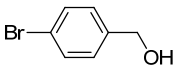
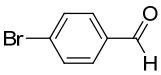
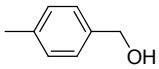
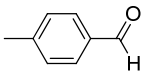
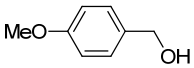
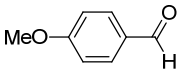
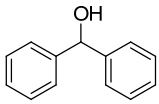
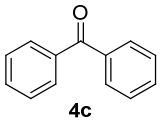
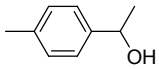
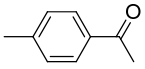
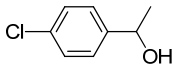
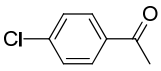
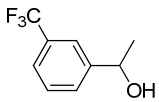
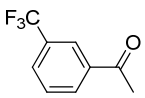
1.3 反应机理

结合相关文献及对照试验结果[15], 我们对芳香烃

表 4 苄醇类底物的氧化 [a]

Table 4 Oxidation of benzyl alcohol analogs



Entry	Structure	Product	Yield[b]/%
1	 **5a**	 **2a**	92
2	 **5b**	 **2f**	84
3	 **5c**	 **2g**	89
4	 **5d**	 **2h**	88
5	 **5e**	 **2c**	90
6	 **5f**	 **2d**	75
7	 **5g**	 **4c**	80
8	 **5h**	 **4d**	93
9	 **5i**	 **4g**	90
10	 **5j**	 **4i**	88

[a] Reaction conditions: benzyl alcohol analogs (5.0 mmol), $Na_2S_2O_8$ (5.0 mmol), MeCN (5 mL), H_2O (5 mL), $NiCl_2$•$6H_2O$ (0.15 mmol), 60 ℃, 2 h; [b] Isolated yield of the product.

类苄位氧化反应机理进行了推测(Scheme 2). 无催化剂时, 甲苯氧化可产生微量的苯甲醛(表 1, Entry 17), 说明

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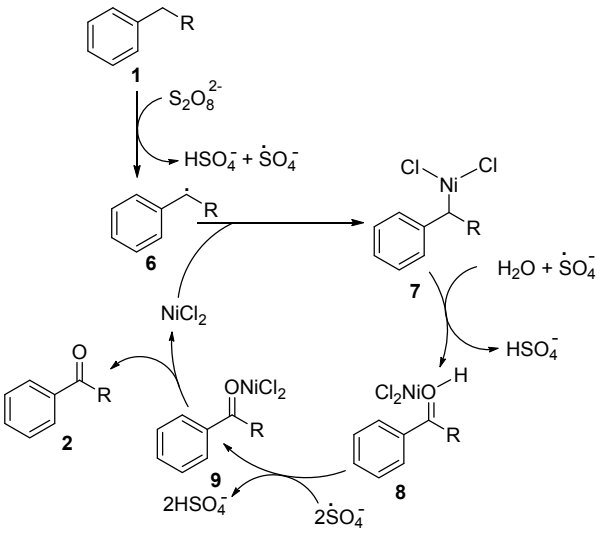
首先是过氧化物分解游离基负离子, 与底物 **1** 作用产生苄位游离基 **6**, 氯化镍与苄基游离基发生作用, 形成苄基镍(III)中间体 **7**. **7** 与水作用形成相应的醇氯化镍复合物 **8**. **8** 与氧化剂快速作用, 产生复合物 **9**, 进一步分解出催化剂及氧化终产物. 对苄醇进行的无催化剂的对照试验结果也表明, 催化剂对苄醇氧化虽有促进反应速度的作用, 其它方面没有显著差别, 说明醇与镍的作用可能为弱作用.



图式 2 可能的反应机理

Scheme 2 Probable mechanism of the oxidation

2 结论

以 $Na_2S_2O_8$ 为氧化剂、MeCN-H_2O 作溶剂、$NiCl_2$ 为催化剂建立了一种高效的芳烃、苄基醇氧化方法, 用于制备芳香族醛、酮类化合物. 该方法操作简易, 催化剂廉价, 在实验室及工业生产上都具有应用价值.

3 实验部分

3.1 仪器与试剂

^{1}H NMR 和 ^{13}C NMR 用 Bruker AV-400 进行分析, 以 TMS 为内标, $CDCl_3$ 作溶剂; 高分辨质谱使用沃特世 XEVO G2-XS QTOF 仪器测定, $CHCl_3$ 作溶剂; 熔点用 X-4 精密显微熔点测定仪测定. 所有药品和试剂均为市售的分析纯或化学纯, 除特别说明外, 未经进一步处理.

3.2 实验方法

3.2.1 芳香烃侧链的氧化

在反应瓶中, 依次加入水(5 mL)、乙腈(5 mL)、$NiCl_2$•$6H_2O$ (0.15 mmol)、甲苯(5.0 mmol). 搅拌均匀后, 加入 $Na_2S_2O_8$ (10.0 mmol), 加热至 60 ℃下反应 6 h. 薄层色谱(TLC)结合气相色谱跟踪反应进程, 待反应完全后, 减压蒸馏除乙腈, 用二氯甲烷萃取(15 mL×3), 合并有机相, 用饱和食盐水洗, 无水 Na_2SO_4 干燥, 减压蒸馏, 除去溶剂. 剩余物用硅胶柱层析[V(乙酸乙酯)∶V(石油醚)=1∶100]分离, 得到目标产物 **2a**.

化合物 **2b**～**2m**, **4a**～**4h** 按化合物 **2a** 的方法合成.

苯甲醛(**2a**): 无色液体, 产率 79%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.99 (s, 1H), 7.90～7.80 (m, 2H), 7.62～7.54 (m, 1H), 7.52～7.46 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 192.47, 136.39, 134.51, 129.76, 129.02; HRMS (ESI) calcd for C_7H_7O $[M+H]^+$ 107.0497, found 107.0486.

2-甲基苯甲醛(**2b**): 无色液体, 产率 70%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.25 (s, 1H), 7.78 (dd, J=7.6, 1.5 Hz, 1H), 7.46 (td, J=7.5, 1.6 Hz, 1H), 7.39～7.31 (m, 1H), 7.25 (d, J=7.5 Hz, 1H), 2.66 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 192.88, 140.54, 134.05, 133.65, 132.03, 131.73, 126.28, 19.44; HRMS (ESI) calcd for C_8H_9O $[M+H]^+$ 121.0653, found 121.0656.

4-甲基苯甲醛(**2c**): 无色液体, 产率 60%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.96 (s, 1H), 7.78 (d, J=8.1 Hz, 2H), 7.33 (d, J=7.8 Hz, 2H), 2.44 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 192.07, 145.59, 134.19, 129.87, 129.73, 21.90; HRMS (ESI) calcd for C_8H_9O $[M+H]^+$ 121.0653, found 121.0637.

4-甲氧基苯甲醛(**2d**): 无色液体, 产率 62%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.66 (s, 1H), 7.74～7.52 (m, 2H), 6.91～6.63 (m, 2H), 3.62 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 190.59, 164.46, 131.72, 129.74, 114.14, 55.28; HRMS (ESI) calcd for $C_8H_9O_2$ $[M+H]^+$ 137.0603, found 137.0582.

1-萘甲醛(**2e**): 无色液体, 产率 45%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.15 (s, 1H), 8.32 (d, J=1.4 Hz, 1H), 8.06～7.83 (m, 4H), 7.69～7.51 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 192.31, 136.47, 134.62, 134.12, 132.65, 129.55, 129.15, 129.12, 128.11, 127.12, 122.77; HRMS (ESI) calcd for $C_{11}H_9O$ $[M+H]^+$ 157.0653, found 157.0639.

4-氟苯甲醛(**2f**): 淡黄色液体, 产率 53%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.81 (s, 1H), 7.83～7.67 (m, 2H), 7.12～6.97 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 190.37, 167.56, 165.01, 132.95, 132.09, 132.00, 116.21, 115.98; HRMS (ESI) calcd for C_7H_6FO $[M+H]^+$ 125.0403, found 125.0408.

4-氯苯甲醛(**2g**): 白色固体, 产率 53%. m.p. 49～51 ℃ (lit.[16] 45～47 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.98 (s, 1H), 7.82 (dd, J=8.6, 2.1 Hz, 2H), 7.48～7.54 (m,

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2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 190.87, 140.93, 134.71, 130.90, 129.44; HRMS (ESI) calcd for C_7H_6ClO $[M+H]^+$ 141.0107, found 141.0077.

4-溴苯甲醛(**2h**): 淡黄色固体, 产率 88%. m.p. 57～59 ℃ (lit.[16] 55～57 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.98 (s, 1H), 7.78～7.73 (m, 2H), 7.71～7.67 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 191.11, 135.06, 132.46, 130.99, 129.80; HRMS (ESI) calcd for C_7H_6BrO $[M+H]^+$ 184.9602, found 184.9595.

2,4-二氯苯甲醛(**2i**): 淡黄色固体, 产率 34%. m.p. 68～70 ℃ (lit.[17] 64～66 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.40 (s, 1H), 7.86 (d, J=8.4 Hz, 1H), 7.46 (d, J=2.0 Hz, 1H), 7.34～7.40 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 188.39, 141.05, 138.48, 130.91, 130.41, 130.29, 127.93. HRMS (ESI) calcd for $C_7H_5Cl_2O$ $[M+H]^+$ 174.9717, found 174.9734.

2,6-二氯苯甲醛(**2j**): 白色固体, 产率 22%. m.p. 62～64 ℃ (lit.[18] 66～68 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.47 (s, 1H), 7.38～7.40 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 188.81, 136.86, 133.61, 130.44, 129.77, 128.49, 128.29; HRMS (ESI) calcd for $C_7H_5Cl_2O$ $[M+H]^+$ 174.9717, found 174.9726.

4-硝基苯甲醛(**2k**): 淡黄色液体, 产率 30%.^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.18 (s, 1H), 8.41 (d, J=7.8 Hz, 2H), 8.20～8.02 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 190.35, 151.13, 140.06, 130.50, 124.32, 77.39, 77.27, 77.07, 76.75.

2-吡啶甲醛(**2l**): 黄色液体, 产率 37%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.12 (s, 1H), 8.90～8.74 (m, 1H), 8.03～7.85 (m, 2H), 7.65～7.49 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 193.30, 152.66, 150.12, 137.05, 127.85, 121.64; HRMS (ESI) calcd for C_6H_6NO $[M+H]^+$ 108.0449, found 108.0419.

2-噻吩甲醛(**2m**): 黄色液体, 产率 39%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.93 (s, 1H), 7.87～7.71 (m, 2H), 7.26～7.18 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 183.09, 143.93, 136.59, 135.19, 128.44; HRMS (ESI) calcd for C_5H_5OS $[M+H]^+$ 113.0061, found 113.0027.

苯乙酮(**4a**): 淡黄色液体, 产率 84%(以异丙苯为底物制备时产率为 66%). ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.99～7.92 (m, 2H), 7.60～7.51 (m, 1H), 7.49～7.40 (m, 2H), 2.59 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 198.16, 137.09, 133.12, 128.58, 128.31, 26.62; HRMS (ESI) calcd for C_8H_9O $[M+H]^+$ 121.0653, found 121.0644.

1-苯基-1-丙酮(**4b**): 淡黄色液体, 产率 63%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.98～7.91 (m, 2H), 7.55～7.49 (m, 1H), 7.45～7.39 (m, 2H), 2.97 (q, J=7.2 Hz, 2H), 1.20 (t, J=7.3 Hz, 3H).; ^{13}C NMR (101 MHz, $CDCl_3$) δ: 199.77, 136.65, 132.47, 128.24, 127.62, 31.29, 7.81; HRMS (ESI) calcd for $C_9H_{11}O$ $[M+H]^+$ 135.0810, found 135.0788.

二苯甲酮(**4c**): 白色固体, 产率 78%. m.p. 48～52 ℃ (lit.[16] 47～52 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.77～7.72 (m, 4H), 7.52～7.45 (m, 2H), 7.41～7.35 (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.41, 137.57, 132.42, 130.01, 128.31; HRMS (ESI) calcd for $C_{13}H_{11}O$ $[M+H]^+$ 183.0810, found 183.0799.

4-甲基苯乙酮(**4d**): 白色固体, 产率 71%. m.p. 48～50 ℃ (lit.[19] 46～48 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.85 (d, J=8.2 Hz, 2H), 7.26～7.22 (m, 2H), 2.56 (s, 3H), 2.40 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 197.84, 143.87, 134.69, 129.23, 128.43, 26.50, 21.60; HRMS (ESI) calcd for $C_9H_{11}O$ $[M+H]^+$ 135.0810, found 135.0794.

4-氟苯乙酮(**4e**): 无色液体, 产率 65%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.82～7.72 (m, 2H), 6.96～7.72 (m, 2H), 2.45 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.23, 166.84, 164.31, 133.48, 130.86, 130.76, 115.54, 115.32, 26.23; HRMS (ESI) calcd for C_8H_8FO $[M+H]^+$ 139.0559, found 139.0559.

4-溴苯乙酮(**4f**): 淡黄色固体, 产率67%. m.p. 112～114 ℃ (lit.[20] 116～118 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.80～7.74 (m, 2H), 7.57～7.50 (m, 2H), 2.55 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.66, 135.69, 131.72, 129.75, 128.09, 26.41.

4-氯苯乙酮(**4g**): 黄色固体, 产率 71%. m.p. 62～64 ℃ (lit.[21] 63～65 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.82～7.53 (m, 2H), 7.40～6.95 (m, 2H), 2.42 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.39, 139.26, 135.29, 129.60, 128.68, 26.34; HRMS (ESI) calcd for C_8H_7ClONa $[M+Na]^+$ 177.0083, found 177.0095.

4-硝基苯乙酮(**4h**): 黄色固体, 产率 64%. m.p. 70～72 ℃ (lit.[20] 92～93 ℃); ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.36～8.27 (m, 2H), 8.19～8.09 (m, 2H), 2.73 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 197.02, 139.71, 135.53, 129.87, 129.03, 26.73; HRMS (ESI) calcd for $C_8H_8NO_3$ $[M+H]^+$ 166.0504, found 166.0509.

3.2.2 苄基醇的氧化

在反应瓶中, 依次加入水(5 mL)、乙腈(5 mL)、$NiCl_2$•$6H_2O$ (0.15 mmol)、苯甲醇(5.0 mmol), 在搅拌均匀后, 加入 $Na_2S_2O_8$ (5.0 mmol), 加热至 60 ℃, 避光条

件下搅拌 2 h. TLC 结合气相色谱跟踪反应进程, 待反应完全后, 减压蒸馏除乙腈, 用二氯甲烷萃取(15 mL×3), 合并有机相, 用饱和食盐水洗, 无水 Na_2SO_4 干燥, 减压蒸馏, 除去溶剂. 剩余物用硅胶柱层析[*V*(乙酸乙酯)∶*V*(石油醚)=1∶100]分离, 得到目标产物 3-三氟甲基苯乙酮(**4i**): 产率 88%. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.12～7.95 (m, 2H), 7.73～7.60 (m, 1H), 7.54～7.42 (m, 1H), 2.52 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ: 196.30, 137.42, 131.35, 131.08, 130.75, 129.17, 124.99, 124.76, 122.28, 26.12; ^{19}F NMR (400 MHz, $CDCl_3$) δ: −63.99; HRMS (ESI) calcd for $C_9H_8F_3O$ $[M+H]^+$ 189.0527, found 189.0558.

辅助材料(Supporting Information) 化合物 **2a**～**2m** 和 **4a**～**4i** 的 ^{1}H NMR, ^{13}C NMR 及 ^{19}F NMR 谱. 这些材料可以免费从本刊网站(http://sioc-journal.cn/)上下载.

References

[1] (a) Sheldon, R. A.; Kochi, J. K. *Metal Catalyzed Oxidations of Organic Compounds*, Academic Press, New York, **1981**.
(b) Trost, B. M.; Fleming, I. *Comprehensive Organic Synthesis* (*Oxidation*), Pergamon, New York, **1991**, Vol. 7.
(c) Zhang, J. T.; Wang, Z. T.; Wang, L.; Wan, C. F.; Zheng, X. Q.; Wang, Z. Y. *Green. Chem.* **2009**, *11*, 1973.

[2] Rao, K. T. V.; Rao, P. S. N.; Nagaraju, P.; Prasad, P. S. S.; Lingaiah, N. *J. Mol.* **2009**, *303*, 84.

[3] (a) Anastas, P.; Eghbali, N. *Chem. Soc. Rev.* **2010**, *39*, 301.
(b) Yiu, S. M.; Wu, Z. B.; Mak, C. K.; Lau, T. C. *J. Am. Chem. Soc.* **2004**, *126*, 14921.
(c) Hudlicky, M. *Oxidations in Organic Chemistry*, American Chemical Society, Washington, DC, **1990**.

[4] (a) Punniyamurthy, T.; Velusamy, S.; Iqbal, J. *Chem. Rev.* **2005**, *105*, 2329.
(b) Shi, Z. Z.; Zhang, C.; Tang, C. H.; Jiao, N. *Chem. Soc. Rev.* **2012**, *41*, 3381.
(c) Collins, T. J.; Ryabov, A. D. *Chem. Rev.* **2017**, *117*, 9140.
(d) Yang, Z. F.; Zhang, H.; Liu, X. R.; Wang, B.; Lutz, A. *Chin. J. Org. Chem.* **2019**, *39*, 59 (in Chinese).
(杨帆致, 张晗, 刘旭日, 王博, Lutz Ackermann, 有机化学, **2019**, *39*, 59.)

[5] (a) Ohkubo, K.; Fukuzumi, S. *Org. Lett.* **2000**, *2*, 3647.
(b) Kei, O.; Kyou, S.; Kohei, M.; Shunichi, F. *J. Am. Chem. Soc.* **2003**, *125*, 12850.
(c) Pahari, S. K.; Pal, P.; Srivastava, D. N.; Ghosh, S. C.; Panda, A. B. *Chem. Commun.* **2015**, *51*, 10322.
(d) Li, S. L.; Zhu, B.; Lee, R.; Qiao, B. K.; Jiang, Z. Y. *Org. Chem. Front.* **2018**, *5*, 380.

[6] (a) Jr, L. Q.; Tolman, W. B. *Nature* **2008**, *455*. 333.
(b) Rickert, A.; Krombach, V.; Hamers, O.; Zorn, H.; Maison, W. G. *Green Chem.* **2012**, *14*, 639.
(c) Roiban, G. D.; Agudo, R.; Reetz, M. T. *Angew. Chem., Int. Ed.* **2014**, *53*, 8659.
(d) Nastri, F.; Chino, M.; Maglio, O.; Damodaran, A. B.; Lu, Y.; Lombardi, A. *Chem. Soc. Rev.* **2016**, *45*, 5020.

[7] (a) Nam, W. *Acc. Chem. Res.* **2007**, *40*, 522.
(b) Ding, Z. D.; Zhu, W.; Li, T.; Shen, R.; Li, Y. X.; Li, Z. J.; Ren, X. H.; Gu, Z. G. *Dalton Trans.* **2017**, *46*, 11372.

[8] (a) Qi, J. Y.; Ma, H. X.; Li, X. J.; Zhou, Z. Y.; Choi, M. C. K.; Chan, A. S. C.; Yang, Q. Y. *Chem. Commun.* **2003**, 1294.
(b) Wang, B.; Mao, W.; Ma, H. Z. *Ind. Eng. Chem. Res.* **2009**, *48*, 440.
(c) Potapenko, E. V.; Andreev, P. Y. *Russ. J. Appl. Chem.* **2011**, *84*, 984.

[9] (a) Lane, B.-S.; Burgess, K. *Chem. Rev.* **2003**, *103*, 2457.
(b) Wang, Y.; Li, H. R.; Yao, J.; Wang, X. C.; Antoniettia, M. *Chem. Sci.* **2011**, *2*, 446.
(c) Shen, D. Y.; Miao, C. X.; Wang, S. F.; Xia, C. G.; Sun, W. *Org. Lett.* **2014**, *16*, 1108.
(d) Verma, S.; Baig, R. B. N.; Nadagouda, M. N.; Varma, R. S. *ACS Sustainable Chem. Eng.* **2016**, *4*, 2333.
(e) Saisaha, P.; Dong, J. J.; Meinds, T. G.; Johannes, W.; Hage, R.; Mecozzi, F.; Kasper, J. B.; Browne, W. R. *ACS Catal.* **2016**, *6*, 3486.
(f) Konstantin, P.; Bryliakov *Chem. Rev.* **2017**, *117*, 11406.

[10] (a) Halina, W.; Soroko, G.; Jacek, M. *Synth. Commun.* **2008**, *38*, 2000.
(b) Hossain, M. M.; Shyu, S. G. *Tetrahedron* **2016**, *72*, 4252.
(c) Xu, W. X.; Zhang, Z. Q.; Zhao, X.; Li, *J. Coord. Chem.* **2017**, *70*, 746.
(d) Chen, Y.; Jie, S. S.; Yang, C. Q.; Liu, Z. G. *Appl. Surf. Sci.* **2017**, *419*, 98.
(e) Sun, Q.; Song, X. Y.; Gao, L.; Chen, W.; Li, Y.; Mao, L.; Yang, J. H. *Chem. Pap.* **2018**, *72*, 2203.

[11] (a) Badri, R.; Adlu, M.; Mohammadi, M. K. *Arabian J. Chem.* **2015**, *8*, 62.
(b) Hu, Y. X.; Zhou, L. H.; Lu, W. J. *Synthesis* **2017**, *49*, 4007.
(c) Han, W.; Zhao, H. Y. *CN 107216242*, **2017** [*Chem. Abstr.* **2017**, *167*, 528688].

[12] Jakob, H.; Leininger, S.; Lehmann, T.; Jacobi, S.; Gutewort, S. *Ullmann's Encyclopedia of Industrial Chemistry*, Weinheim, W. C. Germany, **2012**, Vol. 26, p. 308.

[13] Li, Y. F.; Zhang, H.; Dai, C. W.; Liu, L. C.; Ma, H. F.; Pu, H. Z. *Tetrahedron* **2018**, *74*, 3712.

[14] Lin, X.; Nie, Z. Z.; Zhang, L. Y.; Mei, S. C.; Chen, Y. *Green Chem.* **2017**, *19*, 2164.

[15] Zhang, B. S.; Zhu, R. L.; Liu, Z. G.; Xin, L.; Zhang, J. S. *Org. Chem. Front.* **2016**, *3*, 1326.

[16] Guo, T. F.; Gao, Y.; Li, Z. J.; Liu, J. J.; Guo, K. *Synlett* **2019**, *30*, 329.

[17] Gholizadeh, M.; Baltork, I. M. *Bull. Korean Chem. Soc.* **2005**, *26*, 11.

[18] Castle, R. N.; Riebsomer, J. L. *ACS Sustainable Chem. Eng.* **1955**, *21*, 142.

[19] Richard, R. B.; Louise, J. B. *J. Anal. Appl. Pyrolysis* **2004**, *71*, 223.

[20] Cui, L. Q.; Liu, K.; Zhang, C. *Org. Biomol. Chem.* **2011**, *9*, 2258.

[21] Kaneyuki, H. *Bull. Chem. Soc. Jpn.* **1961**, *35*, 519.

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