Ionic liquid and microwave assisted dehydration of arylalkanols into (E)-arylalkenes under neutral condition

1.1 Introduction:
In chemistry, a dehydration reaction is usually defined as a chemical reaction that involves the loss of water molecule from the reacting species. Thus this reaction belongs to a subset of elimination reactions. Dehydration constitutes one of the important steps of several classical transformations like aldol condensation [March (2001)], Knoevenagel-Doebner condensation [Dale and Hennis (1958)] and Perkin condensation [Solladie et al. (2003)]. Recently, dehydration has emerged as a pivotal element to design conceptually newer cross coupling strategies enabling formation of carbon-carbon bond [Kang et al. (2010)].

1.1.1 Dehydration of alcohols:
Dehydration of alcohols is one of the fundamental and extensively exploited transformations in organic synthesis due to the immense biological importance and synthetic utility of ensuing alkenes [Popławski et al. (2000); Joshi et al. (2005)]. For instance, (E)-arylalkenes have found various applications in the field of pharmaceutical, cosmetics and essential oils etc [Harborne et al. (1999); Sharma (2006)]. In addition, a number of styrenes and polycyclic arylalkenes have been recognized to be important synthons for various bioactive stilbenoids [Alonso et al. (2005)] as well as commercial nonsteroidal anti-inflammatory drugs (NSAID’s) like Naproxen [Kim and Alper (2005); Sinha et al. (2010)] as discussed below:

1.2 Importance of (E)-arylalkenes:
1.2.1 Biological activity of (E)-arylalkenes:
Various methoxylated (E)-arylalkenes are known to be active hypolipidemic agents besides possessing antiplatelet, anticholeretic and antifungal activities [Harborne et al. (1999)]. For instance, Popławski et al. evaluated a series of α-asarone (trans-2,4,5-trimethoxy-1-phenylpropene) isomers for their hypolipidemic and antiplatelet activities [Popławski et al. (2000)]. Results show that α-asarone (1) and related compound 2 (Figure 1) produced significant antithrombotic effects, whereas, compound 3 (Figure 1) was active agent elevating the HDL cholesterol level and lowering the LDL cholesterol level.
Recently, anticonvulsant activity of \(\alpha\)-asarone in mouse model has also been reported [Pages \textit{et al.} (2010)]. In the same vein, phenylbutenes such as \((E)\)-4-(2,4,5-trimethoxyphenyl)but-1-ene and \((E)\)-(2,4,5-trimethoxyphenyl)but-1,3-diene have been found to possess antioxidant, anti-inflammatory and hypolipidemic activities [Jitoe \textit{et al.} (1992); Cruz \textit{et al.} (2001)]. On the other side, phenylethenes such as 4-hydroxy-3-methoxystyrene (4-vinylguaiacol) and 4-hydroxy styrene are well known FEMA GRAS approved flavoring agents [Crouzet \textit{et al.} (1997)] as also mentioned earlier in the introduction (page no 4, section 1.2.1.1.1).

1.2.2 Synthetic applications of arylalkenes:

1.2.2.1 Precursors of nonsteroidal anti-inflammatory drugs:

Kim \textit{et al.} disclosed an efficient conversion of styrenes into respective \(\alpha\)-arylaldehydes via regioselective hydroformylation approach using a diamine rhodium catalyst (Scheme 1) [Kim and Alper (2005)]. These \(\alpha\)-arylaldehydes on further oxidation can be converted into NSAID like Naproxen [Dvorak (1983)].

1.2.2.2 Precursors of bioactive neolignans:

Arylalkenes have also found widespread applications in total synthesis of bioactive neolignans [Sharma (2006)]. For instance, \(\alpha\)-asarone has been utilized for the synthesis of magnoshinin (an anti-inflammatory neolignan) \textit{via} a photochemical reaction in the presence of electron acceptor (Scheme 2) [Kadota \textit{et al.} (1987)].
In addition, various arylalkenes also act as starting materials for the synthesis of biologically and industrially important compounds such as benzaldehydes, cinnamaldehydes and stilbenoids etc as mentioned earlier in the introduction sections 1.2.1.1.1 (page 4) and 1.2.1.2.1 (page 6).

**1.3 Reported methods for the dehydration of alcohols:**
In view of the wide utility of arylalkenes as illustrated above, there has been an upsurge of interest in developing newer dehydration approaches for their synthesis. A brief description of some prevalent dehydration methodologies is given below:

**1.3.1 Acidic catalysts for dehydration of alcohols:**
Conventional protocols for dehydration of alcohols include protic acid catalysts such as H$_2$SO$_4$, H$_3$PO$_4$, PTSA [Alonso et al. (1997); March (2001); Lee et al. (2005)] etc. In addition, various other dehydrating agents like ZnCl$_2$, PCl$_5$, P$_2$O$_5$, POCl$_3$ and activated Si-gel under solvent less conditions etc have been studied for the above transformation [Larock (1989); March (2001)]. For instance, POCl$_3$/pyridine reagent system has been utilized for the synthesis of bioactive $\alpha$-asarone via dehydration of corresponding alcohol [Diaz et al. (1991)]. However, the authors got poor yield of the desired product besides formation of dimer as a side product (Scheme 3).
The above reagent system i.e. POCl₃/pyridine was further investigated for the dehydration of various allylic alcohols into conjugated alkenes (Scheme 4) [Runk et al. (1992)]. However, the method provided moderate yield of desired products along with tedious work up involving quenching of excess POCl₃ with aqueous sodium bicarbonate.

In another report, dehydration of tertiary alcohols has been achieved by employing silica chloride (SiO₂-Cl) as a heterogeneous catalyst (Scheme 5) [Firouzabadi et al. (2003)]. For comparison purpose, the dehydration was also performed with trimethylsilyl chloride (TMSCl). Thus it was found that SiO₂-Cl provided better reaction performance as compared to TMSCl besides easy handling of SiO₂-Cl based reagent.

Lee et al. reported the dehydration of benzylic alcohols into corresponding arylalkenes using p-toluenesulfonic acid (PTSA) as a catalyst and toluene as a solvent (Scheme 6) [Lee et al. (2005)].
Above dehydration catalyst i.e. PTSA was further utilized by Zhang et al. for efficient synthesis of 4,7-dimethoxy-1(H)-indene by the dehydration of corresponding alcohol [Zhang et al. (2007)]. Similarly, PTSA adsorbed on silica gel was used as a catalyst for the dehydration of a number of important alcohols like steroids [D’Onofrio and Scettri (1985)]. Apart from the above methods, various other dehydrating agents such as modified alumina at elevated temperature (200°C or higher) [Becker and Sargis (1970)], methanesulfonyl chloride [Melton and Murry (1975)], dinitrobenzenesulfenyl chloride [Reich et al. (1978)], triester of phosphoric acid [Himmele et al. (1990)], BF₃.OEt₂ [Posner et al. (1991)], oxalyl chloride [Gleiter et al. (1996)] and solid acid catalysts including zeolites [Takahara et al. (2005); Lange and Otten (2006)] have been studied for dehydration of alcohols. Also, some reports disclosing DMSO [Vincent et al. (1962, 1964)] mediated dehydration of benzylic alcohols have been furnished in literature. However, most of the above methodologies are limited by low to moderate yield of products besides generation of lot of waste during work up.

1.3.2 Metal catalysts/salts for dehydration of alcohols:
The dehydration of benzylic alcohols was achieved using methylrhenium trioxide (CH₃ReO₃ or MTO) in dry benzene at room temperature (Scheme 7) [Zhu and Espenson (1996)].

![Scheme 7](image)

Similarly, various copper based reagents such as anhydrous CuSO₄ [Hoffman et al. (1980); Popławski et al. (2000)], copper (II) triflate [Laali et al. (1987)], Si-gel/CuSO₄ [Nishiguchi et al. (1987)], CuCl-DCC [Majetich et al. (1999)], EDC-CuCl₂ [Sai et al. (2003, 2007)] etc have been studied for the dehydration of alcohols.

For instance, Kurata et al. reported the dehydration of tetrathienylallyl alcohol via prolonged refluxing with anhydrous CuSO₄ to form tetrakis (2-thienyl) allene (Scheme 8) [Kurata et al. (1998)].
Similarly, CuSO₄ in toluene has been used for the dehydration of various benzylic alcohols (Scheme 9) [Poplawski et al. (2000)]. However, authors have not disclosed the yield of (E)-phenylpropenes. The resulting phenylpropenes were tested in vitro for hypolipidemic and antiplatelet activities.

Majetich et al. reported the dehydration of benzylic and tertiary alcohols using a catalytical amount of CuCl and DCC in THF [Majetich et al. (1999)]. The in situ formed pseudourea complex on heating at 90°C provided the corresponding arylalkenes along with 1,3-dicyclohexylurea (DCU) as a by product (Scheme 10). However, in some cases, authors have observed the formation of ether (side product) as the sole product as mentioned below:
Zhang et al. disclosed a chiral palladacycle catalyzed dehydration as well as kinetic resolution of 1-hydroxy-2-aryl-1,2-dihydronaphthalenes (Scheme 11). The method provided the optically active products in 35-43% yields with 84-99% ee [Zhang et al. (2008)].

Scheme 11

Recently, Korstanje et al. studied the dehydration of benzylic alcohols to corresponding olefins using a rhenium-based Re$_2$O$_7$ catalyst in toluene (Scheme 12). This catalyst was found superior to H$_2$SO$_4$, a commonly used protic acid catalyst for above transformation [Korstanje et al. (2010)].

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Re$_2$O$_7$ GC Conversion [%]</th>
<th>Olefin yield [%]</th>
<th>H$_2$SO$_4$ GC Conversion [%]</th>
<th>Olefin yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Re$_2$O$_7$ (0.5 mol%) or H$_2$SO$_4$ (2.5 mol%) toluene, 24 h, 100°C</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OH</td>
<td>&gt;99</td>
<td>98</td>
<td>&gt;99</td>
<td>39</td>
</tr>
<tr>
<td>OH</td>
<td>&gt;99</td>
<td>&gt;99</td>
<td>&gt;99</td>
<td>&gt;99</td>
</tr>
<tr>
<td>OH</td>
<td>&gt;99</td>
<td>90</td>
<td>&gt;99</td>
<td>76</td>
</tr>
<tr>
<td>OH</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Scheme 12
1.3.3 Iodine based reagents for dehydration of alcohols:
Dorta et al. reported triphenylbismuth dibromide and iodine (Ph₃BiBr₂-I₂) reagent system for the dehydration of tertiary alcohols (Scheme 13) under an inert atmosphere of argon [Dorta and Suárez (1994)].

![Scheme 13]

In another instance, PPh₃-I₂ combination has been used to promote the regioselective dehydration of tertiary alcohols [Manzaneda et al. (2004)]. However, in case of primary OH group iodination occurred (Scheme 14).

![Scheme 14]

Similarly, molecular iodine (I₂) catalyzed dehydration of various tertiary alcohols into corresponding alkenes has been achieved under solvent-free condition (Scheme 15) [Stavber et al. (2006)]. However, in case of 2-phenylpropane-2-ol (3° alcohol) dehydration followed by cyclodimerisation led to the formation of indane type of product. On the other side, primary and secondary benzyl alcohols under similar reaction condition provided the corresponding ethers (Scheme 15).
From the above discussion, it is clear that a majority of reported protocols for dehydration continue to be afflicted with perennial limitations like lack of generality, formation of side products, employment of expensive, moisture sensitive and toxic catalysts, long reaction times besides the usage of harsh Bronsted/Lewis acids which not only precludes their use with substrates possessing sensitive functional groups but also leads to deleterious environmental impact. In particular, the controlled dehydration of benzyl alcohols into corresponding \((E)\)-arylalkene derivatives has remained a difficult proposition due to the preponderant tendency of incipient benzylic carbocation to participate in competing side reactions and thus leading to the formation of several side products including dimer, polymer or ether type of side products etc (Figure 2) [Majetich et al. (1999); Alesso et al. (2003); Lantano et al. (2004)]. In addition, some of the above protocols result in the formation of a little unwanted toxic \(cis\)-isomer which in turn requires tedious chromatographic separation owing to similar \(R_f\) values of both isomers (cis & trans) [Gates and Swenton (1992); Kim et al. (1999)].

1.4 Green Chemistry context: Use of ionic liquids
A currently rapidly developing area in organic synthesis concerns the design and usage of catalysts which not only possess high activity and selectivity but which are also simultaneously benign to the environment and easily recoverable. In this context, ionic liquids (ILs) have recently attracted considerable interest due to their several inherent virtues like low vapor pressure, easy recyclability, high thermal stability etc [Welton (1999); Wasserscheid and Welton (2008)]. In addition, there have been some interesting reports wherein the peculiar ability of neutral ILs to effectively promote conventional acid/base catalyzed reactions has come to the fore [Meciarova et al. (2007); Parvulescu and Hardacre (2007)]. Although, a few recent reports have also disclosed IL promoted
dehydration of alcohols but the protocols were either limited to substrates like fructose [Matras and Moreau (2003)] or required the indispensable presence of an adjacent cyclopropyl moiety [Ranu et al. (2006)]. To the best of our knowledge, neutral room temperature ionic liquids (RTILs) have not been systematically explored to promote dehydration of problematic benzylic alcohols.

1.5 Results and Discussion:

In order to realize the objective of developing a mild approach for dehydration, 1-(4-methoxyphenyl)propan-1-ol (1a) was irradiated with commercially available ionic liquid 1-butyl-3-methylimidazolium chloride ([bmim]Cl) under microwave (MW) for 8 minutes and the corresponding 4-methoxyphenylpropene (1b) with trans-selectivity (based on $^1$H NMR) was obtained in 72% yield (Table 1, entry 1) along with some side products and unreacted 1a. Encouraged by the above success, various modifications in the reaction conditions such as prolonged reaction time and increased reaction temperature were employed to further increase the reaction performance but to no avail. Consequently we shifted our attention to evaluate the dependence of above reaction on the composition of ILs. Consequently, a range of ILs (Table 1) were investigated to see their effects on the dehydration of 1a. It would be evident from Table 1 that the nature of alkyl chain and anion in the IL play a crucial role in the efficient dehydration of benzyl alcohols. Thus, 1-butyl-3-methylimidazolium hexafluorophosphate ([bmim]PF$_6$) and 1-butyl-3-methylimidazolium tetrafluoroborate ([bmim]BF$_4$) (Table 1, entries 2-3) provided a comparatively inferior yield of 1b along with formation of some side products. However, 1-butyl-3-methylimidazolium bromide ([bmim]Br) (entry 4) was found to enhance the yield of 1b up to 78%, but the best reaction performance was delivered by 1-hexyl-3-methylimidazolium bromide [hmim]Br which provided the product (1b) in 87% yield (100% conversion) within 7 min of MW irradiation (Table 1, entry 5). The above favorable dependence of the reaction on the presence of more lipophilic hexyl side chain allowing easier isolation of products with improved yield has been also observed in a few other reports [Schmidt et al. (2007)]. On the other side, acidic ionic liquid 1-methylimidazolium $p$-toluenesulfonic acid ([Hmim]$p$TSA) or basic ionic liquid 1-butyl-3-methylimidazolium hydroxide ([bmim]OH) provided 1b in only 68% and 55% yields respectively (Table 1, entries 6-7).
It was interesting to observe that no reaction could occur when 1-methylimidazole (precursor for [hmim]Br) was used as a solvent (Table 1, entry 8) for the dehydration of 1a thus ruling out the catalytical activity from residual 1-methylimidazole, if any. Similarly, treatment of 1a with a well known dehydrating agent viz. PTSA/toluene [Lee et al. (2005)] under MW resulted in comparatively lower yield of 1b (46%, entry 9) along with formation of side products thus emphasizing the crucial role of IL for above dehydration. In order to evaluate the role of MW, the above dehydration of 1a with [hmim]Br was also carried out under conventional heating at 140°C for 2 h and 1b was isolated in 74% yield (Table 1, entry 10).

Mechanistically, the above IL promoted dehydration may be occurring through an initial polarization of the C-O bond of carbinol by the imidazolium cation of IL [Ranu et al. (2006)]. Subsequently, an efficient absorption of microwave by above carbinol-ionic liquid

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**Table 1. Effect of different ionic liquids for the dehydration of 1a under microwave**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ionic liquid</th>
<th>Time (min)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-butyl-3-methylimidazolium chloride</td>
<td>8</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>1-butyl-3-methylimidazolium hexafluorophosphate</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>1-butyl-3-methylimidazolium tetrafluoroborate</td>
<td>8</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>1-butyl-3-methylimidazolium bromide</td>
<td>8</td>
<td>78</td>
</tr>
<tr>
<td>5</td>
<td>1-hexyl-3-methylimidazolium bromide</td>
<td>7</td>
<td>87</td>
</tr>
<tr>
<td>6</td>
<td>1-methylimidazolium p-toluenesulfonic acid</td>
<td>10</td>
<td>68</td>
</tr>
<tr>
<td>7</td>
<td>1-butyl-3-methylimidazolium hydroxide</td>
<td>14</td>
<td>55</td>
</tr>
<tr>
<td>8</td>
<td>1-methylimidazole</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>p-toluenesulfonic acid/toluene</td>
<td>12</td>
<td>46</td>
</tr>
<tr>
<td>10</td>
<td>1-hexyl-3-methylimidazolium bromide</td>
<td>2 h</td>
<td>74</td>
</tr>
</tbody>
</table>

*CEM monomode microwave. Reaction conditions: 1.7 mmol of 1a, 1 ml of ionic liquid, (150W, 140°C); Isolated yield of 1b after column chromatography; 1 ml of 1-methyl imidazole was used in place of ionic liquid; 0.15 mmol of p-toluenesulfonic acid, 4 ml toluene; Conventional heating (oil bath, 140°C)*
intermediate results in the elimination of water to provide the respective arylalkene (Figure 3).

![Proposed mechanism of ionic liquid assisted dehydration](image)

**Figure 3.** Proposed mechanism of ionic liquid assisted dehydration

Subsequently, the developed method was extended for the dehydration of a range of optionally substituted benzyl alcohols and their derivatives to obtain the expected product within 6-12 min of reaction time (Table 2).

It was observed that the product yields were comparatively higher with substrates having methoxy substitution at the aromatic ring. The various structurally diverse alcohols were found to undergo smooth dehydration in good to excellent yields (Table 2).

It may be mentioned here that the developed method was also found to be suitable for efficient dehydration of polycyclic aromatic benzyl alcohols (Table 2, entries 5-7, 11 & 14) into corresponding olefins which are important synthons for synthesis of various commercial anti-inflammatory agents [Harrington and Lodewijk (1997)]. In addition, tertiary alcohols (Table 2, entries 20-21) also underwent clean dehydration under the developed reaction conditions. The efficient and neutral nature of above dehydration protocol further prompted us to extend the developed method towards the conversion of acetylated/benzoylated derivatives of benzyl alcohols into respective alkenes due to its immense utility in complex natural product synthesis [Jung et al. (1998); Villamizar et al. (2003)]. However, such transformations are often carried out using harsh bases which preclude their usage in case of substrates containing sensitive functional groups. Consequently, acetylated (Table 2, entries 16-18) and benzoylated (Table 2, entry 19) derivatives of benzyl alcohols were reacted under similar reaction conditions and the corresponding arylalkenes with trans-selectivity were obtained in good yields (80-85%).
**Table 2.** Dehydration of aryl alcohols and their derivatives into corresponding (E)-aryl alkenes with 1-hexyl-3-methylimidazolium bromide under focused microwave^a^  

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate (a)</th>
<th>Reaction Time (min)</th>
<th>Product (b)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H₂CO₃OH</td>
<td>7</td>
<td>H₂CO₃OH</td>
<td>87</td>
</tr>
<tr>
<td>2</td>
<td>H₂CO₃OH</td>
<td>7</td>
<td>H₂CO₃OH</td>
<td>92</td>
</tr>
<tr>
<td>3</td>
<td>H₂CO₃CH₃</td>
<td>6</td>
<td>H₂CO₃CH₃</td>
<td>89</td>
</tr>
<tr>
<td>4</td>
<td>H₂CO₃CH₃</td>
<td>6</td>
<td>H₂CO₃CH₃</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>H₂CO₃CH₃</td>
<td>7</td>
<td>H₂CO₃CH₃</td>
<td>96</td>
</tr>
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<td>6</td>
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<td>7</td>
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<td>H₂CO₃CH₃</td>
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<td>H₂CO₃CH₃</td>
<td>10</td>
<td>H₂CO₃CH₃</td>
<td>79</td>
</tr>
<tr>
<td>9</td>
<td>H₂CO₃CH₃</td>
<td>7</td>
<td>H₂CO₃CH₃</td>
<td>84</td>
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<td>H₂CO₃CH₃</td>
<td>7</td>
<td>H₂CO₃CH₃</td>
<td>91</td>
</tr>
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<td>11</td>
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<td>92</td>
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<td>14</td>
<td>H₂CO₃CH₃</td>
<td>12</td>
<td>H₂CO₃CH₃</td>
<td>87</td>
</tr>
</tbody>
</table>

^a^ R = H, OCH₃, OH, NO₂, C₆H₅, etc.  
R' = H, CH₃, C₂H₅, C₃H₇, etc.  
R" = H, COCH₃, COC₂H₅.
In case of unsymmetrical dialkyl alcohol (Table 2, entry 20) a mixture of two alkenes was obtained in 4:1 ratio wherein the major product was obtained as per Saytzeff’s rule. Similarly, the α,β-unsaturated alcohol (Table 2, entry 15) was converted into corresponding butadiene in 74% yield. However, β-alcohol (Table 2, entry 22) provided the corresponding alkene in lower yield (22%) while no reaction could occur with γ-alcohol (Table 2, entry 24). Thus the method showed selective dehydration of activated benzyl alcohols in comparison to β and γ-alcohols.

It is worthwhile to mention that the developed method allows the dehydration of benzyl alcohols under neutral conditions which not only augments its compatibility with acid sensitive functional groups but also minimizes the formation of unwanted side products. Some recent reports on ionic liquid assisted dehydration have further strengthened our findings [Ignatyev et al. (2009); Valencia and Sayans (2011)].

1.5.1 Reusability of ionic liquid:
In order to check the recyclability of the IL, after completion of reaction the product 1b was extracted with diethylether and the left IL was reused as such for the consequent cycles. A 5-6 % loss in the activity of IL was observed after third cycle of use. It is worth mentioning that prior lyophilization of IL (obtained after each use) for 30 min allowed it to be efficiently used for five subsequent cycles without any loss in the activity.

1.6 Conclusion:
In conclusion, a mild and efficient protocol for dehydration of various benzylic alcohols and their acetylated/benzoylated counterparts into corresponding arylalkenes with trans-selectivity using a recyclable ionic liquid as a reagent and solvent under microwave irradiation is developed. The developed method allowed the hitherto tedious dehydration to be performed under mild and neutral conditions without use of any additional harsh Bronsted/Lewis acids which not only enhances its compatibility with substrates possessing acid sensitive functional groups but also augments its eco-friendly nature. The remarkable selectivity of the developed method towards the dehydration of benzyl alcohols in comparison to β & γ alcohols provides a convenient chemo-selective tool for intricate multistep natural product synthesis.

1.7 Experimental Section:
1.7.1 General Procedure:
The starting materials were either obtained from commercial sources (Merck and Acros) or synthesized from the corresponding benzaldehydes/Grignard reagents [Sharma et al. (2004)] or reduction with sodium borohydride of the corresponding acetophenones/propiophenones [Botteghi et al. (2003)]. The ILs used in this study were obtained either commercially (Merck & Alfa Aesar) or synthesized ([bmim]Br, [hmim]Br, [Hmim]pTSA, [bmim]OH) according to reported methods [Zhao et al. (2004); Nockemann et al. (2005); Ranu and Banerjee (2005)]. The purity of synthesized ILs was checked by NMR before use. The solvents used for isolation/purification of compounds were obtained from commercial sources (Merck) and used without further purification. $^1$H (300 MHz) and
\(^{13}\)C (75.4 MHz) NMR spectra were recorded on a Bruker Avance-300 spectrometer. The following abbreviations were used to designate chemical shift multiplicities: s = singlet, d = doublet, t = triplet, m = multiplet. The melting points were determined on a digital Barnsted Electrothermal 9100 apparatus. CEM Discover© focused microwave (2450 MHz, 300W) was used wherever mentioned. The temperature of reactions in MW experiments was measured by an inbuilt infrared temperature probe that determined the temperature on the surface of reaction flask. The sensor is attached in a feedback loop with an on-board microprocessor to control the temperature rise rate. In the case of conventional heating in an oil bath, the temperature of reaction mixture was monitored by an inner thermometer.

1.7.2 Optimization of reaction conditions:
1.7.2.1 Dehydration of 1-(4-methoxyphenyl)propan-1-ol (1a) using [bmim]Cl (Table 1, entry 1):
A mixture of 1-(4-methoxyphenyl)propan-1-ol (1a, 0.283 g, 1.7 mmol) and ionic liquid [bmim]Cl (1 ml) was irradiated under focused MW system (150W, 140°C) fitted with reflux condenser for 8 min. After the completion of reaction, the reaction mixture was cooled and extracted with diethylether (3x10 ml). The combined organic layer was washed with water (10 ml), dried over anhydrous Na\(_2\)SO\(_4\) and vacuum evaporated. The crude product was purified by column chromatography on silica gel (60-120 mesh size) with a 1:49 mixture of ethylacetate and hexane to provide the corresponding alkene, 1b (0.18 g, 72% yield) as a colorless liquid.

1-Methoxy-4-[(1E)-prop-1-en-1-yl]benzene or 4-Methoxyphenylpropene (1b) [Baxendale et al. (2002)]

\[
\begin{align*}
\text{H}_3\text{C} & \quad \text{C} \quad \text{O} \\
\text{H} & \quad \text{C} \\
\end{align*}
\]

\(^1\)H NMR (300 MHz, CDCl\(_3\)); \(\delta\) (ppm) 7.27 (2H, d, \(J = 8.5\) Hz), 6.85 (2H, d, \(J = 8.5\) Hz), 6.38 (1H, d, \(J = 16.2\) Hz), 6.15–6.03 (1H, m), 3.76 (3H, s), 1.88 (3H, d, \(J = 6.8\) Hz); \(^{13}\)C NMR (75.4 MHz, CDCl\(_3\)); \(\delta\) (ppm) 158.7, 130.9, 130.5, 127.0, 123.4, 114.3, 55.2 and 18.4.

1.7.2.2 Dehydration of 1a using various other ionic liquids [bmim]PF\(_6\), [bmim]BF\(_4\), [bmim]Br, [hmim]Br, [Hmim]\(\rho\)TSA and [bmim]OH under microwave (Table 1, entries 2-7):
1-(4-Methoxyphenyl)propan-1-ol (1a, 0.283 g, 1.7 mmol), was treated separately with the following ionic liquids (1ml each); [bmim]PF\(_6\), [bmim]BF\(_4\), [bmim]Br, [hmim]Br,
[Hmim]pTSA and [bmim]OH, under the MW conditions (for 7 min or more) as mentioned in preceding section. After the completion of reaction, each of the reaction mixture was worked up and purified through column chromatography as mentioned in the section 1.7.2.1. The yield of 1b was obtained in the range of 50 to 87%, wherein [hmim]Br provided the maximum yield of 1b (87%, Table 1, entry 5). The spectral data (1H and 13C NMR) of above 1b matched well with that obtained in section 1.7.2.1.

1.7.2.3 Control experiments:

1.7.2.3.1 Dehydration of 1a using 1-methylimidazole in place of [hmim]Br under microwave (Table 1, entry 8):

To check any background activity from residual 1-methylimidazole (precursor of [hmim]Br), reaction of 1b was carried out in 1-methylimidazole (1 ml) in place of IL under MW for 20 min. However, no product formation occurred.

1.7.2.3.2 Dehydration of 1a using PTSA/toluene in place of [hmim]Br under microwave (Table 1, entry 9):

A mixture of 1a (0.283 g, 1.7 mmol), PTSA (0.15 mmol) in toluene (4 ml) was refluxed under focused MW for 12 min. After the completion of reaction, toluene was evaporated and the crude reaction mixture was purified through column chromatography as mentioned in section 1.7.2.1. However, 1b was obtained in an inferior yield of 46%. The spectral data (1H and 13C NMR) of above 1b matched well with that obtained in section 1.7.2.1.

1.7.2.3.3 Dehydration of 1a in [hmim]Br under conventional heating (Table 1, entry 10):

A mixture of 1-(4-methoxyphenyl)propan-1-ol (1a, 0.283 g, 1.7 mmol) and [hmim]Br (1 ml) was heated in an oil bath at 140°C for 2 h. After the completion of reaction, the work up and column purification (as mentioned in section 1.7.2.1) gave the product 1b as a colorless liquid in 74% yield (0.187 g). The spectral data (1H and 13C NMR) of above 1b matched well with that obtained in section 1.7.2.1.

1.7.2.4 Optimized procedure for the dehydration of 1a using [hmim]Br (Table 2, entry 1):

A mixture of 1-(4-methoxyphenyl)propan-1-ol (1a, 0.283 g, 1.7 mmol) and ionic liquid [hmim]Br (1 ml) was irradiated under focused MW system (150W, 140°C) fitted with reflux condenser for 7 min. After the completion of reaction, the reaction mixture was cooled and extracted with diethylether (3x10 ml). The combined organic layer was washed with water (10 ml), dried over anhydrous Na2SO4 and vacuum evaporated. The crude
product was purified by column chromatography on silica gel (60-120 mesh size) with a 1:49 mixture of ethylacetate and hexane to give 1b (0.22 g, 87% yield) as a colorless liquid. The spectral data ($^1$H and $^{13}$C NMR) of above 1b matched well with that obtained in section 1.7.2.1.

The above procedure was also followed for the dehydration of various other arylalkanols and their derivatives (Table 2, entries 2-25)

1,2-Dimethoxy-4-[(1E)-prop-1-en-1-yl]benzene (2b) [Baxendale et al. (2002)]

\[
\begin{align*}
\text{H}_3\text{CO} & \quad \text{H}_3\text{CO} \\
& \quad \text{O} \\
\end{align*}
\]

Colorless liquid (92%), $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 6.81-6.70 (3H, m), 6.29 (1H, d, $J = 15.6$ Hz), 6.08-5.97 (1H, m), 3.81 (3H, s), 3.78 (3H, s), 1.8 (3H, d, $J = 6.5$ Hz); $^{13}$C NMR (75.4 MHz, CDCl$_3$); $\delta$ (ppm) 148.9, 148.1, 131.1, 130.6, 123.7, 118.6, 111.1, 108.4, 55.7 and 18.4.

1,2,3-Trimethoxy-4-[(1E)-prop-1-en-1-yl]benzene (3b) [Sharma et al. (2004)]

\[
\begin{align*}
\text{H}_3\text{CO} & \quad \text{OCH}_3 \\
& \quad \text{H}_3\text{CO} \\
\end{align*}
\]

Colorless liquid (89%), $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 7.04 (1H, d, $J = 8.5$ Hz), 6.58 (1H, d, $J = 8.7$ Hz), 6.53 (1H, d, $J = 16.2$ Hz), 6.11-5.99 (1H, m), 3.79 (3H, s), 3.77 (3H, s), 3.76 (3H, s), 1.79 (3H, d, $J = 6.6$ Hz); $^{13}$C NMR (75.4 MHz, CDCl$_3$); $\delta$ (ppm) 152.5, 150.9, 142.3, 126.3, 125.1, 125.0, 120.4, 107.7, 61.0, 60.8, 55.9 and 18.8.

1,2,4-Trimethoxy-5-[(1E)-prop-1-en-1-yl]benzene or o-asarone (4b) [Popławski et al. (2000)]

\[
\begin{align*}
\text{H}_3\text{CO} & \quad \text{OCH}_3 \\
& \quad \text{OCH}_3 \\
\end{align*}
\]

White solid (90%), m.p. 43–45°C, $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 6.95 (1H, s), 6.69 (1H, d, $J = 15.9$ Hz), 6.50 (1H, s), 6.16-6.07 (1H, m), 3.89 (3H, s), 3.86 (3H, s), 3.82 (3H, s), 1.89 (3H, d, $J = 6.8$ Hz); $^{13}$C NMR (75.4 MHz, CDCl$_3$); $\delta$ (ppm) 150.6, 148.7, 143.4, 125.0, 124.3, 119.0, 109.8, 98.0, 56.7, 56.4, 56.1 and 18.8.
2-[(1E)-Prop-1-en-1-yl]naphthalene (5b) [Joshi et al. (2005)]

\[
\text{\begin{tikzpicture}
\node at (0,0) {\textbf{5b}};
\end{tikzpicture}}
\]

Colorless oil (96%), \( ^1 \text{H} \) NMR (300 MHz, CDCl\(_3\)); \( \delta \) (ppm) 8.17 (1H, d, \( J = 8.23 \) Hz), 7.87 (1H, d, \( J = 6.8 \) Hz), 7.79 (1H, d, \( J = 7.9 \) Hz), 7.58-7.47 (4H, m), 7.16 (1H, d, \( J = 15.6 \) Hz), 6.35-6.23 (1H, m), 2.05 (3H, d, \( J = 6.8 \) Hz); \( ^{13} \text{C} \) NMR (75.4 MHz, CDCl\(_3\)); \( \delta \) (ppm) 135.8, 133.7, 131.2, 129.0, 128.6, 128.3, 127.3, 125.9, 125.8, 125.7, 124.1, 123.6 and 19.1.

4-[(1E)-Prop-1-en-1-yl]biphenyl (6b) [Okamoto et al. (2005)]

\[
\text{\begin{tikzpicture}
\node at (0,0) {\textbf{6b}};
\end{tikzpicture}}
\]

White viscous liquid (90%), \( ^1 \text{H} \) NMR (300 MHz, CDCl\(_3\)); \( \delta \) (ppm) 7.55-7.41 (4H, m), 7.40-7.25 (5H, m), 6.41 (1H, d, \( J = 16.2 \) Hz), 6.27-6.19 (1H, m), 1.86 (3H, d, \( J = 6.4 \) Hz); \( ^{13} \text{C} \) NMR (75.4 MHz, CDCl\(_3\)); \( \delta \) (ppm) 140.9, 139.5, 137.0, 130.6, 129.3, 127.6, 127.2, 127.0, 126.5 and 18.6.

9-[(1E)-Prop-1-en-1-yl]anthracene (7b) [Griendt and Cerfontain (1980)]

\[
\text{\begin{tikzpicture}
\node at (0,0) {\textbf{7b}};
\end{tikzpicture}}
\]

Pale yellow solid (94%), m.p. 76–78°C, \( ^1 \text{H} \) NMR (300 MHz, CDCl\(_3\)); \( \delta \) (ppm) 8.31-8.26 (3H, m), 7.96-7.92 (2H, m), 7.44-7.39 (4H, m), 7.12 (1H, d, \( J = 16.2 \) Hz), 6.07-5.95 (1H, m), 2.14 (3H, d, \( J = 6.5 \) Hz); \( ^{13} \text{C} \) NMR (75.4 MHz, CDCl\(_3\)); \( \delta \) (ppm) 134.1, 133.7, 131.5, 129.6, 128.6, 127.3, 126.3, 125.8, 125.0 and 19.1.

(1E)-Prop-1-en-1-ylbenzene (8b) [Okamoto et al. (2005)]

\[
\text{\begin{tikzpicture}
\node at (0,0) {\textbf{8b}};
\end{tikzpicture}}
\]

Colorless oil (79%), \( ^1 \text{H} \) NMR (300 MHz, CDCl\(_3\)); \( \delta \) (ppm) 7.42-7.26 (5H, m), 6.54 (1H, d, \( J = 15.9 \) Hz), 6.38-6.27 (1H, m), 1.99 (3H, d, \( J = 6.3 \) Hz); \( ^{13} \text{C} \) NMR (75.4 MHz, CDCl\(_3\)); \( \delta \) (ppm) 138.1, 131.3, 128.6, 126.9, 126.0, 125.7 and 18.6.

1,2-Dimethoxy-4-[(1E)-pent-1-en-1-yl]benzene (9b) [Bigot et al. (1982)]

\[
\text{\begin{tikzpicture}
\node at (0,0) {\textbf{9b}};
\end{tikzpicture}}
\]

Colorless liquid (84%), \( ^1 \text{H} \) NMR (300 MHz, CDCl\(_3\)); \( \delta \) (ppm) 6.90-6.71 (3H, m), 6.28 (1H, d, \( J = 16.4 \) Hz), 6.07-5.97 (1H, m), 3.83 (3H, s), 3.80 (3H, s), 2.14-2.07 (2H, m), 1.48-1.36 (2H, m), 0.88 (3H, t, \( J = 7.4 \) Hz); \( ^{13} \text{C} \) NMR (75.4 MHz,
CDCl$_3$; $\delta$ (ppm) 148.9, 148.1, 131.1, 129.2 129.1, 118.7, 111.1, 108.4, 55.7, 30.8, 22.6 and 13.8.

1-[(1E)-But-1-en-1-yl]-2,4-dimethoxybenzene (10b) [Paulis et al. (1985)]

Colorless liquid (91%), $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 6.93-6.71 (3H, m), 6.30 (1H, d, $J = 15.7$ Hz), 6.14-6.04 (1H, m), 3.84 (3H, s), 3.81 (3H, s), 2.22-2.12 (2H, m), 1.05 (3H, t, $J = 7.3$ Hz); $^{13}$C NMR (75.4 MHz, CDCl$_3$); $\delta$ (ppm) 149.0, 148.2, 131.1, 130.7, 128.3, 118.8, 111.2, 108.5, 55.7, 26.0 and 13.8.

2-[(1E)-But-1-en-1-yl]naphthalene (11b) [Giovanelli et al. (2006)]

Pale yellow liquid (92%), $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 8.14 (1H, d, $J = 8.5$ Hz), 7.67 (1H, d, $J = 7.6$ Hz), 7.58 (1H, d, $J = 8.1$ Hz ), 7.51 (1H, d, $J = 7.2$ Hz), 7.49-7.43 (3H, m), 7.16 (1H, d, $J = 15.7$ Hz), 6.35-6.27 (1H, m), 2.39-2.32 (2H, m), 1.22 (3H, t, $J = 7.2$ Hz); $^{13}$C NMR (75.4 MHz, CDCl$_3$); $\delta$ (ppm) 136.2, 133.7, 131.2, 128.5, 127.3, 126.0, 125.8, 125.7, 125.6, 124.0, 123.6, 26.6 and 14.5.

4-Ethenyl-1,2-dimethoxybenzene (12b) [Nagashima et al. (1999)]

Colorless liquid (74%), $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 6.90 (2H, d, $J = 11.5$ Hz), 6.76 (1H, d, $J = 8.2$ Hz), 6.63-6.53 (1H, m), 5.57 (1H, d, $J = 17.6$ Hz), 5.10 (1H, d, $J = 10.2$ Hz ), 3.83 (3H, s), 3.81 (3H, s); $^{13}$C NMR (75.4 MHz, CDCl$_3$); $\delta$ (ppm) 148.9, 136.5, 130.7, 118.8, 111.8, 111.0, 108.4, 55.9 and 55.8.

4-Ethenyl-2-methoxyphenol or 4-vinylguaiacol (13b) [Sinha et al. (2007)]

Colorless viscous liquid (56%), $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 6.88-6.81 (3H, m), 6.63-6.54 (1H, m), 5.68 (1H, s), 5.57 (1H, d, $J = 17.6$ Hz), 5.09 (1H, d, $J = 10.9$ Hz), 3.84 (3H, s); $^{13}$C NMR (75.4 MHz, CDCl$_3$); $\delta$ (ppm) 146.6, 145.6, 136.6, 130.3, 120.1, 114.4, 111.4, 108.1 and 55.9.

2-Ethenynaphthalene (14b) [Shine and Rangappa (2007)]

White solid (87%), m.p. 62-66°C, $^1$H NMR (300 MHz, CDCl$_3$); $\delta$ (ppm) 7.79-7.74 (4H, m), 7.64 (1H, d, $J = 8.5$ Hz), 7.48-7.41 (2H, m), 6.92-6.83 (1H, m), 5.90
(1H, d, J = 17.6 Hz), 5.35 (1H, d, J = 10.9 Hz); $^{13}$C NMR (75.4 MHz, CDCl$_3$); δ (ppm) 137.0, 135.1, 133.7, 133.2, 128.3, 128.1, 127.8, 126.5, 126.3, 126.0, 123.2 and 114.2.

1-[(1E)-Buta-1,3-dien-1-yl]-4-methoxybenzene (15b) [Roversi et al. (2002)]

White viscous liquid (74%), $^1$H NMR (300 MHz, CDCl$_3$); δ (ppm) 7.30 (2H, d, J = 8.5 Hz), 6.82 (2H, d, J = 8.5 Hz), 6.67-6.58 (1H, m), 5.26 (1H, d, J = 16.7 Hz), 5.08 (1H, d, J = 9.9 Hz), 3.75 (3H, s); $^{13}$C NMR (75.4 MHz, CDCl$_3$); δ (ppm) 159.3, 138.3, 133.3, 129.9, 127.7, 116.5, 114.1 and 55.3.

Following the experimental conditions as discussed in section 1.7.2.4, substrates 16-19 (Table 2, entries 16-19) provides 2b, 4b and 1b respectively.

1-[(2E)-But-2-en-2-yl]-4-methoxybenzene and 1-(But-1-en-2-yl)-4-methoxybenzene (20b & 20b) [Kallstrom et al. (2004)]

Colorless liquid (87%, isomeric mixture in 4:1 ratio), $^1$H NMR (300 MHz, CDCl$_3$); δ (ppm) 7.27-7.18 (2H, m), 7.10 (2/5H, d, J = 7.9 Hz), 6.79-6.72 (2H, m), 5.71 (4/5H, q, J = 6.8 Hz), 3.68 (3H, s), 2.42 (2/5H, q, J = 7.1 Hz), 1.90 (12/5H, s), 1.69 (12/5H, d, J = 6.6 Hz), 1.03 (3/5H, t, J = 7.4 Hz); $^{13}$C NMR (75.4 MHz, CDCl$_3$); δ (ppm) 159.0, 136.7, 134.8, 129.2, 126.5, 126.1, 120.1, 113.1, 109.4, 56.0, 28.1, 25.5, 15.5 and 14.3.

(3-Methylbut-2-en-1-yl)benzene and (3-Methylbut-3-en-1-yl)benzene (21b and 21b) [Giovanelli et al. (2006)]

Colorless liquid (95%, isomeric mixture in 3:1 ratio), $^1$H NMR (300 MHz, CDCl$_3$); δ (ppm) 7.36-7.23 (5H, m), 5.43 (3/4H, t, J = 7.4 Hz), 4.81 (1/2H, d, J = 7.7 Hz), 3.42 (3/2H, d, J = 7.4 Hz), 2.84 (1/2H, t, J = 7.4 Hz), 2.4 (1/2H, t, J = 7.4 Hz), 1.83-1.78 (21/4H, m); $^{13}$C NMR (75.4 MHz, CDCl$_3$); δ (ppm) 145.4, 142.3, 141.9, 132.5, 128.4, 125.9, 123.4, 110.3, 39.7, 34.5, 25.8, 22.7 and 17.9.

Table 2, entry 22, NMR same as compound 1b.
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NMR spectra of some compounds

$^1$H NMR (in CDCl$_3$) spectrum of 1,2,4-trimethoxy-5-[(1E)-prop-1-en-1-yl]benzene or $\alpha$-asarone (4b, Table 2)

$^{13}$C NMR (in CDCl$_3$) spectrum of 1,2,4-trimethoxy-5-[(1E)-prop-1-en-1-yl]benzene or $\alpha$-asarone (4b, Table 2)


**Chapter 1**

![Chemical structure](image)

**1H NMR (in CDCl₃) spectrum of 2-ethynlnaphthalene (14b, Table 2)**

![NMR spectrum](image)

**13C NMR (in CDCl₃) spectrum of 2-ethynlnaphthalene (14b, Table 2)**
$^1$H NMR (in CDCl$_3$) spectrum of 1-[(1E)-buta-1,3-dien-1-yl]-4-methoxybenzene (15b, Table 2)

$^{13}$C NMR (in CDCl$_3$) spectrum of 1-[(1E)-buta-1,3-dien-1-yl]-4-methoxybenzene (15b, Table 2)