Metal-based catalysts containing a phosphonate moiety – from synthesis to applications in organic chemistry

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In dedication to Professor György Keglevich on the occasion of his 65th anniversary

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Abstract

Recently, the development of suitable synthetic methodologies using metal-based catalysts for coupling reactions, oxidation or reduction as well as epoxidation have become topics of great interest. This review article surveys recent achievements in the application of such catalysts as templated porous-metal phosphonates, layered-metal phosphonates, and phosphonate-based metal-organic frameworks (MOFs) in organic syntheses. Additionally, the preparation of various catalysts with defined structure and morphology from organic phosphonate precursors are presented. The versatile properties of phosphonate-containing catalysts offer new and efficient applications in classical as well as modern organic reactions.

Keywords: Catalytic organic synthesis, metal phosphonate, phosphonate catalysts, metal-based catalysts, organic reactions

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1. Introduction

Phosphonates [RPO₃]²⁻ and related [RP(O)₂(OH)]⁻, known derivatives of phosphonic acids RP(O)(OH)₂ due to the presence of a P–C bond, have shown remarkable potential.¹ The capability of coordination and binding properties to suitable metal ions² offers the possibility to create the hybrid metal phosphonates possessing different structures and morphology, as well as physical properties and/or particular chemical reactivity. These materials, distinguished by the presence of extended one-, two-, and three-dimensional structures, are divided into classes, namely layered-metal phosphonates, phosphonate-based MOFs, and templated porous-metal phosphonates.³⁻¹¹ Moreover, the application of organic phosphonates influences the hydrophobic/hydrophilic interactions within materials, frequently enabling the approach of hydrophobic organic molecules to the catalytically-active sites of the metal phosphonate framework. These properties play a significant role in liquid-phase catalytic reactions.

Due to their high chemical and thermal stability as well as high insolubility in many solvents, this class of heterogeneous compounds possesses wide applications, not only in catalytic organic chemistry, but in proton-conduction and energy-storage materials,¹²⁻¹⁶ adsorption and separation,¹⁷⁻¹⁸ biomedical science,¹⁹⁻²¹ and in photocatalytic and electrocatalytic reactions.²²⁻²⁴ The unique combination of organophosphorus precursor(s) and synthetic conditions lead to the desired catalyst to apply in industrial or preparative organic chemistry. Moreover, transition- and some main-group metal elements offer the capability of gain and loss of electrons and/or the corresponding apparent redox ability or Lewis acid-activation properties of the applied catalyst. The additional huge advantage is ease of catalyst recycling, which in turn, affects the economics of the synthesis. For this reason, these compounds are often used in coupling, oxidation, epoxidation, reduction reactions, etc.²⁵⁻³⁴ The goal of this review is to describe recent advances and achievements, particularly the contributions of the last decade, in efficient syntheses of catalysts based on metal-organic phosphonates scaffolds. Moreover, their use in various types of classical and asymmetric organic transformations will be presented. In this mini-review, the literature is covered from the beginning of January 2010. It is important to supplement this review with some others that have been written on various aspects of metal phosphonates, including designing hybrid...
organic-inorganic porous materials and their applications. Applications described in these supplemental reviews, including energy conversion and storage, adsorption of heavy metals, membrane materials and photo/electrocatalysis are beyond the scope of the present review.

2. Heterogenous Catalysts with Phosphonate Moiety - Applications and Short Characteristics

2.1. Coupling reactions
One of the most important branches of modern organic chemistry focuses on carbon-carbon bond formation with the application of various types of catalysts. Among them, the palladium-assisted coupling reaction is the most widely used. Layered materials with a high surface area, and a large amount of exposed active sites, play an important role in the development of new hybrid materials. In addition, the possibility of multiple uses of catalysts in subsequent reaction cycles with a very high degree of substrate conversion and their effective recycling, are crucial factors in reducing costs and the amount of waste generated during the reactions.

One of the latest works of Bhattacharyya et al. has led to the finding of highly efficient heterogeneous catalysts in the Suzuki-Miyaura cross-coupling reaction. The applied catalyst consisted of mesoporous zirconium organocarboxyphosphonate ZrCP1 which was used as a support matrix for mixed-valent Pd (0) / Pd (II) nano-sized aggregates. The sol-gel system, with the use of surfactants as the pore templates, was employed to obtain the catalyst carrier. The reaction of ZrOCl$_2$ x 8H$_2$O with 1-phosphonomethyl-pyrrolidine-2-carboxylic acid 1 was conducted at 130 °C for 3 days with the addition of a cationic surfactant, cetyltrimethylammonium bromide (CTAB). The catalyst support was obtained after treatment with ethanolic HCl for the removal of surfactant. In the next step, ZrCP1 was impregnated with palladium(II) acetate [Pd(OAc)$_2$], which, in combination with the subsequent reduction of absorbed Pd(II), gave CAT1 (Scheme 1). The spectroscopic and structural examinations confirmed the activity of the catalyst beyond the fifth reaction cycle.

![Scheme 1. Synthesis of zirconium-based catalyst CAT1. Reaction conditions: i. ZrOCl$_2$ x 8H$_2$O (1 mmol), CTAB (0.5 mmol), H$_2$O, next 1 (1 mmol), 130 °C, 3 d, next Pd(OAc)$_2$ (2.2 mmol), THF, 130 °C, 12h, then NaBH$_4$ (2.6 mmol), RT, 3h.](image)

Previous works, based on a similar synthetic method, are also known which have proven to be equally effective catalysts in coupling reactions. As the organophosphorus precursors in coupling catalysts, the organophosphonic acids such as mesityl-1,3,5-tris(methylene phosphonic acid 2 and N,N-bis(phosphonomethyl)glycine 3 were used (Figure 1).
The introduction of 2 into layered inorganic solid yielded the organic-inorganic hybrid material. Its applications as a catalyst in Suzuki-Miyaura cross-coupling reactions was reported by Borah et al. Thus, the hydrothermal reaction of ZrOCl₂ x 8H₂O with 2, in the presence of surfactant (CTAB), led to the mesoporous zirconium (IV) phosphonate.³⁹ Next, the final material CAT2 [Pd₀.₅Zr₃(L)₂]xnH₂O, (Pd@ZrCP₂) was obtained by impregnation of Pd(OAc)₂, followed by reduction with sodium borohydride. High catalytic efficiency in the reactions of forming new C-C bonds by Suzuki-Miyaura and Heck coupling reactions has been also reported in the case of palladium nanoparticles embedded on zirconium phosphate glycine diphosphonate (ZrPGly) nanosheets CAT3 (Pd@ZrPGly).⁴⁰ The layered zirconium phosphate-phosphonate Zr₂(PO₄)₃[(O₃PCH₂)₂NCH₂COOH]₂xH₂O (ZrP Gly) was obtained by the reaction of 3 and zirconium (IV) phosphoric acid. Subsequently, treatment of a colloidal dispersion of ZrP Gly in n-propylamine (PA), with palladium(II) acetate, for 1 or 7 or 15 days gave composites CAT3 with formulas [Zr₂(PO₄)₂L²Pd₁.₅(PrNH₂)₀.₃₃], Zr₂(PO₄)(L)₂Pd₁.₅(PrNH₂)₀.₃₃ and Zr₂(PO₄)(L)₂Pd₁.₉₂(PrNH₂)₀.₂₂, respectively (Figure 2).⁴¹ The high availability of carboxyl (or COOH), phosphonate (or PO₃H) and amine groups on the surface of the hybrid layers gives these structures polar properties that favor the immobilization and stabilization of palladium particles. Furthermore, it provided confirmation that propylamine in ZrP Gly dispersion acts as an exfoliating agent, which helps to deposit the palladium on the surface of the layer.⁴¹

All of the above described heterogeneous catalysts were tested in a Suzuki-Miyaura cross-coupling reaction of a series of aryl boronic acids 4 with aryl bromides 5 (Table 1).³⁸-⁴¹ These catalysts allowed for the

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**Figure 1.** The organophosphorus precursors for the synthesis of CAT2 and CAT3.

**Figure 2.** Schematic representation of CAT3.
efficient synthesis of various biphenyls 6 substituted with electron-withdrawing or electron donating groups (EWG or EDG), respectively.

**Table 1.** Suzuki-Miyaura coupling of phenylboronic acid 4 with bromobenzene 5 catalyzed by CAT1 – CAT3

<table>
<thead>
<tr>
<th>R</th>
<th>CAT1 [%]</th>
<th>CAT2 [%]</th>
<th>CAT3 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-CN</td>
<td>98</td>
<td>94(^{b})</td>
<td>99</td>
</tr>
<tr>
<td>p-NO(_2)</td>
<td>95</td>
<td>92</td>
<td>98</td>
</tr>
<tr>
<td>p-COCH(_3)</td>
<td>96</td>
<td>85</td>
<td>99</td>
</tr>
<tr>
<td>m-COCH(_3)</td>
<td>98</td>
<td>51</td>
<td>-</td>
</tr>
<tr>
<td>p-CH(_3)</td>
<td>93</td>
<td>22</td>
<td>97</td>
</tr>
<tr>
<td>p-OCH(_3)</td>
<td>87</td>
<td>29</td>
<td>92</td>
</tr>
<tr>
<td>p-CHO</td>
<td>-</td>
<td>-</td>
<td>98(^{c})</td>
</tr>
</tbody>
</table>

Reaction conditions: *i.* 4 (0.24 mmol), 5 (0.20 mmol), K\(_2\)CO\(_3\) (0.25 mmol), CAT1 (0.22 mol %), EtOH/H\(_2\)O (3:1, v:v), 80 °C, 2-10min; *ii.* 4 (0.24 mmol), 5 (0.20 mmol), K\(_2\)CO\(_3\) (0.20 mmol), CAT2 (0.15 mol %), EtOH, reflux, 6h; *iii.* 4 (1.0 mmol), 5 (1.2 mmol), K\(_2\)CO\(_3\) (1.2 mmol), CAT3 (0.1 mol %), EtOH, 80 °C, 3-24h. \(^{a}\) yield of 6, \(^{b}\) 5 runs: 80-94%, \(^{c}\) 4 runs: 98%.

It is worth mentioning that coupling reactions catalyzed by CAT3 were performed using azeotropic mixtures (84% CH\(_3\)CN in H\(_2\)O and 96% EtOH in H\(_2\)O) in a flow system, which significantly reduces the amount of organic reaction media. This method allows the catalyst to be recovered, and ensures low metal leaching, as determined by the ICP-OES analysis method. The presented results have confirmed the high catalytic activity of composite materials, giving the possibility of immobilizing palladium nanoparticles and carrying out several reaction cycles.\(^{40,41}\)

CAT3 has been proven to be equally effective in Heck coupling reaction of iodo benzene 7 and methyl acrylate 8, providing complete substrate conversion that led to the formation of a new C-C bond.\(^{40}\) The catalyst was used successfully in six reaction cycles with no loss of catalytic activity and afforded 9 in 96 - 98% yields (Scheme 2). It was shown that the leaching of the palladium was at the level of 10 -12 ppm in all of the reaction cycles.
Scheme 2. The Heck reaction of iodobenzene 7 and methyl acrylate 8 catalyzed by CAT3. Reaction conditions: i. 7 (6.0 mmol), 8 (7.2 mmol), TEA (7.2 mmol), CAT3 (0.1 mol %), CH₃CNaq, 120 °C, 3h. TOF = turnover number, TON = turnover frequency.

One of the latest works reports three new NHC – Pd(II) complexes (CAT4-CAT6) based on an imidazolium ligand with a pendant phosphonate ester group(s) or phosphonic acid moiety, which have been used as catalysts in C-C bond formation (Figure 3). Based on the structural analysis, it was determined that the phosphonate ester groups (CAT5 and CAT6) do not participate in the coordination of the palladium atom.

Figure 3. Palladium-based catalyst with phosphonate/phosphonic acid ligands (CAT4 – CAT6).

The obtained catalysts were successfully applied in coupling reactions of aryl boronic acids 10 with substituted aryl chlorides and bromides 11 (Table 2). Moreover, it was confirmed that the catalyst with phosphonic acid moiety (CAT4) showed better catalytic efficiency compared to those containing phosphonate ester groups (CAT5 and CAT6).
Table 2. Suzuki-Miyaura coupling of phenylboronic acid 10 with bromo- or chlorobenzene 11 catalyzed by CAT4 – CAT6

![Diagram of Suzuki-Miyaura coupling]

<table>
<thead>
<tr>
<th>R¹</th>
<th>R²</th>
<th>X</th>
<th>CAT4 [%]ᵃ</th>
<th>CAT5 [%]ᵃ</th>
<th>CAT6 [%]ᵃ</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>p-CH₃</td>
<td>Br</td>
<td>77</td>
<td>74</td>
<td>54</td>
</tr>
<tr>
<td>H</td>
<td>p-OCH₃</td>
<td>Br</td>
<td>93</td>
<td>52</td>
<td>86</td>
</tr>
<tr>
<td>CH₃</td>
<td>m-CH₃</td>
<td>Cl</td>
<td>99</td>
<td>86</td>
<td>99</td>
</tr>
<tr>
<td>CH₃</td>
<td>p-CH₃</td>
<td>Cl</td>
<td>98</td>
<td>74</td>
<td>98</td>
</tr>
</tbody>
</table>

Reaction conditions: i. 10 (0.24 mmol), 11 (0.20 mmol), K₂CO₃ (0.40 mmol), CAT4 – CAT6 (0.5 mol %), iPrOH/H₂O (3:1, v:v), 60 °C, 1-6h. ᵃ yield of 12.

For comparison, the group of mesoporous TiO₂-supported copper(I) phosphonate-containing catalysts has been also proven to be active in the reactions of forming new C-C bonds in coupling reactions.⁴³ Thus, the Sonogashira-type coupling (Scheme 3 A) can be catalyzed by heterogeneous copper(I) bis 1,10-phenanthroline (phen) complexes anchored by the phosphonate moiety onto the TiO₂ surface (Scheme 3 B). The catalyzed-by-surface-modified CAT7 reactions of aryl iodide 13, substituted at the p- or o- positions with the activating [CH₃, t-Bu, OH, or NHC(O)(CF₃)] or deactivating (CN, NO₂ or COOCH₃) groups, and an alkyl or aryl acetylene 14 resulted in coupling products 15 in almost quantitative yields (99%). Reactions occurred in applied conditions such as 5% mol catalyst CAT7, PPh₃, Cs₂CO₃, and toluene as a solvent. Additionally, in the case of phenol or aniline derivatives [R¹ = o- OH, or o- NHC(O)(CF₃)], the subsequent addition to the triple bond occurs, leading to benzofuran or indole derivatives in excellent yields.

Moreover, the excellent catalytic performance of CAT7 on Huisgen 1,3-dipolar cycloadditions to give substituted 1,2,3-triazoles in yields from 92 - 99% has been presented as well.⁴³

The applied catalyst (CAT7) was obtained from phenanthroline ligands (PPhen) containing the phosphonate moiety [(1,10-phenanthrolin-3-yl)phosphonate 16] grafted onto the mesoporous titanium surface, then complexed with copper(I) ions, e.g., [Cu(MeCN)₄PF₆] (Scheme 3 B). The resulting hybrid material, as well as the integrity of immobilized complexes, were characterized by different physicochemical methods. The CAT7 catalyst was successfully applied in a coupling reaction, leading to complete substrate conversion (99%) in 5 reaction cycles. Alternatively, homoleptic and heteroleptic copper(I) complexes of variously-substituted phenanthroline-bearing phosphonate groups were prepared from bis(trimethylsiloxy)phosphoryl derivatives of phenanthroline 16 (PPhen) and, next, embedded into TiO₂ or grafted onto the TiO₂ surface.⁴³
Scheme 3. A. The Sonogashira coupling reaction between aryl iodide 13 and \( \text{R}^2 \)-acetylene derivatives 14, catalyzed by CAT7; B. Synthesis of copper complexes on titanium oxide (CAT7). Reaction conditions: \( \text{i.} \) 13 (0.5 mmol), 14 (0.75 mmol), CAT7 (5 mol%), PPh3 (10 mol%), Cs2CO3 (1 mmol), PhCH3, reflux, 16h; \( \text{ii.} \) 16, TiO2, next Cu(CH3CN)4PF6.

This part involving the coupling reaction has been reflecting the growth of application of metal-organic phosphonate-based catalysts or organic-inorganic hybrid-phosphonate materials. On the other hand, this group of materials is widely present and useful in organic syntheses involving reduction or oxidation reactions.

2.2. Reduction

It is often necessary to reduce, selectively, one group in a molecule without affecting another reducible group. The most common broad-spectrum reducing agents are metal hydrides and hydrogen with a catalyst. Many different hydrogenation catalysts have been investigated in order to find optimal conditions under which a given group will be reduced chemoselectively. Some catalysts, especially containing Pd, Rh, Ru or Ni, are particularly selective towards the reduction of certain classes of compounds.\(^{44,45}\) Below, various reducing catalysts are listed, representing their reactivity of various functional group.

The reactions in this section are grouped into classifications based on bond changes: reduction of triple to double C=C bond, or reduction of a carbonyl C=O group or transformation of nitro compounds into amines. In some cases, the catalytic reduction, followed by intramolecular transesterification, was described.

2.2.1. The reduction of unsaturated C-C bonds. One of the most applied reactions is the stereoselective reduction of triple bonds using catalytic palladium-based hydrogenation. Among various heterogeneous palladium-containing catalysts, the zirconium phosphate-phosphonate nanohybrid material has also been used.\(^{46}\) The nanosheet-form catalysts containing different propylamine contents were prepared as described for CAT3 by changing the initial amount of propylamine (PA) as an exfoliating agent (20, 40, 60 and 80% of the ion exchange capacity). The reduction of alkyne 17 has been shown to proceed selectively to give Z-alkene 18 and, moreover, the leaching of palladium in the solution was negligible (Table 3).
Table 3. Reduction of 3-hexyn-1-ol 17 catalyzed by CAT3 containing different amounts of propylamine (PA)

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Pd% [w/w]</th>
<th>Conversion [%]</th>
<th>TOF [h⁻¹]</th>
<th>Z-Sel. [%]a</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT3-20-PA</td>
<td>19.8</td>
<td>99.9</td>
<td>480</td>
<td>91.2</td>
</tr>
<tr>
<td>CAT3-40-PA</td>
<td>19.4</td>
<td>99.0</td>
<td>297</td>
<td>95.9</td>
</tr>
<tr>
<td>CAT3-60-PA</td>
<td>21.7</td>
<td>99.2</td>
<td>397</td>
<td>96.5</td>
</tr>
<tr>
<td>CAT3-80-PA</td>
<td>19.4</td>
<td>99.9</td>
<td>150</td>
<td>89.8</td>
</tr>
</tbody>
</table>

Reaction conditions: i. 17 (0.2 M, MeOH), H₂, 0.1 MPa, 17/CAT3 ratio (mol/mol): 400. a Z-selectivity (18/(sum of the products)).

The chemoselective catalytic efficiency in the hydrogenation reactions has also been reported using heterogeneous rhodium complexes of phosphonate-containing 2,2′-bipyridine (bipy) ligands on titanium oxide. The obtained catalysts have been used for the reduction of 6-methyl-5-hepten-2-one 19 under hydrogen pressure (4 MPa) to give 20 as the main product (Scheme 4). It was found that the application of CAT8 led to 85% substrate conversion, and 100% selectivity for hydrogenolysis of C=C bonds to get 20. Analogous reductions of 19 using catalysts containing other 2,2′-bipyridine ligands gave substrate conversion from 15 - 99% and distribution of products 20-22 from 70 - 100%, respectively.

Scheme 4. Reduction of 6-methyl-5-hepten-2-one 19 catalyzed by CAT8. Reaction conditions: CAT8/19 (molar ratio 1%), H₂, NaOH/MeOH, 4 MPa, 30 °C, 4h.

The most efficient CAT8 was prepared by immobilization of a RhL₂ complex, containing bipy ligands with covalently-bonded dodecyl linkers ending with phosphonate groups (e.g., 23), on titanium oxide particles (Scheme 5). Due to diverse phosphonate-bipy arrangements depending on the ligands substitution and the numbers of tethers in the RhL₂ species, influencing both microstructures and the location at the solid surface, different catalytic efficiencies have been reported.
Scheme 5. Synthesis of rhodium complexe RhL₂ on titanium oxide CAT8. Reaction conditions: \(\text{23}, \text{[Rh(COD)(Cl)]}_2\)\(^a\) (0.0395 mmol), AgBF₄ (0.079 mmol), MeOH, RT, 1h, next 2,2’-bipyridine (0.16 mmol), 5 min, NaOH (1M), then Ti(OiPr)_4, 2d. \(^a\)COD – 1,5-cyclooctadiene.

2.2.2. The reduction of C=O bond in aldehydes and ketones. There are various possibilities for reducing the carbonyl group of aldehydes and ketones to alcohols. The most common methods consist of the use of nucleophilic or electrophilic hydrides, hydrogen on platinum and ruthenium catalysts or metal in water, etc.\(^{48}\) Less popular reductions based on Pt or Ru catalysts suffered from lower chemoselectivity resulting from additional C=C or C=N reductions in the cases of unsaturated- or imine-containing ketones or aldehydes. For comparison, a high reaction efficiency (nearly 97%) under relatively mild conditions was reported for the Meerwein-Ponndorf-Verley (MPV) reduction of 5-hydroxymethylfurfural (HMF) \(\text{24}\) to 2,5–dihydroxymethylfuran (DHMF) \(\text{25}\), which can be useful as a polymer precursor derived from renewable biomass resources.\(^{49}\) Thus, to obtain \(\text{25}\), zirconium phosphonate catalyst CAT9 (Zr-DTMP) has been used (Scheme 6 A).\(^{50}\) A mesoporous zirconium organic-inorganic material (Scheme 6 B) was obtained by easily combining metal ions with suitable ligands. For this purpose, the solutions of diethylene triaminepenta(methylene phosphonic acid) (DTMP) and zirconium tetrachloride (ZrCl₄) were combined and then TEA was added. The obtained catalyst was successively used in five runs.
Scheme 6. A. Reduction of 5-hydroxymethylfurfural 24 catalyzed by CAT9; B. The structure of CAT9. Reaction conditions: i. 24 (0.5 g), CAT9 (0.3 g), secBuOH (24.5 g), 140 °C, 3h.

Interestingly, it’s the first example of the application of CAT9 for the synthesis of 25. Furthermore, this catalytic system can also be used in selective reduction of levulinic acid (LA), ethyl levulinate (EL) and many others.50

An additional application of zirconium phosphonates in reduction reactions has been shown by Wang et al.51 The authors showed that hybrid zirconium phosphonate materials CAT10 (ZrHEDP), CAT11 (ZrDTPMP), CAT12 (ZrATMP), CAT13 (ZrEDTMP) are efficient catalysts for the catalytic transfer hydrogenation of ethyl levulinate (EL) 26 to γ-valerolactone 27 without external delivery of hydrogen (Scheme 7 A). Hybrid materials were obtained through the reactions of organophosphonic acids such as 1-hydroxyethylidene-1,1-diphosphonic acid (HEDP) 28, diethylene triaminepenta(methylene phosphonic acid) (DTPMPA) 29, ATMP 30, and ethylenediamine tetra(methylene phosphonic acid) (EDTMP) 31, in forms of sodium salts (Scheme 7 B), with ZrOCl₂ in water by the co-precipitation method. The catalysts were reused and demonstrated activity in no fewer than five reaction cycles.
Scheme 7. A. Catalytic transfer hydrogenation of ethyl levulinate 26 catalyzed by CAT10 – CAT13; B. Organophosphorus precursors 28 – 31 used for the synthesis of CAT10 – CAT13. Reaction conditions: i. 26 (1 mmol), CAT10 – CAT13 (200 mg), i-PrOH, 160 °C, 9-12h.

Another widely studied reaction involves the reduction of the C=O bond with the use of zirconium-phosphonate-supported ruthenium catalysts. In particular, Du et al. have applied a chiral Ru catalyst in asymmetric hydrogenation of unsymmetrical benzils 32 to hydrobenzoins 33, and 34 (Scheme 8 A).52 This work is based on the translation of heterogeneous catalysis of a zirconium-phosphonate-supported ruthenium catalyst, in a homogeneous system, by covalent attachment of (R,R)-1,2-diphenylethylenediamine [(R,R)-DPEN] into zirconium phosphonate followed by immobilization of [RuCl2(p-cymene)]. The obtained catalyst (CAT14, Scheme 8 B) ensures excellent activity and high substrate 32 conversion.

Scheme 8. A. Hydrogenation of unsymmetrical benzils 32 catalyzed by CAT14; B. The structure of CAT14. Reaction conditions: i. 32 (0.084 mmol), CAT14 (1.7 wt%, 6.7 × 10⁻⁴ mmol), HCOOH/TEA (1:2, v:v), 50 °C, 40h.

Moreover, the zirconium-phosphonate-supported ruthenium catalysts were tested in reduction reactions, especially in asymmetric hydrogenations.53 The supported ruthenium catalyst was obtained by the
reaction of zirconium phosphonate with Ru(p-cymene)(S-BINAP)Cl₂ (BINAP = 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl) in an inert-gas atmosphere (CAT15, Scheme 9 B). The catalyst activity was measured in the asymmetric hydrogenation of diversely substituted α-ketoesters 35 (Scheme 9 A) to give hydroxyesters with yields of up to 97%, and with high enantioselectivities up to 84% ee. The values obtained were greater in relation to the parent Ru(p-cymene)(S-BINAP)Cl₂ than with what could be strongly correlated to the effect of confinement of the remaining mesopores in the zirconium phosphonate.

Scheme 9. A. Asymmetric hydrogenation of α-ketoesters 35 catalyzed by CAT15; B. The structure of CAT15. Reaction conditions: i. 35/CAT15 ratio = 250, H₂, 4.05 MPa, 80 °C, 1h.

In comparison to zirconium-phosphonate framework as a catalyst, Xu et al. reported highly efficient, chemo- and enantio-selective polystyrene-copolymer-supported Ru catalysts in the asymmetric reduction of carbonyl compounds in water. The reactions performed in water as a solvent are an important trend in green chemistry and have attracted a lot of attention. In this case, the excellent catalytic properties were proven in the transfer hydrogenation of aromatic ketones 38, having either electron-donating or withdrawing substituents, in water, as an environmentally friendly, protic, polar solvent (Scheme 10).

Scheme 10. Asymmetric transfer hydrogenation of acetophenone 38 catalyzed by CAT16. Reaction conditions: i. 38 (0.86 mmol), CAT16 (1.5 wt% Ru), H₂O, HCOOH/TEA (1:3, v:v), 50 °C, 6h.
The resulting alcohols ([R]-configuration) were obtained in high yields (94 - 98%) and enantioselectivities (94 – 98% ee except for the m-NO₂ derivatives) depending on the linker between polystyrene and the ligands (with the most efficient catalyst being CAT16, containing a sulfonamide moiety bonded directly to the phenyl ring). Surprisingly, reduction of the o-anisol derivatives (R = o-OCH₃) gave (S)-alcohol with 96% yield and 94% ee. The applied catalysts were obtained from phosphonates possessing co-polystyrenes bound to the ligands (1R,2R)-(+) -N-1-toluenesulfonyl-1,2-diphenylethylene-1,2-diamine via different nitrogen-containing linkers (Figure 4).

![CAT16](image)

**Figure 4.** The structure of polystyrene Ru catalysts CAT16.

The synthesis involved radical copolymerization of 1-phosphonate styrene with styrenes bearing a linker connected to chiral 1,2-diamine [in the presence of benzoyl peroxide (BPO), THF, 80 °C, 24h], followed by immobilization of [RuCl₂(p-cymene)]₂. The obtained polystyrene copolymers containing Ru particles trapped in nanopores play the role of diffusional channels allowing substrates to access the catalytic sites. Introduction of phosphonate to polymer as supports increased polarity of the polystyrene-based catalyst and solubility in alcohol. Moreover, it was suggested that phosphonate acts as a surfactant, indicated by the good dispersion upon adding TEA in the catalytic reaction. This catalyst can be recycled by centrifugal separation and reused in five consecutive runs.

### 2.2.3. The reduction of nitrocompounds to amines

Both aliphatic and aromatic compounds containing a nitro group can be reduced to amines or anilines. The most common methods are catalytic hydrogenation or application of some metal, e.g., Zn, Sn or Fe, and an acid.

Among various heterogenous palladium-containing catalysts, the zirconium phosphate–phosphonate nanosheet material – CAT3 (described in the coupling reactions section)¹² caused the reduction of aromatic nitro compounds 40 to give aniline derivatives 41 (Table 4). The results showed that the amount of Pd loading on the CAT3 catalyst does not greatly affect the selectivity, and the catalytic efficiency is closely related to the nature of the substituent on the aromatic ring. The presence of a halogen atom in the *meta* position significantly accelerated the kinetics of the reaction (TOF of 683 h⁻¹ for *m*-chloronitrobenzene), while the unsubstituted nitrobenzene was the least reactive (TOF of 50 h⁻¹ for nitrobenzene). Complete chemoselectivity (100%) was achieved for the *meta*-substituted fluorine derivatives, while, in the case of chloro and aldehyde derivatives, the chemoselectivity decreased to 84%.
Table 4. Catalytic reduction of nitrobenzene derivatives 40 catalyzed by CAT3

\[
\begin{align*}
\text{NO}_2 & \quad \xrightarrow{\text{CAT3}} \quad \text{NH}_2 \\
\text{40} & \quad & \text{41}
\end{align*}
\]

72%-99% substrate conversion  
84%-100% chemoselectivity

<table>
<thead>
<tr>
<th>R</th>
<th>Cycle</th>
<th>40/CAT3 ratio</th>
<th>Time [min]</th>
<th>Conversion of 40 [%]</th>
<th>TOF [h(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>100</td>
<td>120</td>
<td>99.9</td>
<td>50</td>
</tr>
<tr>
<td>m-Cl</td>
<td>1</td>
<td>300</td>
<td>20</td>
<td>75.3</td>
<td>683</td>
</tr>
<tr>
<td>m-F</td>
<td>1</td>
<td>200</td>
<td>60</td>
<td>99.9</td>
<td>200</td>
</tr>
<tr>
<td>m-F</td>
<td>2</td>
<td>200</td>
<td>60</td>
<td>99.9</td>
<td>200</td>
</tr>
<tr>
<td>m-F</td>
<td>3</td>
<td>200</td>
<td>60</td>
<td>98.5</td>
<td>197</td>
</tr>
<tr>
<td>p-Br</td>
<td>1</td>
<td>200</td>
<td>60</td>
<td>72.4</td>
<td>145</td>
</tr>
<tr>
<td>p-CHO</td>
<td>1</td>
<td>200</td>
<td>105</td>
<td>99.3</td>
<td>137</td>
</tr>
</tbody>
</table>

Reaction conditions: i. 40 (0.2 M, MeOH), H\(_2\), 0.5 MPa, RT.

Nitroarene reductions can also be catalyzed by Au@Zirconium-Phosphonate Nanoparticles. In 2019, Ferlin et al. presented an inorgano-organic layered material that can be used as an effective catalytic system for the chemoselective, mild, and switchable, reduction of nitroarenes.\(^{55}\) The gold-based catalyst CAT17 [Au@ZrP(AEP)] was tested in the chemoselective reduction of a series of nitroarenes 40 to substituted aminoarenes 41 in EtOH (96%) or EtOH\(_\text{abs}\) (Scheme 11 A). This process is highly efficient and economical because the catalyst can be recycled and reused in the flow-system reaction.

\[
\begin{align*}
\text{NO}_2 & \quad \xrightarrow{\text{CAT17}} \quad \text{NH}_2 \\
\text{40} & \quad & \text{41}
\end{align*}
\]

Scheme 11. A. Reduction of nitrobenzene derivatives 40 catalyzed by CAT17; B. The synthesis of CAT17. Reaction conditions: i. 40 (0.1 mmol), CAT17 (1 mol %), NaBH\(_4\) (6eq.), EtOH\(_\text{abs}\), 30 °C, 1-6h; ii. 42 in PrOH (1g of 42/14 mL PrOH), 43 (43/Zr molar ratio: 1 or 2 or 3), 80 °C, 3 d.

It was proven that the zirconium phosphate aminoethyl phosphonate ZrP(AEP) is suitable for immobilizing gold nanoparticles. The starting material for the synthesis of ZrP(AEP) was prepared using
zirconium phosphate ZrP gel in alcohol (PrOH) based on a Pica et al. method. Thus, in the first step, a solution of zirconyl phosphate in anhydrous alcohol was prepared, and then concentrated phosphoric acid was added to obtain the H₃PO₄/Zr molar ratio (R) equal 2, 4, or 6, respectively, and [H₃PO₄] < 2 M. The introduction of amino groups was possible by means of an anion exchange reaction of the phosphates moiety with the incoming aminoethylphosphonic acid H₂AEP (Scheme 11 B). Finally, the gold nanoparticles were supported on ZrP(AEP)₀.₇. For this purpose, a solution containing AuCl₄⁻ ions was added to a ZrP(AEP) suspension and then reduced with sodium borohydride.

It was also noticed that the used solvent had an effect on the chemoselectivity of the reduction of 44. In the case of ethanol (96%), the main product was the azoxy derivative 45, while use of absolute ethanol led to the aniline derivative 46. Moreover, traces of compound 47 were observed (Scheme 12).

Scheme 12. Reduction of 1-methoxy-4-nitrobenzene 44 catalyzed by CAT17. Reaction conditions: 44 (0.1 mmol), CAT17 (1 mol %), NaBH₄ (6eq.), 30 °C, 3h; i. EtOH (96%): 5 runs (87 – 98% conversion of 44), products ratio: 45:46:47 aver. 97:0:3; ii. EtOHabs: 5 runs (>99% conversion of 44), products ratio: 45:46:47 0:100:0.

In the last few years, a new type of composite of silver nanoparticles (AgNPs) supported by zirconium glyphosate (ZrGP) has been proposed. The tests conducted confirmed the high catalytic activity of the designed composite in the reduction of p-nitrophenol (p-NP) 48 to p-aminophenol 49 using freshly prepared NaBH₄ (Scheme 13 A).

Scheme 13. A. Reduction of p-NP 48 catalyzed by CAT18. B. The synthesis of CAT18. Reaction conditions: i. 48 (H₂O, 0.1 mmol/L), NaBH₄ (H₂O, 0.5 M), CAT18 (10 mg), 25 °C, 10min; ii. 50 (0.44 g), AgNO₃ (0.05 M), H₂O, 80 °C, 6h, then sodium citrate (100 mL, 0.5 M), 98 °C, N₂.
The catalyst could be used 7 times without a clear decrease in conversion of 48. The reaction rate was monitored by UV-Vis absorption; a decreasing band intensity at 400 nm and gradual discoloration of the solution were observed. ZrGP nanosheets 50 were obtained via reaction with ZrOCl₂ x 8H₂O and 40% hydrofluoric acid; the resulting mixture was added to glyphosate in deionized water. A multifunctional nanocomposite CAT18 (Ag/ZrGP) was prepared in situ by mixing AgNO₃ and 50 (Scheme 13 B). Similar conversion of 4-nitrophenol 48 to 4-aminophenol 49 using NaBH₄ and mesoporous nickel phosphate/phosphonate hybrid microspheres, prepared by phosphate-mediated self-assembly methodology was also reported.⁵⁸

Many reduction reactions with participation of a phosphonate-containing catalyst were considered in the previous chapter, however, some oxidation of organic compounds can be accomplished by application of phosphonate precursors as well.

2.3. Oxidation
The reactions in this section are classified into groups depending on the type of bond change involved. These groups are reactions involving the replacement of hydrogen by oxygen (oxidation of hydroxyl group, thioether to sulfoxide, methylene moiety to carbonyl group or aldehydes to carboxylic acids). We included in this category as well, reactions in which oxygen is added to the substrate (epoxidation) and transformations of ketones or aldehydes to carboxylic esters in the Baeyer-Viliger rearrangement.

The oxidation of a methylene group in cycloalkanes 51 has been made using a di-copper (II) complex containing vinylphosphonic acid (VPA) and 1,10-phenanthroline (phen) (Scheme 14). Thus, the CAT19 [Cu₂(µ-VPA₂)(phen)₂(H₂O)₂] complex has been examined as efficient catalysts for the mild oxidation or hydrocarboxylation of cycloalkanes 51, leading to carboxylic acid 52 or a mixture of primary alcohols 53 and ketones 54 (Scheme 14 A).⁵⁹

![Scheme 14](image)

Scheme 14. A. Oxidation or hydrocarboxylation of cycloalkanes 51 catalyzed by CAT19; B. The structure of CAT19. Reaction conditions: i. 51 (1 mmol), CO (2 MPa), K₂S₂O₈ (1.5 mmol), CAT19 (1 μmol), CH₃CN/H₂O, 60 °C, 3 h; ii. 51 (2 mmol), H₂O₂ (10 mmol, 50% in H₂O), CAT19 (1 μmol), CH₃CN/H₂O, 50 °C, 3 h.

As a result, cycloalkanecarboxylic acids 52 (up to 30% yields) or a mixture of cyclic alcohols 53 and ketones 54 (yields 17% to 23%) under mild conditions (50–60 °C, CH₃CN/H₂O) were formed. The physicochemical analyses of the catalyst CAT19 indicated multiple H-bonding interactions leading to a more complex 2D structure. This catalyst also shows moderate proton-conducting properties (σ = 3.65 × 10⁻⁶ S·cm⁻¹).

The application of phosphonate towards green chemistry in organic–inorganic hybrid material was shown by Bhanja et al.⁶⁰ Thus, the selective liquid-phase transformation of cyclohexanone 55 to adipic acid 56 (O₂, H₂O, atm. pressure) using the hybrid iron(II/III)-phosphonate catalyst derived from etidronic acid 57, was reported (Scheme 15 A). Metal phosphonate CAT20 ensures high selectivity (96%), and good substrate conversion (72%). The designed catalyst was obtained using 1-hydroxyethylidene-1,1-diphosphonic acid 57
(FeCl₃, pH 6, Δ, 180 °C, 3 days) (Scheme 15 B), and has been thoroughly characterized by various techniques and crystal-structure determination (BET surface area 236 m² g⁻¹, pore volume of 0.229 cm³ g⁻¹).

**Scheme 15.** A. Oxidation of cyclohexanone 55 catalyzed by CAT20; B. The synthesis of CAT20. Reaction conditions: i. 55 (5.0 mmol), CAT20 (25 mg), O₂, H₂O, 75 °C, 10h; ii. 57 (3 mmol, 60% in H₂O), FeCl₃ (6 mmol), H₂O, NH₂OH to pH 6, 180 °C, 3d.

Phosphonate-containing catalysts have also been used in oxidation reactions. In 2013, Mo et al. presented a novel organic-inorganic hybrid material (ZrNCP) with formula Zr₅(HPO₄)₅[O₅PCH₂N(CH₂CH₂COOH)CH₂PO₃] which has been used in the synthesis of catalyst CAT21 applied in aldehyde oxidations.⁶¹ The presence of the catalyst allowed the formaldehyde oxidation to formic acid with 90% yield. ZrNCP was obtained by combining ZrOCl₂ x 8H₂O, β-alanine-N,N-dimethylidenephosphonic acid (ADMPA) and phosphoric acid. To get the final material CAT21 [ZrNCP-Fe(III)], it was necessary to introduce Fe³⁺ ions into the layered structure with Fe(NO₃)₃ x 9H₂O. Moreover, it was demonstrated that the coordination of an Fe³⁺ ions via nitrogen and carbonyl groups from ZrNCP increased the catalytic activity of the prepared hybrid material significantly.

Thornburg et al. reported examples of selective catalytic oxidations of thioether 58 to sulfoxides 59 with H₂O₂ (Scheme 16 A).⁶² The authors demonstrated the application of catalyst CAT22 (PPA-Nb-SiO₂), formed by modification of Nb-SiO₂ material with phenylphosphonic acid 60 (PPA) at 65 °C (Scheme 16 B).

Additionally, the catalytic studies of cis-cyclooctene epoxidation (as co-reactant in the batch), proved that PPA inhibits direct cyclohexene epoxidation pathways, and sulfoxide is mainly formed, even in the presence of stoichiometric amounts of alkenes.

**Scheme 16.** A. Oxidations of thioether 58 to sulfoxides 59 catalyzed by CAT22; B. The synthesis of CAT22. Reaction conditions: i. 58, CAT22, H₂O₂, CH₃CN, 45 °C; ii. 60 (1 eq.), Nb-SiO₂, (1 eq.), CH₃CN, 65 °C, 2h.

The observed selectivity of this reaction most probably resulted from the preferential binding of a Lewis base such as P=O in CAT22 to thioether 58 and product 59, preventing further oxidation to the sulfone. The
presented studies announced the development of modified catalysts toward commercially relevant applications.

A popular oxidation reaction based on carbon-to-oxygen migrations is the Baeyer-Villiger (BV) rearrangement of ketones or aldehydes with peroxycacids or other peroxy compounds in the presence of acid catalysts. One of the exemplary works is an article of Rocha et al. regarding the use of metal phosphonate–zirconium phenylphosphonate amorphous CAT23 \([\text{Zr}(\text{O}_3\text{PC}_6\text{H}_5)_2], \text{(ZrPPA)}\) in the BV oxidation of \(p\)-methoxybenzaldehyde 61 in the presence of an aqueous solution of hydrogen peroxide and glacial acetic acid (Scheme 17 A). The reaction involves the formation of a formate ester 62 which, under aqueous acidic conditions, is hydrolyzed to the target phenol 63 with a quantitative yield.

\[
\begin{align*}
\text{H}_3\text{CO} & \quad \text{CHO} \quad \text{CAT23} \quad \text{H}_2\text{O} \\
61 & \quad \rightarrow \quad \text{H}_3\text{CO} & \quad \text{O} & \quad \text{H} & \quad \text{OH} \\
& \quad 62 & \quad \text{H}_3\text{CO} & \quad 63 \\

\text{98% substrate conversion}
\end{align*}
\]

**Scheme 17.** A. Baeyer-Villiger oxidation of \(p\)-methoxybenzaldehyde 61 catalyzed by CAT23; B. Schematic representation of CAT23. Reaction conditions: \(i.\) 61 (2 mmol), \(\text{H}_2\text{O}_2/\text{H}_2\text{O} \) (30%, v:v; 8 mmol), \(\text{AcOH} \) (4 mL), CAT23 (0.1 g), 45 \(^\circ\)C, 6h.

CAT23 (Scheme 17 B) was obtained by mixing an aqueous solution of \(\text{ZrOCl}_2 \times 8\text{H}_2\text{O}\) with phenylphosphonic acid (PPA). According to the reaction mechanism, the intermediate species approach the interlayers of CAT23, resulting in greater availability for hydrolysis of 62 to get 63. The metal-phosphonate catalyst ensure over 90% of the substrate conversion and 100% selectivities to \(p\)-methoxyphenol 63, while an analogous reaction, without a catalyst, led to 75% substrate conversion and yielded ester 62.

Another intriguing example is the work of Dutta et al., which used hybrid porous tin(IV) phosphonate CAT24 (HMSnP) for the oxidation of cyclohexanone 55 to adipic acid 64 under liquid-phase conditions (Scheme 18 A). The synthesis was carried out using molecular oxygen (a balloon filled with air) instead of the \(\text{H}_2\text{O}_2\) typical in BV oxidation. In addition, a large adsorption capacity of \(\text{CO}_2\) on the surface of CAT24 was indicated. A synthesized-by-surfactant-templating method hybrid material was obtained in the reaction of pentaethylenehexamine-octakis-(methyl phosphonic acid)hexadecasodium salt 65 (Scheme 18 B) and quaternary ammonium surfactant – cetyl trimethylammonium bromide (CTAB) followed by the addition of \(\text{SnCl}_4 \times 5\text{H}_2\text{O}\), after stirring for 12h. The final material was subjected to hydrothermal treatment at 393K for 48 h. The catalyst can be reused in five reaction cycles without a significant decrease of activity.
Scheme 18. A. Oxidation of cyclohexanone 55 to adipic acid 64 catalysed by CAT24; B. Organophosphorus precursor 65 used for the synthesis of CAT24. Reaction conditions: i. 55 (5.1 mmol), H₂O, 80 °C, 15min, next CAT24 (0.025 g), 80 °C, 5h, balloon filled with air.

Epoxidation is the reaction that has the broadest utility. The addition of oxygen to alkenes yielding epoxide is frequently done using a number of per oxyacids. Phosphonate ligands are also used in the synthesis of epoxidation catalysts. The epoxidation of cyclohexene 66 to cyclohexene oxide 67 (Scheme 19) was verified in reactions catalyzed by immobilized homogeneous molybdenum catalysts anchored on polymer-inorganic zirconium phosphonate-phosphate (ZPS-PVPA), functionalized by various pyridines (CAT25).

Scheme 19. Epoxidation of cyclohexene 66 catalyzed by CAT25. Reaction conditions: i. 66 (1 mmol), TBHP (2 mmol), CAT25 (2 mmol %), n-nonane (internal standard, 1 mmol), 1,2-dichlo roethane, reflux, 1-6h, N₂.

The results have confirmed 99% substrate conversion in laboratory and industrial scales. Moreover, catalyst CAT25 can be recycled and reused in the reaction for up to 9 runs. The catalyst support 68 (ZPS-PVPA) was obtained by reacting styrene-phenylvinylphosphonic acid copolymer (PS-PVPA) with ZrOCl₂ x 8H₂O and sodium orthophosphate. Next, addition of chloromethyl-methyl ether and anhydrous zinc chloride resulted in the formation of chloromethyl-zirconium poly(styrenephenylvinylphosphonate)-phosphate (ZCMPS-PVPA), which was modified with pyridine groups. On such a prepared hybrid material, the immobilization of molybdenum originating from MoO₂(acac)₂ led to CAT25 (Scheme 20).
Scheme 20. Synthesis of CAT25. Reaction conditions: i. 68 (8.55 mmol), chloromethyl methyl ether (9.3 mL), anh. ZnCl$_2$ (14.18 mmol), 45 °C, 8h; ii. ZCMPS-PVPA (5.0 g), toluene, 10 min, RT, then pyridine, 80 °C, 12h; iii. EtOH, RT, 30 min, then MoO$_2$(acac)$_2$, 60 °C, 24h.

Another example of the attractive application of phosphonate-supported catalysts is proposed by He et al., i.e., the epoxidation of cyclohexene 66 to epoxide 67 via transition state 68 (Scheme 21). The reaction was carried out in the presence of the urea-hydrogen peroxide (UHP) adduct as an oxidizing agent. The epoxidation catalyst CAT26 (MTO/ZrPP) was based on methyltrioxorhenium anchored onto zirconium phenylphosphonate (ZrPP), which was obtained by mixing ZrOCl$_2$ x 8H$_2$O, hydrofluoric acid and phenylphosphonic acid (PPA). Methyltrioxorhenium (MTO) was then immobilized by conventional impregnation on the support surface.

Scheme 21. Epoxidation of cyclohexene 66 catalyzed by CAT26. Reaction conditions: i. 66 (9.8 mmol), UHP (19.2 mmol), CAT26 (0.1 g), MeOH, RT, 6h.

The asymmetric epoxidation of α-methylstyrene was examined using chiral (salen)Mn(III) complexes anchored on sulfoalkyl-modified zirconium poly(styrene-isopropenyl phosphonate)-phosphate CAT27 (ZPS-IPPA). The catalysts, and the influence of various supporting linkage lengths were verified in the presence of sodium hypochlorite (NaClO) and 4-phenyl-pyridine N-oxide (PPNO). In addition, it was reported that the catalyst can be recycled and used in 5 runs without significant loss of substrate conversion or ee value. It was the first such example of a salen-type complex that was immobilized by axial coordination.

CAT27 (Figure 5) was synthesized by mixing a linear polystyrene-isopropenyl phosphonic acid (PS-IPPA) copolymer, hydrated sodium orthophosphate, and ZrOCl$_2$ x 8H$_2$O. The final hybrid material was obtained by immobilization of the Jacobsen catalyst into ZPS-IPPA.
The (salen)Mn(III)-grafted catalysts on phosphonate-containing crystalline-layered organic polymer-inorganic hybrid materials have been used to study catalytic asymmetric epoxidation of α-methylstyrene or indene by Huang et al.\textsuperscript{69} The applied hybrid materials \textsuperscript{69} were based on zinc poly(styrene-phenylvinylphosphonate)-phosphates and different amines were used as templates e.g., propylamine (PA) (Scheme 22). Next, \textsuperscript{69} was modified with \textit{p}-phenylenediamine and the chiral (salen)Mn(III) was immobilized, to give effective and stable CAT28. Moreover, due to mesoporous structure of polymer and support pore size in this type of organic-inorganic hybrid material, the enhancement of catalytic activity was observed.

\textbf{Scheme 22.} Synthesis of CAT28 containing chiral salen Mn(III). Reaction conditions: \textit{i}. \textsuperscript{69} (0.59 mmol), CH\textsubscript{3}OCH\textsubscript{2}Cl (1.6 mL), ZnCl\textsubscript{2} (4.2 mmol), next \textit{p}-phenylenediamine, Na\textsubscript{2}CO\textsubscript{3} (0.01 mol), Cul (1 mmol), alcohol (50 mL); then salen Mn(III)Cl (4 mmol), TEA (5 mmol), THF, reflux, 10h.

The enantioselective epoxidation of styrene and its derivatives (Table 5) was studied with the application of the heterogeneous titanium-phosphonate material containing chiral tripodal-architecture-origin amino acids such as phenylglycine (\textbf{TiP-PhGly}) with encapsulated achiral (salen)Mn(III) - CAT29.\textsuperscript{70} In this case, the synthesis
of the peptidic catalyst involved coupling of the amino acids (PhGly) to tris(2- aminoethyl)amine, followed by introduction of the phosphonoacetic acid moieties to get tripodal 70. Subsequent reaction of 70 with Ti(O-i-Pr)₄, and encapsulation of the achiral (salen)Mn(III), gave CAT29 (Scheme 23). Analogous application of leucine (Leu) instead of phenylglycine (PhGly) in 70, and subsequent treatment with Ti(O-i-Pr)₄, led to CAT30, possessing enantioselective catalytic activity verified in epoxide ring opening reactions. The application of this particular catalyst will be discussed in section concerning acid-promoted reactions.

Scheme 23. Synthesis of peptidic catalysts on titanium oxide CAT29 – CAT30; Reaction conditions: i. 70 R = Ph, Mn(III)-salen, Ti(O-i-Pr)₄; ii. 70 R = CH₂-CH(CH₃)₂, Ti(O-i-Pr)₄, DMSO, RT.

The results concerning asymmetric epoxidation of styrene or α-methylstyrene 71 to 72, performed using catalysts CAT27 – 29 are presented in Table 5. The reaction catalysed by CAT27 was performed in the presence of sodium hypochlorite (NaClO) and 4-phenyl-pyridine N-oxide (PPNO) and led to 72 (48% ee) with substrate conversion of 57.6%. As indicated, the obtained enantiomeric excess (ee) value for 72 (R¹ = CH₃, R² = H) was higher after immobilization of (salen)Mn(III) complexes on CAT27 than in the case of the homogeneous Jacobsen catalyst (84% ee and 54% ee, respectively). The asymmetric epoxidation of styrene or α-methylstyrene 71 using catalyst CAT28 (5 mol%) and m-CPBA/NMO as oxidant systems, was carried out at −20 °C in CH₂Cl₂ for 5h to give the α-methylstyrene (or indene) oxides 72 with enantioselectivity 99% ee (or 88% ee), and substrate conversion of 99% (or 96%). The stereochemistry of 72, however, has not been indicated.

For comparison, the reaction catalyzed by CAT29 with aqueous hypochlorite in THF led to 71 with a substrate conversion from 17 - 86%. Additionally, the formation of glycols 73 resulting from epoxide ring opening, with selectivity from 20-65%, and enantioselectivity >99% was observed. The S isomer was the major isomer in all cases.
Table 5. Epoxidation of styrenes 71 catalyzed by CAT27 – CAT29 and hydration of epoxide catalyzed by CAT29

![Chemical Structures](image)

<table>
<thead>
<tr>
<th>Substituents</th>
<th>Catalyst</th>
<th>Epoxide 72 selectivity; %ee</th>
<th>Diol 73 selectivity</th>
<th>Conversion of 71 [%]</th>
</tr>
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<tbody>
<tr>
<td>R¹ = H, R² = H</td>
<td>CAT27</td>
<td>&gt;99; 48ᵇ</td>
<td>0</td>
<td>57.6</td>
</tr>
<tr>
<td>R¹ = CH₃, R² = H</td>
<td>CAT27</td>
<td>&gt;99; 84ᵇ</td>
<td>0</td>
<td>70.1</td>
</tr>
<tr>
<td>R¹ = CH₃, R² = H</td>
<td>CAT28</td>
<td>&gt;99; 99.5ᵇ</td>
<td>0</td>
<td>99.2</td>
</tr>
<tr>
<td>R¹ = H, R² = CH₃</td>
<td>CAT29</td>
<td>25; 36ᶜ</td>
<td>65ᵈ</td>
<td>17</td>
</tr>
<tr>
<td>R¹ = CH₃, R² = H</td>
<td>CAT29</td>
<td>35; 7ᶜ</td>
<td>20ᵈ</td>
<td>84</td>
</tr>
<tr>
<td>R¹ = CH₃, R² = CH₃</td>
<td>CAT29</td>
<td>15; 10ᶜ</td>
<td>40ᵈ</td>
<td>20</td>
</tr>
<tr>
<td>R¹ = CH₃, R² = CH₃</td>
<td>CAT29</td>
<td>25; 5ᶜ</td>
<td>25ᵈ</td>
<td>86</td>
</tr>
</tbody>
</table>

Reaction conditions: i. 71 (1 mmol), nonane (1 mmol), CAT27 (3 mol%), NaOCl in buffered solution (pH 11.3, 0.55M), PPNO (0.38mmol), CH₂Cl₂, 20 °C, 24h; ii. 71 (1 mmol), NMO (5 mmol), m-CPBA (2 mmol), CAT28 (5 mol %), CH₂Cl₂, -20 °C, 5h; iii. 71 (0.1 mmol), NaOCl in buffered solution (0.2 mmol), CAT29 (10 mg), THF, 3 °C, 48h. ᵇ % ee >99, in each case; ᵇ the stereochemistry is not indicated; ᵇ The major isomer is S; ᵇ The S isomer.

The epoxidation of vegetable oils is also exceptionally attractive due to the potential use of the products as stabilizers of polyvinyl chloride. Examples of such epoxidation using organophosphonate catalysts are also known. In 2019, Zou et al. described a novel solid acid catalyst CAT31 based on zirconium poly(styrene-phenylvinyl-phosphonate)-phosphate 74 (ZPS-PVPA).


The final material was obtained via anchoring of the thiol group on 74 {[Zr(PO₃)OH]₁₁₅[O₃PC(Ph)CH₂(CHPhCH₂)ₙ₀₆₅ * xH₂O} and thiol oxidation to sulfonic acid. CAT31 showed high
catalytic activity in the epoxidation of soybean oil with TBHP (tert-butyl hydroperoxide) as an oxidant. The catalyst could be recycled, and reused in 5 runs without greatly decreasing the substrate conversion.\textsuperscript{72}

2.4. Cycloaddition of CO\textsubscript{2} to epoxide

Besides asymmetric synthesis, one of the eco-trends in chemistry is the catalytic capture of CO\textsubscript{2},\textsuperscript{73} which is considered one of greenhouse gases involved in climate warming. As a promising approach, one can envisage the cycloaddition of CO\textsubscript{2} to an epoxide, yielding useful cyclic carbonates.

In view of this topic, the application of a porous copper-phosphonate catalyst was reported by Ai \textit{et al.}\textsuperscript{74} The conversion of small aliphatic as well as aromatic oxiranes \textbf{75} to cyclic carbonates \textbf{76} in yields of up to 99\% was performed in a carbon-dioxide atmosphere and higher pressure (1 MPa), using catalyst CAT32 (at 100 °C) in the presence of TBAB (tetrabutylammonium bromide) as a co-catalyst (Table 6). Furthermore, the copper-phosphonate catalyst CAT33 has proven to be an excellent catalyst in ring-opening reactions of epoxides under ambient conditions, leading to α-methoxyalcohol \textbf{77} with 99\% conversion, and more than 99\% selectivity. This catalyst could be reused in at least 3 cycles in both types of reactions.

For comparison, the analogous cycloadditions of CO\textsubscript{2} to epoxide \textbf{75} were performed using Ni phosphonate as catalyst CAT33.\textsuperscript{75} The high catalytic efficiency of CAT33 at CO\textsubscript{2} pressure of 1 MPa, and room temperature, was demonstrated for small-size aliphatic epoxides, e.g., glycidol or epichlorohydrine (99\% and 83\%, respectively). Analogous reactions of styrene oxide or glycidyl ether \textbf{75}, gave carbonates \textbf{76} with lower yields, even after 48h (8\% or 20\%). A similar tendency of the conversion of epoxide \textbf{75} to carbonate \textbf{76} was observed in the case of the catalytic cycloaddition of CO\textsubscript{2} catalyzed by manganese phosphonate CAT34.\textsuperscript{76} Thus, under the applied conditions of CO\textsubscript{2} (1 MPa), and room temperature, aliphatic oxiranes were efficiently transformed in yields of 77 - 99\%, while styrene oxide and glycidyl phenyl ether \textbf{75} gave products in yields of 4 - 6\%, respectively. Another catalyst used for the CO\textsubscript{2} insertion to epoxides \textbf{75} is CAT35 in the form of organic-inorganic iron-phosphonate nanoparticles, presented by Rosati \textit{et al.}\textsuperscript{77} The synthesized CAT35 efficiently catalysed CO\textsubscript{2} cycloaddition to small-aliphatic oxiranes and bigger styrene oxide or phenyl glycidol ether under mild conditions yielding \textbf{76} in the range of 88 - 97\% (Table 6). The CAT35 was sucessfully reused in five runs with over 90\% substrate conversion.

The authors have proposed a mechanism of \textbf{76} formation involving the activation of the epoxide by phosphonic acid moieties and metal centers in CAT32, simultaneously acting as Brønsted and Lewis acids, respectively.\textsuperscript{74} Subsequent nucleophilic attack of Br\textsuperscript{-} (from TBAB) from the less hindered side causing epoxide opening, followed by CO\textsubscript{2} insertion, led to the obtained \textbf{76}. What is important is that the CO\textsubscript{2} as well as the oxirane \textbf{75} enter and assemble in the porous channels of the catalysts.
Table 6. Cycloaddition using CO$_2$ to epoxides 75 catalyzed by CAT32 - CAT35, and catalytic epoxide ring opening.

![Diagram of cycloaddition]

<table>
<thead>
<tr>
<th>R</th>
<th>CAT32 [%]$^a$</th>
<th>CAT33 [%]$^a$</th>
<th>CAT34 [%]$^a$</th>
<th>CAT35 [%]$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_2$OH</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>97</td>
</tr>
<tr>
<td>CH$_2$Cl</td>
<td>99</td>
<td>83</td>
<td>77</td>
<td>88</td>
</tr>
<tr>
<td>Ph</td>
<td>99</td>
<td>8</td>
<td>4</td>
<td>97</td>
</tr>
<tr>
<td>CH$_2$OPh</td>
<td>99</td>
<td>20</td>
<td>6</td>
<td>96</td>
</tr>
</tbody>
</table>

Reaction conditions: $i.$ 75 (20 mmol), CAT32 (2 μmol), TBAB (0.3 mmol), CO$_2$, 1 MPa, 100 °C. $ii.$ 75 (20 mmol), CAT33 (0.05 mol %) or CAT34 (0.02 mmol), TBAB (0.3 mmol), CO$_2$, 1 MPa, RT, 48h or 36h; $iii.$ 75 (5 mmol), CAT35 (50 mg), TBAB (0.083 mmol), CO$_2$, 100 MPa, RT, 12h; $iv.$ 75 R= Ph (0.2 mmol), CAT32 (2 μmol), 25° C, MeOH $^a$ yield of 76.

In the syntheses of the above-described cycloaddition catalysts, various aromatic or aliphatic phosphonic acids as precursors were employed (Figure 6). The copper phosphonate catalyst CAT32 [Cu$_2$(H$_3$L)$_2$(TPT)$_3$(H$_2$O)$_6$] was synthesized by the reaction of tetra-phenylsilane tetrakis-4-phosphonic acid 78 (H$_8$L), Cu(OAc)$_2$ and a ligand TPT: [5-(4-((1H-1,2,4-triazol-1-yl)phenyl)-1H-tetrazole)] in water at 180 °C for 3 d.$^{74}$ The reaction of rigid tetraphosphonic acid 79 (H$_8$L), nickel(II) nitrate hexahydrate and HF in H$_2$O/MeOH at 150 °C for 3 d gave catalyst CAT33.$^{75}$ For comparison, the Mn (II) catalyst CAT34 was prepared from pyridin-4-yl phosphonic acid 80 (H$_2$L) and manganese (II) acetate tetrahydrate in water at 80 °C (3 d).$^{76}$ Additionally, the application of such a phosphonate precursor as hexamethylenediamine- N,N,N',N'-tetrakis-(methylphosphonic acid) 81 (HDTMP) in the reaction with an aqueous solution of FeCl$_3$ at 150 °C for 24h, led to hybrid material CAT35.$^{77}$
Figure 6. Organophosphorus precursors 78 – 81 used for the synthesis of catalysts CAT32 – 35.

All catalysts were fully characterized by different methods and can be easily separated and reused without significant reduction in the catalytic ability.

2.5. Condensations
Another important class of organic chemistry reactions, in which two or more molecules combine, usually in the presence of a catalyst to form a larger product with a simultaneous loss of water or another small molecules, are condensation reactions. Some of them are catalyzed by acids, although, in the most common condensations, use of a base is necessary.

In 2018, Rosati et al. described the solid Brønsted bases containing phosphonate groups used in the Knoevenagel condensation.78 A condensation has occurred between substituted aldehydes 82 and malononitrile 83 (Scheme 25 A), while as catalysts, zirconium potassium phosphate/phosphonates (CAT36 – CAT38, ZrKPs) (Scheme 25 B) were used. Moreover, the reactions did not require the use of organic solvents. The applied catalysts could be recycled and showed high activity in 5 reaction cycles without structural changes (substrate conversion up to 99%, isolated yields of 84 up to 96%).

Scheme 25. A. Knoevenagel condensation of aldehydes 82 with malononitrile 83 catalyzed by CAT36 – CAT38; B. Schematic representation of CAT36 – CAT38. Reaction conditions: i. 82 (1 mmol), 83 (1 mmol), CAT36 – CAT38 (2 mol %), RT, 1h. a isolated yield of 84.
The catalysts have also been used successfully in Knoevenagel condensation of salicylaldehyde 85 with ethyl cyanoacetate 86 to give biologically important 2-amino-4H-chromene (87, 88). The product was obtained in the form of two diastereoisomers in which the predominant form was the erythro isomer 87 (Table 7). In addition, it was noted that compound 87 left in the CDCl₃ solution epimerizes to the threo isomer 88 (87:88 = 80:20 after 6 h).

**Table 7.** Knoevenagel condensation of salicylaldehyde 85 with ethyl cyanoacetate 86 catalyzed by CAT36 – CAT38

<table>
<thead>
<tr>
<th>Substrat conversion [%]</th>
<th>CAT36 [%]</th>
<th>CAT37 [%]</th>
<th>CAT38 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated yield [%]</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>87/88</td>
<td>97/3</td>
<td>99/1</td>
<td>99/1</td>
</tr>
</tbody>
</table>

Reaction conditions: i. 85 (1 mmol), 86 (2 mmol), CAT36 – CAT38 (5 mol %), 50 °C, 4h.

Amorphous solids (CAT36 – CAT38, Scheme 25 B) were obtained in the reaction of ZrOCl₂ x 8H₂O with a phosphorus source – phosphoric acid and methyl and/or phenylphosphonic acid (P/Zr=3 ratio). The obtained zirconium phosphate/phosphonates (ZrHPSs) were then treated with a solution of t-BuOK. Analogous use of KOH causes changes of the layer composition, and, consequently, decreases the catalyst effectiveness, which was confirmed by ³¹P NMR analysis. It has been shown that the methyl and phenyl groups present on the catalyst layer caused the formation of larger dimension pores, and also influence higher catalytic activity compared to inorganic Zr(KPO₄)₂. ⁷⁸

The above catalysts are an extension of the work of the previously investigated use of zirconium phosphates and methyl and/or phenyl phosphonates-supported L-proline. In 2011, Calogero et al. published a study concerning solid catalysts functionalized by a chiral ligand.⁷⁹ The obtained materials showed high catalytic activity in the asymmetric aldol reaction of cyclohexanone 55 with p-nitrobenzaldehyde 89 (Scheme 26 A). The results confirmed that a presence of the chiral ligand on the surface has an effect on increasing catalytic activity. L-Proline covalently linked with zirconium material ensured a high diastereoselectivity of the reaction, and a large enantiomeric excess (90/91 ratio up to 94:6 and up to 96% ee). The reaction can be carried out both in a mixture of DMF and water (9:1) and the more eco-friendly condition, i.e., solely water.
Scheme 26. A. Aldol reaction of cyclohexanone 55 with p-nitrobenzaldehyde 89 catalyzed by CAT39 – CAT41; B. Schematic representation of CAT39 – CAT41. Reaction conditions: i. 55 (0.625 mmol), 89 (0.125 mmol), CAT39 – CAT41 (0.062 mmol, 0.0375 mmol of P-Prol groups – 30 mol %), DMF/H₂O (9:1, v:v) or H₂O, 30 °C, 4 d.

In order to prepare the catalysts CAT39 – CAT41, trans-4-hydroxy-L-proline was mixed with phosphorus oxychloride to get (4R)-4-phosphonoxy-L-proline. In the next step, the obtained amino acid was immobilized on an inorganic zirconium layer by the reaction with an aq. solution of ZrOCl₂ and methyl and/or phenylphosphonic acids (P/Zr=3 ratio) (Scheme 26B). The solid materials obtained were fully characterized by NMR spectroscopy, TG DTA, ICP-OES and nitrogen adsorption-desorption isotherms.

Organic phosphonate ligands have also found application in the synthesis of an organic-iron nanocatalyst CAT42 (Fe-DTPMP) which catalyzed a tri-component condensation reaction. In 2020, Arpanahi et al. presented a novel organic-inorganic hybrid catalyst based on the ligand, diethylenetriamine penta(methylene phosphonic acid) (DTPMP) 29. The described catalyst showed high activity in condensation reactions between aromatic aldehydes 82, 1,2-diphenyl-1,2-ethanedione 92, and ammonium acetate to 2,4,5-trisubstituted imidazoles 93 (Scheme 27 A).

Scheme 27. A. Tri-component condensation of aromatic aldehydes 82 and 1,2-diphenyl-1,2-ethanedione 92 catalyzed by CAT42; B. The synthesis of CAT42. Reaction conditions: i. 92 (1 mmol), 82 (1 mmol), NH₄OAc (3 mmol), CAT42 (0.05 g), 100 °C, 1h; ii. FeCl₂ (50 mL, 0.25 M), CTAB (1.5 g), 30 °C, 1h, next 29 (25 mL, 0.1 M), NH₃ to pH= 9, 75 °C, 6h.

The authors found that the yields of the heterocyclic compounds were influenced by the substituent from the aromatic ring of the aldehyde. The presence of an electron-withdrawing substituent increases the yield of compound 93 while the opposite effect was observed for an electron-donating group. The tested catalyst provided a short reaction time and the possibility of reuse in 4 runs. Moreover, the reaction did not require the
use of solvents. The described hybrid CAT42 was synthesized by mixing iron (II) chloride (aq. solution) with a surfactant, cetrimonium bromide (CTAB). Then the phosphonate ligand 29 was added, and the reaction mixture was treated with ammonia to pH= 9 (Scheme 27 B). After drying, the precipitated solid was characterized using a number of structural analyses, including FT-IR, TGA, XRD, BET and others.

For comparison, the condensation of various aromatic aldehydes 94 with o-phenylenediamine 95 using an organic–inorganic hybrid porous iron–phosphonate CAT43 gave the benzimidazole derivatives 96 in yields ranging from 30-92% (Scheme 28A). This catalyst was synthesized from hexamethylenediamine-NN,N',N'-tetrakis-(methylphosphonic acid) 81 (HDTMP) and FeCl₃ under different hydrothermal conditions (Scheme 28B), and possessed structures of nanoparticles or nanorods or flake-like morphology.

![Scheme 28. A. Condensation of aromatic aldehydes 94 and o-phenylenediamine 95 catalyzed by CAT43; B. The synthesis of CAT43. Reaction conditions: i. 94 (1 mmol), 95 (1 mmol), CAT43 (30 mg), EtOH (5ml), 298K, 2-3h; ii. FeCl₃(10 mol), H₂O (10g) then 81 (2.54 mol, 25%), 423K or 443K or 453K, 24h.]

The authors proposed a mechanism involving activation of the carbonyl group in aldehyde 94 by the iron center in the catalyst CAT43, followed by attack of the amine group in 95, with the tertiary amine group in the catalyst facilitating elimination of a water molecule to give product 96.

2.6. Other acid-promoted reactions

Most organic reactions occur under acidic conditions. In this part, the application of the Brønsted acidity of the catalyst in organic reactions will be discussed.

Phosphonate-based catalysts are used especially for the conversion of biomass into green chemicals or fuels. An intriguing example of this topic is the work of Liu et al. from 2020 in which the authors presented three-step transformations of sacharides catalyzed by a cobalt-phosphonate CAT44 [Co₂(2,2'-bipy)(H₄L)(H₂O)]H₂O catalyst.
The authors found that the catalyst allowed the formation of hydroxymethylfurfural HMF 24 from cellulose 97 via hydrolysis to glucose. Subsequent glucose isomerization to fructose, and dehydration of fructose yielded 24 (intermediate products confirmed by GC-MS analysis). Starting from cellulose, it is possible to obtain HMF 24 in up to 92% yield (Scheme 29 A). The final yield of 24 was influenced by the weight percent of the catalyst CAT44 and the type of cellulose used (10 wt% CAT44; microcrystalline 97 = 33%; regenerated 97 = 50%, 40 wt% CAT44, regenerated 97 = 59%). The applied catalyst combines two types of acidity, Brønsted acid (phosphonic acid, 78) responsible, among others, for the cellulose hydrolysis, and Lewis acid (cobalt ion as a metal centre) responsible for the glucose to fructose isomerization. The catalyst obtained in hydrothermal reaction of 78 with Co(NO₃)₂ and 2,2-bipyridine (Scheme 29 B), was successfully reused in 4 runs.⁸²

Another studied reaction relying on the Brønsted acidity of the obtained catalyst CAT45 pertained to the conversion of 2-methyl-tetrahydrofuran 98 (2-MTHF) into two pentadiene PD isomers, 99 and 100 (1,3 and 1,4PD). Thus, a one-pot dehydration and decyclization reaction, with the application of a phosphonate-modified material based on a metal-organic framework with UiO-66 topology (CAT45), was demonstrated (Scheme 30).⁸³ The authors reported low and moderate, site-time-dependent yields (~ 23%) in the case of the 98 conversion, and, at the same time, high selectivity to pentadienes (~ 90% on a per C basis), i.e., 22% of 99 and 67% of 100).

Moreover, CAT45’s weak Brønsted acidity was confirmed by the dehydration of i-PrOH in comparison to ethanol, and Hoffman elimination of tert-butylamine.

Synthesis of the MOF-derived catalyst CAT45 involves post-synthetic modifications (PSM) of UiO-66’s well-defined sites with 2-diisopropylphosphono-terephthalic acid 101 as a phosphorus source, by a solvent-assisted ligand exchange method (in KOH/THF). Next, acid treatment (1M HCl, AW), to deprotect the

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Scheme 29. A. Transformation of cellulose 97 to HMF 24 catalyzed by CAT44; B. The synthesis of CAT44. Reaction conditions: i. 97 (200 mg), NaCl (sat.), CAT44 (20 mg), methyl isobutyl ketone, 2-butanol, 200 °C, 1h; ii. Co(NO₃)₂ (0.08 mmol), 78 (0.04 mmol), 2,2-bipyridine (0.04 mmol), H₂O, 180 °C, 3 d.

Scheme 30. Tandem dehydration/decyclization reaction of 2-methyl-tetrahydrofuran 98 catalyzed by CAT45; Reaction conditions: i. 98, CAT45 (0.05 g), 653 Pa, 280 °C, weight hourly space velocity (WHHSV) 0.31 h⁻¹.
phosphonate isopropyl groups gave the possibility of distribution of acid sites throughout the framework (Scheme31). The catalyst has the majority of P-OH bonds with small or no interactions with the zirconium cluster. The catalyst CAT45 (P-UiO66-AW) has also shown high selectivity in three consecutive reaction-regeneration cycles.\textsuperscript{83}

![Scheme 31](image)

**Scheme 31.** The synthesis of CAT45. Reaction conditions: \(i. 101, \text{KOH}_\text{aq}/\text{THF}, \text{then UiO-66, 180 }^\circ\text{C, 5 d, next HCl, 100 }^\circ\text{C, 12h, then activation 120 }^\circ\text{C, 20h.}\)

The interesting example of the application of homochiral titanium phosphonate on a polypeptide scaffold to catalyze diols formation via epoxide opening in an asymmetric manner, was reported by Milo \textit{et al.}\textsuperscript{71} Thus, the enantioselective water addition to racemic styrene oxide and its derivatives 72 was studied with the application of the heterogenous catalyst containing leucine CAT30.\textsuperscript{70} The studied reactions resulted in (S)-diols 73 with 20 - 30% yields, and 95 - 99% ee (Scheme 32).

![Scheme 32](image)

**Scheme 32.** Enantioselective hydration of styrene oxide 72 derivatives catalyzed by CAT30. Reaction conditions: \(i. (R/S)-72 (20 \text{ mL}), \text{THF/H}_2\text{O, pH 7 or 11 (buffer) CAT30 (10 mg), 38 }^\circ\text{C, 72h.}\)

In this particular example, authors proposed the mechanism involving the activation of oxirane by a partially positively-charged peptide yielding carbocation. Next, the enantioselective attack of water directed by homochiral catalyst led to (S)-diol.\textsuperscript{71} It is worth noting that the styrene oxide that did not react remained as a racemic mixture. Additionally, it was observed that enantiomerically-enriched styrene oxide did not racemize under the applied reaction conditions. The synthesis of peptidic titanium-phosphonate homochiral catalyst CAT30\textsuperscript{71} was described in the previous part of this review.
3. Conclusions

Catalysts containing the phosphonate moiety and their applications have been described in a large number of reports, providing insight into their activity depending on metal elements used, the nature of the organophosphorus components, and an organic or inorganic scaffold. The phosphonate-containing catalysts presented in this review are frequently efficient in more than one described category. From the organic chemist’s point of view, this exciting branch of chemistry is worth the interest and development reflected in this review. Considering the development of organic chemistry and reactions such as coupling, epoxidation, reduction or oxidation reactions, etc., modern methods of organic synthesis with catalysts appear to be the most useful. The wide and significant achievements in this field have led to important advances that allow the preparation of more complex organic molecules, useful not only in bioorganic and medicinal chemistry, but in energy-storage materials as well. The application of these efficient and selective methods would help to solve important practical problems in industrial synthesis, safety and environmental protection.

Acknowledgements

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Mateusz Klarek was born in 1994 in Poznań, Poland. In 2016, he earned Bachelor's degree in general chemistry (B.Sc.) from Adam Mickiewicz University (AMU). In 2018, he defended his Master's dissertation (M.Sc.) – Repetitive batch borylative coupling of olefins with vinylboranes in green solvents, written under the supervision of Professor Piotr Pawluć. Currently, he is a PhD candidate of The Department of Synthesis and Structure of Organic Compounds at Adam Mickiewicz University (supervisor: Prof. Magdalena Rapp). His research area covers synthesis and structural studies of fluorine and phosphorus containing organic molecules, especially aziridines and aminophosphonates as biologically active compounds.

Magdalena Rapp graduated in chemistry in 1999 at Adam Mickiewicz University (AMU) in Poznań. In 2003, she defended her doctorate on the synthesis and photochemistry of pyrimidines under the supervision of Prof. Golankiewicz at the same faculty. In the period 2004-2006 she completed a postdoctoral fellowship in the group of Prof. Stanisław Wnuk at the FIU University in Miami, USA, where she gained experience in the chemistry of sugars and nucleosides. In 2006, she started working as an assistant professor at the Department of Synthesis and Structure of Organic Compounds at the Faculty of Chemistry Adam Mickiewicz University in the research group of Prof. Henryk Koroniak. In 2019, she obtained her habilitation for the work related to the synthesis and
stereochemistry of natural compounds analogues. Her research interests focus on both classical and modern organic synthesis, in particular the phosphorus and fluorine organic chemistry.

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