


 Cite this: *RSC Adv.*, 2025, 15, 17591

# Advancements in silver-based nanocatalysts for organic transformations and other applications: a comprehensive review (2019–2024)

 Bhoomi Sachdeva,<sup>a</sup> Nisha,†<sup>a</sup> Baby,†<sup>a</sup> Khushboo Aggarwal,<sup>a</sup> Aarushi Singh,<sup>f</sup> Kamlesh Kumari,<sup>e</sup> Ramesh Chandra<sup>\*bcd</sup> and Snigdha Singh \*<sup>ac</sup>

Over time, nanocomposites have revolutionized materials science, offering numerous applications in fields such as catalysis, environmental purification and treatment, biomedicine and various industries. Among these, silver-based nanocomposites are particularly notable for their remarkable stability, reusability, biocompatibility, and multifunctional medicinal properties. Hence, we present a comprehensive summary of recent developments (2019–2024) in silver-based nanomaterials, focusing on their applications across multiple domains, including catalytic organic transformations, biomedical uses, environmental remediation, and industrial sectors such as food packaging, agriculture and textiles. By highlighting recent advancements and emerging trends, we aim to provide a thorough understanding of the role of silver-based nanocomposites in contemporary science and technology, emphasizing their potential to drive innovation across diverse disciplines.

Received 14th January 2025

Accepted 24th April 2025

DOI: 10.1039/d5ra00336a

[rsc.li/rsc-advances](https://rsc.li/rsc-advances)

## 1. Introduction

Over recent years, nanocomposites have emerged as transformative materials, offering exceptional mechanical, thermal, and electrical properties due to their high surface area-to-volume ratio which results in higher selectivity and activity compared to conventional materials.<sup>1</sup> Typically, nanocomposites are formed by dispersing nanoparticles with diverse functionalities within a matrix, making them highly valuable for modern applications in catalysis,<sup>2</sup> sensing,<sup>3,4</sup> environmental remediation<sup>5</sup> and biomedical fields,<sup>6,7</sup> as well as many more<sup>8,9</sup> (Fig. 1). In the realm of catalysis, nanocomposites exhibit enhanced catalytic activity emerging from the synergistic interactions between their components, leading to the abundant generation of highly effective active sites.<sup>10,11</sup> Although homogeneous catalysis is highly efficient, it is hindered by challenges like complex separation, limited recyclability, and potential contamination of the final products. In contrast, heterogeneous catalysis using nanocomposites overcomes

these challenges by enabling easy separation, enhanced reusability, and minimal contamination.<sup>12,13</sup>

In catalysis, besides the physical state, several other factors influence the reactivity and selectivity of a catalyst. In general, the number and distribution of active sites on the catalyst influence its catalytic activity, making highly porous materials with a large surface area preferable. In particular, the quantum size effect, shape, morphology and exposed crystalline facets of the catalyst structure significantly influence the binding strength of reactants and intermediates, thereby affecting their activity and selectivity in the reaction.<sup>14,15</sup> Moreover, the electronic structures of the nanoparticles vary significantly due to the quantum size effect, which also explains their influence on catalytic activity.<sup>14</sup> Additionally, other nanoscale phenomena such as interatomic distances, coordination numbers, and atomic scale alloying should also be considered.<sup>16</sup> Furthermore, structural and electronic modifications in a catalyst can arise from heterojunction formation, deposition or the use of a support. For example, metal-supported interactions, whether synergetic or cooperative, can significantly influence the activity and selectivity of the active site.<sup>14</sup> Researchers can investigate the impact of structural modifications on catalyst reactivity by employing various *in situ* characterization techniques like EPR, XRD and XPS to better understand the changes.<sup>17,18</sup>

Silver nanoparticles (Ag NPs) feature a high surface area relative to their volume and tuneable surface properties. They are widely recognized for their inherent stability, recyclability, and compatibility in several reactions, enhancing their value across multiple applications over time.<sup>19,20</sup> Over the years, a diverse range of synthetic approaches has been explored, from

<sup>a</sup>Drug Discovery & Development Laboratory, Department of Chemistry, University of Delhi, Delhi-110007, India. E-mail: [ssingh3@chemistry.du.ac.in](mailto:ssingh3@chemistry.du.ac.in)

<sup>b</sup>Dr B. R. Ambedkar Centre for Biomedical Research (ACBR), University of Delhi, Delhi-110007, India

<sup>c</sup>Institute of Nanomedical Science (INMS), University of Delhi, Delhi-110007, India

<sup>d</sup>Maharaja Surajmal Brij University, Bharatpur 321201, Rajasthan, India

<sup>e</sup>Department of Zoology, University of Delhi, Delhi-110007, India

<sup>f</sup>Department of Chemistry, Ramjas College, University of Delhi, Delhi-110007, India

† Equal contribution.



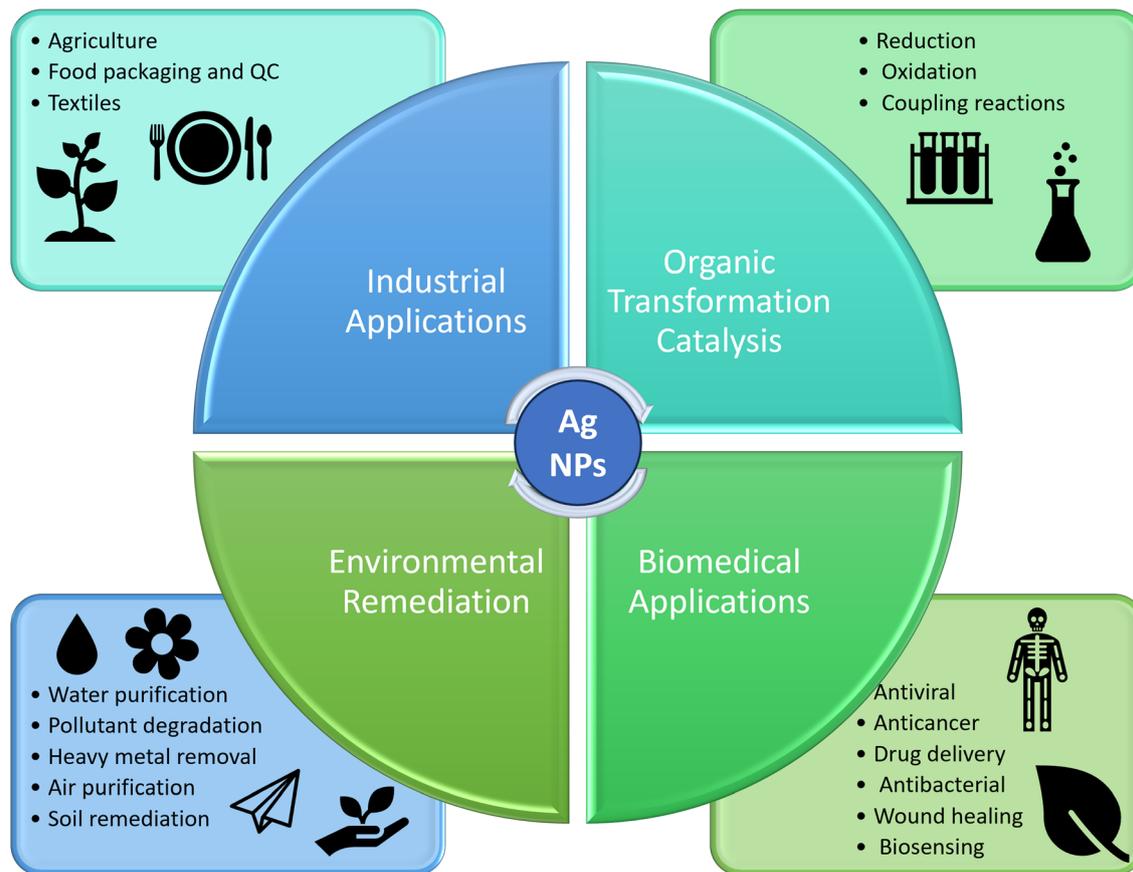


Fig. 1 Silver-based nanocomposites and their applications in different fields.

bottom-up chemical synthesis and top-down physical methods to advanced biological and environmentally friendly techniques.<sup>21,22</sup> Researchers have successfully controlled the physical properties of nanoparticles, which, in turn, dominate their chemical characteristics. This precise control allowed them to tailor the properties and activities of the resulting nanocomposite, optimizing them for catalyzing specific reactions. Typically, Ag NPs are synthesized using chemical reduction methods with reducing agents like amines, citrates, borohydride, and ascorbic acid. To prevent colloidal agglomeration, the reduction process is carried out in the presence of stabilizing, protecting, or capping agents. Additionally, methods such as hydrothermal, microwave, and photochemical processes have been used to enhance the reduction of ionic  $\text{Ag}^+$  to metallic Ag.<sup>23</sup>

Previous literature surveys have reported that Ag NPs exhibit excellent antibacterial,<sup>24</sup> antifungal,<sup>24</sup> antiviral,<sup>25</sup> antifouling<sup>26</sup> and antioxidant<sup>27</sup> properties, which contribute to the biocompatible nature of silver-based nanomaterials. Interestingly, silver being non-toxic, cost effective and environment friendly, has attracted significant attention as a versatile candidate to replace the more expensive or less sustainable metals such as gold, copper, or palladium as precursor materials for various chemical reactions and applications.<sup>28,29</sup>

Among the various nanocatalysts investigated to date, silver-based nanocatalysts have emerged as exceptional,<sup>30</sup> exhibiting high selectivity and efficiency in facilitating various organic transformations. They include key reactions such as reduction,<sup>31,32</sup> oxidation,<sup>33</sup> coupling,<sup>34</sup> and click reactions<sup>28</sup> and many more. By now, many researchers have explored different types of silver-based nanocatalysts such as  $\text{Ag/CeSnO}_x$ ,<sup>35</sup>  $\text{rGO-Ag NPs}$ ,<sup>36</sup>  $\text{Ala-Ag NPs}$ ,<sup>37</sup>  $\text{MWCNTs-NH}_2/\text{Fe}_3\text{O}_4/\text{Ag}$ ,<sup>38</sup>  $\text{KIT-5-bigua-Ag}$ ,<sup>39</sup>  $\text{AgNPs@m-PS-PC}$ ,<sup>40</sup>  $[\text{Ag}/\text{Mg}_4\text{Al-LDH}]$ ,<sup>41</sup>  $\text{Fe}_3\text{O}_4@\text{Creatinine@Ag}$ ,<sup>42</sup>  $\text{ZnO/PANI/Ag}$ ,<sup>43</sup>  $\text{Ag/MOF}$ ,<sup>44</sup>  $\text{Fe}_3\text{O}_4@\text{CS-StOX@Cys@Ag}^+$ ,<sup>45</sup>  $\text{Ag@m-HAp-Si(S)}$ ,<sup>46</sup>  $\text{Ag@HCMP-bpybph}$ ,<sup>47</sup> and others for promoting organic reactions, offering more sustainable environmental friendly alternatives to conventional chemical processes.

Silver-based nanocomposites are not only extensively used in oxidation, reduction, and coupling processes but also exhibit remarkable versatility in various other chemical transformations. For example, these silver-based nanocatalysts have been crucial in the synthesis of xanthene derivatives, which serve as valuable biological scaffolds as well as spiro compounds, known for their medicinal applications. Additionally, they facilitate biodiesel production *via* the transesterification process and are instrumental in catalyzing the synthesis of quinoline and polyhydroquinoline heterocyclic derivatives, which hold significant medicinal importance.



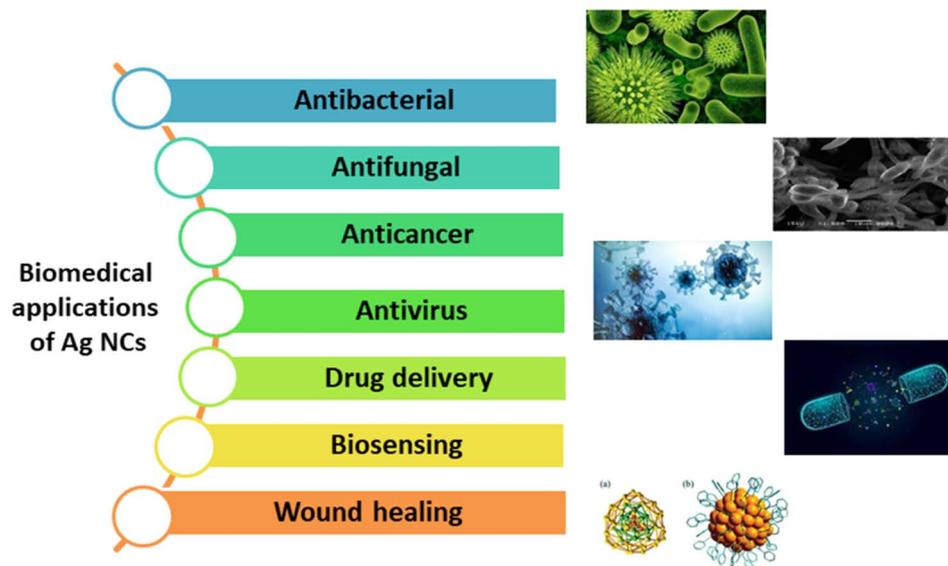


Fig. 2 Applications of Silver based nanocomposites particularly in biomedical field.

Moreover, various silver-based nanocatalysts such as [Ag-P(NAA)],<sup>48</sup> Ag-ZnO/SEP5%,<sup>49</sup> BML@Ag,<sup>50</sup> MMT/Fe<sub>3</sub>O<sub>4</sub>/Ag,<sup>51</sup> Ppy/Ag/Gr,<sup>52</sup> Ag<sub>2</sub>WO<sub>4</sub>/rGO NCs,<sup>53</sup> AGCT,<sup>54</sup> SNC-AgNP<sup>55</sup> have also effectively addressed various environmental concerns including the degradation of pollutants,<sup>56,57</sup> wastewater treatment<sup>58–60</sup> and the conversion of waste materials into valuable products.<sup>61–64</sup> Ag NPs possess biocompatible antimicrobial, antifouling, and antioxidant properties (Fig. 2), making them an ideal choice for various biomedical applications such as, drug delivery,<sup>65,66</sup> wound healing,<sup>67,68</sup> antimicrobial applications and so on.<sup>69–71</sup> Over the years, researchers have developed various silver-based nanomaterials that efficiently cater to these applications. Additionally, numerous studies highlighted the use of silver-based nanocatalysts in industries, including agriculture,<sup>72</sup> textiles,<sup>73,74</sup> and food processing.<sup>75</sup>

In the subsequent sections of this review, we will explore the applications of silver-based nanocatalysts in organic transformations, including, reduction, oxidation, coupling, click reaction and other miscellaneous reactions. We have also highlighted their applications in biomedical, environmental, and industrial fields. By summarizing the latest research findings, we aim to provide a comprehensive overview of the advancements and future prospects of silver-based nanocatalysts in modern science and technology.

## 2. Organic transformations

In this section, we will discuss nano-silver catalyzed organic transformation processes such as reduction, oxidation, coupling reactions, click reactions and more (Fig. 3).

### 2.1 Reduction reactions

**2.1.1 Nitroarene reduction.** The release of nitro group-containing organic compounds into water bodies has anthropogenically polluted our environment, water sources and

marine biological systems. Additionally, 4-nitrophenol (4-NP) is widely employed in the synthesis of various insecticides and pesticides, and its continuous use poses significant risks to both human health and the environment. Therefore, reducing hazardous nitro compounds to their amino form presents an environmentally safer alternative. Recently, several research groups have reported the reduction of nitroarenes using silver-based nanoparticles as catalysts in the presence of NaBH<sub>4</sub> (Scheme 1).<sup>76,77</sup> Exceptionally, some novel nanocatalysts have demonstrated enhanced reusability, sustaining their efficiency for over 10 to 15 consecutive experimental runs.<sup>46,78</sup>

Recently, several studies have highlighted the use of magnetic nanocatalysts for the reduction of nitroarenes.<sup>79,80</sup> Khaleghi *et al.* synthesized a novel silver based nanocomposite, Fe<sub>3</sub>O<sub>4</sub>@Cur/Mel-Ag, and evaluated its catalytic activity in the reduction of nitrobenzene derivatives achieving an impressive 98% yield of the corresponding products.<sup>81</sup> Taheri *et al.*, explained the synergistic interactions between the support and Ag NPs in the designed S-g-C<sub>3</sub>N<sub>4</sub>/starch-Fe<sub>3</sub>O<sub>4</sub>-Ag nanocomposite that exhibited outstanding catalytic activity for nitroarene hydrogenation in presence of NaBH<sub>4</sub>, attaining up to 99% reduction.<sup>82</sup> Thiol functionalized Fe<sub>3</sub>O<sub>4</sub> nanoparticles were utilized to immobilize silver nanoparticles, resulting in the fabrication of a magnetically recyclable Fe<sub>3</sub>O<sub>4</sub>/SiO<sub>2</sub>-Pr-S-Ag nanocomposite, which was employed for the catalytic reduction of 4-NP and the degradation of azo dyes.<sup>83</sup> Subsequently, Veisi *et al.* introduced a Tannic acid coated Fe<sub>3</sub>O<sub>4</sub> nanoparticles to improve silver ion adsorption and reduction through multiple polyphenol interaction with metal ions, to generate a novel magnetic nanocatalyst, Fe<sub>3</sub>O<sub>4</sub>@TA/Ag which facilitated reduction reactions at room temperature.<sup>84</sup>

Moreover, several studies reported the use of Ag NPs synthesized using green methods for the hydrogenation of different Nitroarenes,<sup>31,85,86</sup> while numerous others highlights the degradation of organic pollutants using supported Ag NPs.<sup>87</sup>



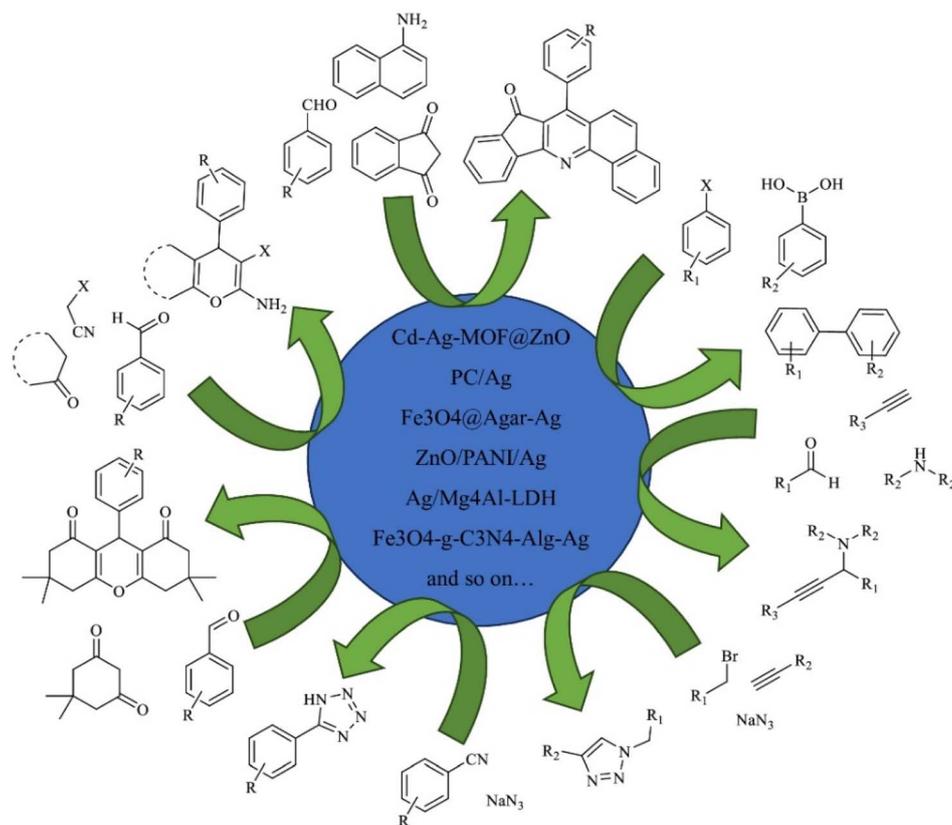
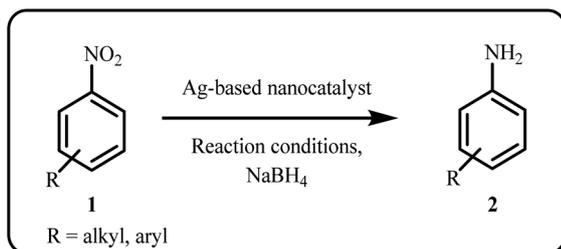
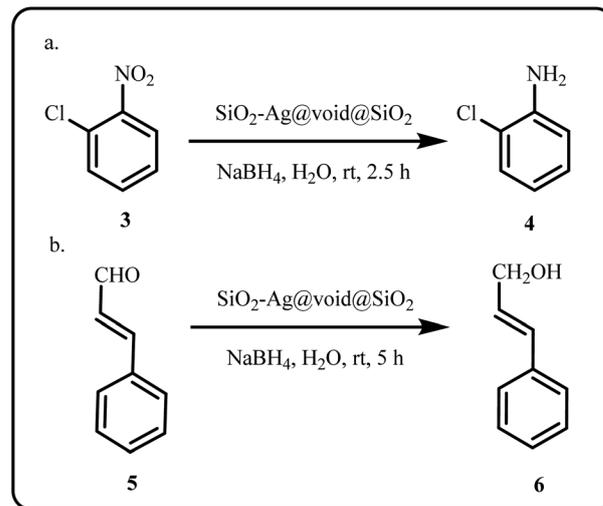


Fig. 3 Different organic transformation reactions using silver nanocatalysts.



Scheme 1 General scheme for reduction of nitroarenes.

Mallakpour *et al.* detailed the eco-friendly synthesis of a silver-based nanocatalyst, the CS/Ag-LDH film, for the reduction of 4-NP, achieving approximately 99% conversion in a brief period.<sup>88</sup> Utilizing lignin as a catalytic support, Xiao *et al.* developed two silver-based nanocatalysts, one with Ag NPs supported on the surface of pre-hydrolyzed lignin (Ag/PL) and other with Ag NPs embedded within lignin (Ag@PL), for the efficient reduction of 4-NP. Ag/PL exhibited higher catalytic efficiency than Ag@PL owing to the increased accessibility and exposure of Ag NPs to reactants.<sup>89</sup> Han *et al.* developed a silver nanoparticle decorated N-doped reduced graphene oxide nanocatalyst (Ag/N-rGO) for the catalytic reduction of 4-NP.<sup>90</sup> The catalytic potential of a Cu-Ag bimetallic nanocatalyst (Cu-Ag/PVA), was realized by Wang *et al.* to effectively reduce nitroarene and compared its catalytic efficiency with monometallic Cu or Ag nanocatalyst.<sup>91</sup> Nguyen

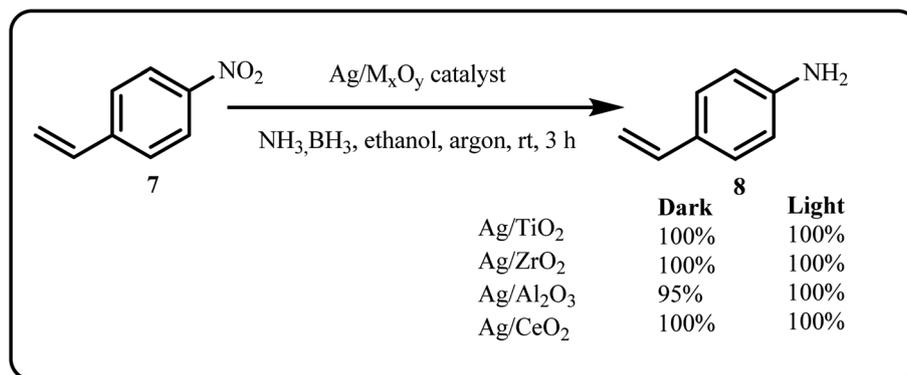


Scheme 2 Chemoselective reduction of (a) 2-nitrochlorobenzene and (b) cinnamaldehyde using  $\text{SiO}_2\text{-Ag@void@SiO}_2$  nanocatalyst (Yin *et al.*<sup>93</sup>).

*et al.* conducted a fascinating investigation on the use of monomeric and polymeric N-heterocyclic carbenes (NHCs)-functionalized Ag NPs in catalysis reaction.<sup>92</sup>

Recently, Yin *et al.* proposed a novel and effective silver-based nanocatalytic system,  $\text{SiO}_2\text{-Ag@void@SiO}_2$ , for





Scheme 3 Chemoselective reduction of *p*-nitrostyrene using Ag/M<sub>x</sub>O<sub>y</sub> nanocatalyst (Verma *et al.*<sup>95</sup>).

Table 1 Comparative analysis of silver-based nanocatalyst for reduction reactions<sup>a</sup>

S. no.	Catalyst	Time (min)	Isolated yield	Reference
1	MWCNTs-NH <sub>2</sub> /Fe <sub>3</sub> O <sub>4</sub> /Ag NPs	30	99	Hamelian <i>et al.</i> <sup>38</sup>
2	Fe <sub>3</sub> O <sub>4</sub> @LP-Ag	8	86–100	Ahmad <i>et al.</i> <sup>80</sup>
3	rGO-Ag NPs	3	100	Sun <i>et al.</i> <sup>36</sup>
4	Cu-Ag/PVA	9	98	Wang <i>et al.</i> <sup>91</sup>
5	Ag@TPPQP CMP	8	90	Kotp <i>et al.</i> <sup>96</sup>
6	Ag NPs	7	75–98	Karvekar <i>et al.</i> <sup>86</sup>
7	Ag@HCMP-bpybph	3	99	Luo <i>et al.</i> <sup>47</sup>
8	CS/Ag-LDH film	5	99	Mallakpour <i>et al.</i> <sup>88</sup>
9	Chitosan-Ag/Fe <sub>2</sub> O <sub>3</sub>	10	92–95	Batakurki <i>et al.</i> <sup>97</sup>
10	Ag NPs	13	98.23	Riaz <i>et al.</i> <sup>85</sup>
11	AgNPs/ZnO/Fe <sub>3</sub> O <sub>4</sub>	7	96	Alula <i>et al.</i> <sup>78</sup>
12	SiO <sub>2</sub> -Ag@void@SiO <sub>2</sub> (SAVS)	150	99	Yin <i>et al.</i> <sup>93</sup>
13	Ag@SrNbO/LDH	1	97	Zhou <i>et al.</i> <sup>94</sup>
14	Ala-Ag NPs	8	95.6	Naaz <i>et al.</i> <sup>37</sup>
15	Fe <sub>3</sub> O <sub>4</sub> @PPy-MAA/Ag	45	80	Das <i>et al.</i> <sup>76</sup>
16	Fe <sub>3</sub> O <sub>4</sub> /SiO <sub>2</sub> -Pr-S-Ag	2	97	Veisi <i>et al.</i> <sup>83</sup>
17	Fe <sub>3</sub> O <sub>4</sub> @TA/Ag	1	99	Veisi <i>et al.</i> <sup>84</sup>
18	Ag/N-rGO	1	90	Han <i>et al.</i> <sup>90</sup>

<sup>a</sup> Reaction conditions: NaBH<sub>4</sub>, H<sub>2</sub>O, rt.

successful chemoselective hydrogenation of 2-nitrochlorobenzene (2-NCB) and cinnamaldehyde (CA) (Scheme 2). The group encapsulated and uniformly dispersed the prepared Ag NPs within hollow silica, leveraging the micro-reactor and confinement effect of the catalyst to achieve high chemoselectivity.<sup>93</sup>

The ternary hybrid, composed of strontium niobate (SrNbO), Ag NPs and nickel-aluminum layered double hydroxide (LDH), was developed by first assembling oppositely charged SrNbO and LDH nanosheets, followed by the *in situ* photo-reduction of silver ions, giving Ag@SrNbO/LDH, which was employed to degrade 4-NP.<sup>94</sup> Verma *et al.* focused on improving the chemoselective reduction of *p*-nitrostyrene to *p*-aminostyrene (Scheme 3). Amongst all, the Ag/TiO<sub>2</sub> nanocatalyst outperformed obtaining a 100% conversion and maximum chemoselectivity of 81%. Additionally, the group tested the reaction under different wavelengths of visible light, with green Light

Emitting Diode (LED) producing the highest activity.<sup>95</sup> Several other nanocatalysts used for reduction reactions are summarized in Table 1.

**2.1.2 Dye degradation.** Industrial wastewater effluents contain numerous harmful organic dyes, including commonly used ones such as Methylene Blue (MB), Congo Red (CR), Methyl Orange (MO), and Rhodamine B (Rh B), which are prevalent in various industries as colouring agents. Apart from these, other dyes including Toluidine blue, Pyronine Y, Direct blue 151, Eosin and more are widely used across different industrial applications (Fig. 4).<sup>31,48,58,86,98–102</sup>

Among these dyes, the catalytic reduction of hazardous azo dyes has recently gained attention from researchers owing to their non-toxic and eco-friendly nature. In particular, various silver-based nanocatalysts such as Ag NPs,<sup>103</sup> Au/Ag/Fe<sub>3</sub>O<sub>4</sub>@PEI@NC,<sup>104</sup> GO-Fe<sub>3</sub>O<sub>4</sub>/PAA/Ag,<sup>105</sup> Ag-MoS<sub>2</sub>,<sup>80</sup> rGO-Ag NPs,<sup>36</sup> Fe<sub>3</sub>O<sub>4</sub>@TA/Ag,<sup>84</sup> Fe<sub>3</sub>O<sub>4</sub>/SiO<sub>2</sub>-Pr-S-Ag,<sup>83</sup> have been explored for



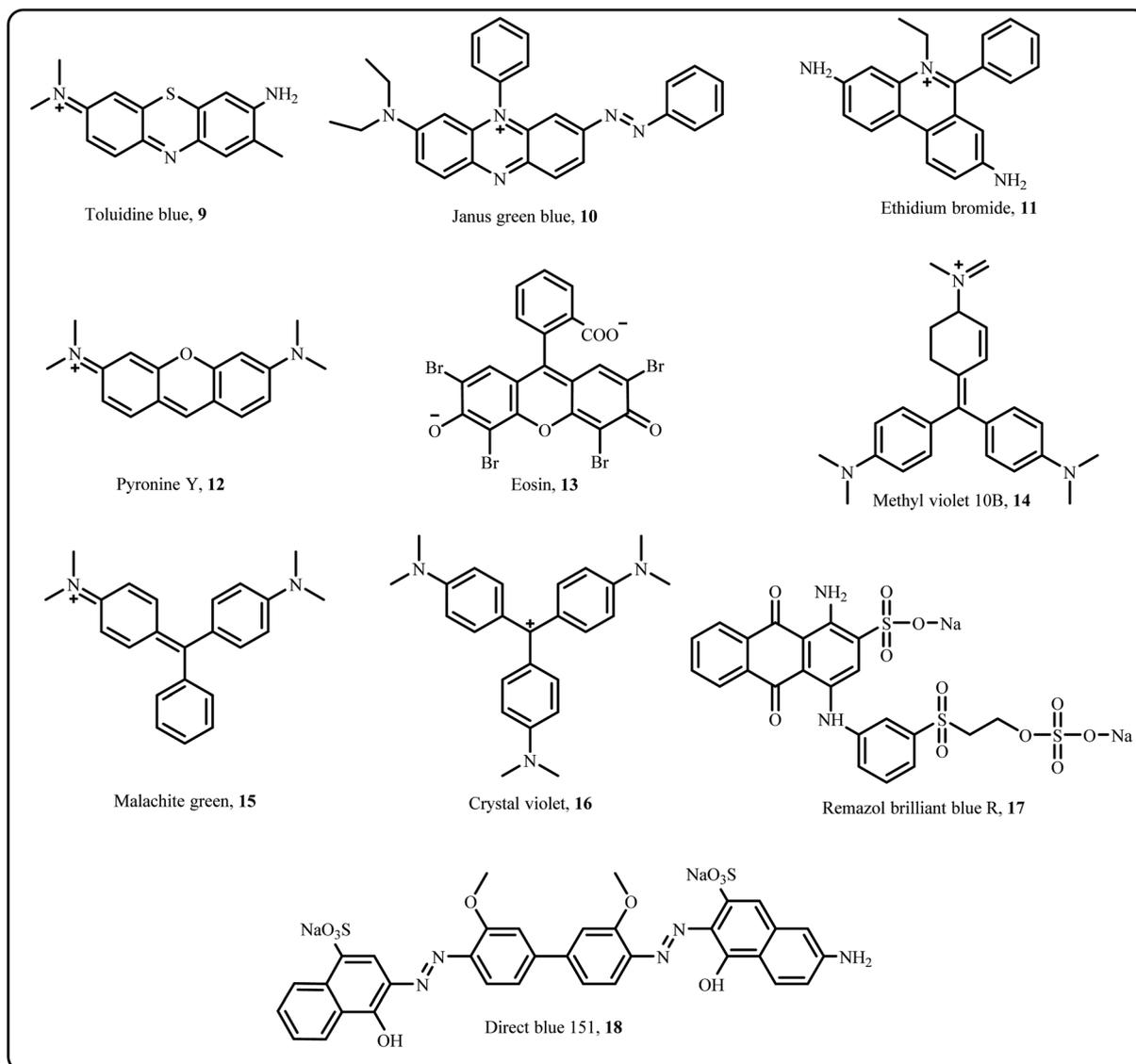
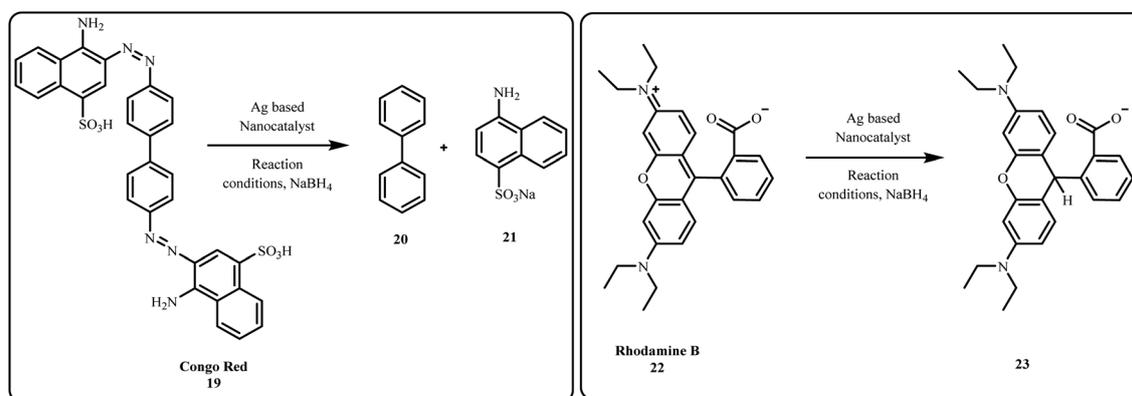
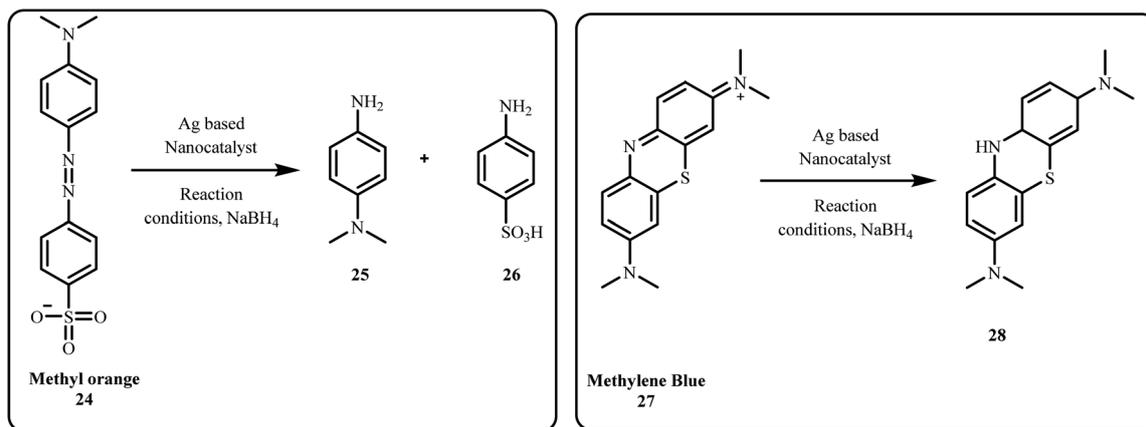


Fig. 4 Organic dyes.



Scheme 4 Degradation of CR and Rh B.





Scheme 5 Degradation of MO and MB.

their effectiveness in these catalytic processes (Schemes 4 and 5).

Biogenically produced Ag NPs extracted from mexican mint (MM) leaf extract (MM-AgNPs) successfully catalyzed the decolorization of various dyes namely, Toluidine blue, CR, and Pyronine Y in the presence of NaBH<sub>4</sub>, making it a promising photo nanocatalyst for dye degradation.<sup>31</sup> Similarly, Thi *et al.* reported that the Ag@AgCl NPs serve as versatile catalysts for the breakdown of azo dyes such as CR by improving the degradation rate by 6–31 times compared to the uncatalyzed reaction.<sup>106</sup> By employing *Bacillus cereus*, Alfryyan *et al.*, bio-synthesized a pair of novel intracellular and extracellular plasmonic silver-based catalysts *via* a one-pot approach and utilized them for catalytic reduction of MB organic dye.<sup>107</sup>

The study by Farooqi *et al.* aimed to evaluate the catalytic performance of a Ag NPs loaded poly(*N*-isopropylacrylamid-co-acrylic acid) [Ag-P(NAA)] microgel system, achieving the complete degradation of malachite green (MG) dye in an aqueous medium in just a few minutes.<sup>48</sup> The study by Karvekar *et al.* presented an innovative approach combining biogenic synthesis of Ag NPs using *Zingiber officinale* rhizome extract with hydrothermally synthesized ZnO NPs to form Ag–ZnO nanocomposites, which were employed for the photocatalytic degradation of MB and crystal violet under natural sunlight.<sup>86</sup> A study utilized Ag/ZnO/Fe<sub>3</sub>O<sub>4</sub> nanocatalyst, synthesized *via* chemical reduction, to catalytically degrade MB demonstrating consistent performance over fifteen consecutive runs without any decline.<sup>78</sup> In a recent study, Pan *et al.* produced a series of visible light-driven Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> nano photocatalysts with varying Ag<sub>2</sub>CO<sub>3</sub> composition to degrade MO and MB, displaying enhanced photocatalytic efficiencies of 94 and 63% respectively. This improvement, compared to individual Ag<sub>2</sub>CO<sub>3</sub> or g-C<sub>3</sub>N<sub>4</sub> catalytic systems, was attributed to the improved dispersion of Ag<sub>2</sub>CO<sub>3</sub> nanoparticles, reduced particle size and the synergistic effect between Ag<sub>2</sub>CO<sub>3</sub> and g-C<sub>3</sub>N<sub>4</sub>.<sup>108</sup>

By opting the precipitation method, Khaneghah *et al.* created a series of ternary photocatalysts, consisting of graphitic carbon nitride nanosheets (GCNNS), carbon dots (CD), and Ag<sub>6</sub>Si<sub>2</sub>O<sub>7</sub> (ASO), denoted as GCNNS/CD/ASO, and assessed the catalytic

effectiveness of these catalysts through various reactions. Among the prepared photocatalysts, GCNNS/CD/ASO with 10% ASO content exhibited the optimum performance in degrading Rh B, outperforming other solitary and binary photocatalytic systems.<sup>109</sup> Thomas *et al.* realized an environment friendly synthesis of Ag NPs by utilising *Myristica fragrans* seed shells extract, an agricultural waste. These NPs were further investigated for the photocatalytic degradation of various dyes such as Rh B (zwitterionic), Remazol brilliant blue reactive (anionic) and methyl violet 10B (cationic), indicating their significant potential for dye degradation.<sup>58</sup>

Green emitting carbon dots were synthesized *via* hydrothermal route, as reported by Ghosh *et al.*, and utilized them to fabricate Ag and Au nanocomposites (CD-AgNP, CD-AuNP). These nanocomposites were explored for degradation of dyes such as CR, MO and Evan's blue (EB), as well as for antibacterial activity.<sup>98</sup> Recently, chitosan-based silver nanoparticles (Ag NPs) combined with TiO<sub>2</sub> and ZnO were used to target the photocatalytic degradation of Acid Red 37 dye. The results showed an improvement in dye degradation, with an increase in Ag NP content leading to a faster reaction rate and lower energy consumption.<sup>110</sup> Similarly, Sodeinde *et al.* prepared reduced graphene oxide–silver (rGO–Ag) nanocomposite *via* green route by using *Corchorus olitorius* extract and waste battery rod powder, achieving 96% photocatalytic degradation of Janus Green Blue (JGB) dye.<sup>99</sup>

Castro *et al.* employed *Anemopsis californica* leaf extract as a reducing agent to fabricate Ag NPs supported on pistachio husk for 100% degradation of a dye containing Direct Blue 151 under natural sunlight.<sup>100</sup> Similarly, green synthesized Ag NPs were employed for the catalytic destruction of organic dyes such as MB, MO and Rh B, attaining excellent degradation of 96%, 71% and 93% respectively. Additionally, these Ag NPs efficiently worked as a colorimetric sensor for detecting Hg<sup>2+</sup> and Fe<sup>3+</sup> ions.<sup>59</sup> Ag NPs were successfully incorporated by Saruchi *et al.* into a cellulose and gelatin-based hydrogel, C-G-g-poly(AA)-AgNPs, which were employed for the catalytic degradation of carcinogenic dyes such as Ethidium Bromide (EtBr) and eosin.<sup>101</sup> Eswaran *et al.*, in his recent study, synthesized Ag NPs using *Kalanchoe brasiliensis* extract (KK-AgNPs) and demonstrated their



Table 2 Different dyes degraded by silver-based nanocomposites<sup>a</sup>

S. no.	Catalyst	Time (min)	Dyes degraded	Reference
1	MWCNTs-NH <sub>2</sub> /Fe <sub>3</sub> O <sub>4</sub> /Ag NPs	1, 2	MB, MO	Hamelian <i>et al.</i> <sup>38</sup>
2	Fe <sub>3</sub> O <sub>4</sub> @LP-Ag	5, 4, 4	MB, MO, CR	Ahmad <i>et al.</i> <sup>80</sup>
3	Au/Ag/Fe <sub>3</sub> O <sub>4</sub> @PEI@NC	6, 14	MB, MO	Iuliano <i>et al.</i> <sup>104</sup>
4	RGO-Ag NPs	15, 15	MB, MO	Das <i>et al.</i> <sup>87</sup>
5	Ag@AgCl	25	CR	Thi <i>et al.</i> <sup>106</sup>
6	rGO-Ag NPs	3	Rh B	Sun <i>et al.</i> <sup>36</sup>
7	Extra and intracellular Ag NPs	80, 150	MB	Alfryyan <i>et al.</i> <sup>107</sup>
8	Ag-P(NAA)	4	Malachite green	Farooqi <i>et al.</i> <sup>48</sup>
9	Ag-ZnO	165	MB	Karvekar <i>et al.</i> <sup>86</sup>
10	Ag NPs	45	MO	Riaz <i>et al.</i> <sup>85</sup>
11	AgNPs/ZnO/Fe <sub>3</sub> O <sub>4</sub>	10	MB	Alula <i>et al.</i> <sup>78</sup>
12	AgNPs@ $\delta$ -FeOOH/PUF	1.3, 3	MO, CR	Mahmoud <i>et al.</i> <sup>111</sup>
13	MnFe <sub>2</sub> O <sub>4</sub> @PDA-Ag	4.3	MB	Gürbüz <i>et al.</i> <sup>79</sup>
14	GO-Fe <sub>3</sub> O <sub>4</sub> /PAA/Ag	0.5, 2	MB, MO	Esmaili <i>et al.</i> <sup>105</sup>
15	Ag-doped MoS <sub>2</sub> nanopetals	1	MB	Ikram <i>et al.</i> <sup>112</sup>
16	Ala-Ag NPs	60, 35	MB, Rh B	Naaz <i>et al.</i> <sup>37</sup>
17	$\kappa$ -CG-s-AgNPs	1, 1	MB, Rh B	Pandey <i>et al.</i> <sup>113</sup>
18	Fe <sub>3</sub> O <sub>4</sub> /SiO <sub>2</sub> -Pr-S-Ag	0.5, 0.66	MB, Rh B	Veisi <i>et al.</i> <sup>83</sup>
19	Fe <sub>3</sub> O <sub>4</sub> @TA/Ag	0.66, 1	MB, Rh B	Veisi <i>et al.</i> <sup>84</sup>
20	Ag <sub>2</sub> WO <sub>4</sub> /rGO NCs	120	MB	Malathi <i>et al.</i> <sup>53</sup>
21	MMT/Fe <sub>3</sub> O <sub>4</sub> /Ag	8	Rh B	Acar <i>et al.</i> <sup>51</sup>
22	VWE-Ag NPs	195, 60	MB, MO	Amjad <i>et al.</i> <sup>114</sup>

<sup>a</sup> Reaction conditions: NaBH<sub>4</sub>, H<sub>2</sub>O, rt.

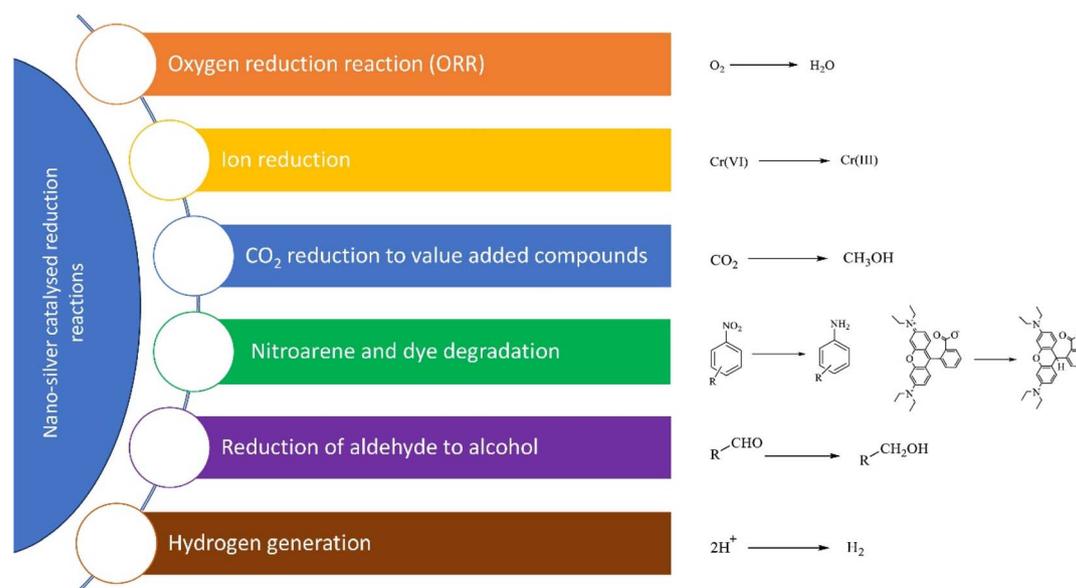


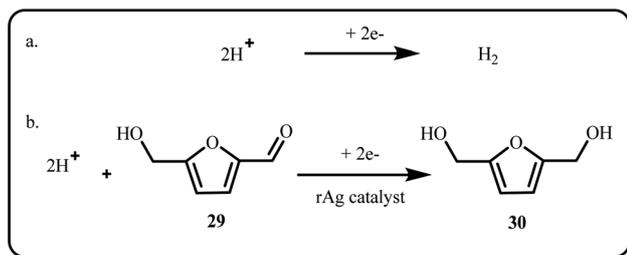
Fig. 5 Nanosilver catalyzed various reduction reactions.

high photocatalytic efficiency in degrading various toxic dyes namely Aniline Blue (86.04%), Toluidine Blue (85.95%), CR (78.85%), Indigo Carmine (84.08%), Auramine O (70.40%), and Pyronin Y (66.41%).<sup>102</sup> Other nanocatalysts listed in Table 2 have also shown effectiveness in degrading the organic dyes (Fig. 4).

**2.1.3 Other reduction reactions.** Over many decades, Ag-based nanocatalysts have been significantly utilized for realizing numerous reduction reactions (Fig. 5). Qin *et al.* developed a novel supramolecular host motif approach for the

electrochemical reduction of CO<sub>2</sub> to Ethanol through hydroxypillar[5]arene extended porous polymer confined Ag catalytic systems, PAF-PA5-Ag-0.8 and PAF-PA5-Ag-1.9. These systems exhibited improved adsorption of \*CO, facilitating ethanol production through C-C coupling, with the former system being the more efficient.<sup>115</sup> Recently, Ahmad *et al.* developed a novel Ag doped ZnO nanocages and investigated their catalytic hydrogenation of CO<sub>2</sub> to methanol, a valuable product, using DFT simulations.<sup>62</sup>





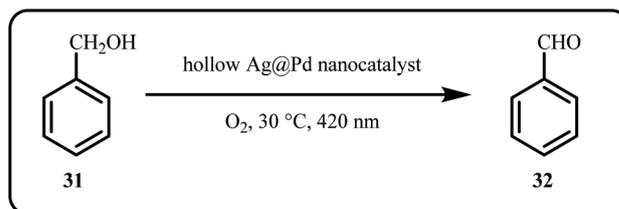
**Scheme 6** (a) Hydrogen evolution and (b) electrochemical hydrogenation of biomass-derived 5-(hydroxymethyl) furfural (Muchharla *et al.*<sup>32</sup>).

In a separate study, Muchharla *et al.* developed rAg and rCu catalytic systems for the hydrogen evolution and electrochemical hydrogenation of biomass-derived 5-(hydroxymethyl) furfural (HMF) (Scheme 6).<sup>32</sup>

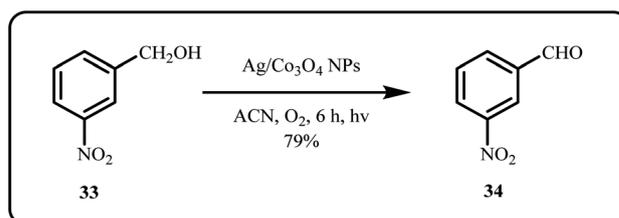
Zhang *et al.* employed a solvothermally synthesized plasmonic Ag/AgCl/NH<sub>2</sub>-UiO-66 for catalytic reduction of Cr(vi) under UV light, where the amine functionalization of UiO-66, along with the hybrid's inorganic–organic nature, significantly enhanced charge separation and transfer efficiency. Additionally, the presence of Ag nanoparticles (Ag NPs) further improved the separation efficiency of photogenerated electrons and holes.<sup>116</sup> In 2024, numerous research studies have focused on efficient oxygen reduction reaction (ORR) using silver-based nanocatalysts. Nandy *et al.* fabricated a bimetallic [(Ag@AuAg)@Ag] nanocatalyst *via* a template-mediated process for an efficient ORR in fuel cells comparable to traditional Pt/C arrangement, while offering superior stability.<sup>117</sup> Similarly, an Ag loaded N-doped graphene (Ag-NGs) nanocomposite with high ORR activity was fabricated by Chen *et al.* by opting a simple and environment friendly microwave plasma technique.<sup>118</sup> Recently, Khaksar *et al.* developed a novel AgVO<sub>3</sub> blended functionalized multiwalled CNT (AgVO<sub>3</sub>@f-MWCNTs) nanocatalyst that exhibited great ORR catalytic activity.<sup>119</sup>

## 2.2 Oxidation reactions

**2.2.1 Oxidation of alcohols.** Many researchers have focused on catalyzing alcohol oxidation.<sup>120</sup> A study by Sobczak *et al.* proposed a one-pot approach for developing a catalyst particularly for the selective oxidation of alcohols while emphasizing on sustainability. The group fabricated silver nanoparticles heavily grafted with stable nitroxide radicals (N–Ag NPs). However, while the N–Ag NPs catalytic system exhibited less satisfactory results with certain alcohols like *n*-heptanol, 1-phenylethanol, and allylic alcohol, it showed high activity and selectivity for primary aromatic alcohols like benzyl alcohol, 4-pyridinemethanol, and furfuryl alcohol, achieving nearly 100% conversion with high yields of the corresponding aldehydes. This efficiency was attained using a reduced amount of catalyst enabling facile purification procedures.<sup>33</sup> Pham *et al.*<sup>121</sup> developed a carbon-supported AgPt nano coral through a self-growth-assisted reduction method as a catalytic system. This system demonstrated exceptional HER performance and methanol



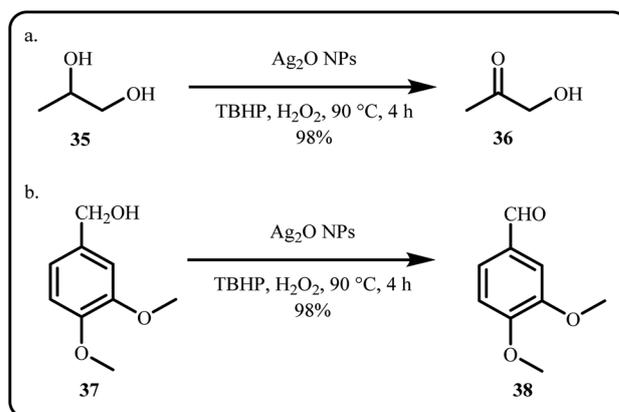
**Scheme 7** Photocatalytic oxidation of benzyl alcohol using hollow Ag@Pd core–shell nanoparticles (Fang *et al.*<sup>123</sup>).



**Scheme 8** Photocatalytic oxidation of aromatic alcohols using Ag/Co<sub>3</sub>O<sub>4</sub> nanoparticles (Ji *et al.*<sup>124</sup>).

oxidation in acidic electrolytes, exhibiting considerably lower overpotential and Tafel slope compared to a commercial carbon-supported Pt-based catalyst, highlighting its superior electrocatalytic efficiency.

Additionally, the catalyst exhibited an improved reaction rate and resistance to CO poisoning during methanol oxidation. This enhanced performance resulted from the synergistic and electronic interactions between Ag and Pt.<sup>121</sup> A novel nanocatalyst, consisting of zeolite, carbon nanotubes (CNT), and silver nanoparticles, was developed for the electrochemical oxidation of propylene glycol (PG) in sulfuric acid solution. The group observed a significant enhancement in the electrocatalytic activity toward propylene glycol oxidation with increasing CNT content, as monitored through techniques like cyclic voltammetry, chronoamperometry, and electrochemical impedance spectroscopy.<sup>122</sup> Fang *et al.* proposed a plasmon-



**Scheme 9** Oxidation of (a) propylene glycol and (b) veratryl alcohol (Devanathan *et al.*<sup>126</sup>).

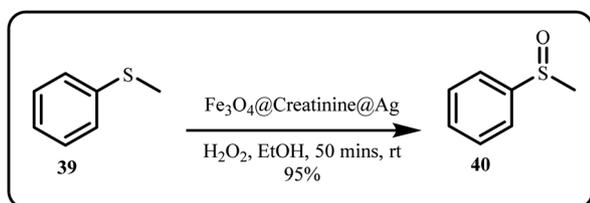


mediated approach to fabricate novel hollow Ag@Pd core-shell nanoparticles, which efficiently catalyzed the oxidation of benzyl alcohols to aldehydes under visible light illumination (Scheme 7).<sup>123</sup>

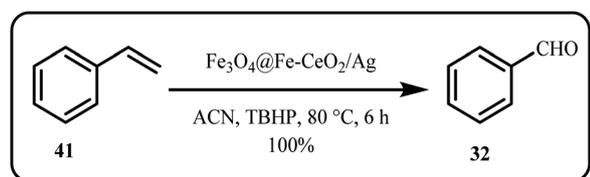
An *in situ* prepared silver supported on cobalt oxide (Ag/Co<sub>3</sub>O<sub>4</sub>) nanocatalyst was applied for the one-pot photocatalytic oxidation of aromatic alcohols (Scheme 8), where 1 wt% of silver-loaded catalyst exhibited optimal performance, showing over 99% selectivity with a conversion rate of 76% toward the desired aldehyde product.<sup>124</sup>

For ethanol electrooxidation, Pawar *et al.* recently developed a Pd@Ag-Zn-rGO catalytic system that exhibited seven times higher catalytic activity than the conventional Pd/C system and outperformed other existing Pd-based systems due to the synergistic interactions between Pd and alloy support.<sup>125</sup> Recently, Devanathan *et al.* proposed silver oxide nanoparticles (Ag<sub>2</sub>O NPs) for the selective oxidation of propylene glycol and veratryl alcohol (Scheme 9).<sup>126</sup>

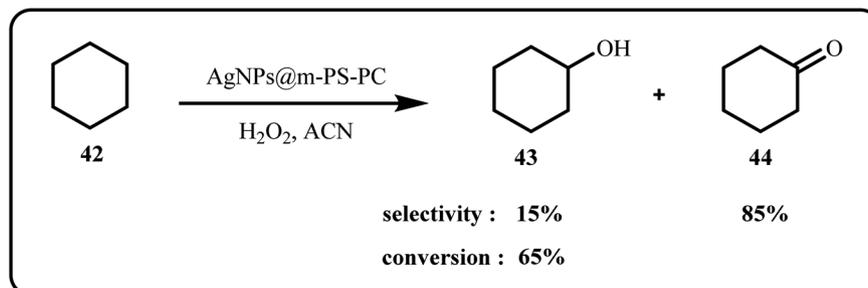
Hatshan *et al.* catalytically oxidised a wide array of aromatic, heterocyclic, allylic, primary, secondary, and aliphatic alcohols to their respective ketones and aldehydes using Ag<sub>2</sub>O-MnO<sub>2</sub>/(X%)N-DG, with N-DG/MnO<sub>2</sub>-(1% Ag<sub>2</sub>O) displaying premium activity with 100% conversion and >99.9% selectivity.<sup>127</sup>



Scheme 10 Oxidation of sulfides catalyzed by Fe<sub>3</sub>O<sub>4</sub>@Creatinine@Ag (Molaei *et al.*<sup>42</sup>).



Scheme 11 Oxidation of styrene catalyzed by Fe<sub>3</sub>O<sub>4</sub>@Fe-CeO<sub>2</sub>/Ag (Ghosh *et al.*<sup>131</sup>).



Scheme 12 Oxidation of cyclohexane catalyzed by AgNPs@m-PS-PC nanocomposite (Salam *et al.*<sup>40</sup>).

**2.2.2 Other oxidation reactions.** Khani *et al.* comparatively studied citric-acid-modified polyaniline (P-CA) and its Ag nanoparticle-modified counterpart (Ag@P-CA) with unmodified polyaniline (PANI) and PANI-modified Ag nanoparticles (Ag@PANI) for the electrochemical oxidation of nitrophenol, where citric acid surface modification improved the monolayer adsorption capacity by reducing the binding affinity while enhancing the conductivity of P-CA and Ag@P-CA, thereby enabling more efficient electrochemical nitrophenol reduction-oxidation.<sup>128</sup>

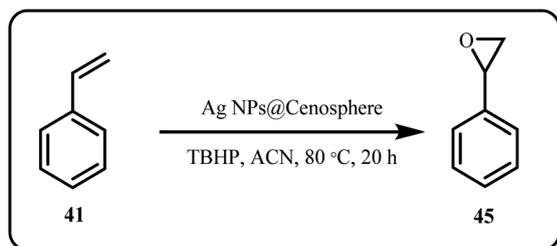
In a recent work, morin, an organic dye, was catalytically degraded with quercetagenin-stabilized Ag NPs (Que-AgNPs) by oxidative means using H<sub>2</sub>O<sub>2</sub>, following pseudo-first-order rate kinetics. Furthermore, the cytotoxicity studies were conducted against HeLa and MCF-7 cell lines where Que-AgNPs exhibited dose-dependent cytotoxic activity.<sup>129</sup> Similarly, Yilmaz *et al.* opted hyaluronic acid-functionalized Ag NPs (HA-AgNPs) for the catalytic oxidative destruction of morin dye with H<sub>2</sub>O<sub>2</sub>.<sup>130</sup>

Molaei *et al.* highlighted the synthesis of a recoverable recyclable magnetic nanocatalyst, Fe<sub>3</sub>O<sub>4</sub>@Creatinine@Ag, prepared *via* functionalizing the surface of Fe<sub>3</sub>O<sub>4</sub> nanoparticles with creatinine attached to Ag NPs. Subsequently, this catalytic system was applied to selectively oxidize sulfides (Scheme 10) and synthesize 5-substituted 1*H*-tetrazoles where the catalyst, affording excellent yields of the corresponding sulfoxides without any harsh reaction conditions.<sup>42</sup>

Recently, Zhang *et al.* employed a tandem catalyst, Ag/CeSnO<sub>x</sub>, as an efficient catalyst to selectively oxidize low-concentration NH<sub>3</sub> from exhaust gases to N<sub>2</sub>.<sup>35</sup> Ghosh *et al.* fabricated a novel ternary composite nanocatalyst, composed of an Ag-decorated Fe<sub>3</sub>O<sub>4</sub> core, Fe-doped CeO<sub>2</sub> shell, and Ag NPs (Fe<sub>3</sub>O<sub>4</sub>@Fe-CeO<sub>2</sub>/Ag), which was employed for the selective oxidation of various alkenes, including styrene, achieving 100% conversion and 95% selectivity for benzaldehyde (Scheme 11). In addition, the catalytic system exhibited remarkable stability over 4 cycles and minimal loss in activity.<sup>131</sup>

Bahadorikhalili *et al.* employed ultrasonic synthesis to successfully develop a novel nanocatalyst, Ag@mHAp-Si(S) by confining Ag NPs over thiourea-functionalized magnetic hydroxyapatite support. Later on, the group applied this catalytic system to effectively oxidize primary amines using urea hydrogen peroxide (UHP).<sup>46</sup> Dey *et al.*, fabricated Cu@Ag/MWCNT nanocomposite that demonstrated extraordinary electrocatalytic performance for the oxidation of borohydride. Moreover, the





Scheme 13 Epoxidation of styrene catalyzed by AgNPs@Cenosphere (Tarasova *et al.*<sup>134</sup>).

synthesized catalyst outperformed the carbon supported Cu@Ag (Cu@Ag/C) system by 3.8 times.<sup>132</sup> In a novel approach, Salam *et al.* designed a nanocatalyst, Ag NPs@m-PS-PC, consisting of Ag NPs, polystyrene amine and 2-pyridinecarbaldehyde. The catalytic activity was evaluated *via* cyclohexane oxidation using hydrogen peroxide (Scheme 12), affording high activity and selectivity as well as green synthesis of carboxylic acids through CO<sub>2</sub> fixation under ambient conditions.<sup>40</sup>

Pugazhenthiran *et al.* employed Ag NPs loaded ZnO nanostructures (Ag-ZnONSTs) for the photocatalytic degradation of ceftiofur sodium (CFS), where Ag NPs loading contributed to the enhanced photocatalytic activity of Ag-ZnONSTs compared to TiO<sub>2</sub> (P25) NPs, with Ag-ZnONRs exhibiting the highest oxidation rate constant ( $k' = 4.6 \times 10^{-4} \text{ s}^{-1}$ ).<sup>133</sup> In 2024, Tarasova *et al.* utilized waste fly-ash cenosphere as a support for Ag nanoparticles, developing a heterogenous catalysts for the epoxidation of styrene (Scheme 13) to produce value added products in high yields.<sup>134</sup>

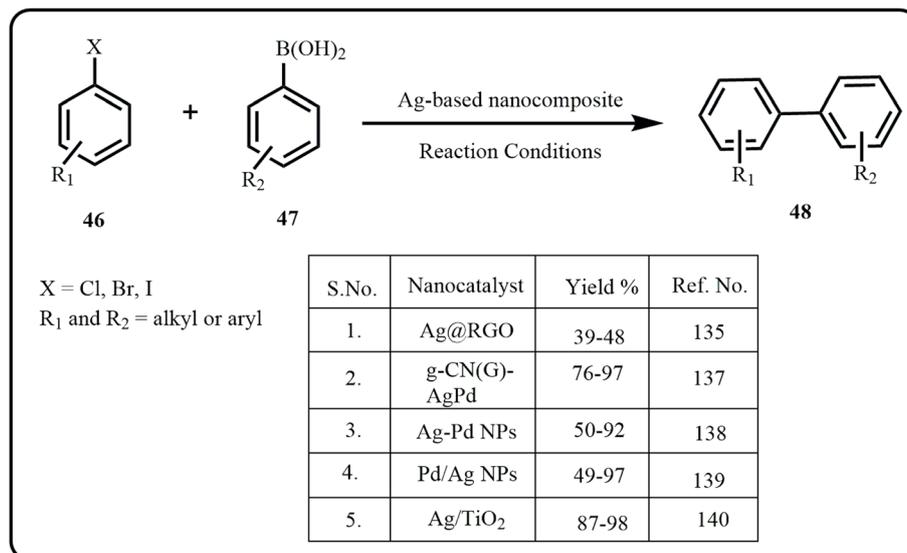
### 2.3 Coupling reactions

Herein, we will review the nanosilver catalyzed Suzuki and A<sup>3</sup> coupling reaction. The Suzuki coupling is a model reaction in forming carbon-carbon bonds with tolerance to various

functional groups, such as esters, ketones, and nitriles to produce a variety of complex molecules having widespread applications in pharmaceuticals, natural products, polymers *etc.*<sup>34</sup> The A<sup>3</sup> coupling is a fascinating multicomponent reaction involving the simultaneous coupling of an aldehyde, an alkyne, and an amine, to provide propargylamines, a class of compounds diversely exploited in the fields of pharmaceuticals, materials science, and beyond.<sup>29</sup>

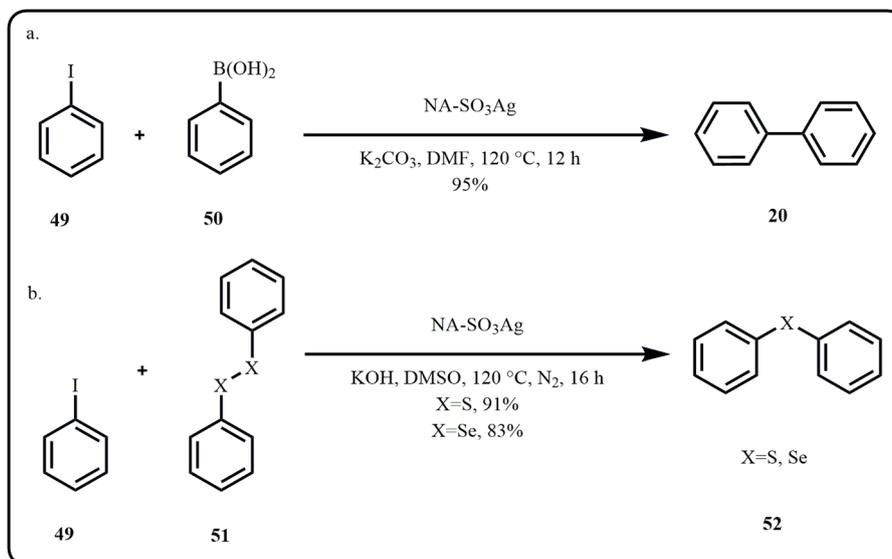
**2.3.1 Suzuki coupling.** Traditionally, the process involved coupling of aryl or vinyl halides with boronic acids or boronate esters under the catalytic influence of palladium. However, challenges such as difficult separation and purification, toxicity and non-reusability of catalysts have enabled researchers to explore Pd-free alternatives without affecting the yield and quality of the obtained products. Herein, we have accounted for numerous research works employing highly efficient recyclable silver-based nanocatalyst in Suzuki-Miyaura cross coupling reaction (Scheme 14). Interestingly, most of these prepared nanocatalysts were reused for 3 to 7 consecutive runs without compromising the yield and quality of the product.<sup>135</sup>

Recently, Ameen *et al.* fabricated metal/metal oxide doped reduced graphene oxide nanocomposites (Ag@RGO, Au@RGO, ZrO<sub>2</sub>@RGO) *via* green routes as a Pd-free catalytic system for Suzuki cross coupling reaction to successfully obtain various biphenyls affording product yield comparable to the conventional palladium-based catalyst, with Ag@RGO offering the highest yield.<sup>135</sup> Nasr *et al.* reported that Ag, Cu, and Au NPs could be incorporated into clay (K-10) supports (SNPS-K-10, GNPS-K-10, and CNPS-K-10) to give clay-based metal nanocatalyst for Suzuki-Miyaura C-C coupling. Interestingly, the group produced numerous biphenyls *via* two synthesis routes—heating and visible light irradiation, wherein significant yields were obtained through visible light irradiation compared with the traditional heating route.<sup>136</sup> Altan *et al.* developed g-CN(G)-AgPd and investigated the effect of band bending over the photocatalytic coupling reaction, that offered excellent yields.



Scheme 14 Synthesis of biaryls *via* Suzuki coupling.



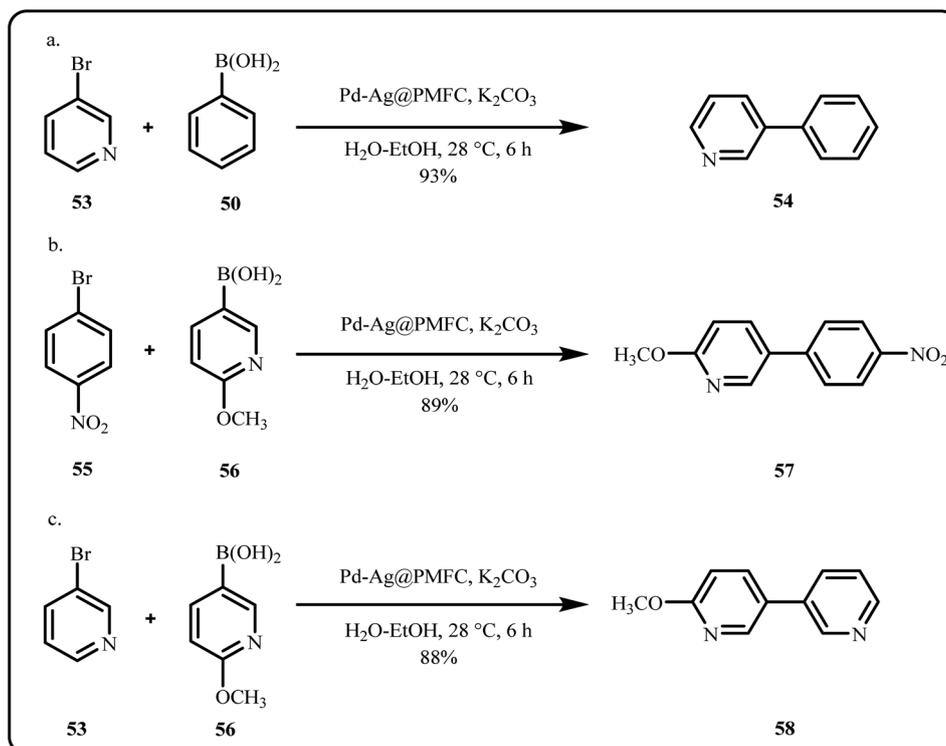


Scheme 15 (a) C–C, (b) C–S and C–Se coupling reactions catalyzed by NA-SO<sub>3</sub>Ag (Zolfaghari *et al.*<sup>141</sup>).

The depletion layer width influenced the Schottky barrier properties of the produced nanocomposite, resulting in their exceptional photocatalytic performance.<sup>137</sup>

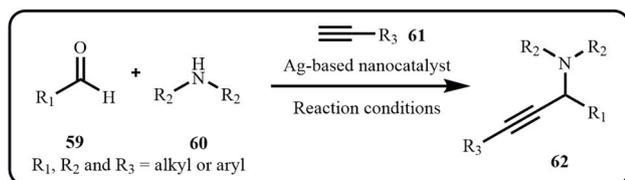
In a report by Shaikh *et al.*, bimetallic Ag–Pd nanoparticles supported on SBA were used for the Suzuki coupling reaction, with natural waste rice husk ash silica serving as a support for the ionic liquid and nanoparticle system, preventing

aggregation, while also demonstrating enhanced catalytic efficiency of the Ag–Pd system over the monometallic counterpart due to synergistic interaction.<sup>138</sup> Fascinated by bimetallic nanoparticle catalysts and metal-reducing bacteria, Kimber *et al.*, highlighted the one-step biosynthesis of two bimetallic nanoparticle catalytic systems, Pd/Ag and Pd/Au, that demonstrated superior catalytic performance in Suzuki–Miyaura cross-



Scheme 16 Bimetallic catalyzed Suzuki–Miyaura coupling (a)–(c) of nitrogen rich heterocycles (Bhattacharjee *et al.*<sup>142</sup>).





Scheme 17 Synthesis of propargylamines *via*  $A^3$  coupling.

coupling reaction compared to monometallic Pd catalytic system.<sup>139</sup> Chen *et al.* discussed the visible-light assisted C–C coupling using an *in situ* prepared Ag/TiO<sub>2</sub> nano photocatalyst. Interestingly, the nanocomposite exhibited enhanced catalytic efficiency emerging from the synergistic interactions between silver and titania.<sup>140</sup> A novel mineral carbonaceous silver-based nanocatalyst, NA-SO<sub>3</sub>Ag, was developed *via* grafting techniques to facilitate C–C, C–S, C–Se coupling reactions to offer excellent yields of various biphenyls, aromatic sulfides, and selenides (Scheme 15).<sup>141</sup>

Recently, Bhattacharjee *et al.* employed waste pomegranate peels to fabricate biocompatible cellulose fibers as an excellent support matrix for bimetallic Pd–Ag nanoclusters (Pd–Ag@PMFC) for catalytic Suzuki–Miyaura coupling of nitrogen-rich heterocycles under visible light conditions (Scheme 16), achieving great results emerging from the synergistic interactions between bimetallic centers.<sup>142</sup>

**2.3.2  $A^3$  coupling.** The  $A^3$  coupling reaction is an important multicomponent reaction for synthesizing propargylamines (Scheme 17), which serve as crucial precursors for a wide range of significant heterocyclic compounds, including pyrroles, pyridines, oxazoles, and others. These derivatives are pivotal in the synthesis of numerous biologically active molecules, such as  $\beta$ -lactams, conformationally restricted peptides, and isosteres, as well as in the development of fungicides, herbicides, and therapeutic drugs. Moreover, propargylamines exhibit diverse biological activities, including anticancer, antimicrobial, and enzyme inhibitory properties. Driven by this, researchers worldwide are focusing on the efficient synthesis of propargylamine. In this context, we present the latest silver nanocatalytic methods for synthesizing propargylamine. Most of the catalytic

systems maintained remarkable reusability for 3 to 10 cycles with minimal loss in activity.<sup>39</sup>

In another study, Aparna *et al.* fabricated silver nanoparticles and integrated them into a metal–organic framework (Ag@UiO-66-SH) that was defectively thiol-functionalized by Zr. The synergistic silver–sulfur interactions enhanced the catalytic activity, leading to significant yields in propargylamine synthesis.<sup>143</sup>

Recently, Xie *et al.* fabricated a Cu<sup>2+</sup>-based MOF and loaded with Ag NPs into the pores to generate an efficient nanocatalyst for the  $A^3$ -coupling reaction.<sup>144</sup> Wang *et al.* efficiently synthesized diverse propargyl amines (70–98%) by utilizing a novel nanocatalytic system prepared by incorporating Ag NPs on biguanide-modified mesoporous silica KIT-5 (KIT-5-bigua-Ag). Furthermore, they explored the biological activity of the material through antioxidant and anticancer assays (IC<sub>50</sub> = 915.221 g mL<sup>-1</sup> against the A549 cell line), making it chemotherapeutic.<sup>39</sup>

Interestingly, Mariconda *et al.* evaluated and compared the efficiency of four novel synthesized NHC-based silver and gold catalysts in  $A^3$  coupling reaction. Herein, the group concluded that the catalytic activity depended on both metal as well as the NHC backbone.<sup>145</sup>

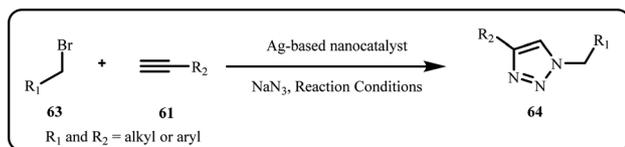
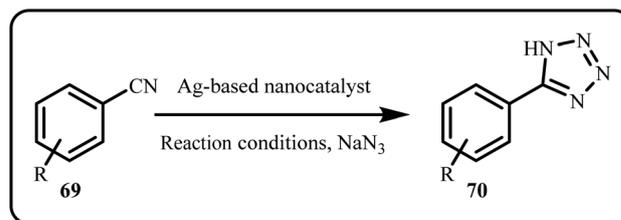
Likewise, Dou *et al.* combined Ag-complexes with Keggin polyoxometalate (POM) to fabricate two novel inorganic–organic Ag-POM hybrids, featuring three-coordinated and distorted tetrahedral configurations, respectively.<sup>146</sup> Driven by an interest in magnetically isolable nano-biocomposites, Ma *et al.* designed and developed a novel core–shell magnetic nanocomposite, Ag/Bigua-CS@Fe<sub>3</sub>O<sub>4</sub>, by integrating silver nanoparticles onto a biguanidine-chitosan (Bigua-CS) dual biomolecular-functionalized coating. They investigated its catalytic performance for one-pot  $A^3$  coupling in water, achieving excellent yields of propargylamine derivatives.<sup>147</sup>

Recently, Rafiee *et al.* concentrated a study involving the synthesis of a novel magnetic bio-nanocatalyst, Fe<sub>3</sub>O<sub>4</sub>@CS-StOX@Cys@Ag<sup>+</sup>, composed of chitosan cross-linked with starch oxide, functionalized with cysteine, and immobilized with Ag ions. The catalytic system was then investigated for its performance *via* one-pot three-component  $A^3$  coupling reaction, achieving great yields of propargylamine derivatives while

Table 3 A comparative study of  $A^3$  coupling catalyzed by Ag nanocomposites

S. no.	Catalyst	Reaction condition	Time (h)	Yield (%)	Reference
1	Ag MNPs	H <sub>2</sub> O, 60 °C	0.5	96	Babaei <i>et al.</i> <sup>148</sup>
2	g-C <sub>3</sub> N <sub>4</sub> -TCT-2AEDSEA-Ag-Cu-Ni	Toluene, 80 °C	8	90	Zarei <i>et al.</i> <sup>149</sup>
3	Ag@UiO-66-SH	ACN, 80 °C	6	98	Aparna <i>et al.</i> <sup>143</sup>
4	Ag-NPs@PDVTA-1	Neat, 100 °C	12	83	Chandra <i>et al.</i> <sup>150</sup>
5	KIT-5-bigua-Ag	H <sub>2</sub> O, 80 °C	8	98	Wang <i>et al.</i> <sup>39</sup>
6	Fe <sub>3</sub> O <sub>4</sub> -g-C <sub>3</sub> N <sub>4</sub> -Alg-Ag	H <sub>2</sub> O, rt	0.25	95	Daraie <i>et al.</i> <sup>151</sup>
7	AgNPs/Fe <sub>3</sub> O <sub>4</sub> @chitosan/PVA	EtOH, ultrasonic 40 °C	0.3	98	Ghasemi <i>et al.</i> <sup>152</sup>
8	CNT-Fe <sub>3</sub> O <sub>4</sub> -fibroin-Ag	Neat, 80 °C	2	92	Akbarzadeh <i>et al.</i> <sup>29</sup>
9	Ag-POMs	CH <sub>3</sub> CN, rt	6	99	Dou <i>et al.</i> <sup>146</sup>
10	Ag/Bigua-CS@Fe <sub>3</sub> O <sub>4</sub> NPs	H <sub>2</sub> O, 80 °C	10	96	Ma <i>et al.</i> <sup>147</sup>
11	Fe <sub>3</sub> O <sub>4</sub> @CS-StOX@Cys@Ag <sup>+</sup>	EtOH, reflux or toluene, 110 °C	0.5 or 1.3	97 or 95	Rafiee <i>et al.</i> <sup>45</sup>
12	Ag/EOS orange NPs	Toluene, 80 °C	8	95	Veisi <i>et al.</i> <sup>153</sup>
13	Fe <sub>3</sub> O <sub>4</sub> @R tinctorum/Ag NPs	H <sub>2</sub> O, 80 °C	8	96	Veisi <i>et al.</i> <sup>154</sup>



Scheme 18 Synthesis of triazole synthesis *via* Click mechanism.Scheme 20 Tetrazole synthesis *via* Click reaction.

offering numerous advantages such as the absence of base, cocatalyst, or side reactions.<sup>45</sup> Similarly, Veisi *et al.* described the robust bio-synthesis of Ag NPs utilizing orange peel extract, that were catalytically explored *via* three-component  $A^3$  coupling affording excellent results.<sup>153</sup> Table 3, displays a comparative study of various nanosilver catalysts used for  $A^3$  coupling.

## 2.4 Click reactions

**2.4.1 Triazole synthesis.** The Click reaction, specifically the Huisgen azide–alkyne cycloaddition (AAC), is a crucial reaction particularly for the one-pot synthesis of triazoles (Scheme 18). Herein, an azide and alkyne undergo  $[3 + 2]$  cycloaddition giving a high yield regioselective 1,2,3-triazole moiety. Triazoles serve as versatile organic compounds finding applications in medicinal chemistry, materials science, polymer chemistry and many more. Conventionally, the reaction requires copper-catalysts, however, many recent researches highlight the use of silver-based catalysts to synthesize triazoles with improved results.<sup>152</sup>

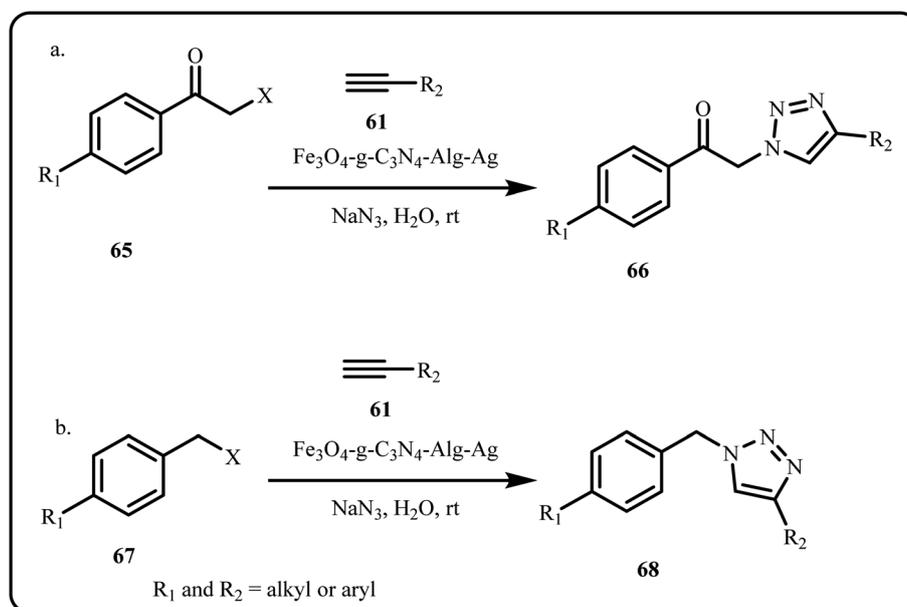
A novel and efficient nanocatalyst,  $\text{Fe}_3\text{O}_4/\text{g-C}_3\text{N}_4/\text{Alginate-Ag}$ , was successfully synthesized and demonstrated promising catalytic activity in the regioselective synthesis of 1,4-disubstituted 1,2,3-triazoles *via* a click reaction in aqueous media

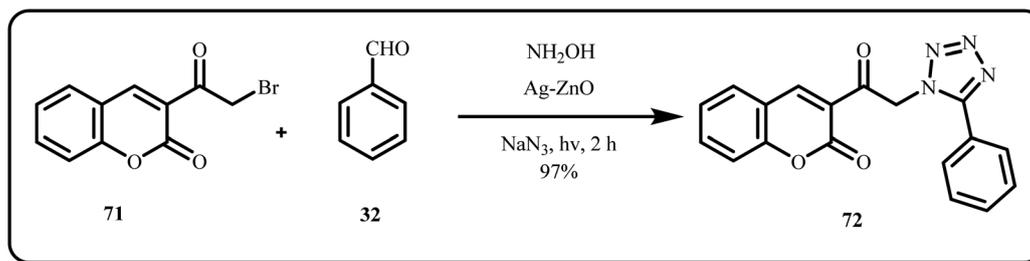
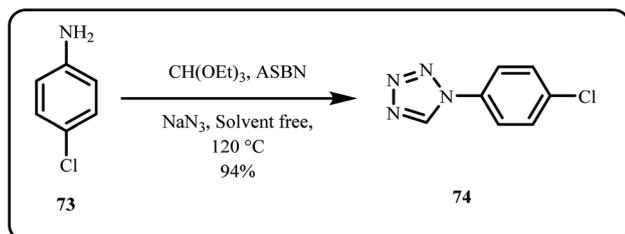
(Scheme 19). This catalyst provided shorter reaction times, higher efficiency, and improved product purity.<sup>151</sup>

Darroudi *et al.* designed and developed a hydrophilic benzimidazole functionalized fumed silica-based fluorescent nanocomposite, highly sensitive and selective to  $\text{Ag}^+$  ions. Subsequently,  $\text{Ag}(\text{I})$  was successfully incorporated, producing  $\text{Ag}(\text{I})@\text{Fum-Pr-Pyr-benzimidazole}$  nanocatalyst that catalytically synthesized 1,4-disubstituted triazoles through a green route.<sup>155</sup> A novel eco-friendly magnetic nanocatalyst,  $\text{AgNPs}/\text{Fe}_3\text{O}_4@\text{chitosan}/\text{PVA}$  was fabricated for the quick one-pot synthesis of triazole derivatives, by functionalizing chitosan biopolymeric chains with PVA, followed by the addition of Ag NPs and  $\text{Fe}_3\text{O}_4$ .<sup>152</sup>

**2.4.2 Tetrazole synthesis.** The Click reaction, adapted for tetrazole synthesis (Scheme 20), represents a pivotal reaction for constructing heterocyclic scaffolds in organic chemistry. Typically, tetrazole synthesis involves the azide-nitrile cycloaddition under low pH conditions, with or without a catalyst, depending on the reaction conditions and substrate compatibility.<sup>42</sup>

A novel material,  $\text{CF}/\text{MC}/\text{HA}/\text{A}$ , was fabricated by Molaei *et al.*, offering an innovative approach for the catalytic synthesis of 5-substituted 1H-tetrazoles *via* green routes. The core-shell

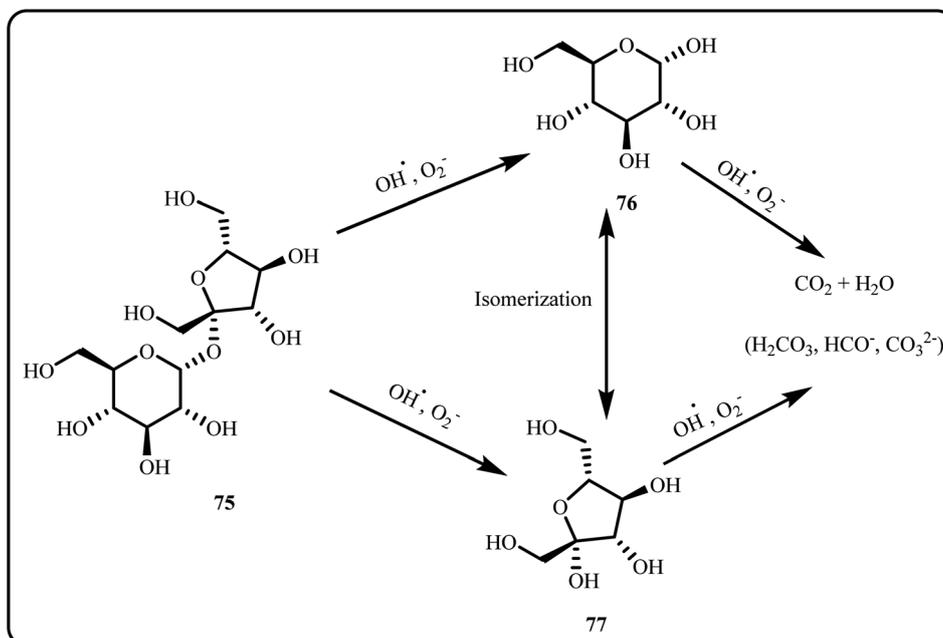
Scheme 19 Synthesis of 1,4-disubstituted 1,2,3-triazoles from (a)  $\alpha$ -halo ketone and (b) alkyl halide using  $\text{Fe}_3\text{O}_4/\text{g-C}_3\text{N}_4/\text{Alg-Ag}$  catalytic system (Daraie *et al.*<sup>151</sup>).

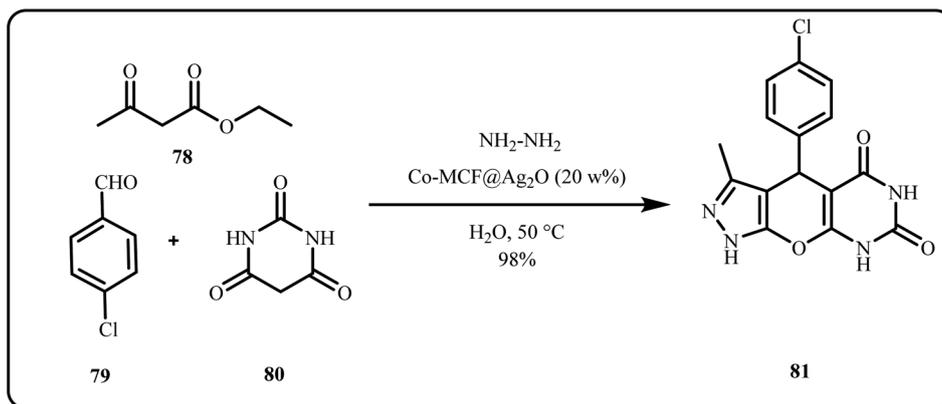
Scheme 21 Photo assisted synthesis of novel (1*H*-tetrazol-5-yl)-coumarin hybrids (Attia *et al.*<sup>158</sup>).Scheme 22 Synthesis of 1*H*-1,2,3,4-tetrazoles using the ASBN catalyst (Nasrollahdeh *et al.*<sup>159</sup>).

structure was attained by modifying Mobil Composition of Matter (MCM-41) NPs with 3,4,5-trihydroxyphenyl acetic acid (HA) and Ag(i) over a mesoporous ferromagnetic  $\text{CoFe}_2\text{O}_4$  (CF) spinel. This innovative strategy provided an effective, reusable catalysts with easy recovery and eliminating the use of hazardous catalysts in an environment-friendly method.<sup>156</sup> Prakash *et al.* introduced biocompatible gum acacia modified Ag-TiO<sub>2</sub> and Ag-SiO<sub>2</sub> nanostructures as heterogeneous catalysts for *in situ* synthesis of 5-substitued 1 *H*-tetrazoles *via* [3 + 2]

cycloaddition using aryl nitriles and sodium azide.<sup>157</sup> Molaei *et al.* functionalized the Fe<sub>3</sub>O<sub>4</sub> surface with 3-chloropropyl-trimethoxysilane, to bind with creatinine, followed by confinement of Ag resulting in Fe<sub>3</sub>O<sub>4</sub>@Creatinine@Ag nanocatalyst. The proposed catalyst system successfully synthesized 5-substitued 1*H*-tetrazoles under mild and eco-friendly conditions.<sup>42</sup> Novel tetrazole-coumarin hybrids were prepared photocatalytically using an Ag/ZnO nanocatalyst and ZnO nanorods *via* a one-pot facile route, affording excellent product yield (Scheme 21). Moreover, some of the synthesized tetrazole derivatives displayed anticancer activity against MCF-7, HepG2, A549 and Wi38 cancer cell lines.<sup>158</sup>

Nasrollahzadeh *et al.* utilized *A. moluccana* extract to synthesize a nanocatalyst comprising of sodium borosilicate glass-supported silver NPs (ASBN) *via* a green route. Herein, this catalytic system was applied for solvent-free [3 + 2] cycloaddition of amines with sodium azide, yielding assorted 1-substitued-1,2,3,4-tetrazoles in a cost-effective and environmental-friendly manner (Scheme 22). Furthermore, protein binding and toxicology studies were conducted to determine the ecological impact.<sup>159</sup>

Scheme 23 Photocatalytic degradation of sucrose using Ag/ZnO (Buengkitcharoen *et al.*<sup>160</sup>).



Scheme 24 One-pot synthesis of pyrazolopyranopyrimidines catalyzed by Co-MOF- $\text{Ag}_2\text{O}$  (Hootifard *et al.*<sup>161</sup>).

### 2.5 Miscellaneous reactions

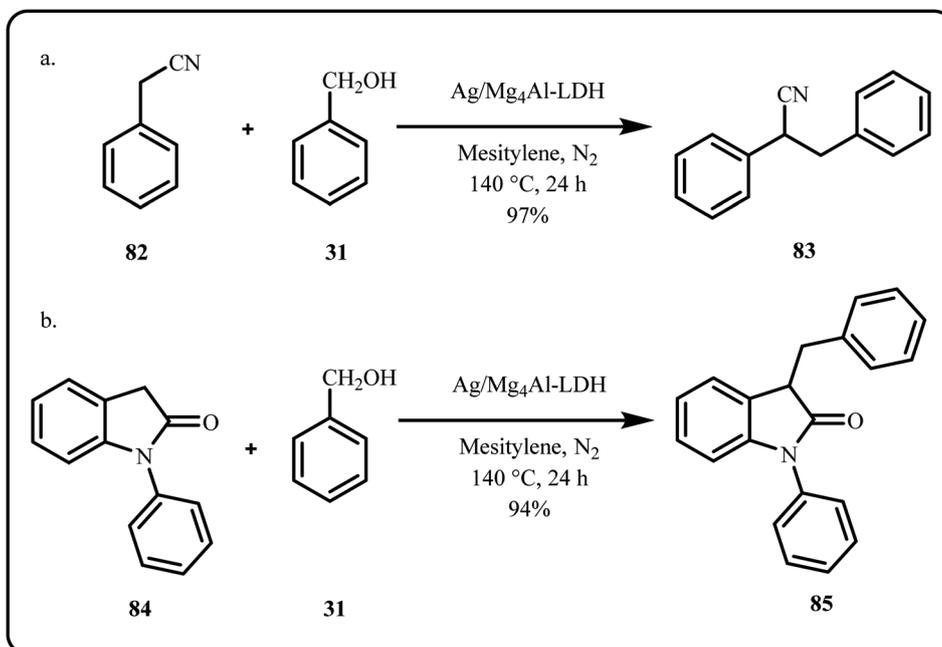
A ZnO and Ag nanoparticle nanocomposite (Ag/ZnO) was synthesized *via* a two-step method, starting with sol-gel auto-combustion followed by ion-impregnation. The incorporation of Ag NPs onto the ZnO surface reduced the electron-hole pair recombination by enabling direct electron transfer to metallic Ag, facilitating better photocatalytic activity. The mechanism involved hydroxyl radicals, to catalytically photodegrade the sucrose into glucose and fructose, eventually leading to its complete conversion into  $\text{CO}_2$  and  $\text{H}_2\text{O}$  (Scheme 23). The 10% Ag/ZnO catalytic system exhibited exceptional condensate degradation up to 90% within 90 minutes.<sup>160</sup>

Hootifard *et al.* opted co-precipitation procedure followed by microwave irradiation to produce a Co-MOF stabilized  $\text{Ag}_2\text{O}$  nanocomposite (Co-MOF@ $\text{Ag}_2\text{O}$ ) and employed it for the one-

pot synthesis of various tricyclic fused pyrazolopyranopyrimidines in water at 50 °C, achieving high yields in short reaction times (Scheme 24). The study highlights cost-effectiveness, catalyst recyclability, and an environmentally friendly, solvent free approach as key advantages.<sup>161</sup>

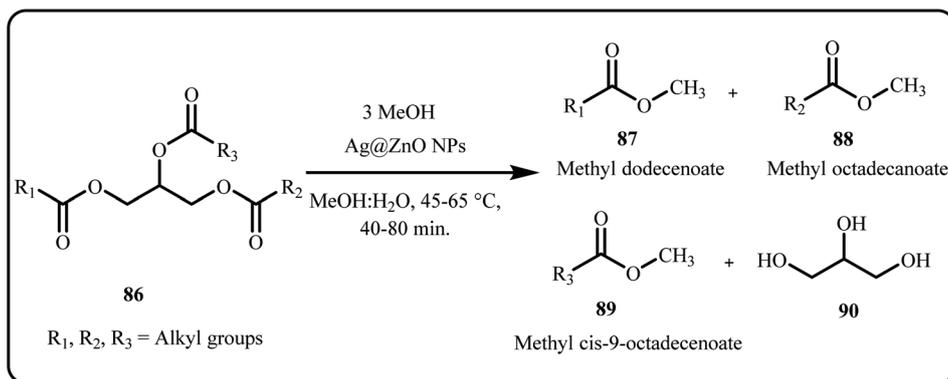
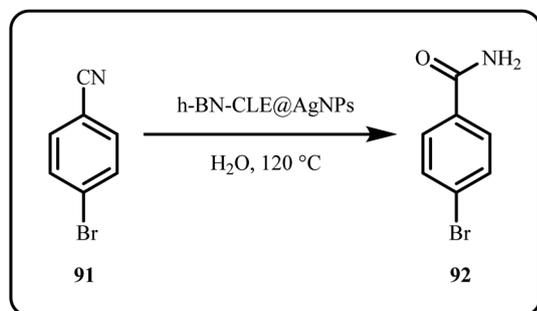
By employing the borrowing hydrogen strategy, a novel heterogeneous silver-catalyst, [Ag/Mg<sub>4</sub>Al-LDH], was utilized for the  $\alpha$ -alkylation of nitriles, oxindoles and carboxylic acid derivatives using alcohols (Scheme 25). Additionally, the nanocatalyst facilitated the cyclization of *N*-[2-(hydroxymethyl)phenyl]-2-phenylacetamides to synthesize 3-aryl-quinolin-2(1*H*)-ones *via* one-pot dehydrogenation and intramolecular  $\alpha$ -alkylation process.<sup>41</sup>

In 2023, Sherif *et al.* developed a green CaO-based eggshell-Ag heterogeneous nanocatalyst to recycle waste cooking oil and convert it into biodiesel. The group prepared the Ag nanoparticles



Scheme 25 [Ag/Mg<sub>4</sub>Al-LDH] catalyzed  $\alpha$ -alkylation of (a) nitriles and (b) oxindoles with alcohols (Aranda *et al.*<sup>41</sup>).



Scheme 26 Transesterification of palm oil triglyceride to form biodiesel (FAME) using ZnO@Ag NPs (Laskar *et al.*<sup>164</sup>).Scheme 27 Amidation of nitriles using h-BN-CLE@AgNPs (Antony *et al.*<sup>165</sup>).

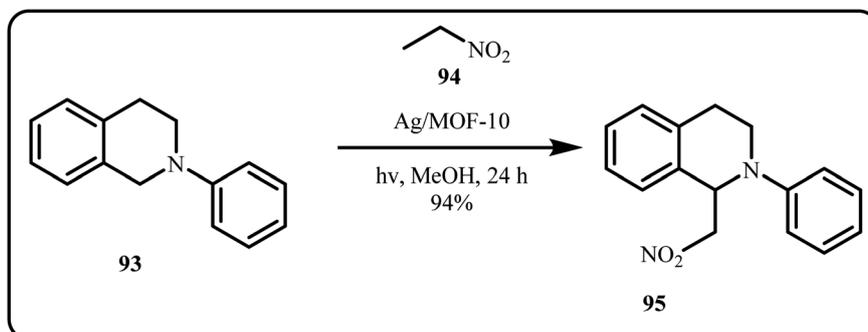
from fenugreek leaf extract and saturated them over eggshell-derived CaO nanoparticles (CaO/Ag). The CaO/Ag catalytic system afforded a 90% biodiesel yield, surpassing the CaO catalytic system attributed to its larger surface area and pore volume.<sup>162</sup> Recently, Zaban *et al.* produced biodiesel from *Aspergillus terreus* KC462061 in presence of gold–silver nanocatalyst (Au@Ag NPs) achieving a maximum yield of 43% in a fast and safe way.<sup>163</sup> Biodiesel synthesis through transesterification of palm oil was efficiently catalyzed by Laskar *et al.* by employing a novel ZnO supported Ag nanocomposite (ZnO@Ag NPs) (Scheme 26). Interestingly, the synthesized ZnO@Ag NPs

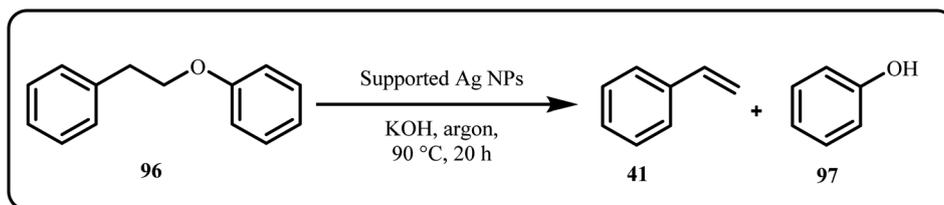
outperformed other catalysts, such as ZnO, Ag, ZnO mixtures, Ag@Al<sub>2</sub>O<sub>3</sub>, and Ag@SiO<sub>2</sub>, achieving an impressive yield of 96%.<sup>164</sup>

Biogenically fabricated Ag NPs, supported on boron nitride (h-BN-CLE@AgNPs) efficiently catalyzed the amidation of nitriles to produce excellent yields of aryl amides (Scheme 27). Furthermore, the nanocatalyst followed an economical and easy synthesis method, and produced non-toxic environment friendly by-products.<sup>165</sup>

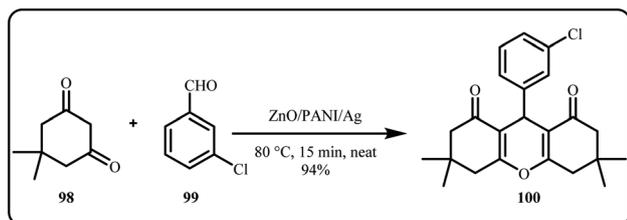
In a recent study, Che *et al.*, developed a novel photocatalyst, Ag/MOF nanocomposite, for cross-dehydrogenation coupling (CDC) reactions (Scheme 28). Using a simple photoreduction method, the Ag nanoparticles were stabilized onto the Metal Organic Framework (MOF) surface, resulting in an efficient and recyclable photocatalyst. The group highlighted that catalytic performance was dependent on nanoparticle size and loading amount, with smaller nanoparticles exhibiting superior activity.<sup>44</sup>

Recently, Han *et al.* presented a novel strategy that utilized illuminated plasmonic silver nanoparticles (Ag NPs) to efficiently abstract hydrogen from the C(sp<sup>3</sup>)-H bond of the C $\alpha$  atom in an alkyl-aryl ether  $\beta$ -O-4 linkage under mild conditions (Scheme 29). The proposed plasmon-driven process selectively abstracted hydrogen from specific C(sp<sup>3</sup>)-H bonds and precisely cleaved C-O bonds to produce aromatic compounds with unsaturated, substituted groups in excellent yields.<sup>166</sup>

Scheme 28 Cross-dehydrogenation coupling reaction photocatalyzed by Ag/MOF-10 (Che *et al.*<sup>44</sup>).



Scheme 29 Hydrogen abstraction of benzylic C $\alpha$  atom for alkyl aryl ether bond cleavage (Han *et al.*<sup>166</sup>).

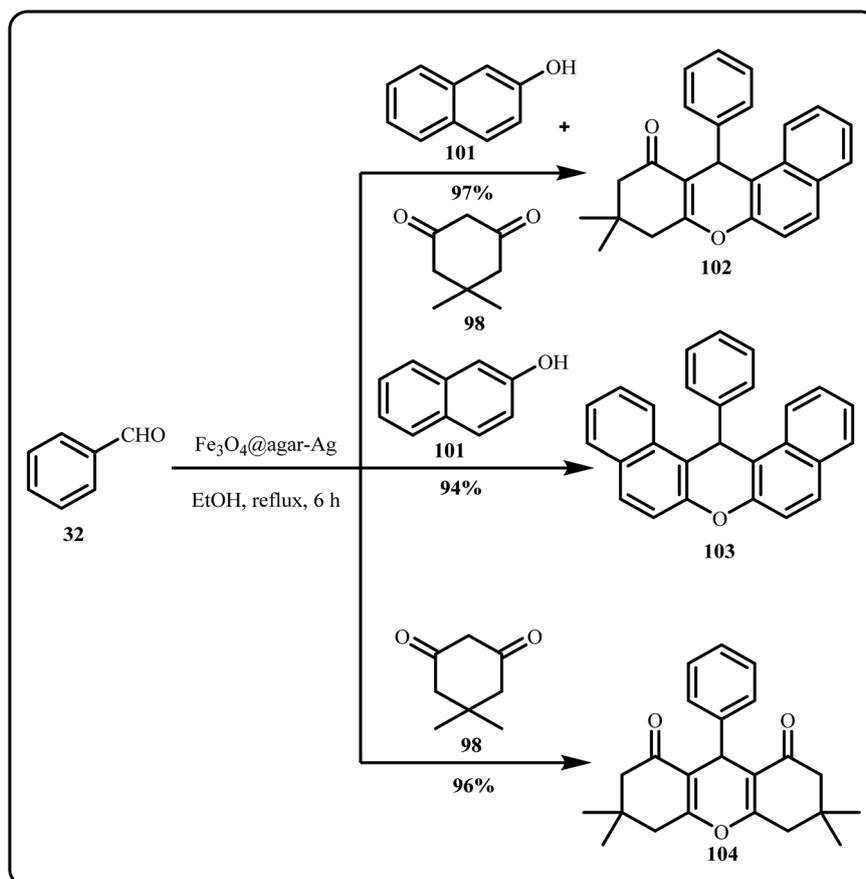


Scheme 30 ZnO/PANI/Ag nanocatalyzed synthesis of xanthen-1,8(2H)-dione derivatives (Nisha *et al.*<sup>43</sup>).

In this work, Nisha *et al.* developed a novel and highly efficient heterogeneous ZnO/polyaniline (PANI)/Ag nanocomposite, for the catalytic one-pot synthesis of xanthen derivatives *via* the condensation of 5,5-dimethylcyclohexane-

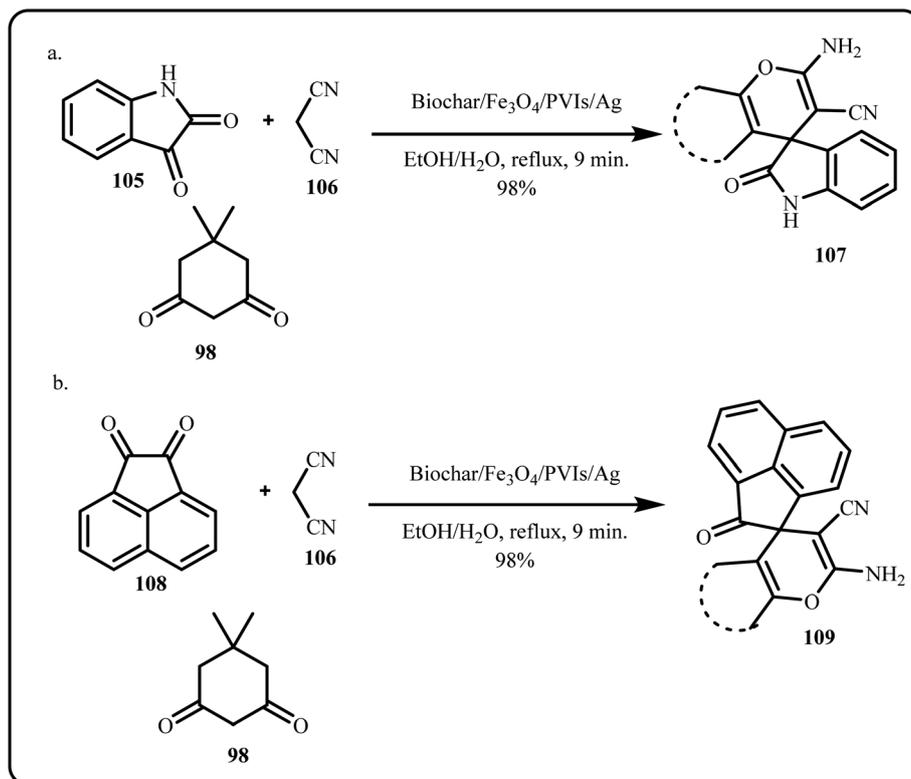
1,3-dione with various aromatic aldehydes under solvent-free conditions at 80 °C, achieving complete conversion in just 15 minutes (Scheme 30). The catalyst offered lesser reaction time, easy work-up and excellent catalyst recyclability for up to 6 cycles, while maintaining high yields.<sup>43</sup>

Recently, Karmakar *et al.* developed an efficient protocol for the cross dehydrogenative coupling (CDC) of xanthen and aromatic compounds using a nanosized bimetallic Ni/Ag@titania catalyst. The catalytic activity was studied through the reaction between caffeine and vanillin, comparing four polymorphic forms of titania-brookite, rutile, anatase and mesoporous out of which Ni/Ag@anatase demonstrated the highest catalytic activity, achieving 88% product formation in dry DMSO, attributed to the high surface area of anatase form. The group also revealed that the reaction's regioselectivity was



Scheme 31 Synthesis of xanthen derivatives using Fe<sub>3</sub>O<sub>4</sub>@Agar-Ag nanocatalyst (Hoseinzade *et al.*<sup>168</sup>).





Scheme 32 Biochar/Fe<sub>3</sub>O<sub>4</sub>/PVIs/Ag catalyzed synthesis of spiro-2-amino-4H-pyran compounds using (a) isatin and (b) acenaphthenequinone (Mohammadi *et al.*<sup>169</sup>).

influenced by the selection of peroxide oxidant, with both TBHP and H<sub>2</sub>O<sub>2</sub> proving effective.<sup>167</sup>

Hoseinzade *et al.* highlighted the production of a novel magnetically recyclable nanocatalyst, Fe<sub>3</sub>O<sub>4</sub>@Agar-Ag, *via in situ* co-precipitation of Fe<sup>2+</sup> and Fe<sup>3+</sup> ions using NH<sub>4</sub>OH in an agar solution, followed by the Ag<sup>+</sup> ion coating and the subsequent reduction with NaBH<sub>4</sub>. The Fe<sub>3</sub>O<sub>4</sub>@Agar-Ag nanocatalyst demonstrated significant catalytic activity in synthesizing various xanthene derivatives, specifically 12-aryl-8,9,10,12-tetrahydrobenzo[*a*]xanthene-11-one, 14-aryl-14H-dibenzo[*a,f*]xanthene and 1,8-dioxo-octahydroxanthene, *via* one-pot condensation of dimedone, aryl aldehydes and 2-naphthol in ethanol (Scheme 31). This method offered simple product isolation, easy catalyst recovery and high yields under eco-friendly conditions, while also eliminating the use of toxic catalysts.<sup>168</sup>

A novel silver nanoparticle catalyst was synthesized by developing poly(1-vinylimidazole) on the surface of magnetic biochar derived from Spear Thistle (biochar/Fe<sub>3</sub>O<sub>4</sub>/PVIm/Ag NPs). The group investigated the catalytic efficiency of the generated nanocatalyst through multicomponent reactions, focused on synthesizing spiro-2-amino-4H-pyrans *i.e.* spirochromenes (Scheme 32). The nanocatalyst offered high stability and reusability while affording high product yields in mild eco-friendly reaction conditions.<sup>169</sup>

Recently, a novel reusuable green silver based biocomposite (PC/AgNPs) was prepared and tested for the catalytic synthesis

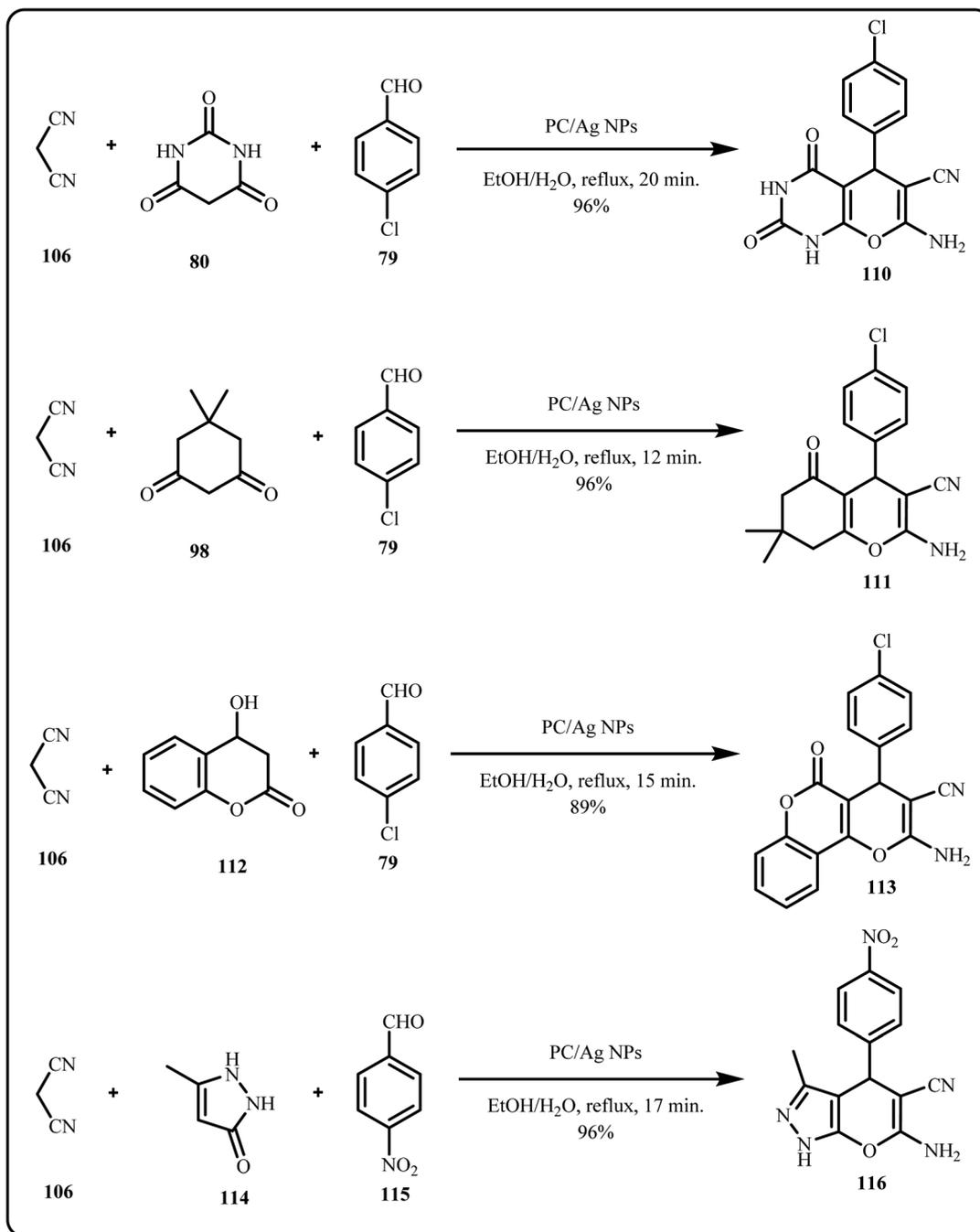
of 2-amino-4H-pyran and functionalized spirochromene derivatives *via* a one-pot, multicomponent reaction (Scheme 33). The prepared catalyst demonstrated high efficiency, easy separation, and reusability for at least three cycles without significant loss of activity.<sup>170</sup>

Recently, Zhang *et al.* developed an Ag(I)-catalyzed synthetic route to produce novel isoquinoline and quinazoline fused 1,2,3-triazoles in good-to-excellent yields (Scheme 34). Mechanistically, the reaction proceeds through condensation and amination cyclization cascade of amino-NH-1,2,3-triazoles with 2-alkynylbenzaldehydes forming three new C–N bonds in a single step, where the –NH group of the triazole ring acts as a nucleophile to give the quinazoline skeleton.<sup>171</sup>

Yakkala *et al.* developed Ag NPs embedded in a poly(perfluorosulfonic) acid cation-exchange membrane (Nafion-211), followed by the sorption and preconcentration of Hg<sup>2+</sup> ions *via* a galvanic reaction that resulted in Hg<sup>0</sup> nanodroplets. Interestingly, the Hg<sup>0</sup> embedded membrane served as a dip catalyst for converting phenylacetylene to acetophenone (Scheme 35). Additionally, the membrane successfully quantified Hg<sup>2+</sup> in real water samples and exhibited potential for safe Hg storage for remediation purposes.<sup>172</sup>

A novel Ag/Pd cocatalyst was employed for direct C–H arylation of fluoroarene chromium tricarbonyl complexes with bromoarenes (Scheme 36). Herein, the catalytic system operated under mild conditions, where Ag(I) facilitated C–H activation, while Pd promoted oxidative addition and reductive





Scheme 33 Catalytic synthesis of 2-amino-4H-pyran and functionalized spirochromene derivatives using PC/Ag NPs (Saneinezhad *et al.*<sup>170</sup>).

elimination in bromoarene, enabling the successful arylation of regioselective fluoroarenes, further enhanced by  $\pi$ -complexation to  $\text{Cr}(\text{CO})_3$ .<sup>173</sup>

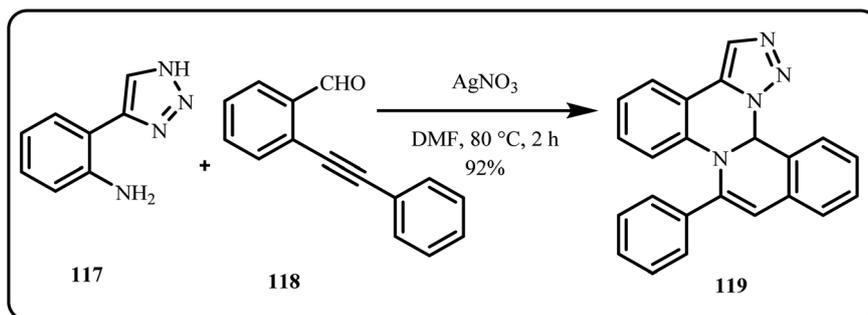
An interesting study by Singh *et al.*, highlighted the use of  $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-Ag}$  nanocatalyst for the synthesis of quinoline heterocyclic derivatives (Scheme 37). Herein, the group coupled aldehyde, amine and 1,3-indanedione to get high yields of products in a shorter time frame.<sup>174</sup>

Similarly, Hoot *et al.* prepared polyhydroquinoline heterocycles with Cd-Ag-MOF@ZnO nanoribbon as the organocatalyst *via*

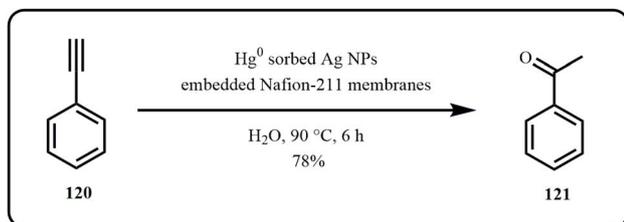
a one-pot Hantzsch condensation under solvent free conditions (Scheme 38). Herein, the products were obtained through a highly efficient and time-saving method in high yield.<sup>175</sup>

Co *et al.* developed binary nickel-silver nanoparticles, supported them on zeolite NaA and investigated the synthesized catalytic system for the dehydrochlorination of 2,4-dichlorophenol and observed a high conversion rate of 91% by using 10% NiAg/ZA.<sup>176</sup> Zuliani *et al.* prepared imidazolones *via* the cyclo isomerization of propargylic ureas through a novel, environmentally friendly approach that employed heterogeneous

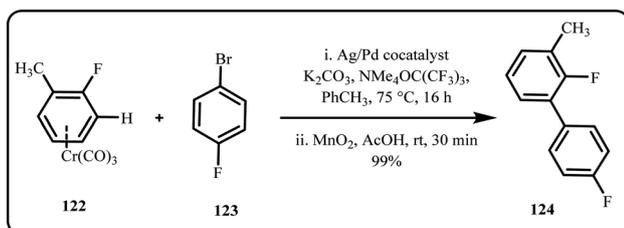




Scheme 34 AgNO<sub>3</sub> catalyzed cyclization of amino-NH-1,2,3-triazoles with 2-alkylbenzaldehyde to give pentacyclic fused triazoles (Zhang *et al.*<sup>171</sup>).



Scheme 35 Catalytic transformation of phenylacetylene to acetophenone using Hg<sup>0</sup> embedded nafion-211 membrane (Yakkala *et al.*<sup>172</sup>).



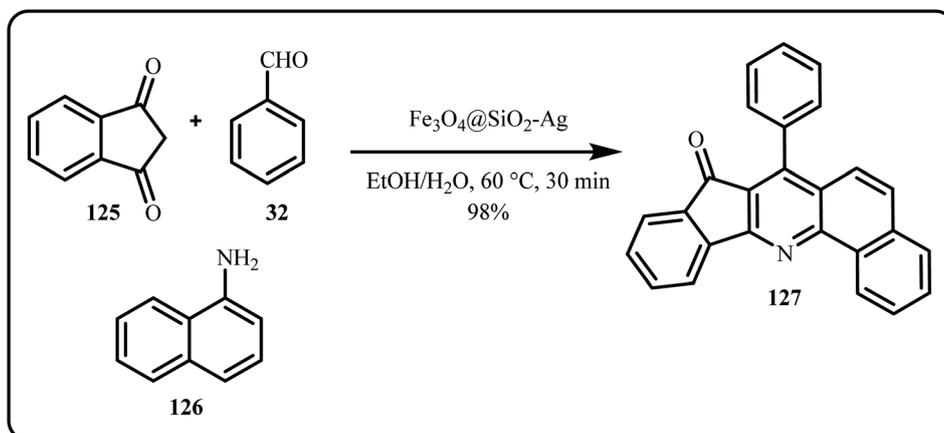
Scheme 36 Ag/Pd co-catalyzed arylation of fluoroarene derivatives with aryl bromides (Panigrahi *et al.*<sup>173</sup>).

catalysis with Au and Ag NPs supported on ALSBA-15 (Scheme 39). Additionally, the group conducted and compared the reactions with conventional and microwave irradiation reaction conditions, wherein microwave heating significantly reduced the reaction time.<sup>177</sup>

In their recent study, Hammouda *et al.* utilized a bio-synthesized Ag-TiO<sub>2</sub> nanocatalyst by using turmeric ethanol extract as the reducing and chelating agent to synthesize novel benzopyrimido[4,5-*d*]azoninone derivatives, achieving yields ranging from good to excellent (57–91%) and also showed good antioxidant activity.<sup>178</sup>

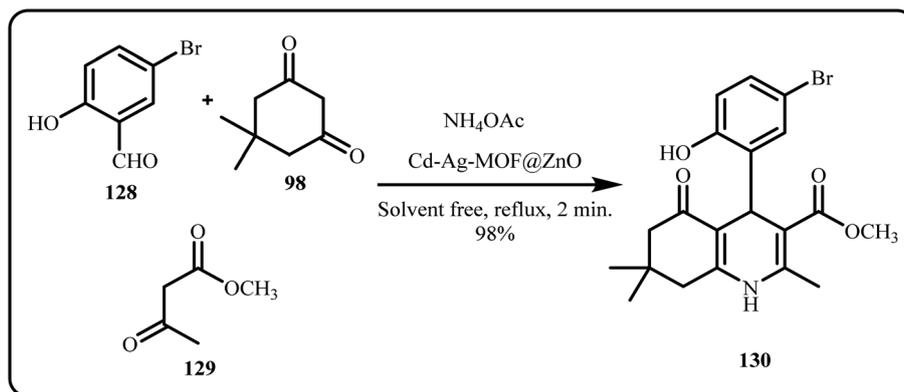
Over years, many researchers have opted CO<sub>2</sub> capture and insertion in order to synthesize valuable organic compounds through various catalysts.<sup>179–181</sup> For example, Yang *et al.* utilized Ag NPs anchored onto triazine-based framework for catalytic CO<sub>2</sub> conversion into  $\alpha$ -alkylidene cyclic carbonates using propargyl alcohols at room temperature (Scheme 40). Interestingly, the N-rich dual active sites worked as both the electron acceptor and donor. Herein, the synthesized catalyst can be easily recovered and reused for at least 10 consecutive cycles while offered high catalytic activity of up to 99%.<sup>182</sup>

Similarly, Roy *et al.* catalyzed carboxylate cyclization of propargyl alcohols to produce  $\alpha$ -alkylidene cyclic carbonates at room temperature with significant yield of 87–98% and >99% selectivity (Scheme 41). Furthermore, the group synthesized

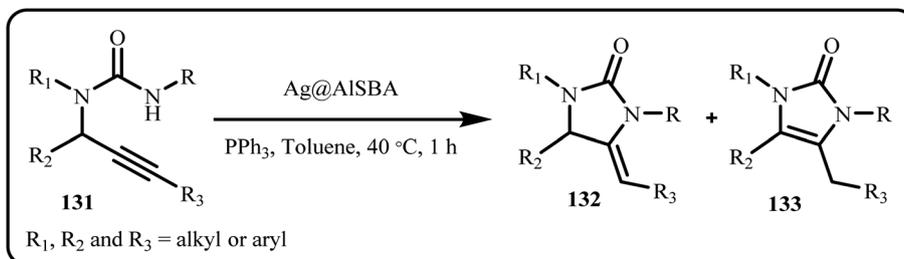


Scheme 37 Catalytic synthesis of quinoline heterocyclic derivatives using Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-Ag (Singh *et al.*<sup>174</sup>).

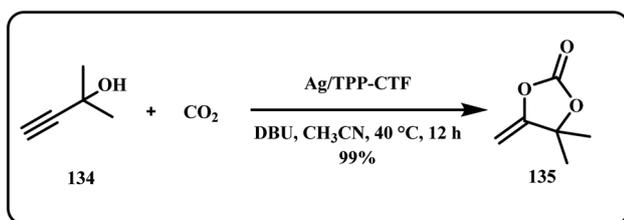




Scheme 38 Catalytic synthesis of polyhydroquinoline heterocycle derivatives using Cd-Ag-MOF@ZnO (Hoot *et al.*<sup>175</sup>).



Scheme 39 Synthesis of imidazolones *via* cycloisomerizations of propargylic ureas (Zuliani *et al.*<sup>177</sup>).

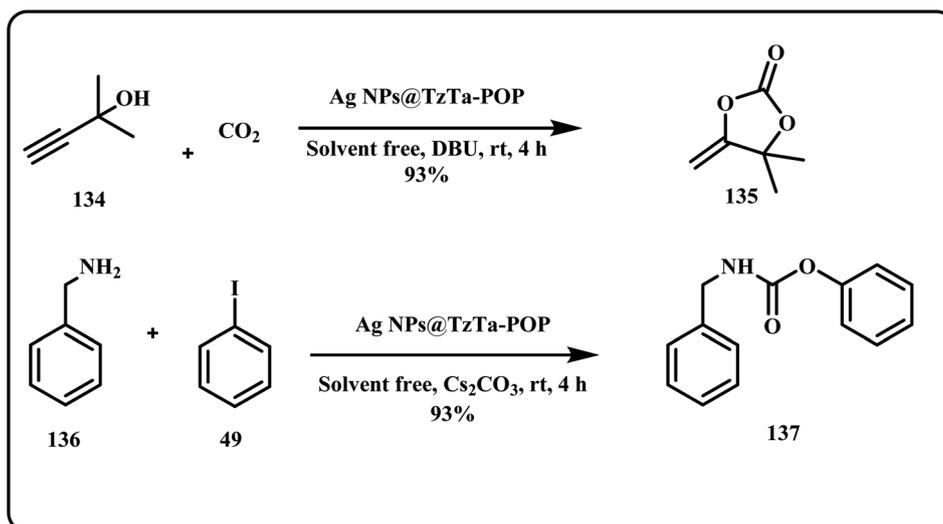


Scheme 40 Synthesis of  $\alpha$ -alkylidene cyclic carbonates *via* CO<sub>2</sub> insertion using propargyl alcohols (Yang *et al.*<sup>182</sup>).

high yield (87–95%) of value-added carbamates from aromatic and aliphatic amines, halides and CO<sub>2</sub>.<sup>183</sup>

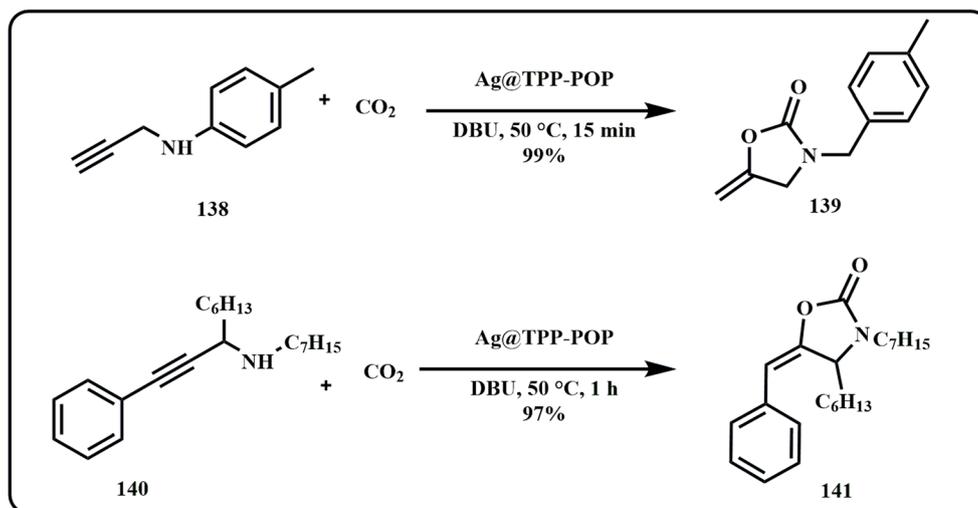
On a similar note, recently Sahoo *et al.* developed an Ag-based catalytic system that efficiently converted terminal and internal propargylic amines into their respective oxazolidinone derivatives, offering high yield of products (Scheme 42).<sup>184</sup>

Recently, Patra *et al.* designed an Ag NP modified thiol MOF-based catalytic system that converted propargylic alcohols and terminal epoxide to respective cyclic carbonates (Scheme 43).

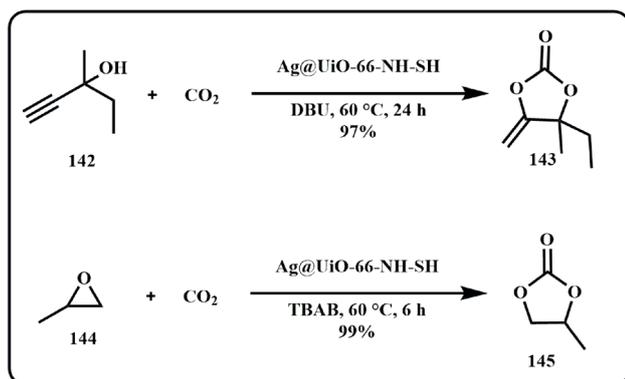


Scheme 41 Ag NPs@TzTa-POP catalyzed synthesis of  $\alpha$ -alkylidene cyclic carbonates and value added carbamates (Roy *et al.*<sup>183</sup>).





Scheme 42 Synthesis of oxazolidinone derivative from propargylic amines using Ag NPs@TzTa-POP catalytic system (Sahoo *et al.*<sup>184</sup>).



Scheme 43 Synthesis of cyclic carbonates using propargylic alcohols and epoxides using Ag@UiO-66-NH-SH catalytic system (Patra *et al.*<sup>185</sup>).

Herein, the group exploited the soft–soft interaction between free standing thiol group and Ag to make multiple catalysts by varying Ag concentration that offered high yield products for both the reactions.<sup>185</sup>

In their recent study, Liu *et al.*, designed a silver/carbon nanocatalyst utilising *Rhizoma coptidis* root as a support for the terminal alkyne halogenation reaction (Scheme 44). Interestingly, the catalyst achieved a catalytic yield of approximately 90% with high stability and reusability for up to 5 cycles.<sup>186</sup>

Similarly, Salam *et al.* reported a silver-based catalytic system (Ag NP@m-PS-PC) for the carboxylation of monosubstituted alkynes to give high yields of respective carboxylic acids without any decline in the catalytic activity for up to 5 cycles (Scheme 45).<sup>40</sup>

Li *et al.* employed ytterbium and silver co-catalyst to prepare pyrrole-fused heterocycles using isocyanide and enynone (Scheme 46). Interestingly, the versatile catalyst sustained various functional groups in the reaction and offered great yields of products.<sup>187</sup>

An interesting study by Liu *et al.* highlights the use of silver based nanocatalyst to prepare various substituted benzofuran-

pyrroles. Not only this, the group also catalytically synthesized indole–pyrrole using the same catalyst (Scheme 47).<sup>188</sup>

Recently, Noor *et al.* demonstrated the AgO catalyzed synthesis of *N*-enoxyimides *via* hydroxyimidation of terminal alkynes (Scheme 48). Herein, the catalyst offered exceptional yields of 96% under mild reaction conditions *via* a simple, scalable and atom efficient method.<sup>189</sup>

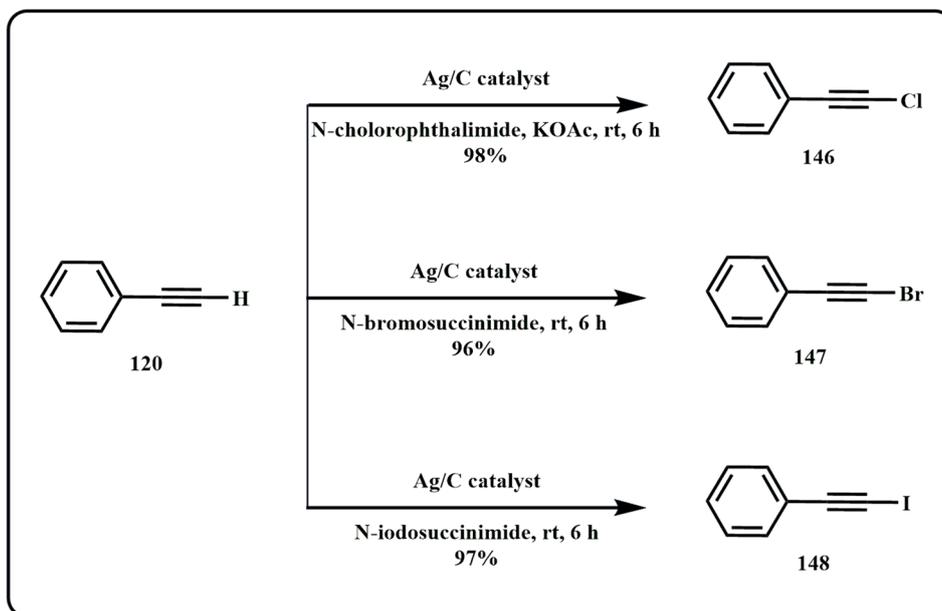
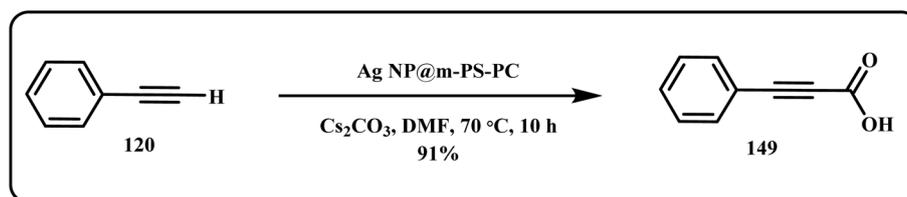
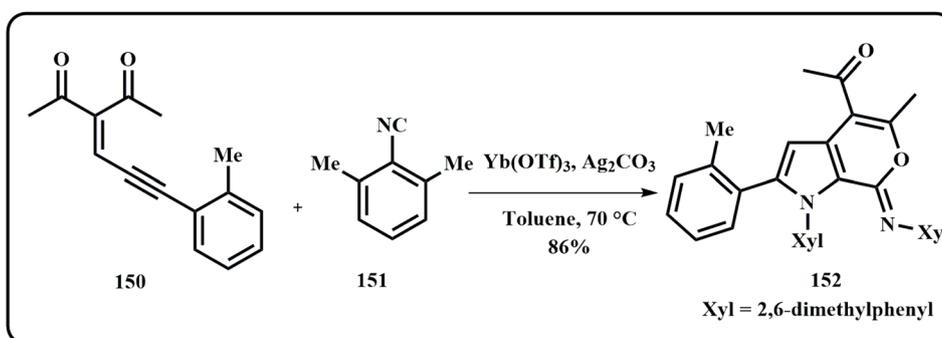
### 3. Biomedical applications

Earlier studies in the literature have shown that Ag NPs possess remarkable antiviral, antifungal, antibacterial, antifouling, and antioxidant properties, which enhance the biocompatibility of silver-based nanomaterials. Attributed from these interesting features, many such nanomaterials are heavily employed for the advancements in biomedical fields<sup>190</sup> such as drug delivery, wound healing and biosensing (Fig. 6).

#### 3.1 Antibacterial

Ag-based nanocomposites have attracted considerable attention for their strong antibacterial properties, making them highly valuable in both biomedical and industrial fields. The unique characteristics of Ag NPs, such as their high surface area<sup>191</sup> and ability to release Ag<sup>+</sup> ions,<sup>192</sup> enable effective interaction with bacterial cells.<sup>193</sup> A typical antibacterial mechanism involves the production of reactive oxygen species (ROS),<sup>194</sup> which cause oxidative stress and damage to the bacterial membranes,<sup>195</sup> proteins, and DNA.<sup>196</sup> Verma *et al.* developed ZnO–Ag nanocomposites by employing solvothermal method and evaluated its antibacterial capabilities through agar well diffusion assay. The antibacterial efficacy of the nanocomposite was observed to have improved with respect to individual nanoparticles, particularly against *E. coli*. When exposed to light, ZnO released toxic substances that killed the germs, while silver enhanced the antibacterial properties.<sup>197</sup> Siewa *et al.* developed AgNPs@CQD, a low



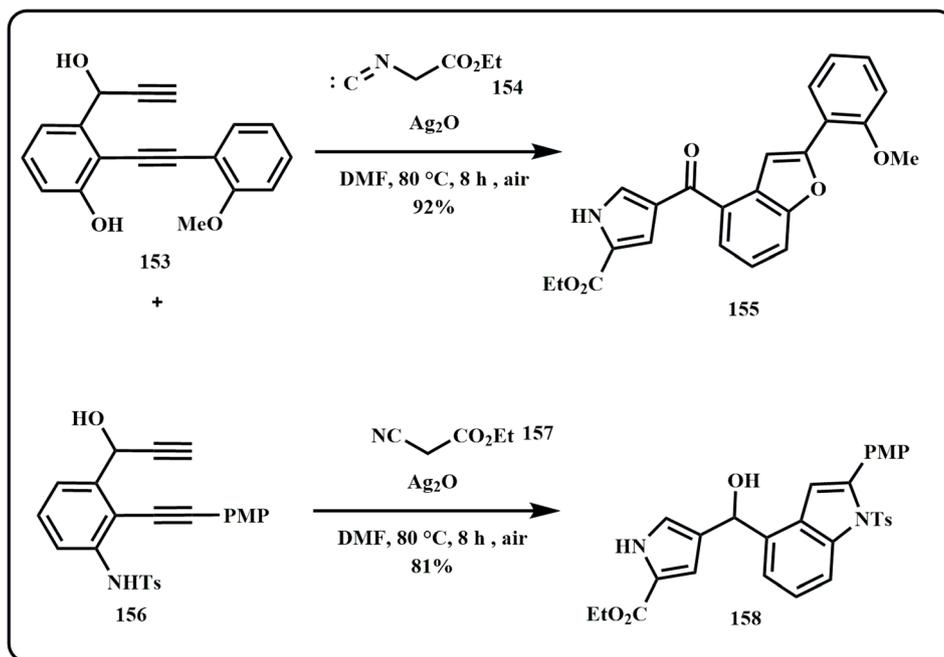
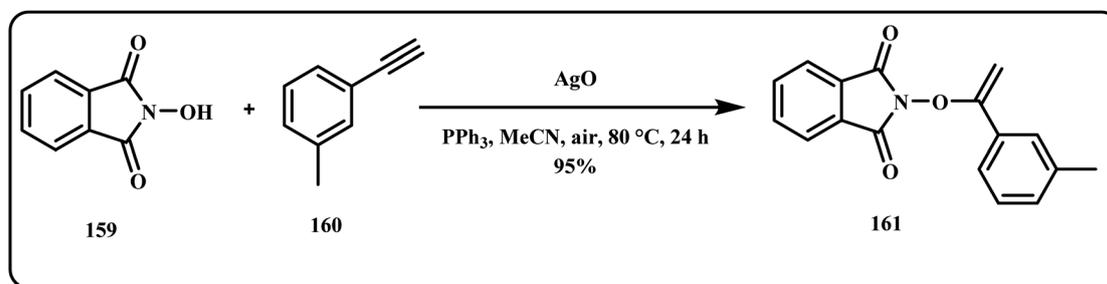
Scheme 44 Alkyne halogenation catalyzed by Ag/C catalytic system (Liu *et al.*<sup>186</sup>).Scheme 45 Carboxylation of monosubstituted alkynes using Ag NP@m-PS-PC catalyst (Salam *et al.*<sup>40</sup>).Scheme 46 Synthesis of pyrrole-fused heterocycles using ytterbium and silver co-catalyst (Li *et al.*<sup>187</sup>).

toxicity nanomaterial synthesized using ecofriendly onion juice. Tested *via* the agar-well diffusion method, it showed strong antibacterial activity, especially at higher concentrations of CQDs.<sup>198</sup> Rabbi *et al.* synthesized Fe<sub>2</sub>O<sub>3</sub>/Ag, an antibacterial nanocomposite, and investigated its effectiveness against four pathogenic bacterial species.<sup>199</sup>

Similarly, Muneeswaran *et al.* developed CS/Ag nanocomposites *via* starch-mediation. Both Ag NPs and CS/Ag NCs exhibited antibacterial efficacy against *Salmonella typhi*, *E. coli*,

*Pseudomonas aeruginosa*, and multidrug-resistant *Klebsiella pneumoniae*, with minimum inhibitory concentrations ranging from 1.3 to 7.8  $\mu\text{g mL}^{-1}$ .<sup>200</sup> Recently, Song *et al.* formulated silver nanoparticles supported on attapulgite clay to develop a new antibacterial material, which successfully eradicated bacteria like *E. coli*.<sup>201</sup> Bharathi *et al.* utilized gum arabic (GA) and Chitosan (CS) to manufacture sustainable and environmentally friendly silver nanocomposites that demonstrated promising inhibition against *Staphylococcus aureus* (18 mm)



Scheme 47 Synthesis of benzofuran-pyrroles and indole-pyrroles using Ag<sub>2</sub>O catalyst (Liu *et al.*<sup>188</sup>).Scheme 48 Synthesis of *N*-enoximides by hydrooxyimidation of terminal alkynes using AgO catalyst (Noor *et al.*<sup>189</sup>).

and *Escherichia coli* (20 mm).<sup>202</sup> Arunpandian *et al.* used a facile hydrothermal route to fabricate Ag/Er<sub>2</sub>O<sub>3</sub>@CuO, a novel nanocomposite that successfully destroyed hazardous bacteria such as *Aeromonas hydrophila* and *Hemophilus influenzae*.<sup>203</sup>

### 3.2 Anticancer

According to multiple reports, U.S. is expected to have over 2 million cancer cases and more than 611 000 related deaths in 2024. Since 1991, rising incidence rates of cancers like breast, prostate, and liver have posed a threat to ongoing progress. Additionally, colorectal and cervical cancers are on the rise among younger adults, with colorectal cancer topping the cancer death charts for men under 50.<sup>204</sup> Ag-based nanocomposites are becoming more and more popular due to their possible uses in the treatment of cancer. Resulting from its nano-size and unique surface properties, they penetrate into the tumor tissues, and effectively target the cancer cells.<sup>205</sup> Ag NP generate ROS, which induce oxidative stress and ultimately lead

to the death of cancer cells. Additionally, they can be combined with other materials, such as medicines, polymers, or graphene, to increase their therapeutic benefits.<sup>206</sup> This makes them a promising approach for cancer treatment, offering fewer side effects and improved selectivity. Recently, Faid *et al.* synthesized GO/Ag NC, which was tested against four different types of cancer cells, H460, HCT116, MDA-MB-468, and FaDu to assess its capacity to kill cancer cells with IC<sub>50</sub> values of 5.5, 6, 9, 7.75 μg mL<sup>-1</sup>, respectively.<sup>207</sup> Similarly, Vankatraman *et al.* used *Morinda citrifolia* leaf extract to create ZnO/Ag NCs that exhibited greater anticancer activity against A549 lung cancer cells, having an IC<sub>50</sub> 242 μg mL<sup>-1</sup>, as opposed to 398 μg mL<sup>-1</sup> for ZnO nanoparticles. Moreover, ZnO/Ag NCs and ZnO NPs were also tested for toxicity against non-cancerous RAW264 macrophage cells, demonstrating IC<sub>50</sub> values of 402 μg mL<sup>-1</sup> and 494 μg mL<sup>-1</sup> respectively.<sup>208</sup> Moghayedi *et al.* designed and developed silver-graphene oxide nanocomposites (Ag-GO) which showed anticancer properties by targeting glioblastoma (U87MG) cancer cells, having an IC<sub>50</sub> value of 270 μg mL<sup>-1</sup>.<sup>209</sup>



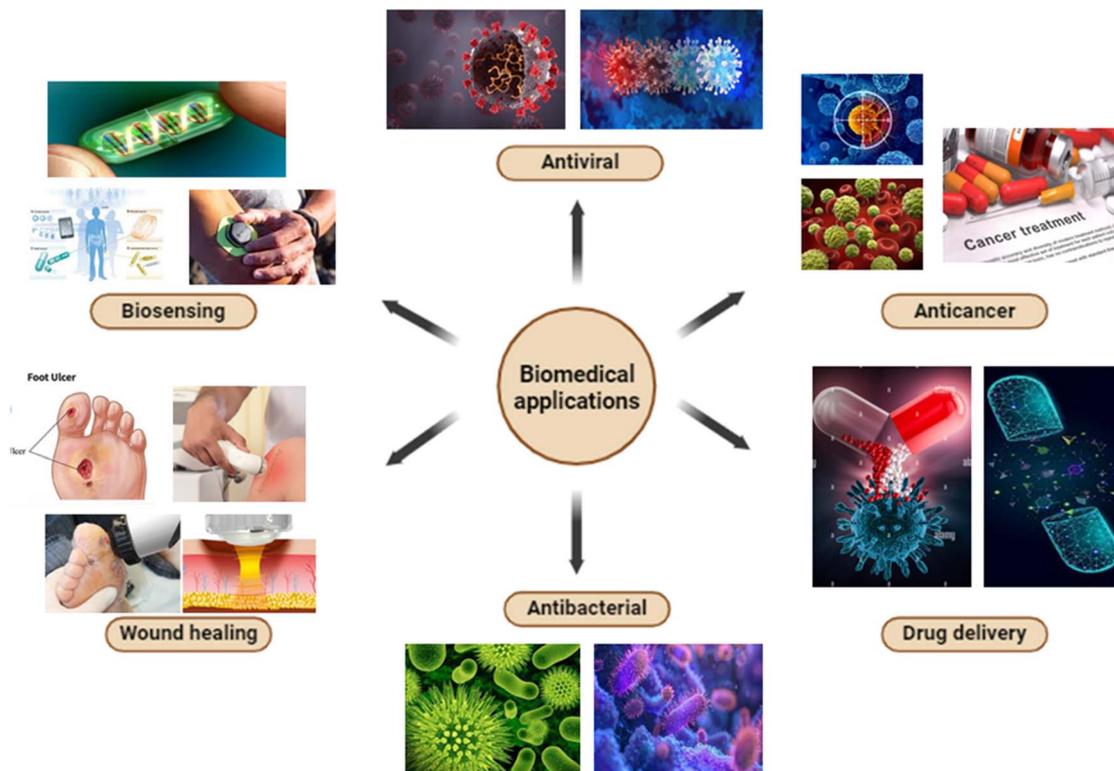


Fig. 6 Biomedical applications of silver nanocomposites.

In a recent study, Zhou *et al.* created a silver-coated magnetic nanoparticles ( $\text{Fe}_3\text{O}_4/\text{Ag}$  NPs) using pomegranate peel extract, that effectively eliminated ovarian cancer cells NIH: OVCAR-3, ES-2, and TOV-21 G.<sup>210</sup> D. Bharathi *et al.* manufactured chitosan/silver nanocomposites (Kf-CS/Ag) which demonstrated strong activity against triple-negative breast cancer (TNBC) cells, especially the MDA-MB-231 cell line, possessing  $\text{IC}_{50}$  value of  $53 \mu\text{g mL}^{-1}$ .<sup>211</sup> Ag NPs coated with reduced graphene oxide (AgNPs@rGO), developed by Balaji *et al.*, exhibited a potent anticancer effect, particularly against MCF-7 breast cancer cells. The green produced Ag NPs and AgNPs@rGO demonstrated significant cytotoxicity, with  $\text{IC}_{50}$  equal to  $100 \mu\text{g mL}^{-1}$  and  $108 \mu\text{g mL}^{-1}$ , respectively.<sup>212</sup>

### 3.3 Antifungal

Antifungal agents are compounds that prevent the growth of or eliminate fungi, helping in the treatment and prevention of fungal infections in humans, animals, and plants. They work by disrupting fungal cell membranes, inhibiting cell wall formation, or interfering with DNA and protein synthesis.<sup>213–215</sup> Ag nanocomposites, known for their potent antifungal properties, are effective against numerous fungal strains and are being explored for applications in medical treatments, coatings, and agriculture for their potent antifungal properties.

Arumugam *et al.* realized silver-embedded carbon nitrides (Ag@g-CN) that exhibited strong antifungal effects against *Candida albicans*, a common pathogen that causes oral infections and showed MIC values ranging from 16 to  $256 \mu\text{g mL}^{-1}$ .<sup>216</sup> Salem *et al.* developed a carboxymethyl cellulose and

silver nanoparticles (CMC-AgNP) composite, which displayed strong activity against filamentous fungus, including *Aspergillus fumigatus*, *A. niger*, and *A. terreus*, making it a potent antifungal drug for pharmaceutical settings.<sup>217</sup> Selvi *et al.* created reduced graphene oxide (Ag/rGO) nanocomposites that exhibited strong antifungal action, especially against *Candida* species, such as *Candida albicans*, *Candida krusei*, and *Candida tropicalis*.<sup>218</sup>

Chowdhury *et al.* developed Cu and Ag NP nanocomposites that demonstrated notable antifungal activity against *Rhizoctonia solani*, the causative agent of sheath blight in rice.<sup>219</sup> Tran *et al.* synthesized lignin@Ag/SiO<sub>2</sub> NPs that demonstrated significant antifungal activity against *Aspergillus flavus*.<sup>220</sup> Muzio *et al.* created a thin film nanocomposite incorporating AgNPs synthesized using a green route that exhibited strong antifungal activity against 16 clinical isolates from five different *Candida* species.<sup>221</sup>

### 3.4 Antiviral

Silver nanocomposites demonstrate significant antiviral activity owing to their distinctive physical and chemical properties.<sup>222</sup> Their composites, often incorporating AgNPs with other substances, can inactivate viruses through mechanisms like oxidative stress generation, disruption of viral replication, and binding to viral proteins.<sup>223,224</sup> Their uses extend across diverse areas such as medical devices,<sup>225</sup> surface coatings,<sup>226</sup> and therapeutic treatments,<sup>227</sup> positioning them as effective solutions for fighting viral infections and improving health outcomes.

The antiviral characteristics of Ag NPs synthesized using *Nigella arvensis* extract were investigated by Elnosary *et al.* wherein, the Ag NPs demonstrated effectiveness against the



HSV-1, HAV, and adenovirus, inhibiting their proliferation by 53.6%, 86%, and 17.3%, respectively.<sup>228</sup> The antiviral activity of green-synthesized Ag<sub>2</sub>O particles (IC<sub>50</sub> = 0.618 μg mL<sup>-1</sup>) generated by Asif *et al.* was significantly higher compared to chemically synthesized Ag<sub>2</sub>O particles (IC<sub>50</sub> = 6.129 μg mL<sup>-1</sup>).<sup>229</sup> Bhatia *et al.* developed metal oxide-based silver nanocomposites, Ag/NiO (AN) (IC<sub>50</sub> = 3.277 μg mL<sup>-1</sup>) and Ag<sub>2</sub>O/NiO/ZnO (A/N/Z) (IC<sub>50</sub> = 2.828 μg mL<sup>-1</sup>), to test their antiviral activity through plaque reduction assays, cytopathic effect analysis, and qRT-PCR showing a significant reduction in chikungunya virus titer.<sup>230</sup>

Chitosan NPs (CS NPs) and Chitosan-Ag (CS-Ag) NCs developed by Ganainy *et al.* exhibited significant antiviral activity against Alfalfa Mosaic Virus (AMV) in pepper plants. When applied topically 24 hours after inoculation, AMV infection was decreased by 90–91% at 400 ppm for CS NPs and 200 ppm for CS-Ag NCs.<sup>231</sup> Xie *et al.* realized two bimetallic AgCu NCs—Ag<sub>2</sub>Cu<sub>2</sub>O<sub>3</sub> and AgCuO<sub>2</sub> that have remarkable antiviral capabilities; achieving a 6-log reduction of the Q beta (Qβ) bacteriophage. Notably, the material's ability to efficiently prevent virus transmission both day and night is demonstrated by the 7.5 log inactivation, resulting from its enhanced antiviral activity under visible light.<sup>232</sup> Demchenko *et al.* developed PLA-Ag-PEI NCs that strongly inhibit viruses such as herpes simplex virus type 1, influenza A virus, and adenovirus serotype 2.<sup>233</sup>

**3.4.1 Ag based nanocomposites vs. SARS CoV-2.** During the covid pandemic, Agnol *et al.* realized thermoplastic polyurethanes and Ag NCs (TPU/AgNPs) that exhibited potent antiviral properties against SARS-CoV-2, achieving an inactivation yield exceeding 99.0%.<sup>234</sup> Similarly, Assis *et al.* made SiO<sub>2</sub>-Ag NCs immobilized on a polymeric ethyl vinyl acetate matrix that demonstrated strong antiviral properties against SARS-CoV-2.<sup>235</sup> Additionally, Morozova *et al.* reported the antiviral properties of silver-based nanomaterials against SARS-CoV-2. To target SARS-CoV-2 and lower the possibility of viral resistance, a hybrid strategy was proposed, utilizing Ag-2S for RNA degradation and Ag nanoparticles to interfere with antigen interactions.<sup>236</sup>

### 3.5 Drug delivery

Ag nanoclusters (NCs) have proven to be highly efficient carriers for drug delivery due to their large surface area, biocompatibility, and customizable properties. To achieve effective targeted delivery, these NCs can be tailored to precisely control drug release, target specific cells or tissues, and minimize unwanted side effects. They function through mechanisms such as controlled release, enhanced cellular uptake, and selective targeting of specific cells.<sup>237,238</sup>

Recently, Hanna *et al.* synthesized a pH sensitive silver nanocomposite (SNCs) that worked as efficient biodegradable carriers for controlled intestinal delivery of 5-fluorouracil.<sup>239</sup> Romdoni *et al.* developed Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-Ag NPs, which demonstrated strong potential as a drug delivery system attributed to their super paramagnetic nature and ability to load anticancer drugs like epirubicin (EPI).<sup>240</sup> In a recent study, Bertão, *et al.* created a zeolite-based delivery system, Ag<sub>4</sub>(5-FU)@Y, that offered a dual-function drug delivery platform combining

antimicrobial silver (Ag<sup>+</sup>) and antineoplastic 5-fluorouracil (5-FU).<sup>241</sup>

Similarly, Mahanty *et al.* developed a biosurfactant (BS)-stabilized Ag NPs that offered enhanced drug delivery applications in combating antimicrobial resistance (AMR).<sup>242</sup> Meligy *et al.* highlighted silver and gold NP-based chitosan nanocomposites that offered an efficient drug delivery platform for cancer treatment.<sup>243</sup> Interestingly, Khafaga *et al.* synthesized a zinc oxide–superparamagnetic iron oxide–silver nanocomposite through green methods, which served as a nano-carrier to improve the anticancer efficacy of sorafenib.<sup>244</sup>

### 3.6 Biosensing

Ag NCs are being exploited as efficient biosensors for the detection of numerous biomolecules<sup>245</sup> such as glucose,<sup>246</sup> proteins,<sup>247</sup> enzymes,<sup>248</sup> cholesterol,<sup>249</sup> and DNA.<sup>250</sup> These materials enhance biosensing capabilities through mechanisms such as localized surface plasmon resonance (LSPR) and electrochemical signal amplification.

Recently, Mahmudin *et al.* described an easy method to detect *Escherichia coli* bacteria using Ag NPs-based localized surface Plasmon resonance (LSPR) biosensors.<sup>251</sup> Pektaş *et al.* realized a novel amperometric glucose biosensor by modifying a carbon paste electrode (CPE) using green-synthesized WT-AgNPs derived from waste tea.<sup>252</sup> Interestingly, Li *et al.* developed a flexible biosensing platform utilizing hollow Prussian blue NCs with ultra-small Ag NPs (Ag-HPB), possessing enhanced electrical conductivity and enzyme loading capacity. This platform demonstrated outstanding biosensing performance, with a sensitivity of 24.37 μA mM<sup>-1</sup> cm<sup>-2</sup> for glucose and a low limit of detection (LOD) of 2.28 pg mL<sup>-1</sup> for trichlorfon (TCF).<sup>253</sup> Saadh *et al.* incorporated Ag-Cu NPs into polyaniline nanotubes (Ag-Cu@PANI) that demonstrated efficient electrochemical detection of dopamine and hydroquinone simultaneously, with detection limits of 0.46 μM and 0.23 mM respectively.<sup>254</sup>

Similarly, Kim *et al.* reported casein hydrolysate peptides-functionalized Ag NPs (CHPs@AgNPs), which exhibited a colorimetric response to AGAs such as streptomycin, producing visible colour changes from yellow to orange, with absorbance peaks at 405 and 520 nm.<sup>255</sup> Selimoglu *et al.* presented an interesting study where they created Ag NPs-doped graphene-based biosensor for prolactin, having LOD as low as 0.55 ng mL<sup>-1</sup>.<sup>256</sup> Sukjee *et al.* detected the EV71 virus using an Ag NPs-based biosensor with a detection limit of 0.0001 PFU mL<sup>-1</sup> in PBS and 0.001 PFU mL<sup>-1</sup> in serum.<sup>257</sup>

### 3.7 Wound healing

Due to the numerous medicinal benefits of silver nanocomposites, there has recently been a notable increase in their applications for wound healing.<sup>258,259</sup> These nanocomposites release silver ions that fight against the bacteria, fungi and viruses to prevent infections that can potentially slow down the wound recovery process. These silver-based nanocomposites ensure rapid wound healing by reducing inflammation, promoting cell growth and migration. As a result, silver



nanocomposites can be integrated into wound dressings to create an optimal healing environment for treating cuts, burns, and wounds, while effectively preventing infection.<sup>260–262</sup>

For example, Aldakheel *et al.* opted microwave irradiation to fabricate Ag NPs, which were then loaded onto chitosan grafted PVA hydrogel to investigate their wound-healing ability in both *in vivo* and *in vitro* rat models. Additionally, they showed notable antibacterial activity against *S. aureus* and *E. coli*.<sup>263</sup> Saghafi *et al.* reported the use of bromelain and Ag NPs incorporated into polycaprolactone/chitosan nanofibers (PCL/CS-Ag NPs-BRO) as a dressing for wound-healing applications. Interestingly, the addition of bromelian and Ag NPs notably improved the tensile strength and antibacterial activity of the nanofibers.<sup>67</sup> In a similar study, Zhang *et al.* (2024) developed electrospun polyasparthydrazide nanofibers embedded with Ag nanoparticles (PAHy/Ag NPs) for wound healing applications. The resulting nanofiber hydrogel mat demonstrated an improved silver release rate of  $9.4 \pm 1.1\%$  and showed strong antibacterial activity, killing 99.99% of both *E. coli* and *S. aureus*. This makes it a promising candidate for use in dressing materials for treating infected wounds, promoting collagen deposition at the wound site.<sup>264</sup> Recently, Lakkim *et al.* addressed the wound healing potential of green-synthesized Ag NPs in mince using the excision wound model in Balb/C mice. Herein, the group observed increased collagen, DNA and protein content in wound samples, making it an efficient antioxidant compound for cutaneous wound treatment as a medicine or ointment.<sup>265</sup> In 2024, Gawad *et al.* developed an efficient antimicrobial wound-healing substance using Ag NPs embedded natural hydrogel for rats with more than 98% wound area contraction in only 2 weeks.<sup>266</sup>

Recently, Vijayakumar *et al.* prepared Ag NP conjugated probiotic bacteria and investigated its bacterial growth inhibition and wound-treating capability. They observed strong antibacterial activity against pathogens and excellent wound closure of 96% through an *in vitro* scratch-wound assay.<sup>267</sup> A novel fibrin/chitosan incorporated Ag nanocomposite was fabricated by Sanmugam *et al.* to level up the antibacterial and wound healing activity. The prepared nanocomposite exhibited antibacterial activity against *P. aeruginosa*, *E. coli*, *S. aureus* and *L. bulgarius* pathogens.<sup>268</sup> Muneeswaran *et al.* prepared chitosan/Ag (CS/Ag) nanocomposites and investigated their microbial inhibition activity against *P. aeruginosa*, *E. coli*, *K. pneumoniae* and *S. typhi*. They observed that CS/Ag nanocomposite outperformed Ag NPs by exhibiting higher biofilm inhibition against *P. aeruginosa* and *K. pneumoniae* while also demonstrating cyto-compatibility with L929 mouse fibroblast cells. Notably, it enhanced cell migration by wound gap closure, making it a suitable wound healing agent for drug-resistant bacterial wound infections.<sup>200</sup>

Recently, Kodasi *et al.* prepared Chitosan-Ag nanocomposite and investigated its catalytic, anticancer, wound healing and antioxidant properties. The group tested normal (L929), lung cancer (A549) and oral cancer (KB-3-1) cell lines to access the anticancer activity, with promising IC<sub>50</sub> values of  $83.52 \mu\text{g mL}^{-1}$ ,  $66.74 \mu\text{g mL}^{-1}$  and  $75.11 \mu\text{g mL}^{-1}$  respectively.<sup>269</sup> Exploiting the biocompatibility and antimicrobial property of silver, Amiri

*et al.* developed an Ag NP-based hydrogel nanocomposite for efficient wound healing process. Herein, they accessed the wound healing capacity through the rat splinted wound method and evaluated wound infection prevention through the rat subcutaneous infection model.<sup>270</sup> In a similar manner, Arghand *et al.* used eugenol coated Ag NPs embedded in an alginate-chitosan nanocomposite which demonstrated enhanced wound healing compared to the alginate-chitosan nanocomposite alone.<sup>271</sup>

Interestingly, Nguyen *et al.* incorporated biosynthesized Ag NPs into passion fruit peel pectin/chitosan biofilm to elevate their antibacterial and wound healing properties, with 100% wound closure after 15 days.<sup>272</sup> Farazin *et al.* fabricated a flexible self-healing nanocomposite that offered rapid wound healing capabilities. Herein, to fabricate the system, they opted gelatin, acrylic acid and tannic acid as a matrix with ZnO and hollow Ag NPs.<sup>273</sup> Recently, silver and gold nanoparticles were designed and developed using *A. macleodii* secreted exopolysaccharide (EPS) that exhibited excellent cell migration, contributing to a rapid wound healing.<sup>274</sup> In 2023, Ebrahimzadeh *et al.* employed quercetin extract for the green synthesis of Ag NPs and studied the *in vivo* and *in vitro* antileishmanial activity. They displayed a promising *in vitro* IC<sub>50</sub> value of  $125 \mu\text{g mL}^{-1}$  against promastigotes. *In vivo*, the infected BALB/c mice were treated with topical application for 21 days, making them a promising antileishmanial drug.<sup>275</sup>

## 4. Environmental applications

Over many years, modernization and industrialization have significantly contributed to the alarming levels of pollutants in the air, water and soil. Additionally, they are also opted for the treatment of various water pollutants such as heavy metals, dyes, and organic contaminants. Furthermore, they are widely utilized in filtration systems to target airborne microbes and pollutants, helping to provide cleaner air.<sup>226,276</sup> Moreover, these nanocomposites could also be used to eliminate organic pollutants or neutralize heavy metals contaminating the soil. Overall, silver nanocomposites hold great potential in improving the environmental conditions by removing, reducing or utilizing harmful substances offering better water, air and soil quality.<sup>10,277,278</sup>

Elevated levels of particulate matter, coming from vehicles, construction sites, burning of fossil and industrial emissions can severely threat human health. Many silver-based nanocomposites have been proved to be effective air filters for this purpose.<sup>279</sup> For example, La *et al.* designed an excellent antibacterial particulate matter filter by integrating Ag/graphene nanocomposite onto textile material. The synthesized material offered a remarkable particulate matter removal of 98.5% along with high antibacterial activity against *E. coli* bacteria.<sup>280</sup> Similarly, Yontar *et al.* developed special filter papers coated with green synthesized Ag and PVA nanocomposite that successfully enhanced the mechanical and antibacterial attributes of the filters.<sup>281</sup>

Not only as air filters, many Ag NCs were also reported as great photocatalyst for the degradation of many volatile organic



compounds (VOCs) such as alcohols,<sup>282</sup> aromatic<sup>283</sup> and aliphatic hydrocarbons,<sup>284</sup> aldehydes,<sup>285</sup> ketones<sup>286</sup> *etc.* For example, Wanwong *et al.* reported a promising multifunctional air filter consisting of electrospun silk nanofiber loaded with Ag-doped TiO<sub>2</sub>. The reported system efficiently filtered about 99% of particulate matter, exhibited high antibacterial properties and demonstrated high photodegradation of formaldehyde.<sup>287</sup> Similarly, Sboui *et al.* opted a simple method to deposit photocatalytic Ag-AgCl/TiO<sub>2</sub> over cellulose film that successfully degraded a variety of VOCs such as ethanol, 1-propanol, 1-butanol, propylamine and propanethiol in gas phase under sunlight.<sup>288</sup>

Additionally, many researchers have reported the use of silver nanocomposites for CO<sub>2</sub> capture and conversion.<sup>64,289</sup> For example, by employing MOFs in their work, Liu *et al.* produced two heterogenous silver-based nanocomposites; core-shell and corner, which exhibited outstanding photocatalytic activity for CO<sub>2</sub> adsorption and reduction reaction under irradiation. Herein, the corner MOF-Ag NC outperformed the core-shell MOF-Ag NC, attributed to its higher surface area to volume ratio.<sup>290</sup> In a similar study, Nosrati *et al.* developed ternary and quaternary hybrid photocatalytic systems using graphene oxide, TiO<sub>2</sub>, Ag<sub>2</sub>O and arginine (GO-TiO<sub>2</sub>-Ag<sub>2</sub>O and GO-TiO<sub>2</sub>-Ag<sub>2</sub>O-Arg). Herein, the developed photonanocatalyst efficiently captured CO<sub>2</sub> and reduced it to methanol under UV and visible light.<sup>291</sup> Interestingly, Li *et al.* highlighted the application of ZnO/Ag/g-C<sub>3</sub>N<sub>4</sub> nanocomposites for excellent photoactivated gas-sensing activity for NO<sub>2</sub> detection.<sup>292</sup>

Apart from their application in dye degradation, many silver nanocomposites are very versatile in sensing and decomposing of various pesticides that pollute the water sources. For example, Singh *et al.* developed highly efficient Ag nanocomposites that exhibited a removal efficiency ranging from 64% to 88.5% for commonly used organophosphate pesticides like chlorpyrifos, malathion, dichlorvos and profenofos.<sup>293</sup> Similarly, Chinnappa *et al.* green synthesized rGO-AgNP NCs and investigated the photocatalytic system for organophosphate chlorpyrifos pesticide degradation.<sup>294</sup> Another recent study by Zheng *et al.* described the photocatalytic destruction of nitenpyram pesticide using Ag@AgCl/ZnAl-LDH nanocomposites achieved only in 45 min.<sup>295</sup> Veerakumar *et al.* designed and developed palladium, silver NPs embedded on ZnO nanostars *via* microwave-hydrothermal method and studied their photocatalytic degradation activity for carcinogenic pesticides such as methyl parathion and herbicides like pendimethalin and trifluralin.<sup>296</sup>

Moreover, many studies also revealed the excellent detection capabilities of pesticides through Ag-based nanocomposites.<sup>297-299</sup> Meanwhile, many recent researches targeted the heavy metal ion detection application in water and soil.<sup>300</sup> For example, silver/graphene oxide nanocomposite developed by Dat *et al.* offered high Hg<sup>2+</sup> sensitivity in water, attaining a limit of detection as low as 19.06 ± 0.42 μg L<sup>-1</sup>. Additionally, the developed nanocomposite attained 100% crystal violet dye removal through adsorption mechanism.<sup>301</sup> Similarly, Şahin *et al.* removed heavy metal ions such as Ni<sup>2+</sup>,

Cu<sup>2+</sup>, Pb<sup>2+</sup>, Cd<sup>2+</sup> from natural water samples by employing Ag NPs and magnetic nanoparticles/nanocomposites.<sup>302</sup>

Interestingly, Shehawy *et al.* realized eco-friendly Ag NPS and studied their adsorbent property for removal of heavy metal such as Fe, Mn, Zn and Cu, achieving an excellent removal efficiency of 97.1% for Fe.<sup>303</sup> Similarly, Amini *et al.* was able to extract trace amounts of heavy metals such as Ni<sup>2+</sup>, Cu<sup>2+</sup>, Mn<sup>2+</sup>, Cr<sup>2+</sup> and Cd<sup>2+</sup> from water and rice samples.<sup>304</sup> Recently, Boas *et al.* developed peptide stabilised Au and Ag NPs that exhibited change in absorbance through a pH-dependent system for the selective and sensitive detection of Hg<sup>2+</sup>, Fe<sup>2+</sup> and Mn<sup>2+</sup>.<sup>305</sup> Moreover, many Ag NCs have been efficiently used as sensors for detecting heavy metal ions, nitrogen containing inorganic species, phenolic compounds, pharmaceuticals, nitroaromatics, natural and synthetic estrogens and more.<sup>306</sup>

## 5. Industrial applications

### 5.1 Agriculture

Agriculture is a vital sector for a nation's survival, as it ensures food supply for the population. Over time, the rising demand for food and related products has surged the focus on improving crop production and reducing agricultural losses. Ag NPs have been widely used to enhance seed germination, promote plant growth, and improve various crop development factors. For instance, Hojjat *et al.* investigated the effect of Ag NPs on lentil seed germination. Upon exposure to Ag nanoparticle, a significant enhancement in seedling growth, seed germination and mean germination time was observed in lentil seeds. Also, they observed that the exposed lentil seeds exhibited higher drought tolerance.<sup>307</sup> Similarly, Antunes *et al.* explored how hyaluronic acid-stabilized Ag NPs (HA-AgNPs) worked as a seed priming agent to impact seed germination in lettuce (*Lactuca sativa* L.).<sup>308</sup> Also, Rahman *et al.* experimented the use of Ag NPs for seed germination and growth performance of pea (*Pisum sativum*).<sup>309</sup> For example, Ansari *et al.* fabricated Ag NPs by using Neem leaf extract (*Azadirachta indica*) and investigated their effect on tomato plant.<sup>310</sup> In their recent study, Sambangi *et al.* employed biogenically synthesized Ag NPs to investigate chickpea plant growth and development. Streptomyces-mediated Ag NPs significantly improved the quality of chickpeas by promoting plant growth traits, nitrogen fixation, boosting defense enzyme activity, increasing yield as well as enhancing Fe, Zn, Mn and K contents.<sup>311</sup>

Khan *et al.* employed pistachio seed coat waste to synthesize Ag NPs, which were then sprayed on eggplant and investigated for their effect.<sup>312</sup> Interestingly, many recent researches have highlighted the use of Ag-based NCs as a quick and easy electrochemical sensor for detection of macronutrients such as nitrogen, potassium, and phosphorus in soil or water to check and improve the agricultural conditions of soil and water in real-time.<sup>313</sup>

### 5.2 Food packaging and quality check

Over decades in the food industry, the research on food packaging hold pivotal importance to ensure safe good quality food.



Researchers are constantly working to design materials that hold good mechanical strength and stability while having biodegradability and antibacterial properties, in order to extend the shelf life of the packaged food. Toxicity concerns due to plastic packing have paved way for researchers to explore natural biopolymers-based metal nanocomposites as packaging materials.<sup>314–319</sup>

For example, Guerraf *et al.* employed cellulose fibers, conducting polymers and Ag NPs to fabricate a nanocomposite, reliable to be used as an active food packaging material.<sup>320</sup> Similarly, Liu *et al.* designed and developed soluble soyabean polysaccharide-based Ag NPs incorporated nanocomposite, that possessed improved UV-barrier and thermal properties.<sup>321</sup> Recently, Abdallah *et al.* used agricultural biowaste to synthesize Ag NPs, which when entrapped into polyurethane nanofibers, notably enhanced their antibacterial and antioxidant attributes, paving way for more improved food safety and storage.<sup>322</sup> Recently, Yang *et al.* realized the novel green synthesis of *P. cocos* polysaccharide as a stabilizing agent for Ag NPs that demonstrated strong antibacterial activity. Subsequently, they incorporated these nanoparticles into chitosan that prolonged the shelf life of strawberries while maintaining their quality.<sup>323</sup>

In addition, Yaqoob *et al.* designed and developed an Ag NPs incorporated bio-composite that demonstrated excellent antioxidant and antimicrobial properties.<sup>324</sup> Novel bacteriocin assisted Ag NPs were realized by Sharma *et al.* and then coated onto cellulose paper to study their use as a packaging material.<sup>325</sup> In a similar manner, Biswal *et al.* biosynthesized Ag NPs that displayed remarkable antibacterial and antioxidant properties that can be exploited for food packaging applications.<sup>326</sup> Majumder *et al.* prepared a protein-based silver nanocomposite film that improved the water barrier characteristics of soy protein isolate making them suitable for storing high-moisture food products.<sup>327</sup>

Similarly, Amrutha *et al.* opted a one-pot method to synthesize Ag NPs using PVA/MC cross-linked and uncross-linked blends and was analysed for their thermal, mechanical and biomedical properties for food packaging application.<sup>328</sup> In a similar manner, Li *et al.* developed antibacterial microcapsules consisting of Ginkgo biloba essential oil as the core with chitosan and gelatin as the capsule material, which were later on modified using green synthesized Ag NPs.<sup>329</sup> In an intriguing study, Ragab *et al.* enhanced the optical, thermal, mechanical, electrical, and antibacterial properties of PVA–chitosan by incorporating biosynthesized Ag NPs. This resulted in the creation of a nanocomposite with potential applications in food storage.<sup>330</sup> Recently, Pandian *et al.* developed a green synthesized Ag NPs and decorated them to fabricate a nanocomposite film, Ag NP/MCC/starch/whey protein, that can be employed as an antibacterial food packaging film in order to extend the shelf life of perishable foods by fighting food pathogens.<sup>331</sup>

In food industry, apart from food packaging, the freshness of food is also essential. Despite being stored efficiently, many environmental factors, namely pH, moisture, presence of oxygen, temperature *etc.* can potentially affect the food products and degrade their nutritive values.<sup>332</sup> For example, Li *et al.* decorated pectin/gelatin films with curcumin and Ag NPs to prepare a renewable biomass-based food packaging material

that possessed great antibacterial activity, mechanical strength, antioxidant activity and hydrophilicity.<sup>333</sup>

Similarly, Xu *et al.* designed a wearable glove sensor for visual identification of tetracycline antibiotics, whose excessive use can cause significant health issues. They combined Ag nanoclusters with an europium-based material to create a fast and highly responsive tetracycline sensor with a notable fluorescent color change. The synthesized nanosensor demonstrated a low detection limit of 10.5 nM, along with high sensitivity and quick response times.<sup>334</sup> In 2024, Wang *et al.* reported a core–shell Au@Ag nanoparticle system sensitive to the presence of acrylamide, a human carcinogen that can potentially damage the human nervous and reproductive system.<sup>335</sup> Similar to this, Anh *et al.* developed a highly sensitive electrochemical Ag-core@Fe<sub>3</sub>O<sub>4</sub> nanosensor for Furazolidone detection in real food samples, excess of which can cause serious antibiotic residues and environmental pollution.<sup>336</sup>

In a recent study, Wang *et al.* designed 4-aminobenzenethiol-functionalized Au@Ag core–shell nanosensor (Au@Ag-4ABT NP) for detecting the presence of carbendazim (CBZ) in food samples.<sup>337</sup> On similar notes, Wang *et al.* designed a novel 2D Au@Ag nanodot array and investigated fruit juices for pesticide contamination.<sup>338</sup> In a similar way, Parnsubsakul *et al.* developed an eco-friendly and disposable AgNP-BNC paper composites that detected pesticides namely, aminothiophenol and methomyl on fruit surface.<sup>339</sup>

### 5.3 Textiles

Leveraging the antimicrobial properties of silver, many researchers are working to enhance textiles with these medicinal benefits. These advanced fabrics can be used not only in the healthcare sector for creating antibacterial surgical gowns, scrub suits, and protective clothing, but also in everyday items such as bedding, tablecloths, curtains, and more.<sup>340</sup> For example, Mondal *et al.* designed antimicrobial fabric by incorporating Ag NPs-chitosan nanocomposite coating on cotton fabric.<sup>341</sup> Similarly, Montemurro *et al.* achieved a long-lasting antibacterial fabric through novel polyoxometalate-modified silver nanocomposites suggesting its wide utility in multiple sectors.<sup>342</sup> Phyto-chemical synthesized Ag NPs were coated on cotton and wool fabrics by Lite *et al.* and investigated their antimicrobial properties against bacteria and fungi.<sup>343</sup> Interestingly, Wu *et al.* fabricated a durable antibacterial fabric pertaining anti-UV characteristics *via* grafting lipoic acid-modified amino compound and depositing Ag NPs over cellulose.<sup>344</sup> In 2023, Plé *et al.* functionalized cotton textile with photoinduced Ag@polymer coating to incorporate antimicrobial activity into fabrics to address microbial proliferation.<sup>345</sup> Green synthesized Ag NPs using mullein extract were deposited on nylon fabric by Kiakhani *et al.* to produce coloured fabrics possessing antibacterial and dyeing properties.<sup>346</sup>

Additionally, many silver-based nanocomposites have been employed for developing smart textiles.<sup>347–349</sup> One such research was performed by Naysmith *et al.* where they coated polypyrrole-conjugated green synthesized Ag NPs that resulted in a low electrical resistance ( $9.56 \times 10^1 \Omega$  per sq.) conductive textile



fabric.<sup>350</sup> Similarly, İlhan *et al.* investigated the electromagnetic interference shielding and antibacterial activity of Ag nano-composite treated yarns.<sup>351</sup> In 2023, Jagadeshvaran *et al.* highlighted the use of Ag NPs deposited cotton core with CNT shell for blocking electromagnetic radiations *via* an absorption–reflection–absorption approach.<sup>352</sup>

Moreover, some functionalized textiles have been employed for environmental remediation as well. For example, Gao *et al.* developed polypyrrole-silver/silver chloride contained multi-functional fabric that was used for photocatalytic destruction of organic pollutants (Rh B, MB, MO) and exhibited antibacterial activity.<sup>353</sup> In 2023, La *et al.* fabricated an antibacterial cloth filter using Ag/graphene-integrated non-woven polypropylene textile. The synthesized material exhibited high particulate matter removal efficiency of 98.5% as well as high antibacterial activity against *E. coli*, making it an efficient air-pollutant filtering system.<sup>280</sup>

## 6. Conclusion

In summary, silver-based nanocomposites have proven to be highly versatile and impactful across various fields, driving significant advancements in material science. Their multi-functional properties—such as stability, reusability, and biocompatibility—along with exceptional catalytic, antimicrobial, and environmental remediation capabilities, make them invaluable tools for tackling contemporary challenges. Whether used in catalytic organic processes, biomedical applications, or environmental cleanup, these nanocomposites consistently surpass conventional materials in both efficiency and specificity. Furthermore, their applications in agriculture, food packaging, and textiles have spurred new innovations, enhancing plant health, food preservation, safety, and material functionality. As research progresses, silver-based nanocomposites are expected to continue playing a key role in technological advancements, providing promising solutions in fields such as environmental protection and healthcare. The developments from 2019 to 2024 presented here emphasize the increasing versatility of these materials, reinforcing their significance in the future of nanotechnology-driven progress.

## Data availability

The data supporting the findings of this study are available upon reasonable request from the corresponding author.

## Conflicts of interest

All the authors declared that they have no conflict of interest.

## Acknowledgements

RC and SS express their sincere gratitude to the Institution of Eminence (Ref. No. /IoE/2024-25/12/FRP) at the University of Delhi and the Institute of Nanomedical Science (INMS) for their invaluable support. Nisha extends her thanks to USIC at the University of Delhi for providing access to instrumental

facilities and to CSIR for awarding her the Junior Research Fellowship (09/045(1792)/2020-EMR-I). RC and SS also acknowledge the financial assistance from the Indo-Russia DST RFBR (INT/RUS/RFBR/389).

## References

- 1 P. Das, *et al.*, MXene/0D nanocomposite architectures: Design, properties and emerging applications, *Mater. Today Nano*, 2023, **24**, 100428.
- 2 Z. Yu, F. Li and Q. Xiang, Carbon dots-based nanocomposites for heterogeneous photocatalysis, *J. Mater. Sci. Technol.*, 2024, **175**, 244–257.
- 3 L. T. Zegebreal, N. A. Tegegne and F. G. Hone, Recent progress in hybrid conducting polymers and metal oxide nanocomposite for room-temperature gas sensor applications: A review, *Sens. Actuators, A*, 2023, **359**, 114472.
- 4 P. Kannan and G. Maduraiveeran, Metal Oxides Nanomaterials and Nanocomposite-Based Electrochemical Sensors for Healthcare Applications, *Biosensors*, 2023, **13**, 542.
- 5 U. Hani, Comprehensive review of polymeric nanocomposite membranes application for water treatment, *Alexandria Eng. J.*, 2023, **72**, 307–321.
- 6 K. Loukelis, Z. A. Helal, A. G. Mikos and M. Chatzinikolaidou, Nanocomposite Bioprinting for Tissue Engineering Applications, *Gels*, 2023, **9**, 103.
- 7 O. K. Abubakre, *et al.*, Carbon nanotube-reinforced polymer nanocomposites for sustainable biomedical applications: A review, *J. Sci.: Adv. Mater. Devices*, 2023, **8**, 100557.
- 8 E. Omanović-Miklićanin, A. Badnjević, A. Kazlagic and M. Hajlovac, Nanocomposites: a brief review, *Health Technol.*, 2020, **10**, 51–59.
- 9 B. Ates, S. Koytepe, A. Ulu, C. Gurses and V. K. Thakur, Chemistry, Structures, and Advanced Applications of Nanocomposites from Biorenewable Resources, *Chem. Rev.*, 2020, **120**, 9304–9362.
- 10 T. K. Das, M. Jesionek, Y. Çelik and A. Poater, Catalytic polymer nanocomposites for environmental remediation of wastewater, *Sci. Total Environ.*, 2023, **901**, 165772.
- 11 Y.-M. Li, J. Hu and M. Zhu, Confining atomically precise nanoclusters in metal–organic frameworks for advanced catalysis, *Coord. Chem. Rev.*, 2023, **495**, 215364.
- 12 T. Chen, Y. Peng, M. Qiu, C. Yi and Z. Xu, Heterogenization of homogeneous catalysts in polymer nanoparticles: From easier recovery and reuse to more efficient catalysis, *Coord. Chem. Rev.*, 2023, **489**, 215195.
- 13 M. E. Kibar, L. Hilal, B. T. Çapa, B. Bahçivanlar and B. B. Abdeljelil, Assessment of Homogeneous and Heterogeneous Catalysts in Transesterification Reaction: A Mini Review, *ChemBioEng Rev.*, 2023, **10**, 412–422.
- 14 D. Uzio and G. Berhault, Factors Governing the Catalytic Reactivity of Metallic Nanoparticles, *Catal. Rev.*, 2010, **52**, 106–131.
- 15 B. Roldan Cuenya and F. Beharfarid, Nanocatalysis: size- and shape-dependent chemisorption and catalytic reactivity, *Surf. Sci. Rep.*, 2015, **70**, 135–187.



- 16 S. Shan, J. Luo, L. Yang and C.-J. Zhong, Nanoalloy catalysts: structural and catalytic properties, *Catal. Sci. Technol.*, 2014, **4**, 3570–3588.
- 17 A. Brückner, In situ electron paramagnetic resonance: a unique tool for analyzing structure–reactivity relationships in heterogeneous catalysis, *Chem. Soc. Rev.*, 2010, **39**, 4673.
- 18 A. I. Frenkel, Applications of extended X-ray absorption fine-structure spectroscopy to studies of bimetallic nanoparticle catalysts, *Chem. Soc. Rev.*, 2012, **41**, 8163.
- 19 G. Magdy, E. Aboelkassim, S. M. Abd Elhaleem and F. Belal, A comprehensive review on silver nanoparticles: Synthesis approaches, characterization techniques, and recent pharmaceutical, environmental, and antimicrobial applications, *Microchem. J.*, 2024, **196**, 109615.
- 20 R. Abbas, *et al.*, Silver Nanoparticles: Synthesis, Structure, Properties and Applications, *Nanomaterials*, 2024, **14**, 1425.
- 21 N. P. U. Nguyen, N. T. Dang, L. Doan and T. T. H. Nguyen, Synthesis of Silver Nanoparticles: From Conventional to 'Modern' Methods—A Review, *Processes*, 2023, **11**, 2617.
- 22 P. Nie, Y. Zhao and H. Xu, Synthesis, applications, toxicity and toxicity mechanisms of silver nanoparticles: A review, *Ecotoxicol. Environ. Saf.*, 2023, **253**, 114636.
- 23 M. Zulfajri, *et al.*, A review on the chemical and biological sensing applications of silver/carbon dots nanocomposites with their interaction mechanisms, *Adv. Colloid Interface Sci.*, 2024, **325**, 103115.
- 24 X. Gong, *et al.*, An overview of green synthesized silver nanoparticles towards bioactive antibacterial, antimicrobial and antifungal applications, *Adv. Colloid Interface Sci.*, 2024, **323**, 103053.
- 25 A. Luceri, R. Francese, D. Lembo, M. Ferraris and C. Balagna, Silver Nanoparticles: Review of Antiviral Properties, Mechanism of Action and Applications, *Microorganisms*, 2023, **11**, 629.
- 26 A. C. Mecha, M. N. Chollom, B. F. Babatunde, E. K. Tetteh and S. Rathilal, Versatile Silver-Nanoparticle-Impregnated Membranes for Water Treatment: A Review, *Membranes*, 2023, **13**, 432.
- 27 V. Maduraimuthu, *et al.*, Antioxidant Activities of Photoinduced Phycogenic Silver Nanoparticles and Their Potential Applications, *Antioxidants*, 2023, **12**, 1298.
- 28 J. Sultana and D. Sarma, Ag-catalyzed azide-alkyne cycloaddition: copper free approaches for synthesis of 1,4-disubstituted 1,2,3-triazoles, *Catal. Rev.*, 2020, **62**, 96–117.
- 29 P. Akbarzadeh and N. Koukabi, Fibroin-functionalized magnetic carbon nanotube as a green support for anchoring silver nanoparticles as a biocatalyst for A3 coupling reaction, *Appl. Organomet. Chem.*, 2020, **34**, e5395.
- 30 B. Ahmed, M. Bilal Tahir, M. Sagir and M. Hassan, Bio-inspired sustainable synthesis of silver nanoparticles as next generation of nanoproduct in antimicrobial and catalytic applications, *Mater. Sci. Eng., B*, 2024, **301**, 117165.
- 31 M. Chandhru, *et al.*, Bio-fabricated silver nanocatalyst for photocatalytic degradation and organic transformation of toxic pollutants, *Mater.*, 2023, **1**, 100023.
- 32 B. Muchharla, *et al.*, Reduced metal nanocatalysts for selective electrochemical hydrogenation of biomass-derived 5-(hydroxymethyl)furfural to 2,5-bis(hydroxymethyl)furan in ambient conditions, *Front. Chem.*, 2023, **11**, 1200469.
- 33 A. Krogul-Sobczak, N. Pisarek, P. Cieciorowski and E. Megiel, Silver Nanoparticles Densely Grafted with Nitroxides as a Recyclable Green Catalyst in the Selective Oxidation of Alcohols, *Nanomaterials*, 2022, **12**, 2542.
- 34 M. Ashraf, *et al.*, Transition metal nanoparticles as nanocatalysts for Suzuki, Heck and Sonogashira cross-coupling reactions, *Coord. Chem. Rev.*, 2023, **476**, 214928.
- 35 Y. Zhang, *et al.*, Elimination of NH<sub>3</sub> by Interfacial Charge Transfer over the Ag/CeSnOx Tandem Catalyst, *ACS Catal.*, 2023, **13**, 1449–1461.
- 36 W. Sun, *et al.*, Biogenic synthesis of reduced graphene oxide decorated with silver nanoparticles (rGO/Ag NPs) using table olive (*olea europaea*) for efficient and rapid catalytic reduction of organic pollutants, *Chemosphere*, 2023, **310**, 136759.
- 37 F. Naaz, U. Farooq, M. A. M. Khan and T. Ahmad, Multifunctional Efficacy of Environmentally Benign Silver Nanospheres for Organic Transformation, Photocatalysis, and Water Remediation, *ACS Omega*, 2020, **5**, 26063–26076.
- 38 M. Hamelian, K. Varmira and H. Veisi, Synthesis heterogeneous and recyclable magnetic nanocatalysts by decorated amino-modified multi-walled carbon nanotubes with iron and silver nanoparticles (MWCNTs-NH<sub>2</sub>/Fe<sub>3</sub>O<sub>4</sub>/Ag NPs) for organic dyes reduction, *Inorg. Chem. Commun.*, 2023, **158**, 111566.
- 39 X. Wang, *et al.*, Ag nanoparticles immobilized on guanidine modified-KIT-5 mesoporous nanostructure: Evaluation of its catalytic activity for synthesis of propargylamines and investigation of its antioxidant and anti-lung cancer effects, *Arabian J. Chem.*, 2022, **15**, 103548.
- 40 N. Salam, *et al.*, AgNPs encapsulated by an amine-functionalized polymer nanocatalyst for CO<sub>2</sub> fixation as a carboxylic acid and the oxidation of cyclohexane under ambient conditions, *New J. Chem.*, 2020, **44**, 5448–5456.
- 41 L. Izquierdo-Aranda, R. Adam and J. R. Cabrero-Antonino, Silver Supported Nanoparticles on [Mg<sub>4</sub>Al-LDH] as an Efficient Catalyst for the  $\alpha$ -Alkylation of Nitriles, Oxindoles and Other Carboxylic Acid Derivatives with Alcohols, *ChemSusChem*, 2023, **16**, e202300818.
- 42 S. Molaei, M. Ghadermazi and N. Moeini, Selectivity adjustment of Fe<sub>3</sub>O<sub>4</sub> MNPs based silver catalyst in oxidation of sulfides with classical and ultrasonic methods and synthesis of 5-substituted 1H-tetrazoles from aryl nitriles in water, *Appl. Surf. Sci. Adv.*, 2022, **7**, 100192.
- 43 Nisha, S. Kohli, N. Sharma and R. Chandra, Development of ZnO/PANI/Ag nanocomposite for synthesis of bioactive xanthene-1,8(2H)-dione derivatives, *Appl. Organomet. Chem.*, 2023, **37**, e7049.
- 44 Y. Che, *et al.*, Ultrasmall Ag nanoparticles on photoactive metal-organic framework boosting aerobic cross-



- dehydrogenative coupling under visible light, *Appl. Surf. Sci.*, 2023, **634**, 157699.
- 45 F. Rafiee and F. Rezaie Karder, Bio-crosslinking of chitosan with oxidized starch, its functionalization with amino acid and magnetization: As a green magnetic support for silver immobilization and its catalytic activity investigation, *Int. J. Biol. Macromol.*, 2020, **146**, 1124–1132.
- 46 S. Bahadorikhalili, H. Arshadi, Z. Afrouzandeh and L. Ma'mani, Ultrasonic promoted synthesis of Ag nanoparticle decorated thiourea-functionalized magnetic hydroxyapatite: a robust inorganic–organic hybrid nanocatalyst for oxidation and reduction reactions, *New J. Chem.*, 2020, **44**, 8840–8848.
- 47 S. Luo, *et al.*, Versatile CMPs as platforms to support Ag nanocatalysts for nitrophenol hydrogenation in continuous flow-through process, *Chem. Eng. J.*, 2022, **442**, 136207.
- 48 Z. H. Farooqi, *et al.*, Catalytic degradation of malachite green using a crosslinked colloidal polymeric system loaded with silver nanoparticles, *Int. J. Environ. Anal. Chem.*, 2022, **102**, 4104–4120.
- 49 M. Akkari, A. Bardaoui, M. A. Djebbi, A. B. H. Amara and R. Chtourou, Hydrothermal synthesis of Ag-doped ZnO/sepiolite nanostructured material for enhanced photocatalytic activity, *Environ. Sci. Pollut. Res.*, 2022, **29**, 67159–67169.
- 50 A. Banu, *et al.*, N-heterocyclic carbene functionalized boehmite-supported silver nanoparticles as nanocatalyst for reduction of environmental pollutants, *Colloids Surf., A*, 2024, **697**, 134372.
- 51 M. K. Acar, T. Altun and I. H. Gubbuk, Synthesis and characterization of silver doped magnetic clay nanocomposite for environmental applications through effective RhB degradation, *Int. J. Environ. Sci. Technol.*, 2023, **20**, 4219–4234.
- 52 V. S. Punnakkal and E. I. Anila, Polypyrrole/silver/graphene ternary nanocomposite synthesis and study on photocatalytic property in degrading Congo red dye under visible light, *Surf. Interfaces*, 2023, **42**, 103342.
- 53 A. Malathi, *et al.*, Enhanced Sun Light Driven Photocatalytic Activity of Silver Tungstate/Reduced Graphene Oxide Nanocomposites for Methylene Blue Dye Degradation, *J. Inorg. Organomet. Polym. Mater.*, 2024, **34**, 1181–1192.
- 54 A. Soni, S. Mishra, D. Vaya and P. K. Surolia, Role of Ag and g-C<sub>3</sub>N<sub>4</sub> over CaTiO<sub>3</sub> for effective photocatalytic degradation of nitrobenzene, *Inorg. Chem. Commun.*, 2024, **159**, 111862.
- 55 S. Zhang, *et al.*, A large-nanosphere/small-nanosphere (cellulose/silver) antibacterial composite with prominent catalytic properties for the degradation of p-nitrophenol, *Appl. Surf. Sci.*, 2023, **608**, 155192.
- 56 R. Begum, *et al.*, Reduction of nitroarenes catalyzed by microgel-stabilized silver nanoparticles, *J. Hazard. Mater.*, 2019, **377**, 399–408.
- 57 Y. Rangraz, F. Nematy and A. Elhampour, Selenium-doped graphitic carbon nitride decorated with Ag NPs as a practical and recyclable nanocatalyst for the hydrogenation of nitro compounds in aqueous media, *Appl. Surf. Sci.*, 2020, **507**, 145164.
- 58 T. Thomas and A. K. Thalla, Synthesis of silver nanoparticles using Myristica fragrans seed shell: Assessment of antibacterial, antioxidant properties and photocatalytic degradation of dyes, *J. Environ. Chem. Eng.*, 2023, **11**, 109585.
- 59 M. Moond, *et al.*, Biosynthesis of Silver Nanoparticles Utilizing Leaf Extract of Trigonella foenum-graecum L. for Catalytic Dyes Degradation and Colorimetric Sensing of Fe<sup>3+</sup>/Hg<sup>2+</sup>, *Molecules*, 2023, **28**, 951.
- 60 G. Palani, *et al.*, Silver Nanoparticles for Waste Water Management, *Molecules*, 2023, **28**, 3520.
- 61 A. K. Senthilkumar, *et al.*, Recent advancements in carbon/metal-based nano-catalysts for the reduction of CO<sub>2</sub> to value-added products, *Chemosphere*, 2024, **364**, 143017.
- 62 S. Ahmad, *et al.*, Sensing and conversion of carbon dioxide to methanol using Ag-decorated zinc oxide nanocatalyst, *Mater. Adv.*, 2024, **5**, 1119–1129.
- 63 P. Chakraborty, *et al.*, Ag-Nanocatalysts Based on Porous Organic Polymers in Chemical Fixation of CO<sub>2</sub> for the N-Methylation and N-Formylation of Amines, *ChemCatChem*, 2024, **16**, e202301539.
- 64 S. Karanjit, *et al.*, A heterogeneous bifunctional silica-supported Ag<sub>2</sub>O/Im<sup>+</sup>Cl<sup>-</sup> catalyst for efficient CO<sub>2</sub> conversion, *Catal. Sci. Technol.*, 2022, **12**, 3778–3785.
- 65 E. Aliakbari, *et al.*, Design and synthesis of silver nanoparticle anchored poly(ionic liquid)s mesoporous for controlled anticancer drug delivery with antimicrobial effect, *Int. J. Environ. Health Res.*, 2024, **34**, 90–102.
- 66 A. B. Pawar, *et al.*, Analysis of Silver Nanoparticles as Carriers of Drug Delivery System, *J. Nano- Electron. Phys.*, 2023, **15**, 04015.
- 67 Y. Saghafi, *et al.*, Bromelain- and Silver Nanoparticle-Loaded Polycaprolactone/Chitosan Nanofibrous Dressings for Skin Wound Healing, *Gels*, 2023, **9**, 672.
- 68 F. M. Aldakheel, M. M. E. Sayed, D. Mohsen, M. H. Fagir and D. K. El Dein, Green Synthesis of Silver Nanoparticles Loaded Hydrogel for Wound Healing; Systematic Review, *Gels*, 2023, **9**, 530.
- 69 H. Chen, C. Tian and L. Zhang, Design and synthesis of dexmedetomidine capped silver nanoparticles: Investigation of its catalytic application for reduction of nitrobenzenes and its effects on anesthetic, anti-inflammatory, antioxidant and analgesic applications, *J. Organomet. Chem.*, 2024, **1017**, 123262.
- 70 M. Goel, A. Sharma and B. Sharma, Recent Advances in Biogenic Silver Nanoparticles for Their Biomedical Applications, *Sustainable Chem.*, 2023, **4**, 61–94.
- 71 F. Rodríguez-Félix, *et al.*, Trends in Sustainable Green Synthesis of Silver Nanoparticles Using Agri-Food Waste Extracts and Their Applications in Health, *J. Nanomater.*, 2022, **2022**, 8874003.
- 72 L. Castillo-Henríquez, *et al.*, Green Synthesis of Gold and Silver Nanoparticles from Plant Extracts and Their Possible Applications as Antimicrobial Agents in the Agricultural Area, *Nanomaterials*, 2020, **10**, 1763.



- 73 Y. Gokce, Z. Aktas, G. Capar, E. Kutlu and P. Anis, Improved antibacterial property of cotton fabrics coated with waste sericin/silver nanocomposite, *Mater. Chem. Phys.*, 2020, **254**, 123508.
- 74 W. Yu, *et al.*, Graphene oxide-silver nanocomposites embedded nanofiber core-spun yarns for durable antibacterial textiles, *J. Colloid Interface Sci.*, 2021, **584**, 164–173.
- 75 N. A. Manikandan, *et al.*, Production of Silver Nano-Inks and Surface Coatings for Anti-Microbial Food Packaging and Its Ecological Impact, *Int. J. Mol. Sci.*, 2023, **24**, 5341.
- 76 R. Das, *et al.*, Silver decorated magnetic nanocomposite (Fe<sub>3</sub>O<sub>4</sub>@PPy-MAA/Ag) as highly active catalyst towards reduction of 4-nitrophenol and toxic organic dyes, *Appl. Catal., B*, 2019, **244**, 546–558.
- 77 S. Denrah and M. Sarkar, Design of experiment for optimization of nitrophenol reduction by green synthesized silver nanocatalyst, *Chem. Eng. Res. Des.*, 2019, **144**, 494–504.
- 78 M. T. Alula, *et al.*, A Highly Stable Silver Nanoparticle Loaded Magnetic Nanocomposite as a Recyclable Catalysts, *J. Cluster Sci.*, 2023, **34**, 2205–2214.
- 79 M. U. Gürbüz, G. Elmacı and A. S. Ertürk, In situ deposition of silver nanoparticles on polydopamine-coated manganese ferrite nanoparticles: Synthesis, characterization, and application to the degradation of organic dye pollutants as an efficient magnetically recyclable nanocatalyst, *Appl. Organomet. Chem.*, 2021, **35**, e6284.
- 80 I. Ahmad, A. Abbasi, Z. M. El Bahy and S. Ikram, Synergistic effect of silver NPs immobilized on Fe<sub>3</sub>O<sub>4</sub>@L-proline magnetic nanocomposite toward the photocatalytic degradation of Victoria blue and reduction of organic pollutants, *Environ. Sci. Pollut. Res.*, 2023, **30**, 78891–78912.
- 81 N. Khaleghi, *et al.*, Silver-assisted reduction of nitroarenes by an Ag-embedded curcumin/melamine-functionalized magnetic nanocatalyst, *Sci. Rep.*, 2023, **13**, 5225.
- 82 S. Taheri, M. M. Heravi and P. Mohammadi, Sulfur-doped graphitic carbon nitride decorated with starch, Fe<sub>3</sub>O<sub>4</sub>, and Ag nanoparticles: As efficient and magnetic recoverable nanocatalyst for hydrogenation of nitroaromatics in aqueous media, *Diamond Relat. Mater.*, 2022, **126**, 109078.
- 83 H. Veisi, S. Razeghi, P. Mohammadi and S. Hemmati, Silver nanoparticles decorated on thiol-modified magnetite nanoparticles (Fe<sub>3</sub>O<sub>4</sub>/SiO<sub>2</sub>-Pr-S-Ag) as a recyclable nanocatalyst for degradation of organic dyes, *Mater. Sci. Eng., C*, 2019, **97**, 624–631.
- 84 H. Veisi, S. B. Moradi, A. Saljooqi and P. Safarimehr, Silver nanoparticle-decorated on tannic acid-modified magnetite nanoparticles (Fe<sub>3</sub>O<sub>4</sub>@TA/Ag) for highly active catalytic reduction of 4-nitrophenol, Rhodamine B and Methylene blue, *Mater. Sci. Eng., C*, 2019, **100**, 445–452.
- 85 M. Riaz, *et al.*, Synthesis of Biogenic Silver Nanocatalyst and their Antibacterial and Organic Pollutants Reduction Ability, *ACS Omega*, 2022, **7**, 14723–14734.
- 86 O. S. Karvekar, *et al.*, Biogenic synthesis of silver anchored ZnO nanorods as nano catalyst for organic transformation reactions and dye degradation, *Appl. Nanosci.*, 2022, **12**, 2207–2226.
- 87 T. K. Das, S. K. Ghosh and N. C. Das, Green synthesis of a reduced graphene oxide/silver nanoparticles-based catalyst for degradation of a wide range of organic pollutants, *Nano-Struct. Nano-Objects*, 2023, **34**, 100960.
- 88 S. Mallakpour and Z. Amini, Green synthesis of Ag ultra-fine nano-catalyst supported on layered double oxide and chitosan: Accelerated reduction of 4-nitrophenol to 4-aminophenol, *J. Cleaner Prod.*, 2022, **381**, 135154.
- 89 W.-Z. Xiao, *et al.*, Fully exposed silver nanoparticles stabilized on pH-responsive lignin-reactors for enhanced 4-nitrophenol reduction, *J. Environ. Chem. Eng.*, 2022, **10**, 107945.
- 90 X.-W. Han, S. Bi, W. Zhang and Z. Yang, One-step fabrication of highly dispersed Ag nanoparticles decorated N-doped reduced graphene oxide heterogeneous nanostructure for the catalytic reduction of 4-nitrophenol, *Colloids Surf., A*, 2019, **574**, 69–77.
- 91 J. Wang, *et al.*, Cu-Ag bimetallic nano-catalyst anchored on polyvinyl alcohol sponge for catalytic reduction of 4-nitrophenol, *Colloids Surf., A*, 2023, **677**, 132450.
- 92 D. T. H. Nguyen, L. R. Shultz, T. Jurca and A. Nazemi, Monomeric and Polymeric Mesoionic N-Heterocyclic Carbene-Tethered Silver Nanoparticles: Synthesis, Stability, and Catalytic Activity, *Langmuir*, 2023, **39**, 3204–3215.
- 93 Z. Yin, F. Yang, J. Chen, C. Sun and S. Cao, Excellent chemoselective hydrogenation of nitroaromatics and unsaturated aldehyde at the confined silver nanospace, *Appl. Catal., A*, 2022, **644**, 118807.
- 94 J. Zhou, *et al.*, Construction of novel Ag@SrNbO/LDH ternary hybrid with high catalytic performance towards the reduction of 4-nitrophenol, *Appl. Surf. Sci.*, 2022, **581**, 152425.
- 95 P. Verma, Y. Kuwahara, K. Mori and H. Yamashita, Visible-light-driven reduction of nitrostyrene utilizing plasmonic silver nanoparticle catalysts immobilized on oxide supports, *Catal. Today*, 2020, **355**, 620–626.
- 96 M. G. Kotp, A. F. M. EL-Mahdy, T.-L. Yang and S.-W. Kuo, A pyridinyl-phenazine conjugated microporous polymer decorated with ultrafine Ag nanoparticles mediates the rapid reduction of nitrophenol, *Microporous Mesoporous Mater.*, 2022, **331**, 111669.
- 97 S. R. Baturki, V. Adimule, M. M. Pai, E. Ahmed and P. Kendrekar, Synthesis of Cs-Ag/Fe<sub>2</sub>O<sub>3</sub> Nanoparticles Using Vitis labrusca Rachis Extract as Green Hybrid Nanocatalyst for the Reduction of Arylnitro Compounds, *Top. Catal.*, 2022, **66**, 1–14.
- 98 P. Ghosh, D. Bairagi, N. Hazra, S. Jana and A. Banerjee, Carbon-Dot-Decorated Silver and Gold Nanocomposites for Antibacterial Activity and Degradation of Organic Dyes, *ACS Appl. Nano Mater.*, 2023, **6**, 18100–18112.
- 99 K. O. Sodeinde, S. O. Olusanya, V. F. Enogheghase and O. S. Lawal, Photocatalytic degradation of Janus Green Blue dye in wastewater by green synthesised reduced



- graphene oxide-silver nanocomposite, *Int. J. Environ. Anal. Chem.*, 2023, **103**, 9019–9035.
- 100 S. G. Hernandez-Castro, L. Z. Flores-López, H. Espinoza-Gomez and G. Alonso-Nuñez, Photocatalytic activity of silver nanoparticles@cellulose nanocomposites, from pistachio husk, in the toxic azo commercial dye degradation, *Int. J. Biol. Macromol.*, 2024, **254**, 127805.
- 101 Saruchi, V. Kumar, D. Bhatt, S. Pandey and A. A. Ghfar, Synthesis and characterization of silver nanoparticle embedded cellulose–gelatin based hybrid hydrogel and its utilization in dye degradation, *RSC Adv.*, 2023, **13**, 8409–8419.
- 102 S. Gokul Eswaran, P. Shahid Afridi and N. Vasimalai, Effective Multi Toxic Dyes Degradation Using Bio-Fabricated Silver Nanoparticles as a Green Catalyst, *Appl. Biochem. Biotechnol.*, 2023, **195**, 3872–3887.
- 103 D. Bharathi, *et al.*, Kiwi Fruit Peel Biowaste Mediated Green Synthesis of Silver Nanoparticles for Enhanced Dye Degradation and Antibacterial Activity, *Waste Biomass Valorization*, 2024, **15**, 1859–1868.
- 104 M. Iuliano, E. Ponticorvo, C. Cirillo, R. Adami and M. Sarno, Catalytic hydrogenation of organic dyes by Ag and Au magnetic nanoparticles supported on nanocellulose from waste pistachio shells, *Mol. Catal.*, 2023, **544**, 113179.
- 105 N. Esmaili, P. Mohammadi, M. Abbaszadeh and H. Sheibani, Green synthesis of silver nanoparticles using *Eucalyptus comadulensis* leaves extract and its immobilization on magnetic nanocomposite (GO-Fe<sub>3</sub>O<sub>4</sub>/PAA/Ag) as a recoverable catalyst for degradation of organic dyes in water., *Appl. Organomet. Chem.*, 2020, **34**, e5547.
- 106 L. A. L. Thi, *et al.*, Green synthesis of Ag@AgCl nanoparticles using purple Cam leaf: characterization and catalytic activity., *Bull. Mater. Sci.*, 2023, **46**, 133.
- 107 N. Alfryyan, M. G. M. Kordy, M. Abdel-Gabbar, H. A. Soliman and M. Shaban, Characterization of the biosynthesized intracellular and extracellular plasmonic silver nanoparticles using *Bacillus cereus* and their catalytic reduction of methylene blue, *Sci. Rep.*, 2022, **12**, 12495.
- 108 S. Pan, B. Jia and Y. Fu, Ag<sub>2</sub>CO<sub>3</sub> nanoparticles decorated g-C<sub>3</sub>N<sub>4</sub> as a high-efficiency catalyst for photocatalytic degradation of organic contaminants., *J. Mater. Sci.: Mater. Electron.*, 2021, **32**, 14464–14476.
- 109 S. Asadzadeh-Khaneghah, A. Habibi-Yangjeh and S. Vadivel, Fabrication of novel g-C<sub>3</sub>N<sub>4</sub> nanosheet/carbon dots/Ag<sub>6</sub>Si<sub>2</sub>O<sub>7</sub> nanocomposites with high stability and enhanced visible-light photocatalytic activity, *J. Taiwan Inst. Chem. Eng.*, 2019, **103**, 94–109.
- 110 H. A. Elbadawy, A. F. Elhusseiny, S. M. Hussein and W. A. Sadik, Sustainable and energy-efficient photocatalytic degradation of textile dye assisted by ecofriendly synthesized silver nanoparticles, *Sci. Rep.*, 2023, **13**, 2302.
- 111 M. E. Mahmoud, M. F. Amira, M. E. Abouelanwar and M. Abdel Salam, Green synthesis and surface decoration of silver nanoparticles onto δ-FeOOH-Polymeric nanocomposite as efficient nanocatalyst for dyes degradation, *J. Environ. Chem. Eng.*, 2021, **9**, 104697.
- 112 M. Ikram, *et al.*, Outstanding performance of silver-decorated MoS<sub>2</sub> nanopetals used as nanocatalyst for synthetic dye degradation, *Phys. E*, 2020, **124**, 114246.
- 113 S. Pandey, J. Y. Do, J. Kim and M. Kang, Fast and highly efficient catalytic degradation of dyes using κ-carrageenan stabilized silver nanoparticles nanocatalyst, *Carbohydr. Polym.*, 2020, **230**, 115597.
- 114 M. Amjad, *et al.*, Biosynthesis of Silver Nanoparticles Using Kitchen Vegetable Waste Extract for Application against Poultry Pathogens, Antimicrobial Activity, and Photocatalytic Dye Degradation, *J. Chem.*, 2023, **2023**, 1–10.
- 115 J. Qin, *et al.*, Hydroxypillar[5]arene-Confined Silver Nanocatalyst for Selective Electrochemical Reduction of CO<sub>2</sub> to Ethanol, *Adv. Funct. Mater.*, 2023, **33**, 2300697.
- 116 Z. Zhang, *et al.*, Construction of ternary Ag/AgCl/NH<sub>2</sub>-UiO-66 hybridized heterojunction for effective photocatalytic hexavalent chromium reduction, *J. Colloid Interface Sci.*, 2019, **555**, 342–351.
- 117 A. Nandy, *et al.*, (Ag@AuAg)@Ag Nanocatalyst for the Electrocatalytic Oxygen Reduction Reaction, *ACS Appl. Nano Mater.*, 2024, **7**, 14889–14897.
- 118 W. Chen, *et al.*, Enhancing performance of nitrogen-doped graphene nano-catalyst for oxygen reduction reaction by Ag loading, *Int. J. Hydrogen Energy*, 2024, **59**, 375–382.
- 119 Z. Khaksar, M. F. Habibi, M. Arvand and R. Rezapour, Improving oxygen reduction reaction of microbial fuel cell by silver vanadate blended functionalized multiwall carbon nanotubes as cathode, *Fuel*, 2024, **373**, 132367.
- 120 S. Karanjit, *et al.*, Hydrotalcite-Supported Ag/Pd Bimetallic Nanoclusters Catalyzed Oxidation and One-Pot Aldol Reaction in Water, *Catalysts*, 2020, **10**, 1120.
- 121 H. Q. Pham and T. T. Huynh, Facile room-temperature fabrication of a silver–platinum nanocoral catalyst towards hydrogen evolution and methanol electro-oxidation, *Mater. Adv.*, 2022, **3**, 1609–1616.
- 122 S. A. Abdel-Gawad and A. M. Fekry, A novel environmental nano-catalyst of zeolite amended with carbon nanotube/silver nanoparticles decorated carbon paste electrode for electro-oxidation of propylene glycol, *Sci. Rep.*, 2022, **12**, 9136.
- 123 Y. Fang, *et al.*, Hollow Ag@Pd Core–Shell Nanoparticles as Photocatalysts for the Plasmon-Mediated Activation of Oxygen and Oxidation of Benzyl Alcohol, *ACS Appl. Nano Mater.*, 2022, **5**, 18438–18447.
- 124 X. Ji, Y. Chen, B. Paul and S. Vadivel, Photocatalytic oxidation of aromatic alcohols over silver supported on cobalt oxide nanostructured catalyst, *J. Alloys Compd.*, 2019, **783**, 583–592.
- 125 N. D. Pawar, J. C. Bhangoji, C. J. Barile, A. G. Awale and S. S. Shendage, Pd nanoparticles supported on silver, zinc, and reduced graphene oxide as a highly active electrocatalyst for ethanol oxidation, *Int. J. Hydrogen Energy*, 2024, **80**, 926–933.



- 126 V. Devanathan, *et al.*, Green synthesis of silver nanoparticles using sustainable bio-fertilizer (Panchakavyam) for the selective oxidation of propylene glycol and veratryl alcohol, *Results Chem.*, 2023, **6**, 101159.
- 127 M. R. Hatshan, *et al.*, Green, Solvent-Free Mechanochemical Synthesis of Nano Ag<sub>2</sub>O/MnO<sub>2</sub>/N-Doped Graphene Nanocomposites: An Efficient Catalyst for Additive-Base-Free Aerial Oxidation of Various Kinds of Alcohols, *ACS Omega*, 2024, **9**, 2770–2782.
- 128 M. Khani, R. Sammynaiken and L. D. Wilson, Electrocatalytic Oxidation of Nitrophenols *via* Ag Nanoparticles Supported on Citric-Acid-Modified Polyaniline, *Catalysts*, 2023, **13**, 465.
- 129 O. Bulut and M. D. Yilmaz, Quercetagenin-Stabilized Silver Nanoparticles for the Oxidation of Morin, *ACS Appl. Nano Mater.*, 2022, **5**, 13761–13767.
- 130 M. D. Yilmaz, N. G. Ozsamur and S. Erbas-Cakmak, Catalytic investigation of hyaluronic acid-stabilized Ag nanoparticles as non-toxic nanocatalysts in the oxidation of morin, *New J. Chem.*, 2024, **48**, 2341–2347.
- 131 T. Ghosh, N. Choudhary and S. M. Mobin, Design and Synthesis of Silver Decorated Fe<sub>3</sub>O<sub>4</sub>@ Fe Doped CeO<sub>2</sub> Core-Shell Ternary Composite as Highly Efficient Nanocatalyst for Selective Oxidation of Alkenes, *ChemistrySelect*, 2020, **5**, 9601–9606.
- 132 S. Dey, *et al.*, Enhanced electrocatalytic activity of Cu@Ag core-shell nano catalyst for borohydride oxidation using MWCNT as catalyst support, *Ionics*, 2023, **29**, 4191–4202.
- 133 N. Pugazhenthiran, *et al.*, Silver nanoparticles modified ZnO nanocatalysts for effective degradation of ceftiofur sodium under UV-vis light illumination, *Chemosphere*, 2023, **313**, 137515.
- 134 N. Tarasova, *et al.*, Fly-Ash Cenosphere as Non-Porous Ag-Nanoparticle Support for Epoxidation of Styrene, *ChemistrySelect*, 2024, **9**, e202401003.
- 135 I. Ameen, *et al.*, Ag, Au and ZrO<sub>2</sub>@reduced graphene oxide nanocomposites; Pd free catalysis of suzuki-miyaura coupling reactions, *Mater. Res. Express*, 2023, **10**, 045102.
- 136 S. Nasr, Application of Doped Clay by Plasmonic Nanoparticles in the Suzuki–Miyaura Cross-Coupling Reaction, *J. Electron. Mater.*, 2023, **52**, 5362–5376.
- 137 O. Altan and E. Kalay, The influence of band bending phenomenon on photocatalytic Suzuki–Miyaura coupling reaction: The case of AgPd alloy nanoparticles supported on graphitic carbon nitride, *Appl. Surf. Sci.*, 2022, **580**, 152287.
- 138 N. M. Shaikh, V. Adimule, G. B. Bagihalli and R. S. Keri, A Novel Mixed Ag–Pd Nanoparticles Supported on SBA Silica Through [DMAP-TMSP-DABCO]OH Basic Ionic Liquid for Suzuki Coupling Reaction, *Top. Catal.*, 2023, **66**, 1–10.
- 139 R. L. Kimber, *et al.*, Biotechnological synthesis of Pd/Ag and Pd/Au nanoparticles for enhanced Suzuki–Miyaura cross-coupling activity, *Microb. Biotechnol.*, 2021, **14**, 2435–2447.
- 140 Y. Chen and L. Feng, Silver nanoparticles doped TiO<sub>2</sub> catalyzed Suzuki-coupling of bromoaryl with phenylboronic acid under visible light, *J. Photochem. Photobiol., B*, 2020, **205**, 111807.
- 141 T. Zolfaghari, M. Soleiman-Beigi and H. Kohzadi, Silver Natural Asphalt Sulfonate (NA-SO<sub>3</sub>Ag): Fabrication and Utilization as a New Heterogeneous, Carbonaceous, and Retrievable Nanocatalyst for C(sp<sup>2</sup>)-X (X = C, S, and Se) Bond Formation, *ACS Omega*, 2023, **8**, 36152–36161.
- 142 P. Bhattacharjee, *et al.*, Bimetallic Pd–Ag nanoclusters decorated micro-cellulose bio-template towards efficient catalytic Suzuki–Miyaura coupling reaction of nitrogen-rich heterocycles, *Green Chem.*, 2022, **24**, 7208–7219.
- 143 R. K. Aparna, S. Mukherjee, S. S. Rose and S. Mandal, Silver Nanoparticle-Incorporated Defect-Engineered Zr-based Metal–Organic Framework for Efficient Multicomponent Catalytic Reactions, *Inorg. Chem.*, 2022, **61**, 16441–16447.
- 144 W. Xie, *et al.*, Cu(II)-Based Metal–Organic Framework Loaded with Silver Nanoparticles as a Catalyst for the A<sub>3</sub>-Coupling Reaction, *ACS Appl. Nano Mater.*, 2024, **7**, 3210–3219.
- 145 A. Mariconda, M. Sirignano, C. Costabile and P. Longo, New NHC- silver and gold complexes active in A<sub>3</sub>-coupling (aldehyde-alkyne-amine) reaction, *Mol. Catal.*, 2020, **480**, 110570.
- 146 M.-Y. Dou, X.-Q. Huang and G.-Y. Yang, Two inorganic–organic hybrid silver-polyoxometalates as reusable catalysts for one-pot synthesis of propargylamines *via* a three-component coupling reaction at room temperature, *CrystEngComm*, 2020, **22**, 2642–2648.
- 147 D. Ma, *et al.*, Immobilized Ag NPs on chitosan-biguanidine coated magnetic nanoparticles for synthesis of propargylamines and treatment of human lung cancer, *Int. J. Biol. Macromol.*, 2020, **165**, 767–775.
- 148 B. Babaei, M. Mamaghani and M. Mokhtary, Clean Synthesis of Propargylamines Using Novel Magnetically Recyclable Silver Nanocatalyst (AgMNPs), *Polycyclic Aromat. Compd.*, 2023, **43**, 396–408.
- 149 M. Zarei, I. Mohammadzadeh, K. Saidi and H. Sheibani, Synthesis of Ag–Cu–Ni Nanoparticles Stabilized on Functionalized g-C<sub>3</sub>N<sub>4</sub> and Investigation of Its Catalytic Activity in the A<sub>3</sub>-Coupling Reaction, *ACS Omega*, 2023, **8**, 18685–18694.
- 150 B. K. Chandra, S. Pal, A. Majee and A. Bhaumik, Ag nanoparticles grafted porous organic polymer as an efficient heterogeneous catalyst for solvent-free A<sub>3</sub> coupling reactions, *Mol. Catal.*, 2022, **531**, 112686.
- 151 M. Daraie, M. M. Heravi, P. Mohammadi and A. Daraie, Silver incorporated into g-C<sub>3</sub>N<sub>4</sub>/Alginate as an efficient and heterogeneous catalyst for promoting click and A<sub>3</sub> and KA<sub>2</sub> coupling reaction, *Sci. Rep.*, 2021, **11**, 14086.
- 152 K. Ghasemi, *et al.*, Magnetic AgNPs/Fe<sub>3</sub>O<sub>4</sub>@chitosan/PVA nanocatalyst for fast one-pot green synthesis of propargylamine and triazole derivatives, *New J. Chem.*, 2021, **45**, 16119–16130.
- 153 H. Veisi, N. Dadres, P. Mohammadi and S. Hemmati, Green synthesis of silver nanoparticles based on oil-water interface method with essential oil of orange peel and its



- application as nanocatalyst for A3 coupling, *Mater. Sci. Eng., C*, 2019, **105**, 110031.
- 154 H. Veisi, L. Mohammadi, S. Hemmati, T. Tamoradi and P. Mohammadi, In Situ Immobilized Silver Nanoparticles on *Rubia tinctorum* Extract-Coated Ultrasmall Iron Oxide Nanoparticles: An Efficient Nanocatalyst with Magnetic Recyclability for Synthesis of Propargylamines by A3 Coupling Reaction, *ACS Omega*, 2019, **4**, 13991–14003.
- 155 M. Darroudi, G. M. Ziarani, J. B. Ghasemi and A. Badiei, Synthesis of Ag(I)@Fum–Pr–Pyr–Benzimidazole and Its Optical and Catalytic Activities in Click Reactions, *ChemistrySelect*, 2021, **6**, 6168–6180.
- 156 S. Molaei and M. Ghadermazi, Silver complex anchored on ordered mesoporous coated cobalt ferrite nanoparticles as highly reusable catalyst for synthesis of tetrazole, *Appl. Surf. Sci. Adv.*, 2023, **18**, 100519.
- 157 S. Prakash, B. Sreedhar and N. V. S. Naidu, Gum Acacia Stabilized Ag-TiO<sub>2</sub> and Ag-SiO<sub>2</sub>: Sustainable Nanocatalysts for Direct and Convenient Synthesis of 5-Substituted 1H-tetrazoles, *SynOpen*, 2023, **07**, 680–689.
- 158 Y. A. Attia, Y. M. A. Mohamed, M. M. Awad and S. Alexeree, Ag doped ZnO nanorods catalyzed photo-triggered synthesis of some novel (1H-tetrazol-5-yl)-coumarin hybrids, *J. Organomet. Chem.*, 2020, **919**, 121320.
- 159 M. Nasrollahzadeh, M. Sajjadi, M. R. Tahsili, M. Shokouhimehr and R. S. Varma, Synthesis of 1-Substituted 1H-1,2,3,4-Tetrazoles Using Biosynthesized Ag/Sodium Borosilicate Nanocomposite, *ACS Omega*, 2019, **4**, 8985–9000.
- 160 L. Buengkitcharoen, *et al.*, Facile synthesis of robust Ag/ZnO composites by sol-gel autocombustion and ion-impregnation for the photocatalytic degradation of sucrose, *Sci. Rep.*, 2023, **13**, 12173.
- 161 G. Hootifard, E. Sheikhhosseini, S. A. Ahmadi and M. Yahyazadehfar, Synthesis and characterization of Co-MOF@Ag<sub>2</sub>O nanocomposite and its application as a nano-organic catalyst for one-pot synthesis of pyrazolopyranopyrimidines, *Sci. Rep.*, 2023, **13**, 17500.
- 162 A. A. El-sherif, *et al.*, Power of recycling waste cooking oil into biodiesel via green CaO-based eggshells/Ag heterogeneous nanocatalyst, *Renewable Energy*, 2023, **202**, 1412–1423.
- 163 M. I. Al-Zaban and A. R. M. Abd El-Aziz, Production of biodiesel from *A. spergillus terreus* KC462061 using gold-silver nanocatalyst, *Green Chem. Lett. Rev.*, 2024, **17**, 2295503.
- 164 I. B. Laskar, L. Rokhum, R. Gupta and S. Chatterjee, Zinc oxide supported silver nanoparticles as a heterogeneous catalyst for production of biodiesel from palm oil, *Environ. Prog. Sustainable Energy*, 2020, **39**, e13369.
- 165 A. M. Antony, M. R. Sonalkumari, M. I. Chamanmalik and S. A. Patil, Phytochemical assisted engineering of silver nanoparticles on hexagonal boron nitride: An efficient nanocatalyst for amidation and reduction reactions in aqueous medium, *Mol. Catal.*, 2024, **564**, 114322.
- 166 P. Han, *et al.*, Plasmonic Silver-Nanoparticle-Catalyzed Hydrogen Abstraction from the C(sp<sup>3</sup>)-H Bond of the Benzylic C $\alpha$  atom for Cleavage of Alkyl Aryl Ether Bonds, *Angew. Chem.*, 2023, **135**, e202215201.
- 167 A. Karmakar, *et al.*, Highly efficient oxidative C–H/C–H cross coupling of xanthenes over bimetallic Ni/Ag@titania: The key role of surface polymorphism and mechanism by surface-enhanced Raman scattering, *J. Catal.*, 2023, **428**, 115206.
- 168 K. Hoseinzade, S. A. Mousavi-Mashhadi and A. Shiri, An efficient and green one-pot synthesis of tetrahydrobenzo [a]xanthenes, 1,8-dioxo-octahydroxanthenes and dibenzo [a,j]xanthenes by Fe<sub>3</sub>O<sub>4</sub>@Agar-Ag as nanocatalyst, *Mol. Diversity*, 2022, **26**, 2745–2759.
- 169 L. Mohammadi, M. M. Heravi, A. Saljooqi and P. Mohammadi, The preparation of polyvinyl imidazole-functionalized magnetic biochar decorated by silver nanoparticles as an efficient catalyst for the synthesis of spiro-2-Amino-4H-pyran compounds, *Sci. Rep.*, 2022, **12**, 22281.
- 170 S. Saneinezhad, L. Mohammadi, V. Zadsirjan, F. F. Bamoharram and M. M. Heravi, Silver nanoparticles-decorated Preyssler functionalized cellulose biocomposite as a novel and efficient catalyst for the synthesis of 2-amino-4H-pyrans and spirochromenes, *Sci. Rep.*, 2020, **10**, 14540.
- 171 S. Zhang, J. Li, T. Xiao, B. Yang and Y. Jiang, Silver-Catalyzed Cascade Cyclization of Amino-NH-1,2,3-Triazoles with 2-Alkynylbenzaldehydes: An Access to Pentacyclic Fused Triazoles, *Molecules*, 2022, **27**, 7567.
- 172 K. Yakkala, S. Chappa, P. B. Rathod, R. N. Gurijala and A. K. Pandey, Silver nanoparticles embedded cation-exchange membrane for remediation of Hg species and application as the dip catalyst in organic transformation, *Mater. Today Chem.*, 2021, **22**, 100547.
- 173 A. Panigrahi, D. Whitaker, I. J. Vitorica-Yrezabal and I. Larrosa, Ag/Pd Cocatalyzed Direct Arylation of Fluoroarene Derivatives with Aryl Bromides, *ACS Catal.*, 2020, **10**, 2100–2107.
- 174 J. Singh, Fe<sub>3</sub>O<sub>4</sub>SiO<sub>2</sub>-Ag Nanocatalyst: a Recyclable Catalyst for the Synthesis of New Derivatives of Quinoline Heterocyclic System, *Nanomater. Chem.*, 2023, **1**, 58–69.
- 175 N. Hoot, *et al.*, Synthesis and Characterization of Novel 2D Ultrathin Nanoribbons Cd-Ag-MOF@ZnO Composite as Organo-Nanocatalyst for Preparation of Polyhydroquinoline Heterocycles, *Polycyclic Aromat. Compd.*, 2024, **44**, 5218–5236.
- 176 T. T. Co, *et al.*, Solvent-Free Synthesized Zeolites NaA-Supported Binary Nickel-Silver Nanoparticles and Their Use as an Efficient Catalyst for Hydrodechlorination of 2,4-Dichlorophenol, *Int. J. Chem. Eng.*, 2024, **2024**, 8844774.
- 177 A. Zuliani, P. Ranjan, R. Luque and E. V. Van Der Eycken, Heterogeneously Catalyzed Synthesis of Imidazolones via Cycloisomerizations of Propargylic Ureas Using Ag and Au/Al SBA-15 Systems, *ACS Sustain. Chem. Eng.*, 2019, **7**, 5568–5575.
- 178 M. M. Hammouda, *et al.*, Synthesis of novel benzopyrimido [4,5-*d*]azoninone analogs catalyzed by biosynthesized Ag-



- TiO<sub>2</sub> core/shell magnetic nanocatalyst and assessment of their antioxidant activity, *RSC Adv.*, 2023, **13**, 32532–32546.
- 179 N. Haque, *et al.*, Silver Nanoparticles Supported on Covalent Organic Framework as a Catalyst for Carboxylative Cyclization with CO<sub>2</sub> for Synthesis of Tetramic and Tetronic Acids, *ACS Appl. Nano Mater.*, 2024, **7**, 11059–11070.
- 180 D. Wu, *et al.*, Light-Assisted CO<sub>2</sub> Cycloaddition over a Nanochannel Cadmium–Organic Framework Loaded with Silver Nanoparticles, *ACS Appl. Nano Mater.*, 2023, **6**, 6197–6207.
- 181 Y. Yang, Y. Li, Y. Lu, Z. Chen and R. Luo, A Three-Dimensional Azo-Bridged Porous Porphyrin Framework Supported Silver Nanoparticles as the State-of-the-Art Catalyst for the Carboxylative Cyclization of Propargylic Alcohols with CO<sub>2</sub> under Ambient Conditions, *ACS Catal.*, 2024, **14**, 10344–10354.
- 182 Y. Yang, Y. Li, Z. Zhang, K. Chen and R. Luo, In Situ Anchoring of Small-Sized Silver Nanoparticles on Porphyrinic Triazine-Based Frameworks for the Conversion of CO<sub>2</sub> into  $\alpha$ -Alkylidene Cyclic Carbonates with Outstanding Catalytic Activities under Ambient Conditions, *ACS Appl. Mater. Interfaces*, 2024, **16**, 411–424.
- 183 A. Roy, *et al.*, AgNPs supported over porous organic polymers for the fixation of CO<sub>2</sub> on propargyl alcohols and amines under solvent-free conditions, *New J. Chem.*, 2023, **47**, 6673–6684.
- 184 A. Sahoo, A. Giri, M. D. W. Hussain, S. Jaiswal and A. Patra, Rapid Conversion of CO<sub>2</sub> Using Propargylic Amines by a Silver Nanoparticle-Loaded Triazole-Based Porous Organic Polymer, *ACS Appl. Nano Mater.*, 2024, **7**, 25054–25064.
- 185 R. Patra and D. Sarma, Silver Nanoparticle-Functionalized Postsynthetically Modified Thiol MOF UiO-66-NH-SH for Efficient CO<sub>2</sub> Fixation, *ACS Appl. Mater. Interfaces*, 2024, **16**, 10196–10210.
- 186 C. Liu, F. Gong, X. Zou, C. Wang and Z. Xiong, Coptis Root-Derived Hierarchical Carbon-Supported Ag Nanoparticles for Efficient and Recyclable Alkyne Halogenation, *Molecules*, 2025, **30**, 567.
- 187 F. Li, *et al.*, Ytterbium and silver co-catalyzed synthesis of pyrrole-fused bicyclic skeletons from enynones and isocyanides, *Chem. Commun.*, 2018, **54**, 6412–6415.
- 188 J.-Q. Liu, X. Chen, A. Shatskiy, M. D. Kärkäs and X.-S. Wang, Silver-Mediated Synthesis of Substituted Benzofuran- and Indole-Pyrroles *via* Sequential Reaction of *ortho*-Alkynylaromatics with Methylene Isocyanides, *J. Org. Chem.*, 2019, **84**, 8998–9006.
- 189 H. Noor, S. Zhang, X. Jia, P. Gao and Y. Yuan, Silver-Catalyzed Markovnikov Addition Hydrofunctionalization of Terminal Alkynes: Synthesis of *N*-Enoxyimides and Oximes, *Org. Lett.*, 2024, **26**, 11150–11155.
- 190 A. Ali, *et al.*, Synthesis and Characterization of Silica, Silver-Silica, and Zinc Oxide-Silica Nanoparticles for Evaluation of Blood Biochemistry, Oxidative Stress, and Hepatotoxicity in Albino Rats, *ACS Omega*, 2023, **8**, 20900–20911.
- 191 R. T. Mogharbel, *et al.*, Superior adsorption and removal of industrial dye from aqueous solution *via* magnetic silver metal-organic framework nanocomposite, *Environ. Technol.*, 2024, **45**, 2558–2574.
- 192 Z. Xu, C. Zhang, X. Wang and D. Liu, Release Strategies of Silver Ions from Materials for Bacterial Killing, *ACS Appl. Bio Mater.*, 2021, **4**, 3985–3999.
- 193 A. S. Joshi, P. Singh and I. Mijakovic, Interactions of Gold and Silver Nanoparticles with Bacterial Biofilms: Molecular Interactions behind Inhibition and Resistance, *Int. J. Mol. Sci.*, 2020, **21**, 7658.
- 194 I. X. Yin, *et al.*, The Antibacterial Mechanism of Silver Nanoparticles and Its Application in Dentistry, *Int. J. Nanomed.*, 2020, **15**, 2555–2562.
- 195 T. Ameh, *et al.*, Silver and Copper Nanoparticles Induce Oxidative Stress in Bacteria and Mammalian Cells, *Nanomaterials*, 2022, **12**, 2402.
- 196 A. A. Sadoon, *et al.*, Silver Ions Caused Faster Diffusive Dynamics of Histone-Like Nucleoid-Structuring Proteins in Live Bacteria, *Appl. Environ. Microbiol.*, 2020, **86**, e02479.
- 197 A. Verma, *et al.*, Fabrication and evaluation of ZnO–Ag nanocomposites exhibiting enhanced antibacterial properties and their potential applications, *Int. J. Nanomed.*, 2024, **137**, 3037–3045.
- 198 L. H. Slewa, B. A. Gozeh, D. S. Ismael, N. Q. FageAbdulla and H. O. Othman, Antibacterial and Antifungal Activity of Ag-NPs Colloids Prepared by a Hydrothermal Reaction in Green Synthesized CQD, *J. Bionanosci.*, 2024, **14**, 2705–2721.
- 199 M. A. Rabbi, *et al.*, Preparation of stable Fe<sub>2</sub>O<sub>3</sub>/Ag nanocomposite particles with catalytic, antioxidant and antibacterial properties, *New J. Chem.*, 2024, **48**, 5278–5288.
- 200 T. Muneeswaran, *et al.*, Starch-mediated synthesis of chitosan/silver nanocomposites for antibacterial, antibiofilm and wound healing applications, *J. Drug Delivery Sci. Technol.*, 2023, **84**, 104424.
- 201 Y. Song, *et al.*, Phyto-mediated synthesis of Ag nanoparticles/attapulgitite nanocomposites using olive leaf extract: Characterization, antibacterial activities and cytotoxicity, *Inorg. Chem. Commun.*, 2023, **151**, 110543.
- 202 D. Bharathi, M. A. Wadaan, R. Mythili and J. Lee, Synthesis of chitosan and gum arabic functionalized silver nanocomposite for efficient removal of methylene blue and antibacterial activity, *Polym. Adv. Technol.*, 2024, **35**, e6356.
- 203 M. Arunpandian, L. T. Parvathi, K. Selvakumar, T. H. Oh and S. Karuthapandian, Facile Construction of Novel Ag/Er<sub>2</sub>O<sub>3</sub>@CuO Nanocomposite for Superior Visible-light-driven Photocatalytic Degradation and Antibacterial Activity, *J. Inorg. Organomet. Polym. Mater.*, 2024, **34**, 759–772.
- 204 R. L. Siegel, A. N. Giaquinto and A. Jemal, Cancer statistics, *Ca-Cancer J. Clin.*, 2024, **74**, 12–49.
- 205 H. T. Draviana, *et al.*, Size and charge effects of metal nanoclusters on antibacterial mechanisms., *J. Nanobiotechnol.*, 2023, **21**, 428.



- 206 I. Zare, *et al.*, Protein-protected metal nanoclusters as diagnostic and therapeutic platforms for biomedical applications, *Mater. Today*, 2023, **66**, 159–193.
- 207 A. H. Faid, M. A. Rafea, S. Gad, M. Sharaky and M. A. Ramadan, Antitumor efficiency and photostability of newly green synthesized silver/graphene oxide nanocomposite on different cancer cell lines, *Cancer Nanotechnol.*, 2024, **15**, 17.
- 208 G. Venkatraman, *et al.*, Morinda citrifolia leaf assisted synthesis of ZnO decorated Ag bio-nanocomposites for in-vitro cytotoxicity, antimicrobial and anticancer applications, *Bioprocess Biosyst. Eng.*, 2024, **47**, 1213–1226.
- 209 M. Moghayed, E. K. Goharshadi, K. Ghazvini and L. Ranjbaran, Assessment of the cytotoxicity of silver-graphene oxide nanocomposites on Escherichia coli and glioblastoma cancer cells, *J. Iran. Chem. Soc.*, 2024, **21**, 1817–1827.
- 210 G. Zhou, Y. You, B. Wang, S. Wang and J. Liu, Green synthesis of magnetic Fe<sub>3</sub>O<sub>4</sub>/Ag nanocomposite using Pomegranate peel extract for the treatment of ovarian cancer, *Arabian J. Chem.*, 2024, **17**, 105394.
- 211 D. Bharathi, *et al.*, Green synthesis of chitosan/silver nanocomposite using kaempferol for triple negative breast cancer therapy and antibacterial activity, *Environ. Res.*, 2023, **238**, 117109.
- 212 V. Balaji, *et al.*, Bio-inspired synthesis of silver nanoparticles and their nanocomposites for antibacterial and anticancer activity: A comparative study, *J. Alloys Compd.*, 2023, **966**, 171503.
- 213 F. Liu, Y. Chen, Y. Huang, Q. Jin and J. Ji, Nanomaterial-based therapeutics for enhanced antifungal therapy, *J. Mater. Chem. B*, 2024, **12**, 9173–9198.
- 214 M. S. D. Silva, *et al.*, Understanding the mechanism of action of protease inhibitors in controlling the growth of the Candida Genus: potential candidates for development of new antifungal molecules, *Arch. Microbiol.*, 2024, **206**, 257.
- 215 C.-W. Zhang, *et al.*, Antifungal natural products and their derivatives: A review of their activity and mechanism of actions, *Pharmacol. Res. - Mod. Chin. Med.*, 2023, **7**, 100262.
- 216 G. Arumugam, *et al.*, Silver Nanoparticle-Embedded Carbon Nitride: Antifungal Activity on *Candida albicans* and Toxicity toward Animal Cells, *ACS Appl. Mater. Interfaces*, 2024, **16**, 25727–25739.
- 217 S. S. Salem, *et al.*, Synthesis of Silver Nanocomposite Based on Carboxymethyl Cellulose: Antibacterial, Antifungal and Anticancer Activities, *Polymers*, 2022, **14**, 3352.
- 218 M. S. G. Selvi, *et al.*, Enhanced antifungal properties of the Ag-decorated GO and rGO nanocomposites for medical applications, *Bull. Mater. Sci.*, 2024, **47**, 27.
- 219 A. R. Chowdhury, *et al.*, Inhibitory role of copper and silver nanocomposite on important bacterial and fungal pathogens in rice (*Oryza sativa*), *Sci. Rep.*, 2024, **14**, 1779.
- 220 N. T. Tran, *et al.*, Ag/SiO<sub>2</sub> nanoparticles stabilization with lignin derived from rice husk for antifungal and antibacterial activities, *Int. J. Biol. Macromol.*, 2023, **230**, 123124.
- 221 L. Di Muzio, *et al.*, Gellan gum-based nanocomposites films containing bio-reduced silver nanoparticles: Synthesis, characterisation and antifungal activity, *Carbohydr. Polym. Technol. Appl.*, 2024, **7**, 100485.
- 222 C. Chikkanayakanahalli Paramesh, A. Giridasappa, A. K. Channapillekoppalu Siddegowda, D. Rangappa and P. Doddakunche Shivaramu, History, introduction, and physicochemical properties of silver nanoparticles, in *Silver Nanoparticles for Drug Delivery*, Elsevier, 2024, pp. 1–38.
- 223 J. Jeevanandam, *et al.*, Synthesis approach-dependent antiviral properties of silver nanoparticles and nanocomposites, *J. Nanostruct. Chem.*, 2022, **12**, 809–831.
- 224 A. Salleh, *et al.*, The Potential of Silver Nanoparticles for Antiviral and Antibacterial Applications: A Mechanism of Action, *Nanomaterials*, 2020, **10**, 1566.
- 225 G. Koşarsoy Ağçeli, Polymer and its nanocomposites as an antimicrobial coating for medical devices and implants, in *Next-Generation Antimicrobial Nanocoatings for Medical Devices and Implants*, Elsevier, 2024, pp. 161–180.
- 226 A. Luceri, *et al.*, Antibacterial and Antiviral Activities of Silver Nanocluster/Silica Composite Coatings Deposited onto Air Filters, *ACS Appl. Mater. Interfaces*, 2024, **16**, 3955–3965.
- 227 A. Kowalska, E. Adamska and B. Grobelna, Medical Applications of Silver and Gold Nanoparticles and Core-Shell Nanostructures Based on Silver or Gold Core: Recent Progress and Innovations, *ChemMedChem*, 2024, **19**, e202300672.
- 228 M. Elnosary, H. Aboelmagd, M. Sofy, A. Sofy and E. Elshazly, Antiviral and Antibacterial Properties of synthesis Silver Nanoparticles with Nigella arvensis Aqueous Extract., *Egypt. J. Chem.*, 2022, **66**, 209–223.
- 229 M. Asif, *et al.*, Synthesis and Characterization of Chemically and Green-Synthesized Silver Oxide Particles for Evaluation of Antiviral and Anticancer Activity, *Pharmaceuticals*, 2024, **17**, 908.
- 230 P. Bhatia, V. A. Singh, R. Rani, M. Nath and S. Tomar, Cellular uptake of metal oxide-based nanocomposites and targeting of chikungunya virus replication protein nsP3, *J. Trace Elem. Med. Biol.*, 2023, **78**, 127176.
- 231 S. M. El-Ganainy, *et al.*, Antiviral Activity of Chitosan Nanoparticles and Chitosan Silver Nanocomposites against Alfalfa Mosaic Virus, *Polymers*, 2023, **15**, 2961.
- 232 J. Xie, *et al.*, Visible-light-sensitive AgCu nanocomposites for sustainable inactivation of virus, *J. Mater. Sci. Technol.*, 2024, **195**, 74–79.
- 233 V. Demchenko, *et al.*, Nanocomposites based on polylactide and silver nanoparticles and their antimicrobial and antiviral applications, *React. Funct. Polym.*, 2022, **170**, 105096.
- 234 L. D. Agnol, H. L. Ornaghi, J. R. Erzen, M. Faccio and O. Bianchi, Production of a thermoplastic polyurethane/silver nanoparticles 3D filament with antiviral properties to combat SARS-CoV-2, *Polym. Eng. Sci.*, 2024, **64**, 130–141.



- 235 M. Assis, *et al.*, SiO<sub>2</sub>-Ag Composite as a Highly Virucidal Material: A Roadmap that Rapidly Eliminates SARS-CoV-2, *Nanomaterials*, 2021, **11**, 638.
- 236 O. V. Morozova, *et al.*, Targeting of Silver Cations, Silver-Cystine Complexes, Ag Nanoclusters, and Nanoparticles towards SARS-CoV-2 RNA and Recombinant Virion Proteins, *Viruses*, 2022, **14**, 902.
- 237 F. Karchoubi, R. Afshar Ghotli, H. Pahlevani and M. Baghban Salehi, New insights into nanocomposite hydrogels; a review on recent advances in characteristics and applications, *Adv. Ind. Eng. Polym. Res.*, 2024, **7**, 54–78.
- 238 B. Essghaier, Silver nanoparticles for pharmaceutical and biomedical applications drug delivery, in *Silver Nanoparticles for Drug Delivery*, Elsevier, 2024, pp. 89–107.
- 239 D. H. Hanna, M. H. El-Mazaly and R. R. Mohamed, Synthesis of biodegradable antimicrobial pH-sensitive silver nanocomposites reliant on chitosan and carrageenan derivatives for 5-fluorouracil drug delivery toward HCT116 cancer cells, *Int. J. Biol. Macromol.*, 2023, **231**, 123364.
- 240 Y. Romdoni, G. T. M. Kadja, Y. Kitamoto and M. Khalil, Synthesis of multifunctional Fe<sub>3</sub>O<sub>4</sub>@SiO<sub>2</sub>-Ag nanocomposite for antibacterial and anticancer drug delivery, *Appl. Surf. Sci.*, 2023, **610**, 155610.
- 241 A. R. Bertão, *et al.*, Preliminary evaluation of zeolite-based platforms as potential dual drug delivery systems against microbial infections in the tumor microenvironment, *Microporous Mesoporous Mater.*, 2024, **364**, 112871.
- 242 R. Mahanty, *et al.*, Biosurfactant-based silver nanoparticles: Recent advances and their applications in antimicrobial drug resistance, *J. Drug Delivery Sci. Technol.*, 2024, **92**, 105382.
- 243 M. A. El-Meligy, *et al.*, Recent Advancements in Metallic Au- and Ag-Based Chitosan Nanocomposite Derivatives for Enhanced Anticancer Drug Delivery, *Molecules*, 2024, **29**, 2393.
- 244 D. S. R. Khafaga, *et al.*, Enhanced anticancer activity of silver doped zinc oxide magnetic nanocarrier loaded with sorafenib for hepatocellular carcinoma treatment, *Sci. Rep.*, 2024, **14**, 15538.
- 245 P. Soundharraj, D. Dhinasekaran, P. Aruna and S. Ganesan, Facile synthesis of biomass silica-silver colloidal nanoparticles and its application as highly sensitive fluorescent biosensor, *Surf. Interfaces*, 2021, **23**, 101010.
- 246 M. Chawla, B. Pramanick, J. K. Randhawa and P. F. Siril, Effect of composition and calcination on the enzymeless glucose detection of Cu-Ag bimetallic nanocomposites, *Mater. Today Commun.*, 2021, **26**, 101815.
- 247 A. Wang, *et al.*, Electrochemical immunosensor for ultrasensitive detection of human papillomavirus type 16 L1 protein based on Ag@AuNPs-GO/SPA, *Anal. Biochem.*, 2023, **660**, 114953.
- 248 Y. Liu, *et al.*, Multicolor colorimetric visual detection of Staphylococcus aureus based on Fe<sub>3</sub>O<sub>4</sub>-Ag-MnO<sub>2</sub> composites nano-oxidative mimetic enzyme, *Anal. Chim. Acta*, 2023, **1239**, 340654.
- 249 G. Dikmen, Surface enhanced Raman spectroscopy sensor based on silver nanoparticles/multi wall carbon nanotubes for ultrasensitive detection of cholesterol, *Adv. Ind. Eng. Polym. Res.*, 2023, **303**, 123235.
- 250 Y. Jung, J. Kim, N. H. Kim and H. G. Kim, Ag-ZnO Nanocomposites as a 3D Metal-Enhanced Fluorescence Substrate for the Fluorescence Detection of DNA, *ACS Appl. Nano Mater.*, 2023, **6**, 976–985.
- 251 L. Mahmudin, *et al.*, Silver nanoparticles-based localized surface plasmon resonance biosensor for Escherichia coli detection, *Adv. Ind. Eng. Polym. Res.*, 2024, **311**, 123985.
- 252 S. Ü. Pektaş, M. Keskin, O. C. Bodur and F. Arslan, Green synthesis of silver nanoparticles and designing a new amperometric biosensor to determine glucose levels, *J. Food Compos. Anal.*, 2024, **129**, 106133.
- 253 R. Li, *et al.*, Hollow Prussian blue with ultrafine silver nanoparticle agents (Ag-HPB) integrated sensitive and flexible biosensing platform with highly enzyme loading capability, *Talanta*, 2024, **266**, 125036.
- 254 M. J. Saadh, *et al.*, Silver@copper-polyaniline nanotubes: Synthesis, characterization and biosensor analytical study, *Results Chem.*, 2024, **9**, 101614.
- 255 D.-Y. Kim, *et al.*, Development of Novel Peptide-Modified Silver Nanoparticle-Based Rapid Biosensors for Detecting Aminoglycoside Antibiotics, *J. Agric. Food Chem.*, 2023, **71**, 12883–12898.
- 256 F. Selimoğlu, *et al.*, Silver nanoparticle doped graphene-based impedimetric biosensor towards sensitive detection of procalcitonin, *Mater. Chem. Phys.*, 2023, **297**, 127339.
- 257 W. Sukjee, *et al.*, EV71 virus induced silver nanoparticles self-assembly in polymer composites with an application as virus biosensor, *Sens. Actuators, B*, 2023, **393**, 134324.
- 258 N. Assad, *et al.*, Diffused sunlight assisted green synthesis of silver nanoparticles using *Cotoneaster nummularia* polar extract for antimicrobial and wound healing applications, *Nat. Prod. Res.*, 2023, 1–15.
- 259 A. Bharali, *et al.*, Green synthesis of silver nanoparticles using hydroalcoholic root extract of *Potentilla fulgens* and evaluation of its cutaneous wound healing potential, *Mater. Today Commun.*, 2023, **35**, 106050.
- 260 L. L. S. Munhoz, *et al.*, Bacterial cellulose membrane incorporated with silver nanoparticles for wound healing in animal model, *Biochem. Biophys. Res. Commun.*, 2023, **654**, 47–54.
- 261 S. Majeed, *et al.*, Wound healing and antidiabetic properties of green synthesized silver nanoparticles in 3T3-L1 mouse embryo fibroblast cells through 2-NBDG expression, *Inorg. Chem. Commun.*, 2024, **159**, 111692.
- 262 Y. Dutt, *et al.*, Silver Nanoparticles Phytofabricated through *Azadirachta indica*: Anticancer, Apoptotic, and Wound-Healing Properties, *Antibiotics*, 2023, **12**, 121.
- 263 F. Aldakheel, *et al.*, Silver Nanoparticles Loaded on Chitosan-g-PVA Hydrogel for the Wound-Healing Applications, *Molecules*, 2023, **28**, 3241.
- 264 C. Zhang, *et al.*, Electrospun polyasparthydrazide nanofibrous hydrogel loading with in-situ synthesized



- silver nanoparticles for full-thickness skin wound healing application, *Mater. Des.*, 2024, **239**, 112818.
- 265 V. Lakkim, *et al.*, Antioxidant Efficacy of Green-Synthesized Silver Nanoparticles Promotes Wound Healing in Mice, *Pharmaceutics*, 2023, **15**, 1517.
- 266 R. Abdel-Gawad, R. Osman, G. A. S. Awad and N. Mortada, Wound healing potential of silver nanoparticles embedded in optimized bio-inspired hybridized chitosan soft and dry hydrogel, *Carbohydr. Polym.*, 2024, **324**, 121526.
- 267 G. Vijayakumar, H. J. Kim and S. K. Rangarajulu, In Vitro Antibacterial and Wound Healing Activities Evoked by Silver Nanoparticles Synthesized through Probiotic Bacteria, *Antibiotics*, 2023, **12**, 141.
- 268 A. Sanmugam, *et al.*, Fabrication of chitosan/fibrin- armored multifunctional silver nanocomposites to improve antibacterial and wound healing activities, *Int. J. Biol. Macromol.*, 2024, **257**, 128598.
- 269 B. Kodasi, *et al.*, Novel jointured green synthesis of chitosan-silver nanocomposite: An approach towards reduction of nitroarenes, anti-proliferative, wound healing and antioxidant applications, *Int. J. Biol. Macromol.*, 2023, **246**, 125578.
- 270 N. Amiri, *et al.*, Antibacterial Thermosensitive Silver-Hydrogel Nanocomposite Improves Wound Healing, *Gels*, 2023, **9**, 542.
- 271 N. Arghand, S. Reisi, B. Karimi, E. M. Khorasgani and R. Heidari, Biosynthesis of Nanocomposite Alginate-Chitosan Loaded with Silver Nanoparticles Coated with Eugenol/Quercetin to Enhance Wound Healing, *J. Bionanosci.*, 2024, **14**, 5149–5166.
- 272 T. T. T. Nguyen, *et al.*, Passion fruit peel pectin/chitosan based antibacterial films incorporated with biosynthesized silver nanoparticles for wound healing application, *Alexandria Eng. J.*, 2023, **69**, 419–430.
- 273 A. Farazin, M. Mohammadimehr and H. Naeimi, Flexible self-healing nanocomposite based gelatin/tannic acid/acrylic acid reinforced with zinc oxide nanoparticles and hollow silver nanoparticles based on porous silica for rapid wound healing, *Int. J. Biol. Macromol.*, 2023, **241**, 124572.
- 274 P. Concórdio-Reis, *et al.*, Bioactive exopolysaccharide-composites based on gold and silver nanoparticles tailored for wound healing, *Mater. Today Commun.*, 2023, **34**, 105351.
- 275 A. Ebrahimzadeh, *et al.*, Topically Applied Luteolin/Quercetin-Capped Silver Nanoparticle Ointment as Antileishmanial Composite: Acceleration Wound Healing in BALB/c Mice, *Adv. Mater. Sci. Eng.*, 2023, **2023**, 1–11.
- 276 J. Chen, *et al.*, Multifunctional Z-scheme CuxO/Ag/SrTiO<sub>3</sub> heterojunction for photothermocatalytic VOCs degradation and antibiosis, *Appl. Surf. Sci.*, 2023, **618**, 153275.
- 277 M. S. A. Darwish, M. H. Mostafa and L. M. Al-Harbi, Polymeric Nanocomposites for Environmental and Industrial Applications, *Int. J. Mol. Sci.*, 2022, **23**, 1023.
- 278 M. H. M. Facure, R. Schneider, L. A. Mercante and D. S. Correa, A review on graphene quantum dots and their nanocomposites: from laboratory synthesis towards agricultural and environmental applications, *Environ. Sci.: Nano*, 2020, **7**, 3710–3734.
- 279 R. Chueachot, V. Promarak and S. Saengsuwan, Enhancing antibacterial activity and air filtration performance in electrospun hybrid air filters of chitosan (CS)/AgNPs/PVA/cellulose acetate: Effect of CS/AgNPs ratio, *Sep. Purif. Technol.*, 2024, **338**, 126515.
- 280 D. D. La, *et al.*, Fabrication of Antibacterial Ag/Graphene-Integrated Non-woven Polypropylene Textile for Air Pollutant Filtering, *Waste Biomass Valorization*, 2023, **14**, 3275–3284.
- 281 A. K. Yontar, O. Yontar and S. ÇeviK, Multifunctional Polymer Nanocomposite Coated Antibacterial Filters for Air-Purification, *Ömer Halisdemir Üniversitesi Mühendis. Bilim. Derg.*, 2024, **13**, 509–521.
- 282 H. Li, *et al.*, Highly sensitive volatile organic compounds monitoring enabling by silver-nanowire@metal-organic frameworks core-shell heterostructure, *Talanta*, 2024, **280**, 126713.
- 283 Q. Zhu, *et al.*, Mechanochemical synthesis of Ag/TiO<sub>2</sub>@PANI nanocomposites for enhanced toluene photocatalytic degradation under near-ultraviolet light, *Chin. J. Chem. Eng.*, 2024, **75**, 222–229.
- 284 C. D. A. Gusmão, *et al.*, Enhanced visible light photocatalytic VOC oxidation via Ag-loaded TiO<sub>2</sub>/SiO<sub>2</sub> materials, *J. Mater. Sci.*, 2024, **59**, 1215–1234.
- 285 C. Mao, H. Ling, L. Yi, R. Zhu and G. Zhang, Revealing the critical roles of silver species on TNT film for photocatalytic decomposition of volatile organic pollutants under UV or visible light irradiation: From mechanism study to scaled-up test, *Chem. Eng. J.*, 2023, **473**, 145366.
- 286 M. Abidi, *et al.*, Dynamics of VOCs degradation and bacterial inactivation at the interface of AgxO/Ag/TiO<sub>2</sub> prepared by HiPIMS under indoor light, *J. Photochem. Photobiol., A*, 2023, **435**, 114321.
- 287 S. Wanwong, W. Sangkhun, P. Jiamboonsri and T. Butburee, Electrospun silk nanofiber loaded with Ag-doped TiO<sub>2</sub> with high-reactive facet as multifunctional air filter, *RSC Adv.*, 2023, **13**, 25729–25737.
- 288 M. Sboui, *et al.*, Flexible Ag-AgCl/TiO<sub>2</sub>/cellulose biocomposite film for solar photocatalytic degradation of VOCs, *Chem. Eng. Sci.*, 2024, **298**, 120374.
- 289 M. N. K. Wihadi, Fabrication of new in-situ ternary nano/microcomposite LDH/Ag<sub>2</sub>O/Bayerite in trimetallic NiAg/Al layered double hydroxides for CO<sub>2</sub> capture material, *Greenhouse Gases: Sci. Technol.*, 2024, **14**, 561–571.
- 290 J.-J. Liu, Z.-W. Jiang and S.-W. Hsu, Investigation of the Performance of Heterogeneous MOF-Silver Nanocube Nanocomposites as CO<sub>2</sub> Reduction Photocatalysts by In Situ Raman Spectroscopy, *ACS Appl. Mater. Interfaces*, 2023, **15**, 6716–6725.
- 291 A. Nosrati, S. Javanshir, F. Feyzi and S. Amirnejat, Effective CO<sub>2</sub> Capture and Selective Photocatalytic Conversion into CH<sub>3</sub>OH by Hierarchical Nanostructured GO-TiO<sub>2</sub>-Ag<sub>2</sub>O and GO-TiO<sub>2</sub>-Ag<sub>2</sub>O-Arg, *ACS Omega*, 2023, **8**, 3981–3991.



- 292 H. Li, *et al.*, Facile synthesis of ZnO/Ag/g-C<sub>3</sub>N<sub>4</sub> nanocomposites for multiple applications in photocatalytic degradation and photoactivated NO<sub>2</sub> sensing, *Appl. Surf. Sci.*, 2023, **638**, 158010.
- 293 V. Singh, A. Duhan and D. K. Malik, Removal of chlorpyrifos, Malathion, Dichlorvos and Profenofos by nanocomposite containing AgNP, *Indian J. Chem. Technol.*, 2023, **30**, 398–402.
- 294 K. Chinnappa, P. Karuna Ananthai, P. P. Srinivasan and C. Dharmaraj Glorybai, Green synthesis of rGO-AgNP composite using Curcubita maxima extract for enhanced photocatalytic degradation of the organophosphate pesticide chlorpyrifos, *Environ. Sci. Pollut. Res.*, 2022, **29**, 58121–58132.
- 295 J. Zheng, *et al.*, Facile synthesis of Ag@AgCl/ZnAl-LDH sesame balls nanocomposites with enhanced photocatalytic performance for the degradation of neonicotinoid pesticides, *Chem. Eng. J.*, 2022, **446**, 136485.
- 296 P. Veerakumar, A. Sangili, K. Saranya, A. Pandikumar and K.-C. Lin, Palladium and silver nanoparticles embedded on zinc oxide nanostars for photocatalytic degradation of pesticides and herbicides, *Chem. Eng. J.*, 2021, **410**, 128434.
- 297 S. Bhandari, *et al.*, Sensing of Alphacypermethrin Pesticide Using Modified Electrode of Chitosan-Silver Nanowire Nanocomposite Langmuir Blodgett Film, *Int. J. Environ. Anal. Chem.*, 2024, **104**, 1817–1837.
- 298 A. Özcan, F. Hamid and A. A. Özcan, Synthesizing of a nanocomposite based on the formation of silver nanoparticles on fumed silica to develop an electrochemical sensor for carbendazim detection, *Talanta*, 2021, **222**, 121591.
- 299 Md. A. Rashed, *et al.*, Highly sensitive and selective electrochemical sensor for detecting imidacloprid pesticide using novel silver nanoparticles/mesoporous carbon/hematite ore ternary nanocomposite, *J. Environ. Chem. Eng.*, 2022, **10**, 108364.
- 300 S. Jeong, S. Yang, Y. J. Lee and S. H. Lee, Laser-induced graphene incorporated with silver nanoparticles applied for heavy metal multi-detection, *J. Mater. Chem. A*, 2023, **11**, 13409–13418.
- 301 N. M. Dat, *et al.*, Silver/graphene oxide nanocomposite: Process optimization of mercury sensing and investigation of crystal violet removal, *Inorg. Chem. Commun.*, 2023, **151**, 110613.
- 302 M. Şahin, M. Atasoy, Y. Arslan and D. Yildiz, Removal of Ni(II), Cu(II), Pb(II), and Cd(II) from Aqueous Phases by Silver Nanoparticles and Magnetic Nanoparticles/Nanocomposites, *ACS Omega*, 2023, **8**, 34834–34843.
- 303 A. S. El Shehawy, A. Elsayed, O. A. El-Shehaby and E. M. Ali, Potentiality of the green synthesized silver nanoparticles for heavy metal removal using *Laurencia papillosa* seaweed, *Egypt. J. Aquat. Res.*, 2023, **49**, 513–519.
- 304 S. Amini, S. H. Kandeh, H. Ebrahimzadeh and P. Khodayari, Electrospun composite nanofibers modified with silver nanoparticles for extraction of trace heavy metals from water and rice samples: An highly efficient and reproducible sorbent, *Food Chem.*, 2023, **420**, 136122.
- 305 D. Boas, S. Remennik and M. Reches, Peptide-capped Au and Ag nanoparticles: Detection of heavy metals and photochemical core/shell formation, *J. Colloid Interface Sci.*, 2023, **631**, 66–76.
- 306 I. Ivanišević, The Role of Silver Nanoparticles in Electrochemical Sensors for Aquatic Environmental Analysis, *Sensors*, 2023, **23**, 3692.
- 307 S. S. Hojjat, The effect of silver nanoparticle on lentil seed germination under drought stress, *Int. J. Farming Allied Sci.*, 2016, **5**, 208–212.
- 308 D. R. Antunes, *et al.*, Effect of hyaluronic acid-stabilized silver nanoparticles on lettuce (*Lactuca sativa* L.) seed germination, *Chemosphere*, 2024, **364**, 143080.
- 309 M. S. Rahman, A. Chakraborty, A. Kibria and M. J. Hossain, Effects of silver nanoparticles on seed germination and growth performance of pea (*Pisum sativum*), *Plant Nano Biol.*, 2023, **5**, 100042.
- 310 M. Ansari, *et al.*, Plant mediated fabrication of silver nanoparticles, process optimization, and impact on tomato plant, *Sci. Rep.*, 2023, **13**, 18048.
- 311 P. Sambangi and S. Gopalakrishnan, Streptomyces-mediated synthesis of silver nanoparticles for enhanced growth, yield, and grain nutrients in chickpea, *Biocatal. Agric. Biotechnol.*, 2023, **47**, 102567.
- 312 M. Khan, *et al.*, Synthesis of biogenic silver nanoparticles from the seed coat waste of pistachio (*Pistacia vera*) and their effect on the growth of eggplant, *Nanotechnol. Rev.*, 2021, **10**, 1789–1800.
- 313 M. I. Hossain, *et al.*, Development of electrochemical sensors for quick detection of environmental (soil and water) NPK ions, *RSC Adv.*, 2024, **14**, 9137–9158.
- 314 F. Tornuk and P. K. Akman, Biodegradable polymer nanocomposites for food packaging applications, in *Biodegradable and Biocompatible Polymer Nanocomposites*, Elsevier, 2023, pp. 639–674.
- 315 T. Gasti, *et al.*, Physicochemical and Antibacterial Evaluation of Poly (Vinyl Alcohol)/Guar Gum/Silver Nanocomposite Films for Food Packaging Applications, *J. Polym. Environ.*, 2021, **29**, 3347–3363.
- 316 Y. He, H. Li, X. Fei and L. Peng, Carboxymethyl cellulose/cellulose nanocrystals immobilized silver nanoparticles as an effective coating to improve barrier and antibacterial properties of paper for food packaging applications, *Carbohydr. Polym.*, 2021, **252**, 117156.
- 317 S. Ediyilyam, *et al.*, Chitosan/Gelatin/Silver Nanoparticles Composites Films for Biodegradable Food Packaging Applications, *Polymers*, 2021, **13**, 1680.
- 318 K. Pal, P. Sarkar, A. Anis, K. Wiszumirska and M. Jarzębski, Polysaccharide-Based Nanocomposites for Food Packaging Applications, *Materials*, 2021, **14**, 5549.
- 319 O. M. Atta, *et al.*, Silver Decorated Bacterial Cellulose Nanocomposites as Antimicrobial Food Packaging Materials, *ES Food Agrofor.*, 2021, **6**, 12–26.
- 320 A. El Guerraf, *et al.*, Multifunctional Smart Conducting Polymers–Silver Nanocomposites-Modified Biocellulose Fibers for Innovative Food Packaging Applications, *Ind. Eng. Chem. Res.*, 2023, **62**, 4540–4553.



- 321 J. Liu, *et al.*, Soluble soybean polysaccharide films containing in-situ generated silver nanoparticles for antibacterial food packaging applications, *Food Packag. Shelf Life*, 2022, **31**, 100800.
- 322 S. Elshahat Abdallah, W. M. Elmessery, F. E. Elfallawi and K. R. Shoueir, Utilizing agricultural biowaste for food safety: Integrating naturally synthesized silver nanoparticles as antibacterial coating, *Inorg. Chem. Commun.*, 2024, **163**, 112337.
- 323 X. Yang, Y. Niu, Y. Fan, T. Zheng and J. Fan, Green synthesis of Poria cocos polysaccharides-silver nanoparticles and their applications in food packaging, *Int. J. Biol. Macromol.*, 2024, **269**, 131928.
- 324 N. Yaqoob, A. Zahira, S. Kamal, M. Almas and S. Rehman, Development of multifunctional bioactive food packaging based on silver nanoparticles/grape fruit peel extract reinforced PVA composites, *Mater. Today Commun.*, 2023, **37**, 107529.
- 325 S. Sharma, N. Sharma and N. Kaushal, Utilization of novel bacteriocin synthesized silver nanoparticles (AgNPs) for their application in antimicrobial packaging for preservation of tomato fruit, *Front. Sustainable Food Syst.*, 2023, **7**, 1072738.
- 326 A. K. Biswal and P. K. Misra, Biosynthesis and characterization of silver nanoparticles for prospective application in food packaging and biomedical fields, *Mater. Chem. Phys.*, 2020, **250**, 123014.
- 327 S. Majumder, S. Huang, J. Zhou, Y. Wang and S. George, Tannic acid-loaded halloysite clay grafted with silver nanoparticles enhanced the mechanical and antimicrobial properties of soy protein isolate films for food-packaging applications, *Food Packag. Shelf Life*, 2023, **39**, 101142.
- 328 N. R. Amrutha, *et al.*, Silver Nanoparticles Incorporated PVA-MC Blends: A Systematic Approach To Understand Its Properties For Food Packaging Applications, *ChemistrySelect*, 2023, **8**, e202205031.
- 329 L. Li, *et al.*, Antibacterial Chitosan-Gelatin Microcapsules Modified with Green-Synthesized Silver Nanoparticles for Food Packaging, *J. Renewable Mater.*, 2023, **11**, 291–307.
- 330 H. M. Ragab, *et al.*, Improving the optical, thermal, mechanical, electrical properties and antibacterial activity of PVA-chitosan by biosynthesized Ag nanoparticles: Eco-friendly nanocomposites for food packaging applications, *Int. J. Biol. Macromol.*, 2024, **264**, 130668.
- 331 H. Pandian, K. Senthilkumar, M. Venkata Ratnam, M. Naveenkumar and S. Samraj, Azadirachta indica leaf extract mediated silver nanoparticles impregnated nano composite film (AgNP/MCC/starch/whey protein) for food packaging applications, *Environ. Res.*, 2023, **216**, 114641.
- 332 A. Shruti, N. Bage and P. Kar, Nanomaterials based sensors for analysis of food safety, *Food Chem.*, 2024, **433**, 137284.
- 333 S. Li, *et al.*, Curcumin and silver nanoparticles loaded antibacterial multifunctional pectin/gelatin films for food packaging applications, *Int. J. Biol. Macromol.*, 2024, **266**, 131248.
- 334 J. Xu, *et al.*, A wearable gloved sensor based on fluorescent Ag nanoparticles and europium complexes for visualized assessment of tetracycline in food samples, *Food Chem.*, 2023, **424**, 136376.
- 335 H. Wang, *et al.*, SERS Sensor Based on Core-Shell Au@Ag Nanoparticles for the Sensitive Detection of Acrylamide in Foods, *Food Anal. Methods*, 2024, **17**, 585–593.
- 336 N. T. Anh, *et al.*, Promoting Electron Transfer Kinetics and Adsorption Capacity for the Detection of Furazolidone in Real Food Samples by Using Ag-core@Fe<sub>3</sub>O<sub>4</sub>-Shell-Based Electrochemical Sensing Platform, *J. Electrochem. Soc.*, 2023, **170**, 017510.
- 337 K. Wang, D.-W. Sun, H. Pu and Q. Wei, A rapid dual-channel readout approach for sensing carbendazim with 4-aminobenzenethiol-functionalized core-shell Au@Ag nanoparticles, *Analyst*, 2020, **145**, 1801–1809.
- 338 K. Wang, D.-W. Sun, H. Pu and Q. Wei, Two-dimensional Au@Ag nanodot array for sensing dual-fungicides in fruit juices with surface-enhanced Raman spectroscopy technique, *Food Chem.*, 2020, **310**, 125923.
- 339 A. Parnsubsakul, *et al.*, Silver nanoparticle/bacterial nanocellulose paper composites for paste-and-read SERS detection of pesticides on fruit surfaces, *Carbohydr. Polym.*, 2020, **235**, 115956.
- 340 A. Ali, *et al.*, A comparative performance of antibacterial effectiveness of copper and silver coated textiles., *J. Ind. Text.*, 2023, **53**, 15280837221134990.
- 341 M. S. Mondal, A. Paul and M. Rhaman, Recycling of silver nanoparticles from electronic waste *via* green synthesis and application of AgNPs-chitosan based nanocomposite on textile material., *Sci. Rep.*, 2023, **13**, 13798.
- 342 M. Montemurro, *et al.*, A novel optimized polyoxometalate-modified silver nanocomposite. Application to the development of antibacterial textiles., *Mater. Today Commun.*, 2023, **35**, 106284.
- 343 M. C. Lite, *et al.*, Phytochemical Synthesis of Silver Nanoparticles and Their Antimicrobial Investigation on Cotton and Wool Textiles, *Materials*, 2023, **16**, 3924.
- 344 L. Wu, *et al.*, Construction of durable antibacterial cellulose textiles through grafting dynamic disulfide-containing amino-compound and nanosilver deposition, *Int. J. Biol. Macromol.*, 2024, **259**, 129085.
- 345 J. Plé, *et al.*, Antimicrobial and mechanical properties of functionalized textile by nanoarchitected photoinduced Ag@polymer coating, *Beilstein J. Nanotechnol.*, 2023, **14**, 95–109.
- 346 M. Sadeghi-Kiakhani, E. Hashemi and M.-M. Norouzi, Clean synthesis of silver nanoparticles (AgNPs) on polyamide fabrics by Verbascum thapsus L. (mullein) extract: characterization, colorimetric, antibacterial, and colorfastness studies, *Environ. Sci. Pollut. Res.*, 2024, **31**, 32637–32648.
- 347 A. J. A. Al-Gburi, *et al.*, Superconductive and flexible antenna based on a tri-nanocomposite of graphene nanoplatelets, silver, and copper for wearable electronic devices, *J. Sci.: Adv. Mater. Devices*, 2024, **9**, 100773.



- 348 A. Khan, *et al.*, A review on advanced nanocomposites materials based smart textile biosensor for healthcare monitoring from human sweat, *Sens. Actuators, A*, 2023, **350**, 114093.
- 349 S. Lj. Stupar, *et al.*, Functional nano-silver decorated textiles for wearable electronics and electromagnetic interference shielding, *Mater. Today Commun.*, 2023, **34**, 105312.
- 350 A. Naysmith, N. S. Mian and S. Rana, Development of conductive textile fabric using Plackett–Burman optimized green synthesized silver nanoparticles and *in situ* polymerized polypyrrole, *Green Chem. Lett. Rev.*, 2023, **16**, 2158690.
- 351 İ. İlhan, İ. Özkan and Ö. Uslukul, An Experimental Study on EMI Shielding and Antibacterial Activity of Woven Fabrics Including Silver Nanocomposite Yarns, *AATCC J. Res.*, 2024, **11**, 124–138.
- 352 P. L. Jagadeshvaran and S. Bose, Nano silver-deposited cotton textile core with carbon nanostructure-filled shell for suppression of electromagnetic radiation *via* absorption-reflection-absorption, *Mater. Chem. Phys.*, 2023, **293**, 126897.
- 353 C. Gao, *et al.*, Multifunctional fabrics embedded with polypyrrole-silver/silver chloride nanocomposites for solar-driven steam generation and photocatalytic decontamination, *Sep. Purif. Technol.*, 2023, **323**, 12447.

