

1 **Cellulose-deconstruction potential of nano-biocatalytic systems: A strategic drive**
2 **from designing to sustainable applications of immobilized cellulases**

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22 **Abstract**

23 Nanostructured materials along with an added value of polymers-based support carriers
24 have gained high interest and considered ideal for enzyme immobilization. The recently
25 emerged nanoscience interface in the form of nanostructured materials combined with
26 immobilized-enzyme-based bio-catalysis has now become research and development
27 frontiers in advance and applied bio-catalysis engineering. With the involvement of
28 nanoscience, various polymers have been thoroughly developed and exploited to
29 nanostructured engineer constructs as ideal support carriers/matrices. Such
30 nanotechnologically engineered support carriers/matrix possess unique structural,
31 physicochemical, and functional attributes which equilibrate principal factors and

32 strengthen the biocatalysts efficacy for multipurpose applications. In addition, nano-
33 supported catalysts are potential alternatives that can outstrip several limitations of
34 conventional biocatalysts, such as reduced catalytic efficacy and turnover, low mass
35 transfer efficiency, instability during the reaction, and most importantly, partial, or
36 complete inhibition/deactivation. In this context, engineering robust and highly efficient
37 biocatalysts is an industrially relevant prerequisite. This review comprehensively covered
38 various biopolymers and nanostructured materials, including silica, hybrid nanoflower,
39 nanotubes or nanofibers, nanomembranes, graphene oxide nanoparticles, metal-oxide
40 frameworks, and magnetic nanoparticles as robust matrices for cellulase immobilization.
41 The work is further enriched by spotlighting applied and industrially relevant
42 considerations of nano-immobilized cellulases. For instance, owing to the cellulose-
43 deconstruction features of nano-immobilized cellulases, the applications like
44 lignocellulosic biomass conversion into industrially useful products or biofuels, improved
45 paper sheet density and pulp beat in paper and pulp industry, fruit juice clarification in
46 food industry are evident examples of cellulases, thereof are discussed in this work.

47 **Keywords:** Cellulose-deconstructing enzymes; Immobilization; Nanostructured carriers;
48 Polymeric supports; Bio-catalysis; Sustainability; Food industry

49

50 **1. Introduction**

51 Enzymes are extremely efficient biocatalysts being extensively employed in various
52 industrial and biotechnological processes. Cellulase (EC 3.2.1.4) is one of the important
53 enzymes, frequently used for the hydrolysis of 1,4-glycosidic linkages among cellulose
54 molecules to synthesize monosaccharides subunits. Cellulases exhibit numerous
55 applications in pharmaceutical, pulp & paper, detergents, chemical, food, and biomedical
56 sectors [1-4]. Moreover, cellulases could be employed for the fermentation of
57 lignocellulosic biomass to produce biofuels [5-8]. However, much concern has been
58 devoted towards the stability and reusability of cellulases that restricted its industrial
59 applications [9-13]. Recently, the microbial production of cellulases using cost-effective
60 methodologies, and to overcome the research challenges has been remarkably
61 considered for the cellulases to improve industrial applications [14,15]. Although cellulase
62 enzyme exhibit several applications in industrial and biomedical sectors, majority of these

63 cellulase types suffer from low pH and thermal stabilities in various media. Moreover, their
64 utilization is also restricted because of their lack of recyclability. Various methods e.g.,
65 chemical modifications, protein engineering, and their immobilization in different
66 biopolymers and nanomaterials could be used to enhance enzymatic stability and
67 recyclability potential [10,11,13,14,16]. Figure 1 shows significant potential of
68 nanomaterials for enzyme immobilization [17]. Among all, immobilization provides more
69 benefits regarding heterogeneous catalytic reactions and to overcome the lack of
70 recyclability [18,19].

71 Immobilization methodologies could be divided into three major classes such as (i)
72 surface immobilization [20,21]; (ii) self-immobilization [22]; and (iii) entrapment [23-25].
73 These methodologies are extensively adopted for the immobilization of biocatalysts that
74 could be inorganic or organic, e.g., polymers, polysaccharides, proteins, activated carbon,
75 and metal nanoparticles [13,16,26]. However, the efficiency of immobilized biocatalyst on
76 its stability, support separation from product, extent of recyclability, and the activity after
77 immobilization are the key factors which are carefully considered while using a support
78 material [10]. Among all supports, nanostructured materials have special place regarding
79 their distinguished high surface area along with other characteristic features that enable
80 higher enzyme loading efficacy (Figure 2) [17,22,27]. However, the enzymes
81 immobilization using nanostructured materials may be restricted due to the issues with
82 recovery, such as filtration or centrifugation for industrial biotechnological applications,
83 which have created serious issues with the processes e.g., extraction and purification of
84 enzymes. These limitations could be removed by employing magnetic nanoparticles as a
85 promising support material for biomolecules e.g., nucleic acids, antibodies, enzymes, and
86 peptides, with high recovery and recyclability potential [9,28]. The convenient process for
87 the recovery of magnetic nanocarriers from the reaction mixture could be the employment
88 of magnetic field and their less toxic nature make these nano-supports as promising
89 materials for enzyme immobilization [9,22,29]. Except these several biopolymer and
90 nano-structured supports have also been employed for the immobilization of cellulases
91 for functional applications.

92 Typically, there are four different immobilization modes of enzymes e.g., entrapment,
93 covalent attachment, physical adsorption, and crosslinking. Attachment of enzymes and

94 support matrix can be covalently or weakly and physical or chemical [10]. Physical
95 attachment of enzyme with support matrix is relatively weaker than covalent binding, and
96 it has lower capability of keeping enzyme fixed to the support matrix. The support
97 materials are generally polymers/biopolymers, and nanocarriers. In entrapment, the
98 enzymes are integrated on a membrane apparatus such as polymer network e.g., an
99 organic polymer or a silica sol-gel, desolate fiber, or a microcapsule. The formation of a
100 polymer network is required for entrapment in the presence of enzyme. The formation of
101 enzyme aggregates or crosslinking crystals by the utilization of crosslinking or bifunctional
102 agent is another mode of immobilization of enzymes [30]. Carrier-binding or physical
103 adsorption mode of immobilization uses water-insoluble carriers e.g., synthetic polymers,
104 polysaccharide derivatives, and glass [31,32]. In covalent binding or crosslinking,
105 crosslinker reagent e.g., hexamethylene diisocyanate, bisdiazobenzidine, and
106 glutaraldehyde are required [33]. Different polymers such as carrageenan, collagen, and
107 cellulose are used by entrapment mode. However, membrane confinement require the
108 formation of microcapsules and liposomes [34,35].

109 Immobilization of enzymes using membrane entrapment method is reported to be an
110 excellent biochemical engineering approach because it enable continuous operations,
111 stability enhancement, and retention in bioreactors. In membrane bioreactor, physical
112 adsorption immobilization reduce the loss of catalytic activity of enzymes and enhance
113 the recyclability potential ultimately decreasing the bioprocess cost [36]. The enzyme
114 immobilization is preferred over free enzymes due to its long-term availability that reduce
115 the excessive purification methodologies. The enzyme recovery method could be the
116 ultrafiltration which require the utilization of membrane systems allowing the passage of
117 small molecules and keeping the enzyme in bioreactors. Membrane fouling is another
118 important factor to consider while the operation and development of membrane system
119 because it effects the performance, operational cost, cleaning needs, and pretreatment
120 requirements [37]. There are few other modes of enzymatic immobilization which could
121 be the combination of above-mentioned processes, which are particular for specific
122 enzyme or matrix. Nevertheless, not a single method or support matrix is efficient for all
123 enzyme kinds and their usage because of array of different product utilization,
124 characteristics of enzymes, substrates, and products, and the chemical composition.

125 This review discusses the current advancements in engineering aspects of novel nano-
126 structured and biopolymer-based support materials for their effective deployment for
127 cellulase immobilization (Figure 3). Moreover, the exceptional features of various
128 nanomaterials such as silica, hybrid nanoflower, carbon nanotubes/nanofibers,
129 nanomembranes, graphene oxide nanoparticles, and metal-oxide frameworks have also
130 been reviewed as robust matrices for cellulase immobilization. Several biotechnological
131 applications of immobilized cellulases such as cellulose hydrolysis, pulp and paper
132 industry, food industry, and other potential multifunctional applications have also been
133 reviewed in this article.

134 **2. Immobilization of cellulases on polymers-based supports**

135 **2.1 Cellulases immobilization on Ca-alginate**

136 Ca-alginate entrapment is an important strategy for the immobilization of enzymes [25].
137 Alginates are biopolymers which are commonly present in the market as water soluble
138 Na-algicates. Ca-alginate entrapment is recognized as inexpensive, non-toxic, rapid, and
139 versatile technique for the immobilization of various cells and enzymes [38]. Alginates are
140 biopolymers obtained from marine plants, composed of unbranched linear polymer chains
141 consisting of α -(1,4)-linked L-guluronic acid, and β -(1,4)-linked D-mannuronic acid
142 residues. It results in the development of thermostable and biocompatible hydrogels in
143 the occurrence of Ca^{2+} ions [39,40]. The use of alginate as immobilization support for
144 bioprocessing application provides high thermo- and pH stable gels to use at room
145 temperature. Alginates synthesize gels with most divalent and multivalent cations. In
146 addition, the gelation could not be induced by Mg^{2+} and monovalent ions, however, Sr^{2+}
147 and Ba^{2+} induce stronger alginate gels than Ca^{2+} . However, the use of Ca-alginate gels
148 for enzymes immobilization has commonly been reported [25,41-43].

149 Andriani et al. [41] studied the immobilization of cellulase produced by *Bacillus subtilis*
150 strain isolated from puffer fish, using carboxy methyl cellulase (CMC) as substrate and
151 Ca-alginate as support-material. Different factors were optimized such as calcium
152 chloride concentration, sodium alginate concentration, pH, and temperature. The enzyme
153 showed high stability at pH 6, however, no changes were observed at maximum pH
154 before and after immobilization. The enzyme with greater stability was achievable at the
155 2% sodium alginate and 0.15 M calcium chloride solution. As compared to the free

156 enzyme, the slight increase in K_m and V_{max} was attained by kinetic studies. The
157 immobilized enzyme showed high recyclability up to four times without significant loss in
158 initial activity. The enzyme lost its activity at 30 °C within three days but the storage
159 stability was more efficient at 4 °C and remained active up to 12 days [41]. Similarly, Viet
160 et al. [44] studied cellulase immobilization using Ca-alginate entrapment. The 2% of
161 sodium alginate content was reported efficient for the formation of stable alginate beads.
162 The CMC was used as a substrate to analyze the cellulase activity. The beads with 3 mm
163 diameter and 30 min immobilized time showed the maximum (83.645%) efficiency for
164 enzyme immobilization. The optimum pH 4.5 was observed for cellulase immobilization.
165 As compared to the free cellulase, the highest optimum temperature of 55 °C and 60 °C
166 was calculated from immobilized enzyme. The 69.2% activity retention after 5 consecutive
167 cycles indicated good storage stability of immobilized enzyme [44].

168 Sankarraj and Nallathambi, [45] immobilized cellulase enzyme on to hybrid Con-A
169 (concanavalin A) covered by the calcium alginate–starch beads. The jack beans were
170 used to isolate the Con-A and SDS-PAGE analysis was used for the determination of
171 crude protein. The high storage stability and mechanical properties were observed by the
172 immobilized cellulase that even after a month of incubation, showed 100% and 85%
173 activities at 4 °C and 30 °C, respectively. The free form of enzyme maintained 20% of its
174 activity even after 5 consecutively repeated experiments, however, the immobilized
175 cellulase retained 70% of its activity that demonstrates its better thermal stability after
176 immobilization. The research provided a facile process for the immobilization of cellulase
177 for improved stability and recyclability perspective [45]. Another study conducted by
178 Abdel-Sater et al. [46] reported cellulase production by *Penicillium brevicompactum*
179 specie and the enzyme was immobilized in Chitosan-alginate beads using magnetic
180 nanocarriers and glutaraldehyde as crosslinking agents. The optimizational results
181 indicated pH 6 and 30 °C temperature to achieve the maximum cellulase activity in the
182 medium containing sodium nitrate and palm date leaves incubated for 9 days. The high
183 structural stability was observed after the ammonium sulfate precipitation due to the two-
184 folded increase in enzymatic activities. It was observed that acidic pH and high
185 temperature favors the precipitated enzyme. The maximum activity at pH 5.5 and 50 °C
186 temperature was achieved by immobilized cellulase which was remained excellent up to

187 80 °C. Different conditions such as resistant to microbial invade, nontoxicity,
188 biocompatibility, easy synthesis, and moderate gelatin conditions play important role for
189 the desirability of enzyme encapsulated within alginate beads. For different
190 biotechnological and industrial demands, the immobilized enzyme shows the usefulness
191 proven by the study [46].

192 In a recent report, Imran et al. [42] studied the production of cellulase from *Aspergillus*
193 *tubingensis*, and the enzyme was immobilized using Ca-alginate as support material. The
194 excellent increase in catalytic activity and stability was determined. As compared to the
195 free enzyme after 26 h incubation, the immobilized cellulase showed 82% thermostability
196 at high temperature (75 °C). For both free and Ca-alginate immobilized cellulase, the
197 enzymatic activities were decreased after the 20th day of incubation. The activity of
198 cellulase ($179 \pm 0.4 \text{ UmL}^{-1}\text{min}^{-1}$) for xerogel matrix was obtained at 45 °C and it exhibited
199 the activity of ($174 \pm 0.4 \text{ UmL}^{-1}\text{min}^{-1}$) at pH 4.5. The highest K_m values were noticed for
200 the immobilized enzyme as compared to the free cellulase; however, lowest K_m was
201 observed by xerogel immobilized enzyme. The enhanced tolerance capacity of 75–82%
202 was observed for the immobilized cellulase on Ca-alginate and xerogel matrix in
203 opposition of activators and or inhibitors like EDTA, SDS, Hg²⁺, Co²⁺, and Ca²⁺ [42]. These
204 studies proved the immobilized cellulase as an excellent candidate for industrial and
205 biotechnological uses due to enhanced fruit juice saccharification.

206 **2.2 Cellulases immobilization on chitosan**

207 Chitosan as a functional material, offers various desirable characteristics including
208 hydrophilicity, gel forming properties, heavy metal ions chelation, antibacterial properties,
209 physiological inertness, nontoxicity, biodegradability, biocompatibility, and remarkable
210 affinity to proteins. Due to these novel features, chitosan-based materials are yet under-
211 studied, and can be expected to be frequently explored in near future for various
212 bioprocessing applications including immobilization supports [25,47,48]. For instance,
213 Abd El-Ghaffar and Hashem, [49] studied the immobilization of cellulase enzyme onto
214 chitosan, chitosan–4-amino butyric acid, and chitosan–L-glutamic acid supports using
215 covalent crosslinking approach. The assay was performed at 25 °C and pH 7, and
216 retention in cellulase activities were observed for the chitosan, chitosan–4-aminobutyric
217 acid crosslinked with 1% of glutaric dialdehyde, and chitosan–L-glutamic acid as 65.52%,

63.19%, and 85.32%. As compared with free enzyme, immobilized enzyme exhibited better pH, thermal, and storage stability profiles. The immobilized enzyme maintained 60% of its initial activity 6-times from its original activity after the immobilization on chitosan-GDA (1%). The change was not observed even after the 10th cycle for chitosan-glutamic acid-GDA (1%) and chitosan-4-aminobutyric acid-GDA (1%) immobilized cellulase. For above-mentioned carriers, the 70% and 50% of activities were maintained after the 25 consecutively repeated experiments [49]. Similarly, Miao et al. [50] used Fe₃O₄ nanoparticles onto chitosan for direct immobilization of cellulases *via* glutaraldehyde crosslinking to form nano-supports of magnetic chitosan microspheres. Different conditions for enzyme immobilization were also optimized which indicated 5 h incubation, 15 mL (0.1 mg/mL) enzyme, temperature 30 °C and pH 7. The enzymatic recovery was 73.5 mg/g (71.6%) of maximum solid loading rate was observed for medium-chain triglycerides (MCTs) at optimized conditions. The immobilized cellulase can be regenerated and reused without significant loss in activity for 3 consecutive experiments. However, the better storage stability and thermal optima were observed for the immobilized cellulase as compared with free cellulase [50].

Sánchez-Ramírez et al. [28] studied the production and immobilization of *Trichoderma reesei* cellulase using chitosan-coated magnetic nanocarriers as support material *via* glutaraldehyde as coupling agent. Magnetic nanocarriers (around 10 nm diameter) were formed after cellulase immobilization however, 8 nm diameter was observed before immobilization. The enhanced thermal and storage stability was analyzed for immobilized cellulase along with the 37% retention of initial activity. The magnetic field was applied to separate the cellulase and after 15 cycles of CMC hydrolysis, immobilized enzyme maintained around 80% of its initial activity. Kinetic studies indicated about 8 times increase in K_m value of immobilized enzymes as compared with free enzyme. The hydrolyzed *Agave atrovirens* leaves-based lignocellulosic material showed the ability to reuse in material hydrolysis up to four consecutively repeated experiments with 50 % of activity retention. Lignocellulose hydrolysis showed the yield near to the activity obtained from free enzyme [28]. Similarly, Díaz-Hernández et al. [51] studied cellulase and xylanase immobilization by chitosan coated magnetic iron oxide nanoparticles produced in single step *via* alkaline precipitation to get maximum enzyme loading. Overall, 93%

249 magnetic saturation of the magnetite was achieved by the crosslinking of chitosan-coated
250 magnetite particles ($\text{Fe}_3\text{O}_4@\text{chitosan}$) with cellulase and xylanase enzymes. The
251 characterizational analysis indicated that the 12 mg enzyme per 1 g of magnetic support,
252 and 162 mg of chitosan was coated on 1 g of nanocomposite. The crosslinking between
253 cellulase and $\text{Fe}_3\text{O}_4@\text{chitosan}$ support was confirmed by characterization analysis. The
254 average particle size of 230–430 nm was reported for supports before and after
255 immobilization [51].

256 Mo et al. [52] used sugarcane bagasse to prepare the porous biochar which was covered
257 with varying quantities of chitosan for cellulase immobilization using glutaraldehyde as
258 the crosslinker (Figure 4). Characterizational analysis indicated that high thermal and pH
259 stability after immobilization. Furthermore, the good reusability and activity was also
260 observed for these three types of immobilized cellulases. For cellulase@CS25, the
261 support maintained the better morphology of porous biochar with the feeding ratio
262 (biochar: chitosan, 0.5 g:25 mg). The associated immobilized cellulase demonstrated the
263 90.8 % of glucose production even after 10 repeated experiments and maintained 67 %
264 activity of free enzyme at pH 4 and 60 °C [52]. In another study, Mo and Qiu, [53] prepared
265 porous biochar by pyrolyzing sugarcane bagasse followed by calcination for the
266 magnetization with $\gamma\text{-Fe}_2\text{O}_3$. The synthesized chitosan/magnetic porous biochar was
267 employed as an immobilization support material for cellulase by covalent bonding after
268 fabrication with chitosan activated by glutaraldehyde. The pH 5 and temperature 25 °C
269 for 12 h of incubation showed 80.5 mg cellulase/g support amount for efficient
270 immobilization of cellulase. Varying pH and temperature were used to study the CMC
271 hydrolysis Both free and immobilized enzymes showed optimum values as pH 4 and
272 temperature of 60 °C. The relatively high enzyme recovery of 73.0% was recorded for the
273 immobilized cellulase. Moreover, the slower maximum reaction velocity (V_{\max}) and higher
274 K_m values were reported than free cellulase [53].

275 **2.3 Cellulases immobilization on hybrid polymers-based supports**

276 Various hybrid polymer-based support matrices have been reported for the immobilization
277 of cellulases for bioprocessing applications. For instance, the use of reversible insoluble-
278 soluble enteric polymer coupled with carbodiimide to perform covalent immobilization of
279 a commercial cellulase was performed by Yu et al. [54]. The binding efficiency (81.08%)

of covalently immobilized Eudragit-cellulase was greater as compared with non-covalent Eudragit-cellulase (56.83%). The optimum pH 5 and temperature 50 °C caused the increase in the relative activity of both immobilized and free cellulase; however, more increase in pH and temperature showed the negative impacts on the activity of both native cellulase and covalent Eudragit-cellulase. The higher pH and temperature showed higher stability for the covalent Eudragit-cellulase. The free cellulase had the K_m value of 2.89 g/L, less than that of covalent Eudragit-cellulase (4.78 g/L). The immobilization on the Eudragit S-100 tend to increase the affinity of the cellulase to its substrate [54].

Ince et al. [55] used surface initiated-atomic transfer radical polymerization for grafting the poly(styrene-divinylbenzene) (PS-DVB) microspheres with the polystyrene. In next step, sulfuric acid in the existence of P_2O_5 was used to proceed the sulfonation of the grafted polystyrene chains. Aniline (4.8 mmol/g) was applied on the surface to neutralize the sulfonic acid groups. The oxidation of potassium persulfate was carried out to provide the self-doped and thick (16 μ m) PANI layers on the microstructures. The oxidized potassium persulfate was further used to polymerize the adsorbed aniline achieved by previous stage. The adsorption/crosslinking methodologies were used to immobilize the cellulase on the polyaniline coated PS-DVB-g-PS micro-spheres. As compared with free enzyme, the immobilized cellulase had the excellent storage stability, higher maintenance of activities relative to the temperature and pH [55]. Similarly, Romo-Sánchez et al. [56] studied immobilization of two enzymes (cellulase and xylanase) on two polymeric support matrices (alginate-chitin and chitosan-chitin) via different chemical ways such as crosslinking-adsorption, reticulation, and adsorption to improve stability and recyclability of enzymes. The chitosan polymer was proved as an ideal support by giving 170 μ g/mL of optimal enzyme concentration for cellulase. However, 127.5 μ g/mL for the xylanase. Moreover, the optimal pH binding of cellulase was 4.5 and for xylanase was 5.0. The immobilization procedure showed the better stability after the application of lower amounts of glutaraldehyde. The use of glutaraldehyde enabled the activity retention up to 64% after immobilization of cellulase for 19 cycles [56].

The use of core–shell polymer–protein nanocarriers for cellulase immobilization was reported by a recent study [57]. The immobilization of His6-tagged cellulases with controlled spatial orientation of enzymes was achieved through the synthesis of functional

311 polymeric micelles that collectively potent towards the hydrolysis of cellulose known as
312 cellulosomes. The one-pot reversible addition–fragmentation chain-transfer
313 polymerization was used for the formation of poly(styrene)-b-poly(styrene-alt-maleic
314 anhydride), followed by the usage of nitrilotriacetic acid (NTA) to attain amphiphilic block
315 copolymer. The Ni-NTA-functionalized micelles were prepared by the mixing of self-
316 assembled polymer with the solution of NiSO₄. These functionalized micelles were able
317 to synthesize core–shell nanostructures with cellulases as the immobilized biocatalyst
318 after the capturing of His6-tagged cellulases. Synergistic analysis has been achieved in
319 this study resulting from over twofold activity enhancement because of the site specificity
320 and close proximity of site particular oriented enzymes [57].

321 **2.4 Cellulases immobilization on other polymers**

322 The development of cellulase bioconjugates with N-iso propyl methyl acrylamide with N-
323 (Hydroxymethyl) acrylamide and methyl acrylate for recyclable thermo-responsive
324 immobilization support was studied by Ding et al. [58]. The process of construction of
325 bioconjugate is shown in Figure 5 [58]. Small-molecular quenching was applied for the
326 adjustments of the LCST by the aminoxy polymerization of N-isopropylmethacrylamide
327 (PNMN). PNMN by carbodiimide bioconjugate (PNMN-C) was covalently linked with the
328 cellulase. The highest immobilization yield was 83.2% for the polymer-cellulase
329 bioconjugate construction under the optimized conditions. The free cellulase revealed the
330 maximum activity at 55.0 °C (pH 5.0) as compared to the polymer-cellulase bioconjugates
331 at 50.0 °C (pH 5.0). After repeated five hydrolysis experiments, 85.2% of initial activity
332 was maintained for polymer-cellulase bioconjugate. As compared to the LCST, PNMN
333 could be collected as precipitate after dissolving and efficient use at 50.0 °C [58].

334 The impactful carriers favorable for the cellulase immobilization were investigated by Tata
335 et al. [59] by free radical cross-linking co-polymerization in reverse suspension to prepare
336 the copolymers of divinylbenzene (DVB) and N-vinylformamide (NFV). The variation of
337 spherical and crosslinking nanoparticles with variable sizes were used for the synthesis
338 of nanocarriers types based on P(NVF-co-DVB). The three (VAM-co-DVB) polymers with
339 vinylamine units were achieved after the hydrolysis of the formamide carrier group into
340 the amino groups. The vinyl formamide groups (without glutaraldehyde) and VAM (with
341 glutaraldehyde) were used for cellulase immobilization. The efficient immobilization of

342 cellulase was achieved by tested carriers that act as excellent support materials. But as
343 compared to the native enzyme, the enzyme immobilized on the P(VAM-co-
344 DVB0.27)/2000/350 carrier showed the highest catalytic activity [59].
345 The production of cellulose-derived bioethanol was studied by cellulase enzyme
346 immobilization to enhance the catalytic productivity and cellulase reusability [60]. The
347 visible light induced graft polymerization on low-density polyethylene films, fabricated by
348 a layered structure with a thin poly(ethylene glycol) gels as the inner layer and sodium
349 polyacrylate (PAANa) brush as the outer layer. This hierarchical support showed for the
350 immobilization of two enzymes i.e., cellulase and β -glucosidase. The β -glucosidase from
351 the LDPE surface was *in situ* entrapped into inside hydrogels layer during the polymeric
352 grafting to improve the catalytic efficiency additionally to cellulase. The cellulase was
353 covalently immobilized on to the outer PAANa brush layer during the reinitiating of sodium
354 acrylate after its polymerization on the PEG hydrogel layer. The β -glucosidase could
355 attain the high activity after the graft polymerization because of the slight reaction such
356 as visible-light irradiation. The optimal temperature of cellulase and the β -glucosidase or
357 the optimal pH did not change during the immobilization. But after the immobilization, the
358 sudden shift of pH 5.0 was observed in case of cellulase. The dual enzyme system
359 showed the 82% and 20% enhanced enzymatic efficiency contrasting with the original
360 activity of isolated BG/cellulase immobilization system and single cellulase system. The
361 repeated experiments up to 10 cycles of CMC hydrolysis relative to original activity shows
362 high stability and recyclability of enzyme after immobilization [60].

363 **3. Cellulases immobilization on nanosupports**

364 **3.1 Cellulases immobilization on silica-based supports**

365 The electrostatic interaction is an important factor to consider for the intensification of
366 adsorption rate, while dealing with immobilized cellulases and other enzymes. Therefore,
367 the development of opposite surface charges on the enzyme and the carrier is considered
368 as basic factor [61]. Secondly, the adjustment of pore size for the entrapment of enzymes
369 is essentially must not be so large that it will cause desorption. Therefore, the similarity is
370 necessarily required in the mesopores size and the molecular dimensions of the
371 biocatalysts [25,62]. Cellulases exhibit high affinity with hydrophobic surfaces, therefore,
372 the hydrophobic groups of silica surfaces also have significant role in enzyme adsorption

373 and desorption. Poorakbar et al. [63] developed mesoporous silica-magnetic Au-NPs
374 core-shell for the immobilization of cellulase enzyme. Santa Barbara Amorphous-15
375 (SBA-15) was used for the early immobilization of cellulase on mesoporous silica-based
376 nano-support [64,65]. The accommodation of bulky enzymes was carried on the SBA-15
377 because of its larger pores size. Takimoto et al. [66] studied the cellulase produced from
378 *Trichoderma viride*, immobilized on SBA-15 nanosupports with different pore sizes of 4,
379 8.9, and 11 nm. The SBA-15 (isoelectric point (*pl*) = 3) was negatively charged and the
380 cellulase (*pl* = 4.9) was positively charged. The electrostatic interactions were considered
381 as the driving force for the enzymatic adsorption on nano-supports [66]. The
382 measurements were taken at pH 4.0 and 37 °C for cellulase activity determination based
383 on the hydrolysis of crystalline cellulose. The highest activity was reported by the use of
384 intermediate pore sized support, regardless of conviction that the largest pore size
385 support indicated the smallest increase in the amount of absorbed enzyme. The smaller
386 pores of silica were not enough to penetrate the large microcrystalline cellulose. The
387 cellulase was primary entrapped in the interior of the pores (11 nm sized) support,
388 however, in case of .9 nm pore size, the cellulase molecules were located at or very close
389 to the entrance of the pores. The immobilized nanobiocatalyst showed improved storage
390 stability and recyclability [66].

391 Hartono et al. [67] studied the immobilization of cellulase *via* physical adsorption using
392 organo-operational FDU-12 type mesoporous silica-based supports. The immobilization
393 showed favorable behavior towards FDU-12 materials with larger pore size and high pore
394 connectivity. However, the desired interaction between enzyme and silica support was
395 achieved by surface modification through selective functionalization. This development
396 was carried out by the co-condensation of organosilanes (trimethylbenzene), vinyl-
397 (VTMS) trialkoxysilane, 3-mercaptopropyl (MPTMS), 3-aminopropyl- (APTES) and
398 TEOS. S-APTES and S-VTMS were selected for further studies. The loading capacity of
399 S-APTES (21.80 mg/g) was higher than the S-VTMS (18.19 mg/g). While, the FDU-12
400 had the 10.35 mg/g of support loading capacity, which was less than both functionalized
401 nanocomposites. The adsorption pH 4.8 gave the negative charge to the support matrices
402 and the enzymes which contributed to the loading capacity of S-VTMS to provide the
403 hydrophobic interactions between the vinyl group and the enzyme. The CMC hydrolysis

404 revealed higher activity retention (up to 70% of the free enzyme) for S-VTMS, while the
405 S-APTES showed less activity (3.4%) of the free enzyme. The formation of amide bonds
406 at the enzyme active site imparted less S-APTES activity due to the active site of cellulase
407 which contained these residues. The benign microenvironment for cellulase activity was
408 developed due to the presence of hydrophobicity in S-VTMS. The S-VTMS reattained
409 100% of its initial activity after 15 days with very minute leaching [67].

410 Harmoko et al. [68] investigated the co-condensation optimization of tetraethyl
411 orthosilicate (TEOS) and conc. vinyltrimethoxysilane (VTMS) in term of particle size for
412 cellulase immobilization. The nano and micro particles were synthesized by varying the
413 VTMS/TEOS ratio along with pore entrance of 5-6 nm and pore size of 9-10 nm. This
414 study revealed the higher activity for the cellulase immobilized on silica nanoparticles in
415 contrast to microparticles with immobilized cellulase. This feature was explained by higher
416 microparticle channel length that caused the inactivity of enzyme. The efficient contact
417 between enzyme and substrate was observed due to the short channel length of
418 nanoparticles which prevent the formation of inactive site along the pore channels [68].
419 Similarly, Chang et al. [69] developed silica nanoparticles of ultra large pore (20–40 nm)
420 and small pore size of 2-5 nm. Dimethyl phthalate as pore expander was utilized for the
421 formation of larger pore sized materials by co-condensation with 3-
422 aminopropyltrimethoxysilane. They immobilized the enzyme on large porous silica by
423 both physical adsorption and covalent binding. The functionalized silica was prepared by
424 covalent crosslinking of cellulase to (3-triethoxysilylpropyl) succinic acid anhydride (TESP-
425 SA). High immobilization efficiency was reported by large pore sized silica as compared
426 with smaller pore size. The presence of both Si-OH and Si-NH₂ groups provided the larger
427 pore size to the silica supports than cellulase molecule size. Therefore, electrostatic
428 interaction between cellulase and Si-NH₂ enabled easy physical adsorption [69].

429 The ionic liquid method was applied to synthesize the oligomers of cellulose. The glucose
430 yield of free cellulase was approximately 85% which plotted further against the glucose
431 yields of the three biocatalysts were 33.30%, 77.89%, and 83.79%, respectively. The
432 importance of pore size of the host material was proved by the results [70]. The carboxylic
433 groups showed the binding with the cellulose-binding domain. The covalent crosslinking
434 was shown by the storage stability of TESP-SA that hinder enzyme leaching, however, it

435 showed 86.56% of glucose yield after 23 days' storage at room temperature. The direct
436 linkages between carboxylic acids possibly present in the active site of the enzyme and
437 –NH₂ of APTES was avoided by the operated silica-surface with APTES, followed by
438 glutaraldehyde crosslinking. The steric constraints are avoided by the glutaraldehyde
439 acting as a spacer arm between the matrix and the enzyme. In another study, Kannan
440 and Jasra, [71] studied the *Penicillium funiculosum* cellulase immobilization on meso-
441 cellular foams *via* covalent linking. The operated reactions was consisted of APTES with
442 amino functionalization and glutaraldehyde crosslinking. The pore size was decreased
443 from 21.8 nm to 10.8 nm by the crosslinking of meso-cellular foams; however, the pores
444 had sufficient vacuum for cellulase shelter. The modified meso-cellular silica with surface-
445 functional groups for CMC hydrolysis was shown with greater activity of the immobilized
446 enzyme. Furthermore, the immobilized enzyme showed higher V_{max} (9.8 U/mg) in contrast
447 to free enzyme (5.3 U/mg). The enzyme and meso-cellular silica surface revealed
448 opposite charges at pH 5. However, the diffusion of substrate molecules and enzyme was
449 easy due to larger pore size. Moreover, 66% of the initial activity was retained after 15
450 reaction cycles which exhibited excellent stability of immobilized cellulase [71].
451 Yin et al. [72] studied the immobilization of cellulase enzyme using mesoporous silica
452 (SBA-7) as support material without the NaBH₄ reducing. They found 8-fold increase in
453 V_{max} assigned to the stability enhancement after immobilization. Limited substrate
454 diffusion was observed inside the pores due to increased K_m value. The support materials
455 maintained the enzymatic tertiary structure at high temperature. The multi-point
456 attachment caused the higher activity of immobilized cellulase in broad range of pH and
457 increase in thermal stability at 60 °C. After 11 cycles of reaction, the 88% of initial activity
458 was conserved for immobilized cellulase. Similarly, Zhang et al. [73] studied
459 immobilization of cellulase on silica gel by covalent linking. Herein, the used surface
460 functionalization reduced the industrial-silica pore size from 10.6–16.2 nm to 7.7–10.6
461 nm. The loaded cellulase retained 7% of its initial activity in CMC hydrolysis with quantity
462 of 18.8 mg/g of silica gel. The activity loss was observed in three steps during reuse for
463 immobilized enzyme. The 82-100% of activity was reattained from 1st to 7th cycle, 60-
464 48% from 8th to 13th cycle, and 23-36% from 14th to 26th cycle. It was observed that the
465 enzyme desorption by support caused decomposition of outer surface and denaturation

in the vicinity of the pores at the 2nd stage. The conformational structure shifting was reported to protect the cellulase inside the pores. The storage of immobilized enzyme at 4 °C for 32 days retained the 92.4% of its initial activity and high storage ability [73]. Ungurean et al. [74] studied *Trichoderma reesei* cellulase immobilization using binary and tertiary mixtures of tetramethyl orthosilicate (TMOS) with methyl-(MeTMOS), and phenyl-trimethoxysilane (PhTMOS) for the development of nanobiocatalyst using sol–gel encapsulation method. MeTMOS/TMOS with 3:1 molar ratio and no additives were used to derive the best operating materials at 4.8 pH in CMC hydrolysis experiment. This study reported more than 90% of total enzyme recovery. The hydrolysis of microcrystalline cellulose (Avicel PH101) was used to study the catalytic efficiency of the entrapped enzyme. The decrease of the kinetic nature was observed by immobilized enzyme and longer reactions; however, after 24 h reaction, the immobilized enzyme showed the less glucose yield than the free one. The immobilized enzyme showed the 10–20% higher thermal stability as compared to free cellulase and increase in pH stability was observed in the pH domain 5.5–7.0. The rigidity provides the protection against undesirable modifications by preventing the denaturation and microenvironment inside the porous structure. An enhancement of enzyme/substrate affinity was used to explain the half K_m for the immobilized cellulase as compared to free one. The mass transfer resistance within the sol–gel matrix showed threefold decrease in V_{max} . The 20% leaching after the 6th cycle described the effective reusability potential for various applications [74]. Chen et al. [75] studied the synthesis of two mesoporous silicates having pore size of 3.8 and 17.6 nm, and the cellulase immobilization was performed by pure physical adsorption method. The pore size of the mesostructured support was associated with the enzyme loading. The 1.2-times higher cellulase loading was observed for MS-17.6 pore size. Some cellulase molecules of MS-3.8 played role in blocking the pore entrance. However, the cellulase molecules were easily well managed and adjustable into the MS-17.6 due to larger space. The opposite trend with respect to loading was observed during the measurement of activity of the two biocatalysts, in the CMC hydrolysis at 50 °C and pH 5.0. The MS-17.6 showed the less specificity of 26.6% as compared to the MS-3.8 displayed a higher specific activity (63.3% of free cellulase). The MS-3.8 was observed to increase the availability of active site, trapping of molecules in the pore entrance and

497 conserving the native structure of cellulase. The conformational flexibility of cellulase
498 lowered its activity because of the obstruction caused by the dense and ordered
499 arrangement of MS-17.6. However, the interaction of substrate with the enzyme require
500 the conformational change [75].

501 **3.2 Cellulases immobilization on non-magnetic magnetic nanostructures**

502 Different methodologies have been designed to gain wide range of enzymatic applications
503 following low toxicity, enzyme recovery, excellent separation from the reaction mixture,
504 and improved stability for cellulase immobilization on magnetic nanoparticles (MNPs).
505 The cellulase immobilization on MNPs was proceeded by both the nonspecific physical
506 adsorption and covalent binding [20]. Different binding types have been observed such
507 as hydrophobic or stacking interactions, van der Walls, and electrostatic forces during the
508 enzyme's interaction with the surface of nanomaterials by non-covalent binding [76]. The
509 protein leakage from the surface of nanomaterial was observed as the major drawback
510 from the non-covalent immobilization. The leakage from the carrier and high operational
511 stability was observed during the covalent binding of enzymes [77]. The nanomaterials
512 characteristics such as size, functionalization and structure greatly influence the catalytic
513 behavior and stability of cellulase to determine the effect of magnetic nanoparticles [78].
514 The conformation and biological function of conjugated enzymes, adsorption effect, and
515 nanomaterial interaction with protein molecules are greatly influenced by the surface
516 chemistry of these nanomaterials [79]. For example, aiming to increase the enzymatic
517 stability, the immobilization was performed on superparamagnetic nanoparticles through
518 ionic linking [80]. Figure 6 shows cellulase immobilization onto iron oxide nanoparticle
519 surfaces [78].

520 In different experiment to increase the magnetization of nanoparticles and saturation, an
521 activated magnetic support using zinc doping was applied for cellulase immobilization by
522 Abraham et al. [81]. The loading of the enzyme was increased by series of porous
523 terpolymers with crosslinking through suspension and polymerization [82]. In a recent
524 study, Abbaszadeh and Hejazi, [83] immobilized *Aspergillus niger* cellulase using amine
525 functionalized Fe₃O₄ magnetic nanoparticles via metal binding affinity immobilization. The
526 nano-biocatalytic characterization was performed for the cellulase immobilization by the
527 addition of any intermediate, and copper was selected as ligand for enzyme loading on

528 magnetic nano-supports in buffering surroundings. The relative enzyme activity 91% was
529 determined, and the amount of enzyme 164 mg/g of magnetic nano-supports, under the
530 optimized conditions. The immobilized enzyme exhibited more stability than free enzyme
531 tested by CMC hydrolysis at 1% concentration. Moreover, after five cycles of reusability,
532 immobilized enzyme reattained 73% of its initial activity. After 8 days of storage at 4 °C,
533 the immobilized cellulase reattained 84% of their initial activity and 70% of initial activity
534 for free cellulase [83].

535 Mo et al. [84] studied the cellulase immobilization using porous biochar-based support
536 material obtained from lignocellulose biomass due to its attractive properties i.e., poly-
537 porous structure and high specific surface area. The preparation of γ -Fe₂O₃ combined
538 with poly-porous biochar was performed by calcination which was used as support
539 material for the immobilization of cellulase. The highest immobilization capacity (266
540 mg/g) was achieved for cellulase immobilization with relative 73.6% activity as compared
541 with free enzyme. The results indicated that by increasing temperature, endothermal
542 process was occurred, which resulted high cellulase adsorption. Similarly, Paz-Cedeno
543 et al. [85] studied the immobilization of cellulase and xylanase enzymes using graphene
544 oxide-magnetic nanoparticles (GO-MNPs) as support-material for efficient synthesis of
545 cellulosic ethanol and other useful compounds. Homogeneous distribution of MNPs onto
546 the graphene oxide nanosheets was observed. The nanobiocatalysts were developed by
547 covalent crosslinking using hydroxysuccinimide and 1-ethyl-3-(3-
548 dimethylaminopropyl)carbodiimide. The designed nanobiocatalyst showed enhanced
549 efficacy for sugarcane bagasse hydrolysis and showed relative activities 66%, 70%, 70%,
550 88% after ten consecutively repeated experiments for xylanase, β -xylosidase,
551 endoglucanase, and β -glucosidase, respectively. The 80% and 50% nanobiocatalysts
552 efficiency was reported for cellulose and xylan hydrolysis, respectively. The results
553 indicated it as a potential candidate for cellulosic ethanol production.

554 **3.3 Cellulases immobilization on cross-linked enzyme aggregates**

555 The attractive concept that offers valuable technology is explained by the cross-linked
556 enzyme aggregates (CLEAs). Potential advantages of CLEAs are shown in Figure 7 [86].
557 Generally, the procedure of making CLEAs include physical precipitation followed by
558 glutaraldehyde crosslinking [87,88]. The resulting CLEAs exhibit improved enzymatic

activity and recyclability up to several folds than native enzyme [89]. However, the optimum recovery and handling of CLEAs is difficult because they are mechanically fragile [90]. Kim et al. [91] reported the formation of CLEAs entrapped in mesoporous silica, which did not show leaching through narrow channels. Moreover, significantly high enzyme loading, and improved activity was reported after CLEAs immobilization. The one-pot bioconversion of lignocellulosic biomass to fermentable sugars was achieved through the preparation of CLEAs with xylanase, cellulase and β -1,3-glucanase [92]. The development of CLEAs was carried out by three-phase partitioning (TPP) method. The crosslinking time of 7.5 h was given with glutaraldehyde (100 mM) as a chemical crosslinker. The initial 70% of activity was reattained at 70 °C compared to 30% for the free enzyme indicating good thermal stability of CLEAs. After the incubation for 11 weeks at 4 °C, more than 97% of activity was observed indicating excellent storage stability of CLEAs in contrast to 65% of initial activity for free enzymes. The reuse of CLEAs was made possible due to the presence of free enzymes in the hydrolysate inhibiting their restoration. The CLEAs caused the maximum hydrolysis of ammonia about 83.5% in 48 h while the free enzymes hydrolyzed the sugarcane bagasse about 73% [92]. Similarly, Perzon et al. [93] studied the formation of cellulase-CLEAs via precipitation and crosslinking method which proved as rapid and multifunctional way. There is still needed to elucidate the association between the process parameters and cellulase-CLEA final activity. The CLEAs made from cellulase (EC 3.2.1.4) were optimized for various factors. The different temperature, crosslinking time, and crosslinking concentrations were used for three types of participants such as ammonium sulfate, polyethylene glycol, tert-butyl alcohol. The polyethylene glycol and ammonium sulfate-CLEAs were recovered 29% and 17% of the free enzyme activity, respectively. However, the CLEAs synthesized with tert-butyl alcohol were inactive. The ammonium sulfate-CLEA only recovered 10% of its activity after one cycle whereas the polyethylene glycol-CLEA recovered 40% of the initial activity after four cycles which demonstrated the significance of precipitant on final CLEA activity instead of enzymatic activity in re-solubilization. The ammonium sulfate showed better performance in CLEAs while PEG was not capable to precipitate enzyme [93]. In another study, the supercritical carbon dioxide was used for the activation of cross-linked cellulase aggregates by Podrepšek et al. [94]. Several precipitating reagents such

590 as propanol, tetrahydrofuran, 2-propanol, acetone, ammonium sulphate, ethanol, and
591 methanol were used to analyze the enzyme precipitation. The highest enzyme activity
592 was achieved by the immobilized enzyme using optimized enzyme concentration of BSA
593 and glutaraldehyde. This study presented the efficient and cost-effective biosynthetic
594 process using 0.0625% glutaraldehyde concentration, and precipitant ethanol. The
595 enhanced level of reusability and stability of immobilized cellulase was reported. This
596 study also indicated more catalytic sites on spherical structure of CLEAs with high surface
597 area. The introduction of new catalytic sites proved beneficial for the nanobiocatalyst [94].
598 Due to increased depletion of fossil fuels, an alternative energy production way was
599 investigated using enzymatic conversion methodologies using renewable biomass
600 resources and formation of high-value chemicals are being promoted [95-100]. The
601 efficient pH and thermal stability, and recyclability have been reported by the enzymes
602 after immobilization. Jia et al. [101] studied the novel magnetic CLEAs development for
603 the immobilization of cellulase. High thermal and pH stability was observed by the CLEAs
604 immobilized enzyme as compared to free enzyme. The immobilized cellulase maintained
605 the 74% of its initial activity along with the successful magnetic separation after the
606 continual six repeated cycles of CMC hydrolysis. The immobilized enzyme showed the
607 high potential for biomass conversion, indicated by reusability (38% activity retention) up
608 to 4 cycles of biomass conversion and 21% yield during the hydrolyze of bamboo biomass
609 [101].

610 Jafari Khorshidi et al. [102] conducted study on the amine-functionalized $\text{Fe}_3\text{O}_4@\text{silica}$
611 core-shell magnetic nanoparticles for the immobilization of cross-linked aggregates
612 (CLEAs) of cellulase aiming to increase usability for the industrial bioconversion of
613 lignocellulosic materials to glucose and other renewable biomaterials. The significant
614 change was not observed in optimum temperature during the acidic behavior switched by
615 the optimum pH of the cellulase cocktail upon immobilization (cellulase CLEA–MNP). The
616 free cellulase lost all of its activity while the cellulase-CLEAs–MNP maintained about 45%
617 of its initial activity. However, at 80 °C, immobilized cellulase maintained 65% of highest
618 activity than the free enzyme. The highest thermal stability was developed at 65°C.
619 Cellulase CLEAs–MNP reattained 30% of its initial activity through six cycles of reusability
620 after the acute decrease during two cycles of CMC hydrolysis [102]. Similarly, Li et al.

621 [103] synthesized a new carrier-free cross-linked aggregates of cellulase (CLEAs-C)
622 through $(\text{NH}_4)_2\text{SO}_4$ precipitation and glutaraldehyde crosslinking. As a precipitant, 95%
623 of ammonium sulfate was used to prepare cellulase-CLEAs. The 50 mg/mL cellulase
624 concentration and 3% (v/v) glutaraldehyde was used in order to acquire the excellent
625 enzymatic activity. The optimum temperature was found to be 60 °C, while the pH 3.0
626 was found most effective. The CLEAs maintained the 80% of initial activity during the
627 storage for 28 days at 4 °C [103].

628 **3.4 Cellulases immobilization on metal oxide nanoparticles**

629 Different kinds of metal oxides (TiO_2 , ZnO , $\text{Fe}_2\text{O}_3/\text{Fe}_3\text{O}_4$, Bi_2O_3 , CeO_2 , SiO_2 , MoO_2) are
630 important for various applications including usability in gas sensors, dye sensitized solar
631 cells, and their catalytic, antimicrobial, electronic, electrical conductivity, and high optical
632 characteristics [104-106]. However, the high cost and environmental factors influence the
633 recovery and reusability of nanostructures. Therefore, immobilization and incorporation
634 are carried out by distinct type of substrates but finding of an appropriate substrate is still
635 a major concern. Various metal oxide nanostructures have been immobilized due to its
636 natural biopolymer properties. In paper matrices, the retention issues are resolved by
637 using the retention aids, binders, and appropriate linkers to conduct the immobilization
638 and incorporation [107,108]. The use of metal oxide nanoparticles for catalytic
639 immobilization purpose have widely been investigated [108-110]. For instance, Jordan et
640 al. [109] studied the immobilization of cellulase enzyme onto magnetic iron oxide (Fe_3O_4)
641 nanoparticles *via* carbodiimide activation and covalent binding. After the binding of
642 complex, no significant change in size was observed in the magnetic particles, and SEM
643 micrographs revealed a mean diameter of 13.3 nm. Enzyme was supported on the
644 saturation point occurred at a weight ratio of 0.02 and low enzyme loadings demonstrated
645 the maximum binding of 90%. The relative peak enzyme activity was analyzed at 50 °C
646 and enhanced stability was observed over the boarder range of temperature by thermal
647 measurements of nanoparticles. The shift in optimum pH from 4.0 to 5.0 was observed
648 by the ionic forces between the enzyme and support surface [109].
649 Xu et al. [111] studied cellulase immobilization on magnetic Fe_3O_4 nanoparticles through
650 glutaraldehyde crosslinking. No structural or particle size changes were observed by
651 binding step, and the mean diameter of 11.5 nm was observed in all the nanosized

652 particles of the magnetic particles with or without bound cellulase. The covalent binding
653 was observed between residual amine groups on magnetic Fe₃O₄ nanoparticles and
654 amine groups of the cellulase efficiently controlled the binding capacity of cellulase. As
655 compared to the free enzyme, improved storage stability and wider ranges of pH and
656 temperature was observed by immobilized cellulase. Immobilized cellulase showed the
657 greater affinity for cellulosic substrate than the free enzyme determined by the enzyme
658 kinetics. The hydrolysis of steam-exploded corn stalks and bleached sulfa the bagasse
659 pulp demonstrated the efficient performance for the immobilized cellulase [111]. Han et
660 al. [112] conducted a study for cellulase immobilization using the surface of magnetic-
661 Fe₃O₄ nano-supports modified by dendritic polymer 4-arm-PEG-NH₂. The covalently
662 immobilized cellulase was prepared by the glutaraldehyde that act as coupling agent for
663 the magnetic supports. Different characteristics such as reusability, storage stability,
664 optimum temperature, Michaelis constant, thermal stability and PH were analyzed.
665 Results indicated 132 mg/g loading ability of cellulase with wider range of pH,
666 temperature, storage, and functional stability as compared to the free cellulase. The 76%
667 increased catalytic activity was observed by immobilized cellulase as compared to the
668 free cellulase [112].

669 Abbaszadeh and Hejazi, [83] conducted metal affinity immobilization of cellulase on the
670 amine functionalized Fe₃O₄ magnetic nanoparticles (MNPs). The process was carried out
671 without any addition of intermediates, and copper was chosen as ligand and loaded on to
672 magnetic nanoparticles in buffering solution. The relative enzyme activity (91%) was
673 reported, and the amount of immobilized enzyme was 164 mg/g of MNPs under optimized
674 conditions (Cu/MNPs = 1, E/MNPs = 0.11, pH = 6). In contrast to the free enzyme, the
675 immobilized cellulase showed more stability tested by repeated CMC hydrolysis at 1%
676 concentration. Furthermore, 73% of initial activity of immobilized cellulase was reattained
677 after the 5 cycles of usability. The storage step at 4 °C showed the 70 and 84% of initial
678 activity for free and immobilized cellulase after the 8 days storage. This study proved as
679 an excellent candidate for various biotechnological and industrial sectors [83].

680 **3.5 Cellulases immobilization on carbon nanotubes/nanorods**

681 Different strategies have been applied for the synthesis of nanotubes of transition metal
682 chalcogenide materials such as the chemical vapour deposition, use of solid templates

and chalcogenization, etc. Carbon nanotubes formed by such transition metal chalcogenide materials are maybe single walled (SWCNT) or multi walled (MWCNT). Significant research has been conducted to immobilize biocatalysts on these carbon nanotubes and nanoroads. For instance, Mubarak et al. [113] studied the immobilization of cellulase enzyme on functionalized-MWCNT using physical absorption process to overcome the catalytic stability and efficiency issues. The optimum enzyme immobilization percentage of 97% was attained by the usage of 4 mg/mL enzyme concentration. The optimum reaction conditions were reported as 50 °C temperature and pH 5. Characterizational results indicated high efficiency of nanobiocatalyst because cellulase-MWCNT nanocomposite retained 52% of its initial activity after six repeated experiments of CMC hydrolysis. The convenient separation and high stability make it a robust candidate for various applications [113].

Ahmad and Khare, [114] reported the immobilization *Aspergillus niger* cellulase onto functionalized-MWCNT by carbodiimide crosslinking. MWCNT impart useful characteristics including rapid electrode kinetics, high edge-to-plane ratio, enhanced electronic properties and improved tensile characteristics because of structural arrangements. The nanobiocatalyst designed under optimized conditions exhibited high thermal and pH stability, with up to 85% activity retention. The half-life of nanobiocatalyst was 4-folds higher than free enzyme at 70 °C temperature. Two folds increase in K_m value of resulted nanobiocatalyst towards the substrate was reported. High reusability potential was reported by 10 consecutively repeated experiments without much actual enzymatic activity loss, which make it potential candidate for effective cellulose hydrolysis. Similarly, Ma'an et al. [115] studied the production of cellulase from *Trichoderma reesei* and the enzyme was immobilized on functionalized-MWCNTs via covalent crosslinking. Different parameters were optimized to get efficient immobilization yield which indicated three most influential parameters i.e., temperature, pH, and EDC concentration. The optimized conditions were 30°C temperature, 4.5 pH, and 1 mL (10 mg/mL) of EDC. The highest immobilization yield (98%) was achieved using above-mentioned optimized conditions [115].

Li et al., [116] reported novel method for immobilization of cellulase using combined sodium alginate and MWCNT. The optimizational results indicated temperature 40 °C and

pH 3.0. Cellulase activity retention (71.2% of its initial activity) was reported after 1 month of storage at 4 °C temperature. The nanobiocatalyst showed up to 70% of its initial activity after 7 consecutively repeated experiments of cellulose hydrolysis. Moreover, high thermal and pH stability, storage stability, and recyclability was reported which showed potential for biotechnological applications. Similarly, Azahari et al. [117] reported cellulase production from *Trichoderma reesei*, and its successful immobilization was performed using MWCNTs by physical absorption. The nanobiocatalyst showed enhanced pH and thermal stability profiles as compared with free cellulase at pre-optimized conditions of pH 5 and temperature 50 °C. After consecutive 3 experiments up to 60% of cellulase activity retention was demonstrated by nano-conjugates [117]. The easy separation, high thermal and pH stability, and excellent reusability of CNT immobilized enzyme make them robust catalyst for various biotechnological and industrial applications.

3.6 Cellulases immobilization on graphene oxides nanoparticles

Cellulase immobilization was performed by the development of graphene-based nano-supports with controlled pH and temperature and magnetoresponsive properties [118]. The 2D immobilization supports created the issue of geometric drawback which was resolved by the synthesis of closed copied free functionalized biocatalyst under similar reaction environment. The covalent immobilization showed the betterment in the bio-receptivity of graphene supports and supramolecular assembly of oppositely charged quenched polyelectrolytes and maghemite–magnetite nanoparticles on 2D graphene supports. The chances of recovery and reuse of the enzyme over multiple cycles were achieved by the incorporation of magnetic nanoparticles. The 55% of initial activity was exhibited by immobilized enzymes after four repeated experiments. The effective tool to control the activity of immobilized enzymes was achieved through the modified degree of polyelectrolyte swelling by the controlled temperature and pH. In contrast to the immobilized enzymes without the brushes, the immobilized enzyme with stiffed polyelectrolyte brushes showed the 1.5-fold betterment in the activity at pH 5.1 and 50 °C temperature [118].

Gao et al. [119] used the etherification and diazotization for the synthesis of functionalized graphene oxide and implantation with hydrophobic spacer P-β-sulfuric acid ester ethyl sulfone aniline. The immobilization of cellulase through covalent bonding was attained by

the functionalized graphene oxide as a nano-support. The high immobilization yield and efficiency of above 90% were observed after the optimization of reaction parameters. The significant betterment was observed in thermal and functional stabilities of immobilized cellulase as compared to the free cellulase. The increase of six-fold higher thermal stability was observed by immobilized enzyme (533 min) in contrast to the half-life of free cellulase (89 min) at 50 °C. Furthermore, the immobilized cellulase showed the highest catalytic activity due to linkage between substrate and immobilized enzyme ($K_m = 2.19$ g/L) as compared to the free cellulase ($K_m = 3.84$ g/L). Similarly, Dutta et al. [119] used the graphene oxide as nano-support reinforced with magnesium oxide nanoparticles (MgN). The *Bacillus subtilis* cellulase was immobilized on GO nano-support crosslinked with glutaraldehyde which increased 3.5-folds increase in enzyme activity at 90 °C and 2.98-folds increase in enzymatic activity at 8 °C. In contrast to the untreated enzyme, the MgN-cellulase graphene oxide showed 5-folds and 4.7-folds increase in V_{max} at 8 °C and 90 °C and 6.7-folds decrease in K_m at 8 °C and 34-folds at 90 °C was reported. In contrast to the natural enzyme, GO-MgN-cellulase showed the half-life of 41.6-folds at 8 °C while 72.5-fold half-life at 90 °C. The storage stability of GO-MgN-cellulase was observed at 4 °C for more than 120 days and the enzymatic activity was maintained even after 12 repeated uses [119].

Paz-Cedeno et al. [85] studied the immobilization of cellulase on magnetic graphene oxide nanoparticles (GO-MNP) as support-material. The immobilized biocatalysts were designed by carbodiimide crosslinking. The developed nanobiocatalyst showed enhanced efficacy for sugarcane bagasse hydrolysis and showed relative activities 66%, 70%, 70%, 88% after ten consecutively repeated experiments for xylanase, β-xylosidase, endoglucanase, and β-glucosidase, respectively. The 80% and 50% nanobiocatalysts efficiency was reported for cellulose and xylan hydrolysis, respectively. The results indicated it as a potential candidate for cellulosic ethanol production. Similarly, Zhang et al. [120] studied the co-immobilization of glucose oxidase and cellulase using graphene oxide as support-material. The one-pot modification of gluconic acid from CMC due to feasible control of loading enzymes with different sorts was reported. The multi enzyme systems had the superficial pH 5 and temperature 40 °C. The values of kinetic constants were $V_{max} = 0.18 \pm 0.01 \mu\text{mol.L}^{-1}\text{s}^{-1}$, $K_{cat}/K_m = 24.12 \pm 0.52$ (17.74 ± 0.85) $\text{s}^{-1} \text{mmol}^{-1}\text{L}$ and

776 $K_m = 0.15 \pm 0.02$ (0.43 ± 0.09) mmol.L $^{-1}$. The loading abilities of cellulase and glucose
777 oxidase on nanobiocatalyst were 49.07 ± 7.47 mg/g and 10.22 ± 2.03 mg/g. After seven
778 cycles, almost 65% of the initial activity was reattained by immobilized catalysts.
779 Remarkably, the $63.82 \pm 8.03\%$ conversion of gluconic acid was observed within 2 h of
780 treatment [120].

781 **3.7 Cellulases immobilization on nanostructured hybrid organic-inorganic
782 nanosupports**

783 There has been a growing interest in designing hybrid organic-inorganic nanosupports
784 for potential applications in biocatalytic immobilization with the aim to improve recyclability
785 and stability for bioprocessing applications [121,122]. The development of organic-
786 inorganic hybrid nanostructure is quite convenient, but it requires up to three days, which
787 restrict their workability. Therefore, Batule and coworkers designed a sonochemical
788 method, which can rapidly (within 5 min) synthesize organic-inorganic hybrid nanoflowers,
789 apparently due to sonication method causing quick self-assembly of copper phosphate,
790 delivering high energy to the structure [123]. These newly designed hybrid nanoflowers
791 exhibited improved stability and recyclability with similar morphology to those synthesized
792 by conventional method. Studies have primarily reported copper ions for the synthesis of
793 hybrid nanomaterials; however, various other inorganic ions have also been used for this
794 purpose [124]. The immobilization of cellulase using TiO₂-lignin hybrid support *via*
795 physical absorption was reported by Zdarta et al, [125]. The immobilized cellulase was
796 precipitated by the physical adsorptions on the inorganic–organic hybrid matrix. Different
797 parameters were chosen for the early immobilization such as the 5 mg/mL enzyme
798 solution, 6 h process time, and pH 5. The free and immobilized cellulase were analyzed
799 and compared in terms of storage stability, impacts of pH and number of catalytic cycle
800 sequences. The thermal and chemical stability, immobilization time and amount of
801 enzyme solution were improved during this study evaluated by the dependence of
802 catalytic activity of the immobilized enzyme on the early immobilization factors. The
803 immobilized cellulase retained over 80% of its initial activity after 3 h at 50 °C and pH 6.0.
804 The free enzyme showed the half-life of 63 min while the nanobiocatalyst showed the
805 half-life of 307 min. The immobilized cellulase maintained over 90% of its initial catalytic
806 characteristics after the ten repeated cycles. This novel study illustrated the convenient

and excellent mode for the production of hybrid titanium dioxide–lignin material and its utilization for the immobilization of cellulase as a support material. Over the several cycles, this method proved as efficient way to utilize commercially without any expiration of characteristics. Other biocatalysts could also apply this strategy for the immobilization [125].

Dragomirescu et al. [126] immobilized the cellulase produced from *Aspergillus niger* by the entrapment in the Na-alginate gels and in Na-alginate/silica gel-hybrid materials. Sol-gel method was used to attain silica gel by using two precursors tetra ethoxy silane and tetra methoxy silane. The results for the similar loadings showed that the mixed organic-inorganic nano-supports showed the less CMCase activities, as compared to the CMCase activities obtained by Na-alginate which was 1.12-1.17-times higher noticing by comparing the enzymatic activities of the immobilized products. The 13% activity of the cellulase was maintained after 4 cycles for the cellulase immobilized in three types of aforementioned organic-inorganic gel matrices. The relative activity was 98% more than the initial for the immobilized *Aspergillus niger* CMCase after one hour of storage at 37 °C and pH 3.0 [126]. In addition, the immobilization of enzymes has also been studied by the new type of nanomaterial known as nanoflowers that acts as novel nano-support. These are hybrid in nature because of their organic and inorganic combination. The organic portion is formulated by DNA and protein; however, the inorganic portion is made up with metal ion such Cu, Mn, or Ca. The analytical science and catalysis have reported to use the inorganic nanoflowers until the introduction of organic–inorganic nanoflowers. These hybrid nanoflowers are reported to have superior features over the free or immobilized enzymes due to the different properties such as higher stability and catalytic activity, simple production, and greater surface area than the spherical nanoparticles. The five different types of hybrid-nanoflowers are capsular nanoflowers, protein manganese, copper-DNA, protein-copper, and calcium-protein nanoflowers [127,128].

3.8 Cellulases immobilization on metal organic frameworks

The metal organic frameworks are synthesized from the particular metal ions and certain organic linkers. Further, the metal organic frameworks are species of highly ordered microporous crystalline hybrid materials and identified as the porous coordination polymers. Mostly used metal ions are actinide elements, alkaline-earth metals, transition

metals and p-block elements for the construction of metal organic framework [129]. But the included organic linkers are sulfonates, carboxylates, amines, nitrates, and phosphates. The magnetic organic frameworks demonstrate the unique features such as plentiful binding interactions for the selection of reactant such as uniform aperture size, comparatively high thermal, mechanical, and chemical stability, adjustable topological structure, large particular area, intrinsic crystalline structure, adjustable ultrahigh porosity, pore volumes and eximious optoelectronic characteristics (Figure 8) [130,131].

The development of novel cellulase immobilized magnetic organic framework composite system with increased reusability and stability for cellulose hydrolysis was performed by Ahmed et al. [132] using physical absorption method. The extra anchoring sites of NH₂ groups showed higher protein loading by NH₂-functionalized metal organic framework as compared to the precursor UiO-66. Moreover, pH tolerance and increased thermostability were also shown by the immobilized cellulase. The abundance of NH₂ and COOH functional groups on the MOFs increase the stability of cellulase after its absorption and chances of composite recovery were achieved through the mild centrifugation because of the heterogeneity offered by the NH₂ and COOH groups. The maximum activity gained was 85% at 55 °C while utilized at 80 °C and the residual activities were 72% after ten cycles and 65% after 30 days storage. The development of cellulase-MOF composite with ultrahigh operations and durability for research revealed the auspicious future by this study [132].

Qi, Luo & Wan, [133] prepared UIO-66-NH₂ metal organic framework for cellulase immobilization purposes. The highest enzymatic recovery and protein loading efficiency of 78.4% was exhibited by as-prepared immobilized nanobiocatalyst. As compared to the free form, the immobilized cellulase showed high catalytic efficiency, pH stability, and thermal stability on the magnetic organic framework of UIO-66-NH₂. The good recycling ability for 5 consecutive runs was determined by the immobilized enzyme. Moreover, better tolerance towards two inhibitors (formic acid and vanillin) present in lignocellulosic pre-hydrolysates was shown by the immobilized cellulase in contrast to the free one. The immobilized cellulase showed 16.8% and 21.5% higher activity than free enzyme in the presence of 5 g/L of formic acid and vanillin. The hydrolysis showed the betterment in yield which was 18.7% and 19.6% for the aforementioned amounts of formic acid and

vanillin. This study suggested that the inhibitory impacts of several pretreatment inhibitors on cellulase can be enhanced by the immobilization [133].

Zhou et al. [12] studied cellulase immobilization to attain high ionic liquid tolerance and development of enzymatic hydrolysis biomass *in situ*. The study used four kinds of organic metal frameworks including PCN-250, ZIF-8, UIO-66-NH₂, and MIL-100-Fe. Physical adsorption method was used for immobilization. The largest enzyme adsorption capacity (176.16 mg/g) was exhibited by ZIF-8 nano-supports. The activity of immobilized cellulase was analyzed using CMC and filter paper as substrates in the presence of ethyl-3-methylimidazolium diethyl phosphate ([Emim]DEP). As compared to the free cellulase, the superior ionic liquid tolerance was achieved by the immobilized cellulase (0% to 50%, v/v). The activity of the CMCase and filter paper cellulase were enhanced by 112.59% and 59.86% in 50% (v/v) [Emim]DEP by the specific demonstration in ionic liquid tolerance of ZIF-8-immobilized cellulase. The involved ionic liquid showed that the immobilized cellulase can cause the decrease of cellulase inactivation and was linked to the kinetic parameters as the immobilized cellulase had a lower equilibrium dissociation constant value and a higher final enzyme plateau activity value in a reaction system. As compared to the free cellulase, 50% (v/v) [Emim]DEP, the ultimate 92.92% increase was observed in the ZIF-8-immobilized cellulase with *in situ* hydrolysis of bagasse [12].

4. Biotechnological applications of cellulases

4.1 Applications in cellulose hydrolysis

The current scenario showed the significance of lignocellulosic biomass conversion into industrially useful products or biofuels. The municipal wastes, industrial waste materials, and agricultural byproducts are considered as the major forms of cellulosic biomass [134,135]. Bioconversion of lignocellulosic biomass to fermentable sugars by immobilized magnetic cellulolytic enzyme cocktails is illustrated in Figure 9 [135]. Relevant to these industries, the major concern is to eliminate these wastes from the environment. These industrial wastes are converted into different forms like biohydrogen, biomethane, bioethanol, and sugars with the assistance of cellulose digesting enzymes. Different factors are responsible for affecting the enzymatic hydrolysis such as enzyme linked factors (enzyme compatibility, product inhibition, thermal sensitivity, specificity, origin of enzyme and enzyme processability) and structural properties of solid substrate [136]. The

900 crude oil prices are indicating the increasing for the worldwide demand of fuels. The
901 facility of fossil fuel is diminishing at highest speed. The modification of lignocellulosic
902 biomass to bioethanol is possible due to the action of cellulase [137,138]. Plants have a
903 defense barrier named lignin for the enzymes to perform on celluloses. Therefore, the
904 modification of hemicellulose and cellulose biomass into smaller size sugars by the action
905 of cellulase is achieved by the pretreatment on the plants to remove the lignin from them.
906 Then fermentation is proceeded further to convert the sugars into the ethanol [139]. The
907 biomass conversion into ethanol was more conveniently obtained from *Penicillium*
908 cellulase [140]. In solid waste management, cellulase enzyme is being used to convert
909 the agricultural solid wastes into beneficial products [141,142]. The wastes lignocellulosic
910 materials are also reported to produce renewable energy sources such as bio-methane
911 and bio-hydrogen [143]. Lignocellulose hydrolysis have been showed by the immobilized
912 enzyme nearly equal to the activity obtained from free enzyme; however, high stability
913 and recyclability potential have been reported after immobilization [28]. Similarly, Ingle et
914 al. [144] studied the lignocellulosic biomass conversion by immobilized and free
915 cellulases for bioethanol production. Comparative evaluation of biomass hydrolysis from
916 both free and immobilized cellulase showed that free enzyme converted 78% cellulose to
917 glucose after 24 hours at 40 °C while, immobilized enzyme showed 72% activity in similar
918 environment. Furthermore, efficient recovery by magnetic field and recyclability up to 3rd
919 cycle was noticed which suggested 68% and 52% hydrolysis after second and third cycle,
920 respectively. These findings suggest the convenient recovery of cellulase after
921 immobilization and high reusability with improved thermal and pH stability profiles which
922 make this process useful in biotechnological sectors.

923 **4.2 Applications in pulp and paper industry**

924 The demands of paper and pulp have been enhanced by the enzyme cellulase due to the
925 different requirements of daily uses such as production of paper towels and sanitary pads,
926 bio-modification of fibers, betterment wastewater of the papermills, removing of toners
927 and ink coating from papers and for bio-mechanical pulping [145]. The woody raw
928 material along with stiffness, bulk, and high number of fines are achieved by mechanical
929 pulping such as grinding and refining of woody raw materials [146]. The downside of
930 mechanical pulping is high expenditure of energy, although the attained fibers are used

931 to produce papers of different quality. Moreover, the efficient hand sheet strength
932 properties and substantial energy savings (20–40%) are observed during refining of
933 cellulase pulping from white-rot fungi by the biochemical pulping as compared to the
934 mechanical pulping [147]. The lower degree of hydrolysis and reduce viscosity of pulp
935 were observed in endoglucanase [148]. The high productivity and trouble-free printing
936 procedure are acquired by the bio-modification of fibers that uses cellulase and
937 hemicellulose and enhances the paper sheet density and pulp beat ability [147]. The
938 recycling of waste papers such as books, magazines and newspapers can be
939 accomplished by cellulases. Thereafter, fibers could be reused in ethanol synthesis and
940 in manufacturing newspapers through bleaching. The discoloration of different sorts of
941 paper wastes have been carried out by cellulase alone or in combination with xylanases.
942 There are few benefits of enzymatic bleaching such as reduced fine particles, strength
943 enhancement, better fiber brightness and prevention of alkali [149]. Yang et al. [150]
944 reported the catalytic degradation potential of methyl orange using Ag-Pt nano-
945 constructs. The enzymatic bleaching by cellulase at acidic pH decrease the
946 environmental pollution, modification in ink particle size distribution, facilitates the
947 bleaching step and prevention of alkaline yellowing [151,152]. Yassin et al. [153] studied
948 both immobilized and free cellulases for the development of cellulose nanofibers. The
949 results indicated high thermal and mechanical stability by gel-immobilized cellulase. In
950 addition, high activity retention (85%) after six repeated experiments showed good
951 recyclability potential after immobilization. The immobilized cellulose showed high
952 potential to disintegrate cellulose into nanofibrils of diameter (15-35 nm) with varying
953 length. These results indicated high applicability for paper and pulp industry and
954 packaging industry applications.

955 **4.3 Applications in food industry**

956 In food industries cellulase are used for several purposes. The nutritive juice yield with
957 better stability and less processing time is achieved by the maximum liquefaction of
958 smashed fruit pulps which continuous crushing by macerating enzyme having cellulase
959 with pectinases and hemicellulases. The decrease in viscosity, texture and cloud stability
960 of purees and juices are upgraded by macerating enzymes [154]. The higher levels of
961 antioxidants and vitamin E is observed in olive oil extracted by macerating enzymes with

962 slower initiation of rancidness [9]. The extraction of olive oil was improved by an enzyme
963 olivex which was attained by the intermixing of cellulases and hemicellulases from
964 *Aspergillus aculeatus* along with pectinase [155]. The coloring agent production for food
965 can also be achieved by cellulase [156]. The carotenoids are responsible for providing
966 the colors for many plants from red to yellow and these are also considered as the major
967 group of coloring substances in nature. The carotenoids have continuous demand in
968 market, and they are used as food colorants due to their null toxicity, natural sources,
969 high versatility, alluring characteristics and lipo- and hydro soluble colorants [157].

970 **4.4 Applications in biofuel production**

971 Enzyme immobilization using variety of different biopolymers and nanostructured
972 materials for biofuels production using biomass hydrolysis strategies have widely been
973 reported. For this purpose, various nanomaterials including nano-porous silica, carbon
974 nanotubes, graphene, nanocomposites, nanofibers, and others provide excellent support
975 material for biocatalytic immobilization. Immobilized enzymes show high operational and
976 thermal stability, and convenient recyclability using various simple chemical and physical
977 methodologies. For biofuel production, two enzymes namely, lipases and cellulases are
978 key candidates for biofuel production through various production methodologies.
979 Environmentally friendly biomass hydrolysis can be improved in terms of reusability,
980 efficiency, thermal and pH stability using enzymes immobilization technology [25].
981 Cellulases immobilization have been studied using variety of different biopolymers and
982 nanostructured materials which have previously been discussed in section 2 and 3. For
983 biofuel production applications, cellulase immobilization has been performed on silica
984 [6,36], polymeric nanostructures [158]. Affinity-tagged cellulases were investigated for co-
985 immobilization using magnetic silicon nanoparticles doped with gold using one-pot
986 cellulose hydrolysis [159]. Approaches to enhance biofuels production in the presence of
987 cellulase are shown in Figure 10 [6].

988 **5. Challenges, prospects, and conclusions**

989 Nanobiotechnological advancements are the important part of human life, especially in
990 the field of industrial. Due to the increase in human and environmental population, nano-
991 biotechnology manipulates biomaterials to improve the product yield. Cellulase is the
992 most frequently employed enzyme that convert cellulosic biomass into monosaccharide

993 building blocks which are further used for the synthesis of value-added products e.g.,
994 biofuels. Although extensive developments have been made in the immobilization of
995 enzymes using variety of different polymeric/biopolymeric, and nanostructured supports,
996 few critical issues are needed to be addressed before the industrial-scale applications of
997 nanomaterials-immobilized enzymes. It is demanded to obtain deep acquaintance and
998 insight on the influence of nanocarriers on enzymes and other biomolecules. For instance,
999 in depth studies on structural influences on nano-constructs, type of activation agent on
1000 enzymatic loading, functionalization, orientation of bounded proteins could assist in
1001 designing the optimized enzymatic systems. Moreover, such enzymatic methodologies
1002 need to be cost-effective and highly efficient. Therefore, the major challenge for the
1003 scientists is to design and optimize novel processes with improved enzymatic stability,
1004 activity, recyclability, and cost issues, along with easy down-stream processing from the
1005 reaction mixture.

1006 The recent advancements in nanostructured immobilization methodologies have shown
1007 high potential as novel nanobiocatalysts, which can further be optimized in terms of
1008 catalytic efficiency. The re-designing and engineering of novel nanomaterial-based
1009 systems for enzyme immobilization with finely tuned functionalities and structural
1010 features, exhibiting high biocompatibility, minimal toxicity, and insignificant
1011 environmentally hazardous influences accompanied by the choice of appropriate
1012 immobilization protocol might lead to the development of functionalized nanobiocatalytic
1013 systems in the field of energy and biofuel production, biosensing, organic synthesis,
1014 biotransformation, and industrial biocatalysis [122]. The use of magnetic nanocarriers is
1015 becoming interesting due to easy enzyme separation from the reaction mixture which
1016 significantly reduce the catalytic reutilization cost. Different nanostructures having
1017 diversified functional groups as immobilization support exist i.e., inorganic-organic
1018 hybrids, silica-based, metal oxide-based, CLEAs, magnetic, carbon nanotubes (SWCNT
1019 and MWCNT), graphene oxide and others. Despite current advancements, novel
1020 methodologies are still required to achieve highly efficient nanobiocatalysts for bioprocess
1021 applications. Since the recyclability is the major concern to reduce the production cost;
1022 therefore, convenient down-stream processing without actual loss in catalytic efficiency

1023 could be the interesting research area in this regard. Studies show that immobilization
1024 have potential to impart such useful characteristics to biocatalysts.

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1030 **Conflict of interests**

1031 The author(s) declare no conflicting interests.

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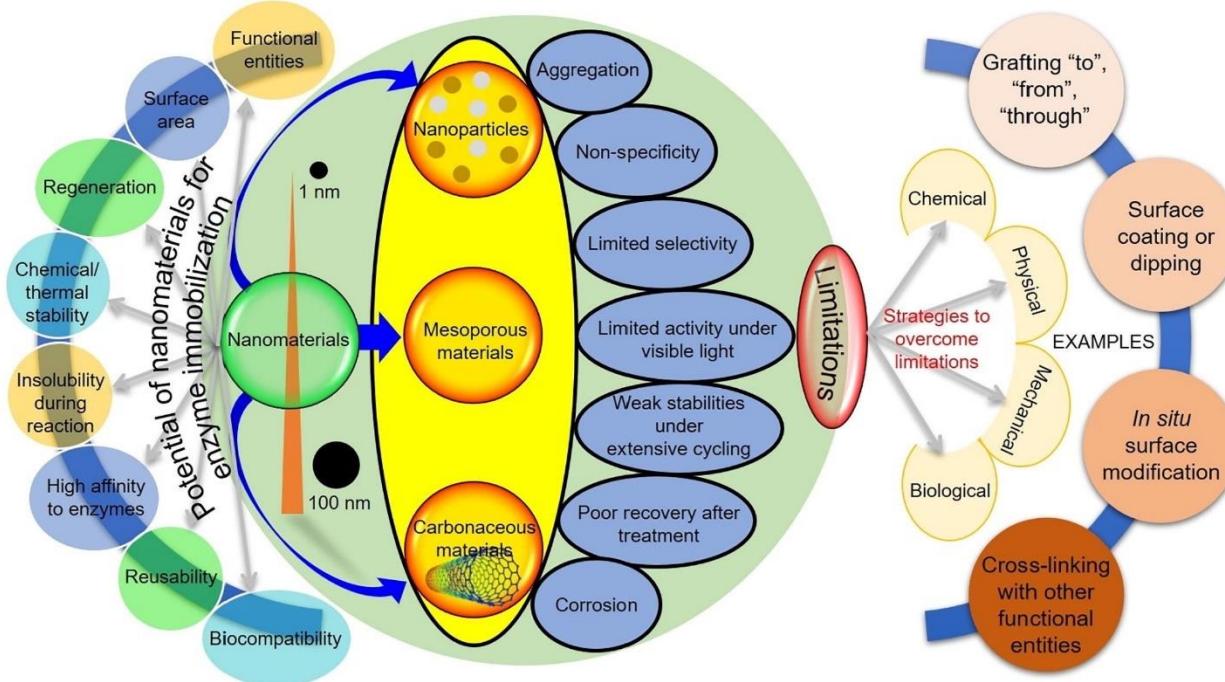
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1598 **Figure captions**
1599 **Figure 1** Significant potential of nanomaterials for enzyme immobilization. Reprinted from
1600 Ref. [17] with permission from Elsevier. License Number: 5081540394562.
1601 **Figure 2** Advantages of nanomaterials as enzyme immobilization platforms.
1602 **Figure 3** Stepwise illustration of cellulose-deconstruction potential of cellulase based
1603 nano-biocatalytic systems as a strategic drive from designing to sustainable applications.
1604 **Figure 4** Schematic illustration of the preparatory method of chitosan/magnetic porous
1605 biochar as support for cellulase immobilization in the presence of glutaraldehyde (GA) as
1606 a cross-linker. Initially, sugarcane bagasse was used to prepare biochar via pyrolysis in
1607 the presence of potassium hydroxide (KOH). In the following step, calcination was
1608 performed to engineer magnetic biochar which was subjected to chitosan coating and
1609 used for cellulase immobilization by GA activation. The bar graph given in red color at the
1610 bottom left corner shows the effect of recycling on the glucose productivity of immobilized
1611 cellulase. Reprinted from Ref. [53] with permission under the terms and conditions of the
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1613 **Figure 5** The process of construction of bioconjugates. Reprinted from Ref. [58] with
1614 permission from Elsevier. License Number: 5081660389521.
1615 **Figure 6** Cellulase immobilization on iron oxide nanoparticle surfaces. Reprinted from
1616 Ref. [78] with permission from Springer Nature. License Number: 5081660693327.
1617 **Figure 7** Potential advantages of CLEAs. Reprinted from Ref. [86] with permission from
1618 Taylor & Francis. License Number: 5081660850455.
1619 **Figure 8** Diagrammatic sketches of enzyme immobilization onto MOF surface by covalent
1620 grafting. (A) Direct covalent grafting between MOF and enzyme; (B) A dye-tagging
1621 strategy for enzyme immobilization on MOF surface. Reprinted from Ref. [130] with
1622 permission from Elsevier. License Number: 5081660986472.
1623 **Figure 9** Bioconversion of lignocellulosic biomass to fermentable sugars by immobilized
1624 magnetic cellulolytic enzyme cocktails. Reprinted from Ref. [135] with permission from
1625 American Chemical Society.
1626 **Figure 10** Approaches to enhance biofuels production in the presence of cellulase.
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1629 **List of Figures**



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1631 **Figure 1**

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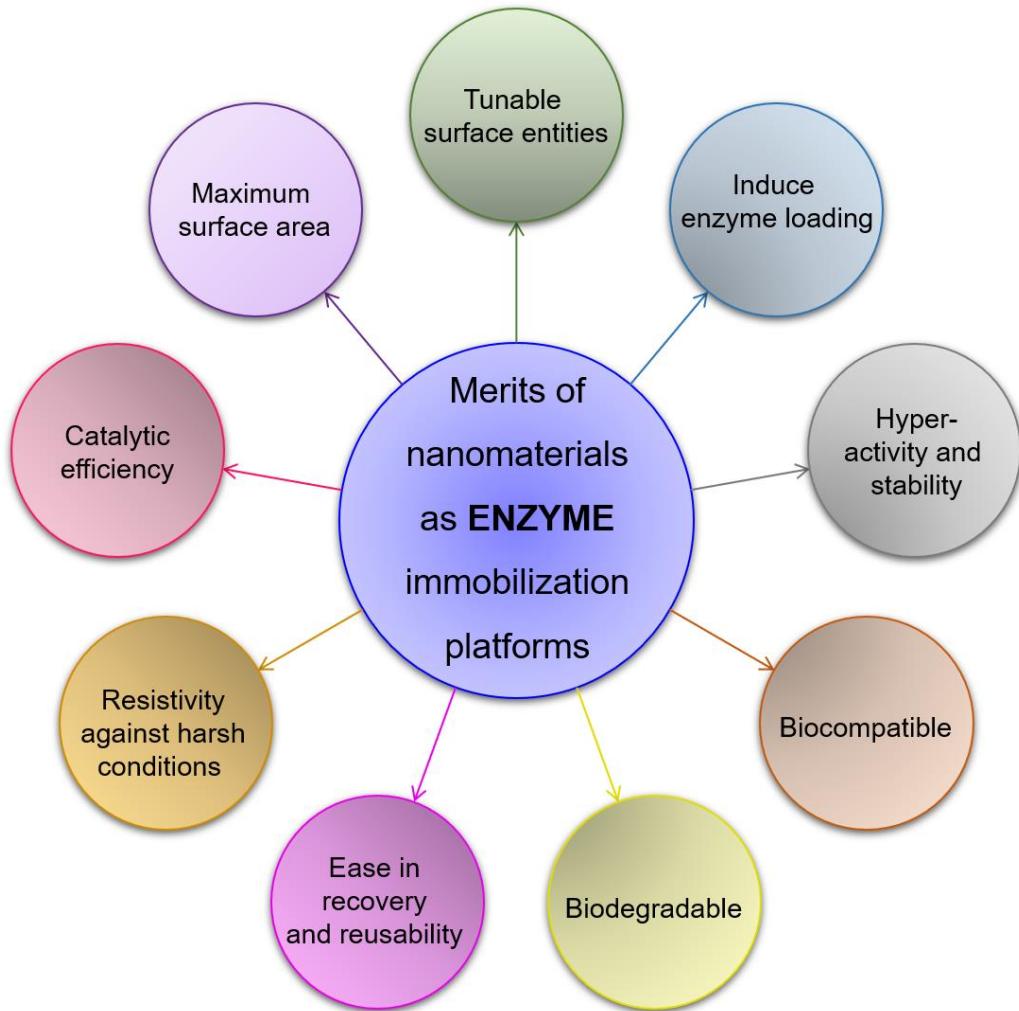
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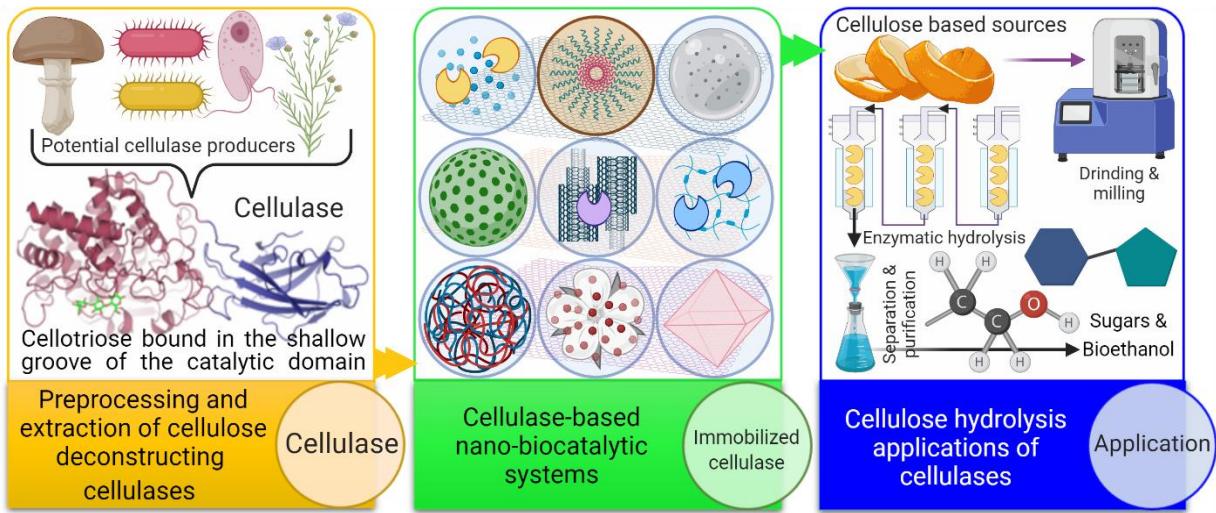
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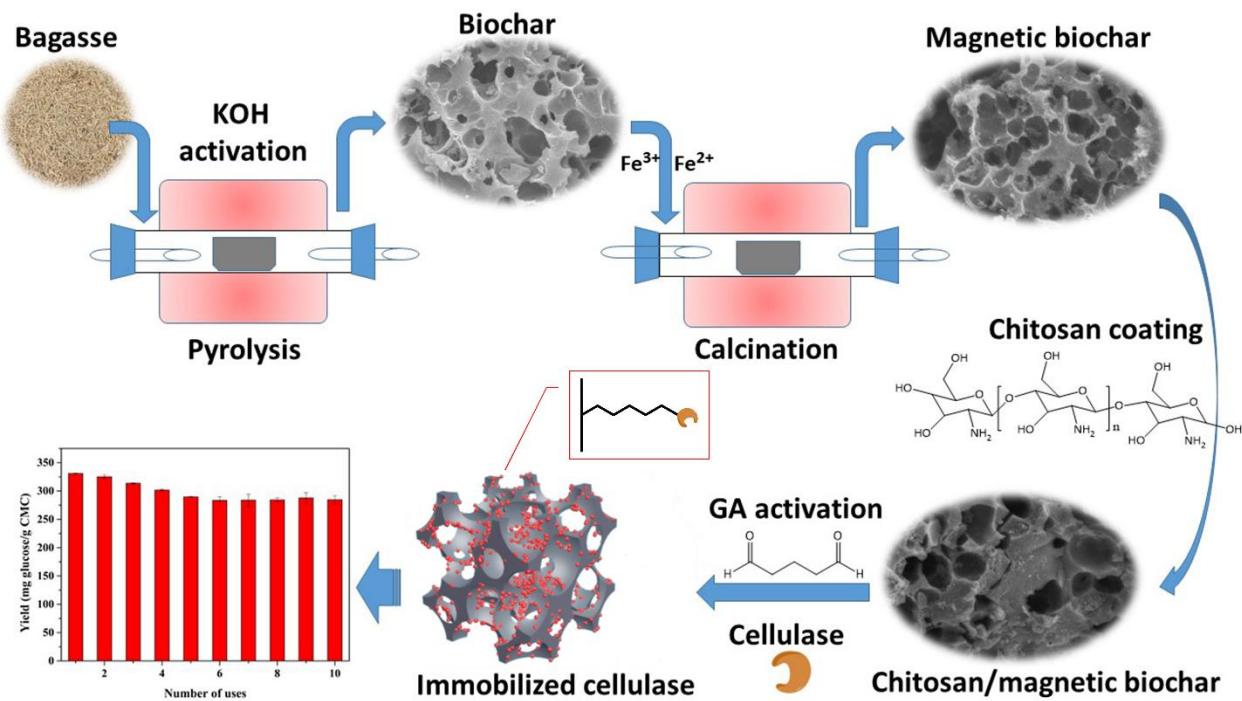
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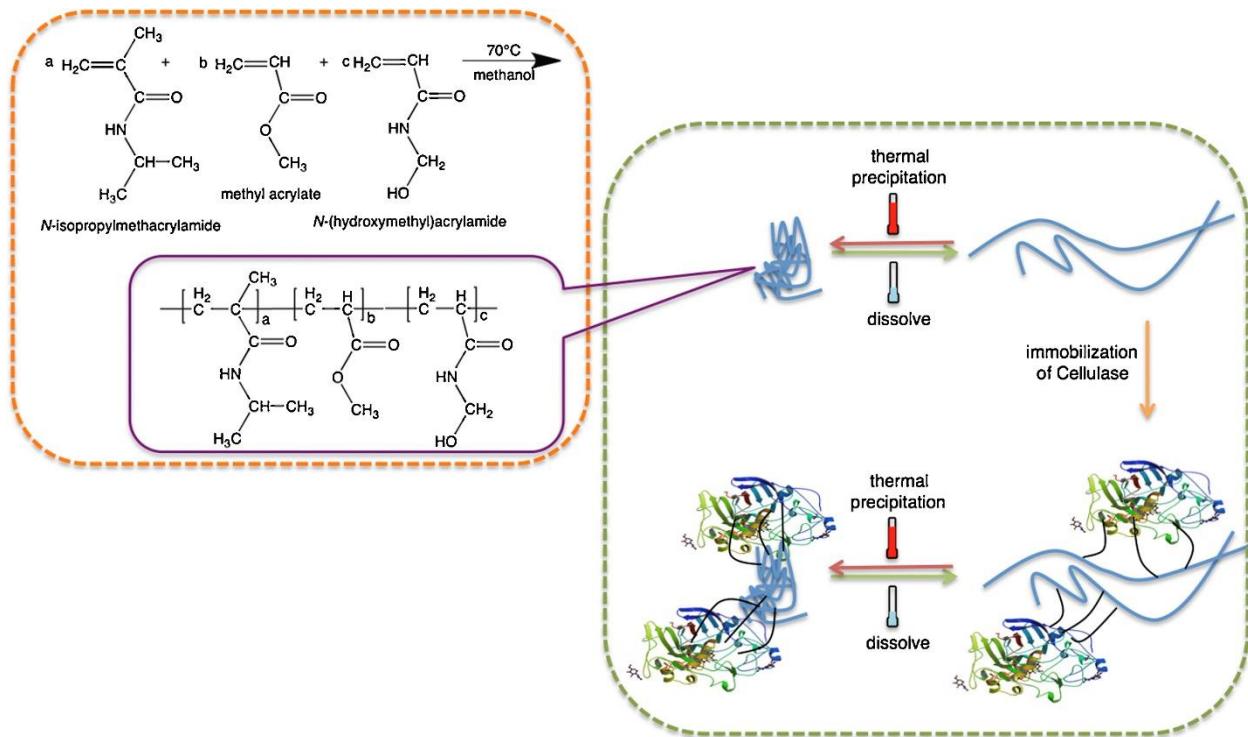
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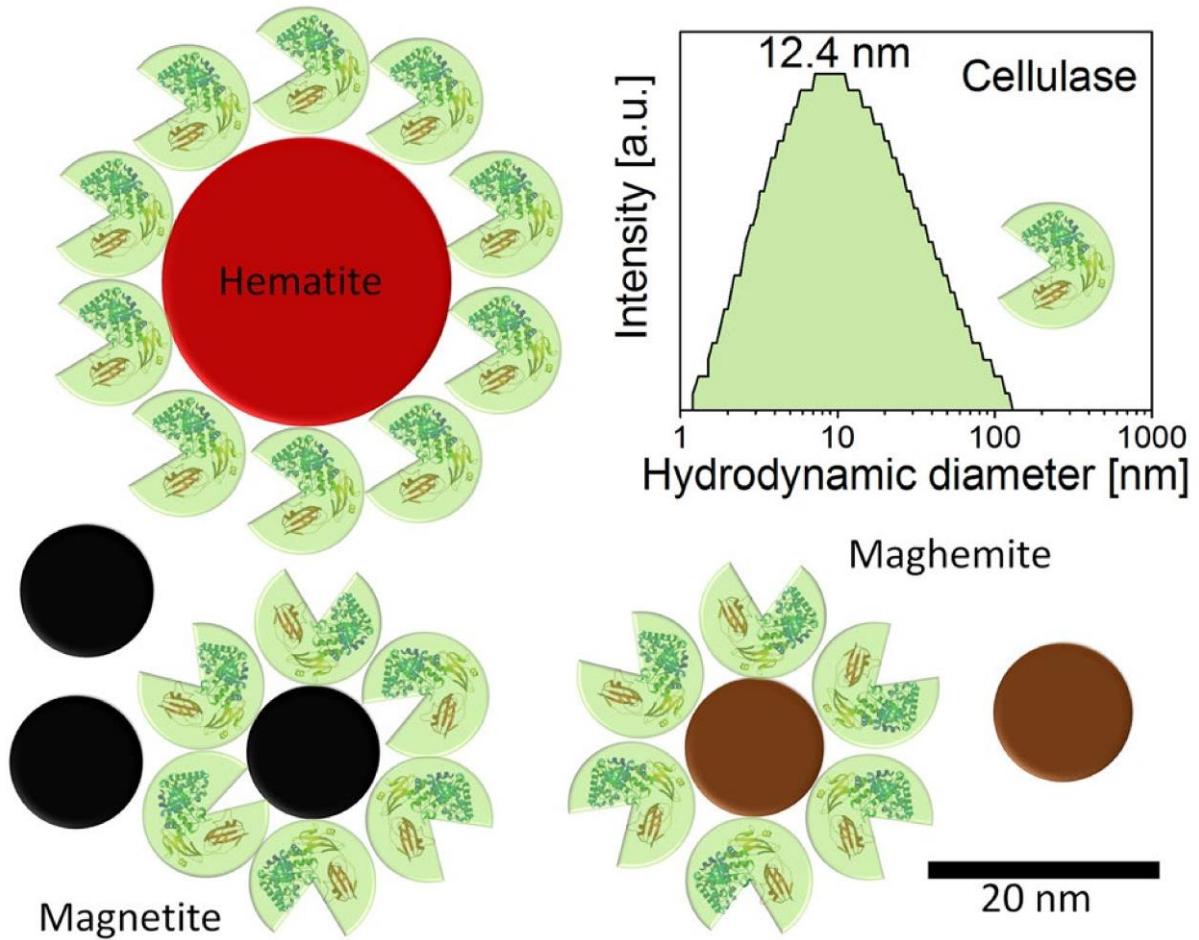
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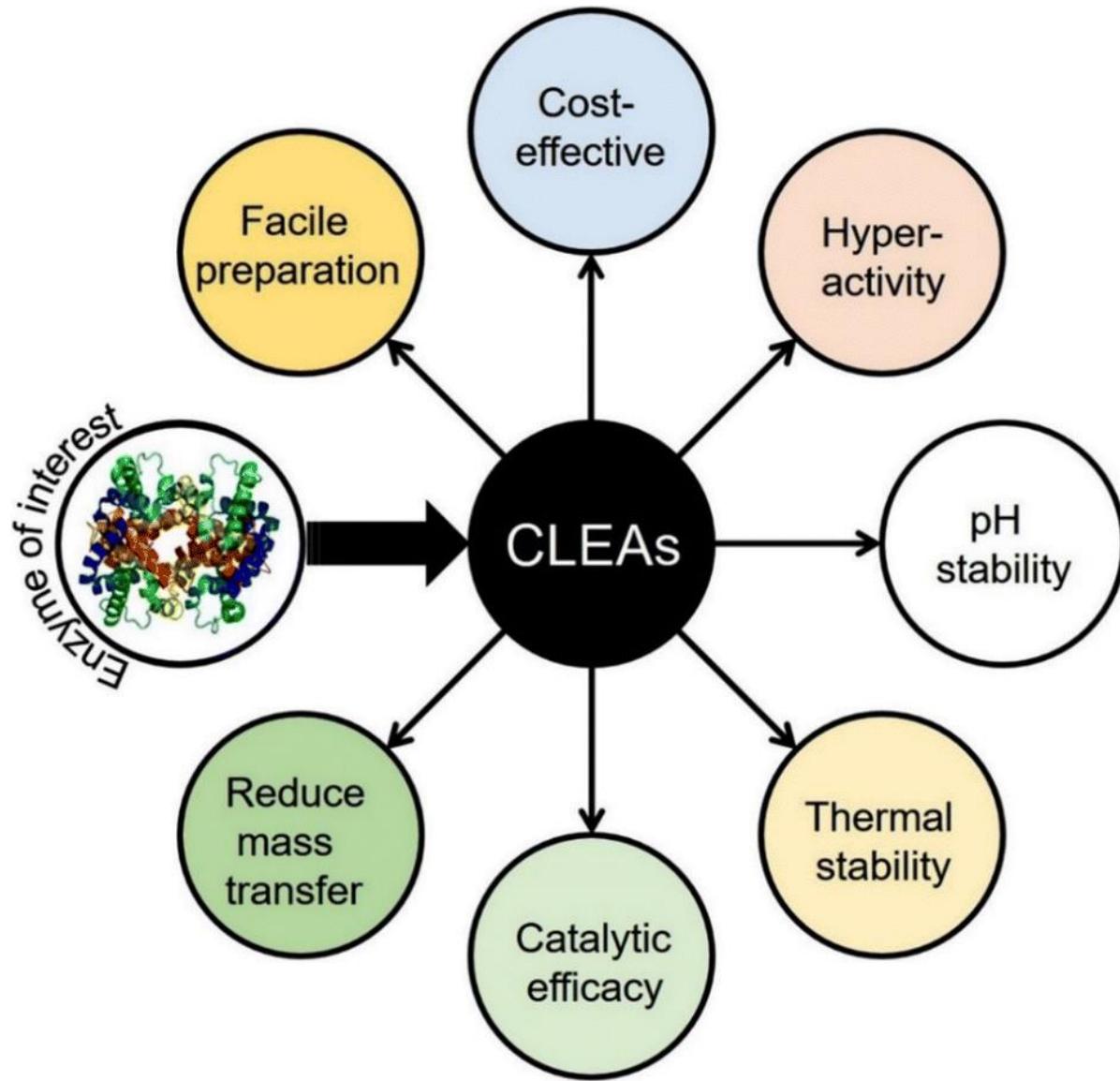
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1736 **Figure 7**

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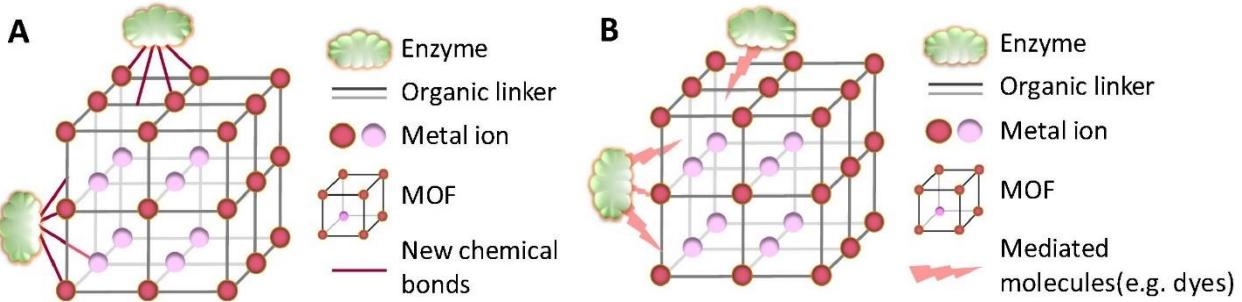
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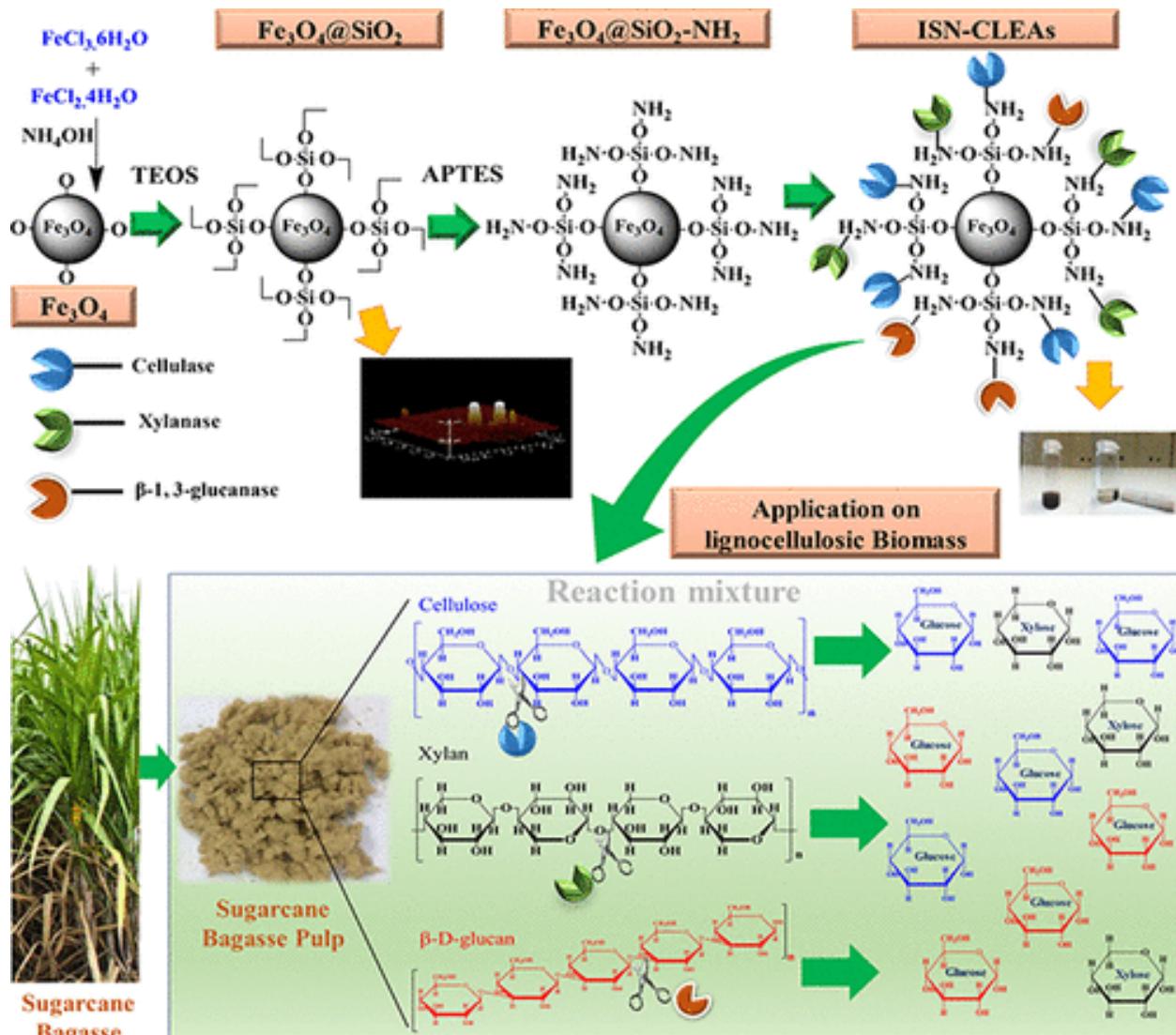
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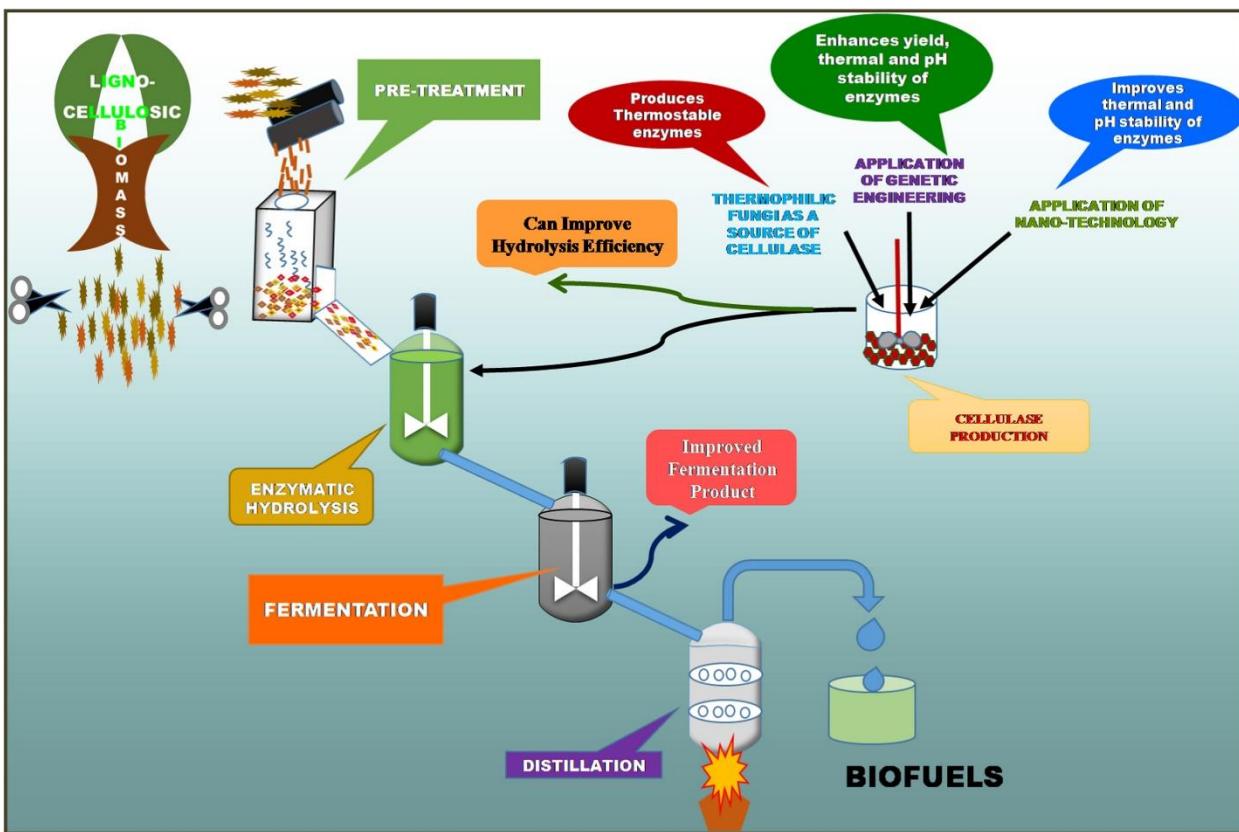
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1801 **List of Tables**

1802 **Table 1** Polymer-based supports for cellulase immobilization with binding method,
 1803 stability/recyclability, and industrial applications.

Immobilization support	Binding method	Stability/ Recyclability potential	Industrial applications	References
Ca-alginate	Entrapment	High activity retention up to four cycles	-	[41]
Ca-alginate-xerogel matrix	Entrapment	-	Fruit juice clarification	[42]
Na-alginate polyethylene	Glutaraldehyde crosslinking	Up to 53% activity after 3 cycles	Enzymatic MCC hydrolysis	[43]
Ca-alginate	Entrapment	45% retention after 3 days, with stability at 4 °C for 12 days and at 30 °C for 3 days	Enzymatic CMC hydrolysis	[41]
Ca-alginate	Entrapment	69.2% activity retention after 5 cycles	-	[44]
Chitosan-Magnetic NPs	Entrapment	Excellent thermal stability at 80 °C	-	[46]
Chitosan amino condensation adduct	Crosslinking and covalent attachment	Up to 70% activity retention after 25 cycles	-	[49]
Chitosan-iron oxide	Glutaraldehyde crosslinking	No significant loss for 3 consecutive cycles	-	[50]
Chitosan-magnetic nanoparticles	Chemical crosslinking	Up to 80% activity retention for 15 cycles	Lignocellulose hydrolysis	[28]
Chitosan-magnetic nanoparticles	Alkaline precipitation	High stability	-	[51]
Chitosan-porous biochar	Covalent linking	-	Enzymatic CMC hydrolysis	[53]

1805 **Table 2** Nanocarriers for cellulase immobilization with binding method,
 1806 stability/recyclability, and industrial applications.

Immobilization support	Binding method	Stability/Recyclability potential	Industrial applications	References
MWCNT	Covalent binding	-	Fruit bunches degradation	[115]
GO@CMC- <i>g</i> -poly(AMPS-co-AAm)	Physical crosslinking	90.5% activity retention after 5 cycles	Lignocellulosic biomass hydrolysis	[160]
MWCNT	Physical absorption	52% activity retention after 6 cycles	Food and agricultural sector applications	[113]
Functionalized Fe ₂ O ₃ /Fe ₃ O ₄ nanoparticles	Novel rapid combustion method	71% activity retention after 5 cycles	-	[161]
PEGylated GO nanosheets	Chemical linking	Up to 73% activity retention after 3 cycles	Saccharification of lignocellulose	[162]
Magnetic iron oxide nanoparticles	Glutaraldehyde crosslinking	50.34% activity retention after 4 saccharification cycles	Saccharification of rice straw	[163]
Rice husk silica ash	Physical adsorption	58.8% activity retention after 3 cycles	Hydrolysis of sugarcane bagasse	[164]
Core-shell mesoporous magnetic AuNPs	Chemical method	57% activity retention after 4 cycles	-	[63]
Wrinkled silica nanoparticles	Physical adsorption	High recyclability	-	[165]
Mesoporous silica (SBA-15)	Encapsulation	Up to 70% activity retention after four weeks incubation	-	[66]
Mesoporous silica (FDU-12)	Physical adsorption	Almost 100% of its activity retention after 15 days incubation	-	[67]
Iron oxide nanoparticles	Physical adsorption	High recyclability	-	[78]

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