catalysts

MDPI

*Review*

# The Organic-Functionalized Silica Nanoparticles as Lipase Carriers for Biocatalytic Application: Future Perspective in Biodegradation

**Jelena Milovanović [1], Katarina Banjanac [2], Jasmina Nikolić [3], Jasmina Nikodinović-Runić [1,*] and Nevena Ž. Prlainović [3,*]**

[1] Institute of Molecular Genetics and Genetic Engineering, University of Belgrade, Vojvode Stepe 444a, 11042 Belgrade, Serbia; jelena.milovanovic@imgge.bg.ac.rs
[2] Innovation Center of Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Serbia; kbanjanac@tmf.bg.ac.rs
[3] Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Serbia; jasmina@tmf.bg.ac.rs
* Correspondence: jasmina.nikodinovic@imgge.bg.ac.rs (J.N.-R.); nprlainovic@tmf.bg.ac.rs (N.Ž.P.)

**Abstract:** Over the past three decades, organic reactions catalyzed by lipase have been extensively studied. To overcome the drawbacks of free enzymes and develop new and sustainable biocatalysts, various insoluble forms of lipases were examined. Especially interesting are lipases immobilized on silica nanoparticles (SiNPs) due to their promising unique and advantageous physicochemical properties. Therefore, the present paper presents an overview of different organic functionalization methods of SiNP surfaces to create a more favorable microenvironment for lipase molecules. Given the high commercial value of lipases in biotechnological applications, the second part of this paper highlights the key industrial sectors utilizing these nanobiocatalysts. This review discusses the key industrial applications of silica-based lipase nanobiocatalysts, including biodiesel production, flavor ester synthesis, and pharmaceutical applications such as racemization. Special attention is given to emerging technologies, particularly the use of immobilized lipases in polymer biodegradation and polymerization reactions. These advances have paved the way for innovative solutions, such as self-degrading bioplastics, which hold significant promise for sustainable materials and environmental protection. This comprehensive overview underscores the transformative potential of lipase–SiNP nanobiocatalysts in both industrial and environmental contexts.

**Keywords:** lipase immobilization; biocatalyst; silica nanoparticles; biodiesel production; flavor esters; polymer degradation; polymerization



Academic Editor: Chia-Hung Kuo

Received: 6 December 2024
Revised: 27 December 2024
Accepted: 6 January 2025
Published: 9 January 2025

**Citation:** Milovanović, J.; Banjanac, K.; Nikolić, J.; Nikodinović-Runić, J.; Prlainović, N.Ž. The Organic -Functionalized Silica Nanoparticles as Lipase Carriers for Biocatalytic Application: Future Perspective in Biodegradation. *Catalysts* **2025**, *15*, 54. https://doi.org/10.3390/catal15010054



## 1. Introduction

Enzymes are remarkable biocatalysts, offering sustainable and efficient processes due to their ability to function under mild conditions with greater specificity. However, their industrial application faces significant limitations, including low stability under operational conditions, challenging recovery, limited reusability, and susceptibility to denaturation [1–3]. Over time, the development of science and technology has led to overcoming some of the most critical limitations. Thus, in the last two decades, advances in protein engineering and directed evolution techniques have dramatically changed the availability of enzymes in large quantities [4]. Nonetheless, recombinant DNA enabled

the expression of a substantial number of enzymes in a relatively short time and at relatively limited expense [4]. Another perceived drawback is the limited stability under harsh conditions in organic synthesis and the challenging recovery from the reaction media. These challenges have led to extensive research into enzyme immobilization as a promising solution. Immobilization enhances enzyme stability, reusability, and activity by attaching enzymes to solid carriers, making them more suitable for industrial use. The stabilization is mainly due to multi-subunit immobilization, prevention of aggregation and autolysis, and rigidification of the enzyme structure [5]. Additionally, immobilization facilitates the easy separation and reuse of enzymes, making the process more cost-effective and efficient for industrial applications. One of the most critical tasks in developing insoluble immobilized enzymes is selecting a suitable carrier. The properties of the carrier significantly affect the conditions and method of enzyme binding [6,7]. Numerous investigations have explored various nanocarriers—including organic, inorganic, and polymeric materials such as graphene, carbon nanotubes, mesoporous silica, liposomes, and nanostructured metal–oxide frameworks—for hosting enzymes [8–12]. These nanomaterials have demonstrated remarkable potential due to their ability to provide robust platforms for improving enzyme functionality and efficiency. However, their use still presents several challenges, particularly regarding stabilization, toxicity, and accumulation in living organisms. Toxicity is a critical issue, as nanomaterials can penetrate tissues and cells, potentially causing oxidative stress, inflammation, and genotoxic effects [13].

Despite challenges, nanomaterials offer advanced performance compared to macroscopic materials [14]. In contrast, macroscopic materials are easier to handle, more commercial, and provide a stable environment for enzymes, but they often have lower surface area and catalytic efficiency, as well as diffusion limitations.

Among the many materials investigated, silica nanoparticles (SiNPs), as cost-effective materials, stand out as highly effective carriers for enzyme immobilization due to their unique properties. SiNPs offer high surface area, low mass transfer resistance, tunable surface chemistry, and superior enzyme loading capacity. These features not only improve enzyme stability and efficiency but also facilitate long-term storage and recycling, addressing key challenges in industrial biocatalysis [15]. Moreover, SiNPs are generally recognized as nontoxic by the United States Food and Drug Administration [16]. Furthermore, the surface of SiNPs can be modified with functional groups (-OH, -COOH, -$NH_2$) to enhance enzyme attachment and tailor the system for specific applications, expanding their versatility. For example, their use in organic solvent-containing reactions has shown significant promise, particularly for enhancing lipase stability.

Although a variety of enzymes are used in industrial applications, the most significant are hydrolases, which play a crucial role in numerous biochemical processes. Among them, lipases occupy a special place due to their ability to catalyze the esterification and hydrolysis of fats and oils, making them essential in industries such as food processing, biodiesel production, and pharmaceuticals [17–21]. Most recently, lipases have appeared as promising biocatalysts for the degradation of plastics, making them attractive in the field of environmental protection and waste reduction [22–24]. Moreover, obtained hydrolyzed monomeric units can be further processed in various industries [25]. Also, in recent years, some unconventional alternative/promiscuous reactions can be found [26].

The current review focuses on the immobilization of lipase on inorganic materials, specifically silica nanoparticles (SiNPs), over the past 14 years (since 2010). It has been previously reported that SiNPs enhance enzyme activity and durability by providing a suitable environment and facilitating even distribution across the surface [27]. The aim is to provide a comprehensive guide on various surface modification approaches and further application of such prepared carriers for lipase immobilization. Special attention

will be given to the application of these biocatalytic systems in usual lipase reactions such as esterification and transesterification, including biodiesel production, flavor esters, antioxidant molecules, and racemization reactions, with a particular focus on polymer degradation and biosynthesis.

Additionally, this review aims to inspire innovative approaches for lipase immobilization, expanding their potential for sustainable polymer degradation and potential future research directions towards managing plastic pollution.

## 2. Nanoparticles as Support for Lipase Immobilization

Nanomaterials (NMs) represent the class of materials with at least one dimension in the range of 1–100 nm [28]. Their outstanding features have led to widespread applications and significant progress in the development of many fields such as biomedicine, the food industry, catalysis, sensing, environmental protection, and others. The effectiveness of enzymes immobilized on NMs is determined by several factors, including the immobilization methods, the types of NMs utilized, and their physicochemical properties such as particle size, aggregation behavior, dimensions, and the coupling or modifying agents applied. The main mechanisms of lipase immobilization on NMs, as reported in the existing literature, can be grouped in the following categories: physical adsorption [29,30], covalent binding [30], encapsulation/entrapment [31,32], cross-linking [33], affinity binding [34], and self-assembled monolayers (SAMs) [35]. Each of these methods can be optimized for specific application and enzyme type, considering factors such as enzyme stability, activity, and the intended use of the immobilized system. There are more than 1300 currently available nanomaterials [36], while the immobilization of lipase is most commonly carried out on nanoparticles (NPs), nanotubes (NTs), and nanofibrous membranes (NFMs) [30]. In the past decade, studies on nanotubes (NTs) have increased significantly due to their versatile and beneficial properties. NTs, with their nanoscale diameters, offer a high specific surface area, and their length facilitates easy filtration for gentle recovery. Both carbon and non-carbon NTs, including multi-walled and single-walled types, have been used for lipase immobilization [12,30]. Nanofibrous membranes (NFMs) are frequently used for lipase immobilization, and although they do not have nanoscale diameters (<100 nm), their nanoscale pore sizes enhance enzyme activity retention [37,38]. NPs are the most important NMs for lipase immobilization with multiple applications in bioprocesses [39]. Nanoparticles are primarily categorized as spherical materials with all nanoscale dimensions but can be further categorized according to different criteria such as dimension range, morphology, composition, and uniformity [40]. Their extensive applications are primarily influenced by their chemical composition, as illustrated by the various types of nanoparticles depicted in Figure 1.

This review explores recent advancements, various mechanisms, and the impact of silica nanoparticles (SiNPs) on the immobilization and activity of lipase, while also discussing potential future directions for enhancing immobilization techniques and improving overall enzymatic performance. Additionally, this review highlights the challenges and opportunities in integrating immobilized lipase systems into industrial applications.

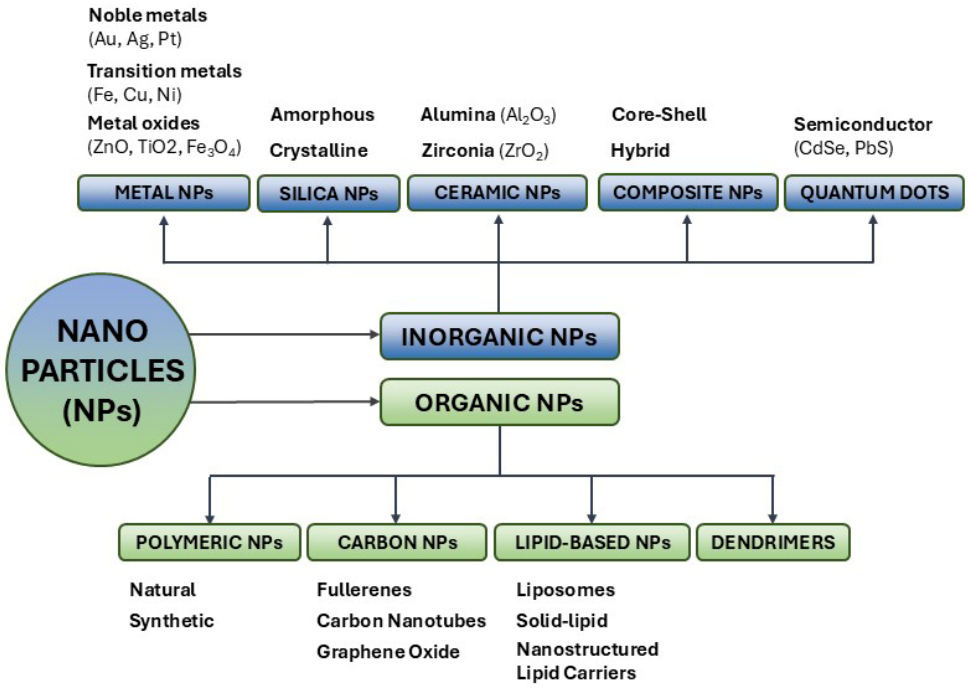


**Figure 1.** Nanoparticle classification based on chemical structure.

### *2.1. Silica Nanoparticles*

Inorganic NPs are considered promising materials, as they can be formed in nature, for example, in volcanic eruptions or forest fires, so they do not harm the environment/ecosystem [36]. Generally, inorganic-based nanomaterials can comprise a metal or non-metal element or be an oxide, hydroxide, chalcogenide, or phosphate compound [41]. It has been shown that the immobilization of enzymes on nano-inorganic support materials significantly improves kinetic parameters and thermal and pH stability [42]. The most suitable materials for lipase attachment are gold (Au), silver (Ag), silica ($SiO_2$), and iron oxides ($Fe_3O_4$) [43,44]. Among these materials, silica-based nanoparticles (SiNPs) are attractive due to their straightforward synthesis, colloidal stability, adjustable particle size, simple surface modification, biocompatibility, and feasible large-scale production [45].

Ever since Cruz et al. started studying the adsorption of *Candida antarctica* (CAL B) lipase, fumed silica has attracted huge attention as an enzyme support [46]. Generally, two types of SiNPs, non-porous (N-SiNPs) and mesoporous nanoparticles (M-SiNPs), are used for lipase immobilization. They are among the most exploited nanoscaled materials because they have shown outstanding lipase yield and efficiency improvement [47]. They are both amorphous, with N-SiNPs having no special structural shape, while M-SiNPs are characterized by mesopores with a 2–50 nm pore size (Figure 2) [48].

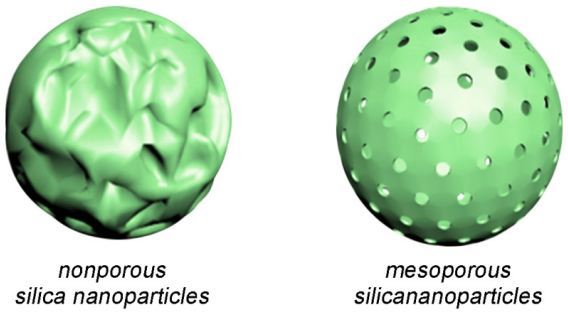


**Figure 2.** Simplified representation of silica nanoparticle surfaces typically used for enzyme immobilization.

N- and M-SiNP materials offer a large surface area along with excellent thermal, mechanical, and chemical stability. Their affordability and easy availability make them highly advantageous compared to other types of immobilization support [15]. This is why nanoparticles should be considered seriously as a potential lipase carrier for industrial applications [47]. Whether porous or non-porous, silica nanoparticles have hydrophilic surfaces covered with silanol groups (Si-OH). Hydroxyl groups make the surface exceptionally suitable for electrostatic adsorption and their relatively easy functionalization for covalent binding of organic molecules as enzymes.

One of the disadvantages of using SiNPs for immobilization is their tendency to be difficult to recover from a mixture. By incorporating magnetic properties, these silica nanoparticles can be easily attracted to an external magnetic field, allowing for straightforward and efficient separation from the solution. In several studies, silica nanoparticles have been modified with $Fe_3O_4$ to become magnetic. This modification is particularly beneficial because nanoparticles can present challenges in separation [44].

Considering the previously mentioned, further in this text, we will focus on silica nanoparticles (SiNPs) and $Fe_3O_4$@SiNPs (magnetic SiNPs) and their alteration methods for improving lipase performances.

### *2.2. Strategies for Lipase Immobilization on Silica Nanoparticles*

Modification and preparation of SiNPs form lipase immobilization represent the critical step in enhancing the biocatalytic productivity. Different strategies include surface functionalization with various chemical reagents, thereby ensuring stable and efficient enzyme binding. Table 1 summarizes the immobilization techniques of lipases from various sources for different applications, providing an overview of the methods discussed. This table highlights the diverse strategies used for lipase immobilization, emphasizing their applicability across a range of industrial and biocatalytic processes. In Figure 3, the surface modification strategies are graphically grouped to illustrate the various methods previously described for modifying SiNPs for use in lipase immobilization. The figure showcases the pathways that have been detailed, highlighting the different chemical approaches employed to achieve stable and efficient enzyme binding. As mentioned, Cruz et al. were pioneers in the use of raw/(non-modified) SiNPs for lipase adsorption. They successfully opened the door towards increased applicability of CAL B in organic solvents [46,49]. Later, various forms of non-modified porous SiNPs (wrinkled [50], hollowed [51], virus-like [52]) were used as carriers. Adsorption onto raw SiNPs is a simple immobilization technique. Herein, the nature of the interactions between the silica surface and the enzyme molecule is governed by the immobilization conditions (particularly pH value). Considering that, in general, immobilization takes place at pH lower than 7, it is clear that the enzyme is attached to the carrier surface through electrostatic attractions with anionic ($-O^-$) form of hydroxyl groups and hydrogen interactions with non-ionized -OH groups. Time has shown that the surface of unmodified SiNPs is unsuitable for lipase immobilization due to rapid enzyme denaturation and a marked decrease in catalytic activity caused by the proximity of the charged silica surface. To make the microenvironment more suitable for the lipase molecules, the next step toward obtaining nanobiocatalysts with better performance was a modification of the nano-silica surface. Hence, the introduction of various functionalities in SiNPs has been extensively studied. For biocatalyst preparation, modification is usually attained by simple grafting, because after the introduction, groups are located on the external surface (N-SiNPs) and/or close to the pore entrance (M-SiNPs), thus available to the enzyme.

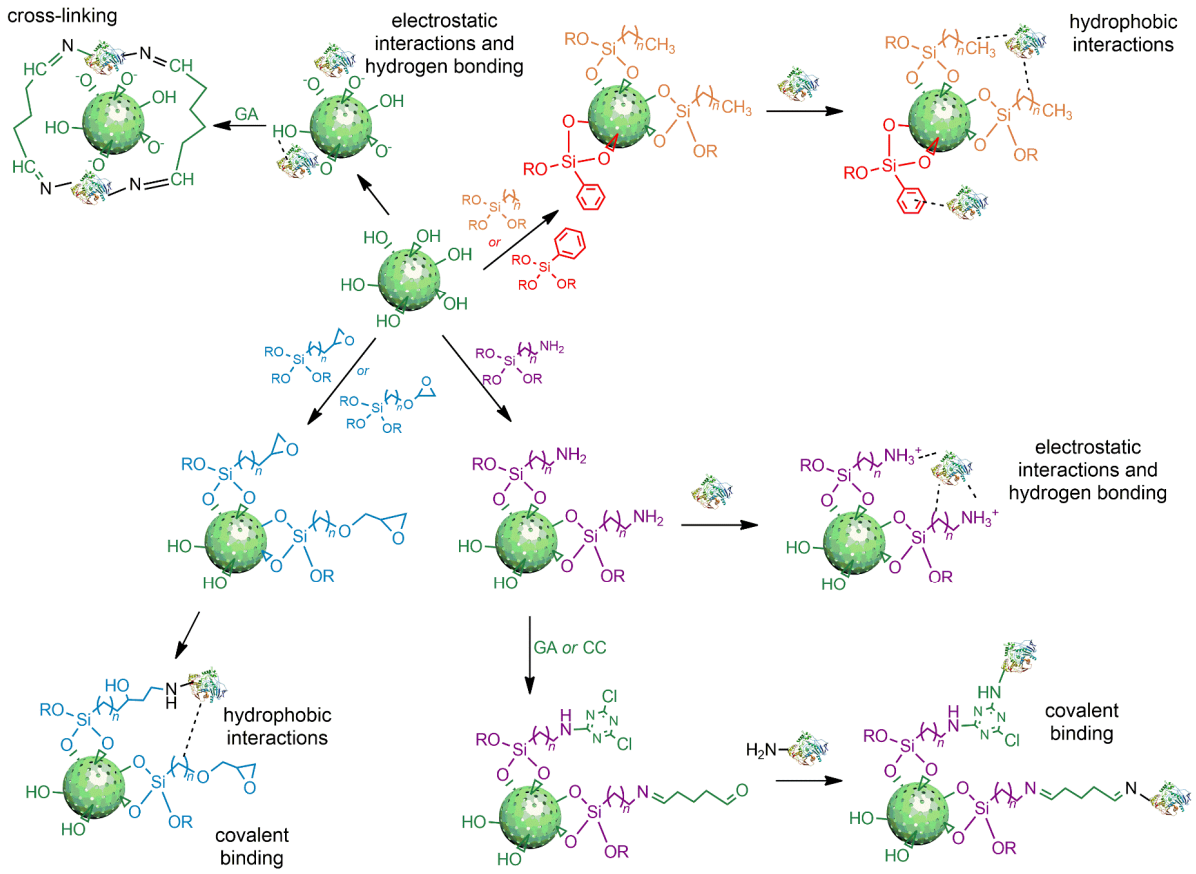


**Figure 3.** Schematic representation of SiNPs modification routes.

The most common method to functionalize the silica surface with different groups is to react with appropriate bifunctional coupling agents commonly organosilanes. Typically, modification to introduce amino groups was accomplished using 3-aminopropyltriethoxy/methoxysilane (APTES or APTMS). Adsorption of lipase on the surface where charged (-$^{+}NH_3$) groups are distant from the carrier surface was studied by several research groups [53–56]. In this case, adsorption is governed by hydrogen bonding and electrostatic attraction to negatively charged (-$COO^{-}$) groups on the lipase molecule surface. Sadighi et al. obtain nano-silica lipase biocatalysts introducing amino groups by coating M-SiNPs with polyethyleneimine (PEI) and physically adsorbing lipase [57]. Although they disrupt enzyme activity, electrostatic interactions are not strong enough to prevent enzyme desorption, and thus the possibility of recycling the catalyst is disabled. Additionally, prevention of enzyme leakage can be achieved in the matrix by cross-linking with glutaraldehyde (GA) [58–65].

Bearing in mind that the lipase molecules possess a specific domain and exhibit greater activity in a hydrophobic environment, it is possible to enhance catalytic activity by creating a more hydrophobic microenvironment with organosilanes such as OCTES, TMODS, TMPS, and TMPHS [66–69]. Jin et al. studied the catalytic performance of immobilized PCL with various hydrophobic/hydrophilic surfaces and found that the most hydrophobic silica nanomaterial showed the highest activity [70]. No matter what kind of bonding interactions, adsorption is generally weak. So, to obtain a stable and durable nanobiocatalyst, it is necessary to establish a covalent bond between the carrier and the enzyme. Formation of a strong covalent bond is impossible without the chemical modification of silica. There are several ways to form the desired bond; the most common is introducing epoxy groups on the support surface. Epoxy groups can then react with nucleophilic ones on the lipase surface (particularly with terminal amino groups). It has

been proposed that the immobilization of enzymes on epoxy-functionalized supports occurs via a two-step binding mechanism [71]. First, the enzyme is physically adsorbed (hydrophobic interactions) on the carrier. This brings nucleophile groups (amino, thiol, or hydroxyl groups) on the enzyme's surface close to the oxirane groups of the support, making it possible to react with the oxirane groups and form very stable C-N, C-S, and C-O bonds. As mentioned previously, epoxy groups are also introduced using a bifunctional agent, most often (3-glycidoxypropyl)trimethoxylsilane (GOPTMS) [72–76], (3-glycidoxypropyl)methyldiethoxylsilane (GOPMDMS) [77], or glycidyl methacrylate (GMA) [78–80]. A covalent bond can also be formed if amino-functionalized nano-silica was further modified with CC or GA to introduce reactive chloride or aldehyde groups, respectively [56,59,65].

Another, but not very often used strategy for silica-based carriers is forming an amide bond between previously introduced carboxylic or amino groups of support and amino or carboxylic groups of the enzyme with the help of carbodiimide coupling reagent EDC, often used in combination with N-hydroxysuccinimide (NHS) [81,82].

**Table 1.** Summarized SiNP surface modification techniques and lipase immobilization methods with highlighted biotechnological application.

| Support | Lipase Source | Modification | Immobilization Method | Application | Ref |
|---|---|---|---|---|---|
| f-SiNPs | CAL B | - | Adsorption | Geranyl acetate synthesis | [46] |
| f-SiNPs | CAL B | - | Adsorption | Geranyl acetate synthesis | [49] |
| w-SiNPs | CRL | - | Adsorption | Biodiesel | [50] |
| M-SiNPs | BCL | - | Adsorption | Biodiesel | [51] |
| SiNPs | CRL | - | Adsorption | Racemization of ibuprofen | [52] |
| N-SiNPs | CRL | →APTES; →APTES → CC | Adsorption + covalent | p-NPP hydrolysis | [56] |
| M-SiNPs | PPL | →APTES | Adsorption | Triacetin hydrolysis | [53] |
| SiNPs | TLL | →APTES; →OCTES | Adsorption | Cetyl octanoate, cetyl stearate, and cetyl oleate synthesis | [54] |
| M-SiNPs | RML | →APTMS → AA → CiC | covalent | Racemization of ibuprofen | [83] |
| M-SiN (flower) | CAL | →APTMS | Adsorption | Ethyl levulinate synthesis | [55] |
| M-SiNPs | TLL | →PEI | Adsorption | Ethyl valerate synthesis (apple flavor) | [57] |
| M-SiNPs | CRL | →APTES → GA | Cross-linking | Olive oil hydrolysis | [58] |
| SiNPs (virus like) | CAL B | →APTES → GA | Cross-linking | Lauryl levulinate synthesis | [84] |
| SiNPs | CRL | →APTES → GA | Cross-linking | Racemization of naproxen | [59] |
| $Fe_3O_4$@SiNPs | NS81006 from ANL | →APTES → GA; →MPTMS → GA | Cross-linking | Biodiesel | [60] |
| $Fe_3O_4$@SiNPs | CRL | →APTES → GA | Cross-linking | p-NPA hydrolysis | [61] |
| $Fe_3O_4$@SiNP/GO | CRL | →APTES → GA | Cross-linking | Ethyl valerate synthesis | [62] |
| $Fe_3O_4$@SiNPs | BCL | →GA | Cross-linking | Biodiesel | [63] |
| $Fe_3O_4$@SiNPs | PPL | →APTES → GA | Cross-linking | p-NPP hydrolysis | [64] |
| SiNPs | CAL B | →GA | Cross-linking | p-NPP hydrolysis | [85] |
| $Fe_3O_4$@SiNPs | ROL | →APTES → GA | Covalent | Biodiesel | [65] |
| SiNPs | RNL | →ClPTES | Adsorption | Quinizarin diester hydrolysis | [66] |

**Table 1.** *Cont.*

| Support | Lipase Source | Modification | Immobilization Method | Application | Ref |
|---|---|---|---|---|---|
| h-SiNPs | CRL | →TMPS<br>→TMPhS<br>→TMOS<br>→TMODS | Adsorption | Phytosterol ester synthesis | [67] |
| $Fe_3O_4$@SiNPs | BL sp. | →TPDACl | Adsorption | Biodiesel | [68] |
| w-SiNPs | CRL | →PDTES | Adsorption | Biodiesel | [69] |
| f-SiNPs | CRL | →GOPTMS | Covalent | Flavor ester synthesis | [76] |
| M-SiNPs | CALB; TLL; RML | →GOPTMS | Covalent | Biodiesel | [74] |
| SiNPs | TLL | →OTMS + GOPMDMS | Covalent | Biodiesel | [77] |
| SiNPs | CRL | → pGMA<br>→pGMA → $Cys_{(EDC+NHS)}$ | Covalent | p-NPP hydrolysis | [78] |
| SiNPs | CRL | APTES→BIBB → p(GMA-*co*-SBMA) | Covalent and adsorption | p-NPP hydrolysis | [79] |
| SiNPs | RML | →GOPTMS | Covalent | Fish oil hydrolysis | [72] |
| $Fe_3O_4$@SiNPs | CAL B | →GOPTMS | Covalent | Biodiesel | [75] |
| M-SiNPs | CAL B<br>RML | →GOPTMS | Covalent | Racemization of ibuprofen | [73] |
| $Fe_3O_4$@SiNPs | CRL | →GMA | Covalent | Olive oil hydrolysis | [80] |
| M-SiNPs | CAL B | →CPTES → $H_2OS_4$ | Covalent (EDC+NHS) | Tributyrin hydrolysis | [81] |
| $Fe_3O_4$@SiNPs | PPL | →APTES → SA | Covalent (EDC+NHS) | Inhibitor screening | [82] |
| SiNPs<br>$Fe_3O_4$@SiNPs | FE-01 from TLL | →APTMS → GA | Covalent | Degradation of PCL | [24] |
| SiNPs | BCL | →GOPTMS;<br>→APTMS → HDGE<br>→APTES → GA; | Covalent | Degradation of PCL | [23] |
| M-SiNPs | PPL | →APTES → DTMS → GA;<br>→DTMS → GA;<br>→APTMS → HDGE,<br>→GOPTMS;<br>→GOPMTS → PEI → GA, | Covalent | Synthesis of biodegradable polymer | [86] |

f-SiNP—fumed silica nanoparticles; N-SiNPs—non-porous silica nanoparticles; M-SiNPs—mesoporous silica nanoparticles; w-SiNPs—wrinkled silica nanoparticles; m-SiNPs—magnetic silica nanoparticles; GO—graphene oxide; h-SiNPs—hollow silica nanoparticles; CALB—*Candida antarctica* lipase B; CRL—*Candida rugosa* lipase; BCL—*Burkholderia cepacia* lipase PPL—*Porcine pancreatic* lipase; TLL—*Thermomyces lanuginosus* lipase; RML—*Rhizomucor miehei* lipase; CAL—*Candida antarctica* lipase; ANL—Aspergillus niger lipase; ROL—*Rhizopus oryzae* lipase; RNL—*Rhizopus niveus* lipase; BL—*Burkholderia* lipase; APTES—3-(Aminopropyl)triethoxysilane; CC—cyanuric chloride; OCTES—(octyl)silane; APTMS—3-(Aminopropyl)trimethoxysilane; AA—acetaldehyde; CiC—cyclohexyl isocyanide; PEI—polyethylenimine; GA—Glutaraldehyde; MPTMS—3-mercaptopropyltrimethoxysilane; ClPTES—(3-Chloropropyl)triethoxysilane; TMPS—trimethoxypropylsilane; TMPhS—trimethoxyphenylsilane; TMOS—trimethoxyoctylsilane; TMODS—trimethoxyoctadecylsilane; TPDACl—[3-(Trimethoxysilyl) propyl] octadecyl dimethyl ammonium chloride; PDTES—perfluorodecyltriethoxysilane; GOPTMS—3-Glycidyloxypropyl trimethoxysilane; OTMS—octyl trimethoxysilane; GOPMDMS—(3-Glycidoxypropyl)methyldiethoxysilane; pGMA—poly(glycidyl methacrylate); EDC—1-Ethyl-3-(3-dimethylaminopropyl)carbodiimide; NHS—N-Hydroxysuccinimide; BIBB—2-bromoisobutylol bromide; SBMA—sulfobetaine methacrylate; CPTES—(3-cyanopropyl)trimethoxysilane; SA—succinic anhydride; PCL—poly-ε-caprolacton; HDGE—1,6-hexanedioldiglycidyl ether, DTMS—(n-dodecyl)trimethoxysilane; p-NPA—*p*-Nitrophenyl acetate; *p*-NPP—*p*-Nitrophenyl palmitate.

## 3. Application of Lipase SiNPs

Lipases (triacylglycerol acylhydrolase, EC 3.1.1.3) are enzymes primarily known for catalyzing the hydrolysis of triacylglycerols into free fatty acids, diacylglycerols, monoacyl-

glycerols, and glycerol. However, their catalytic versatility extends beyond this, as they can hydrolyze various other esters and catalyze the formation of ester bonds through the reaction between acids and alcohols (Figure 4). Lipases are the most extensively utilized enzymes in organic synthesis due to their wide range of applications [87].

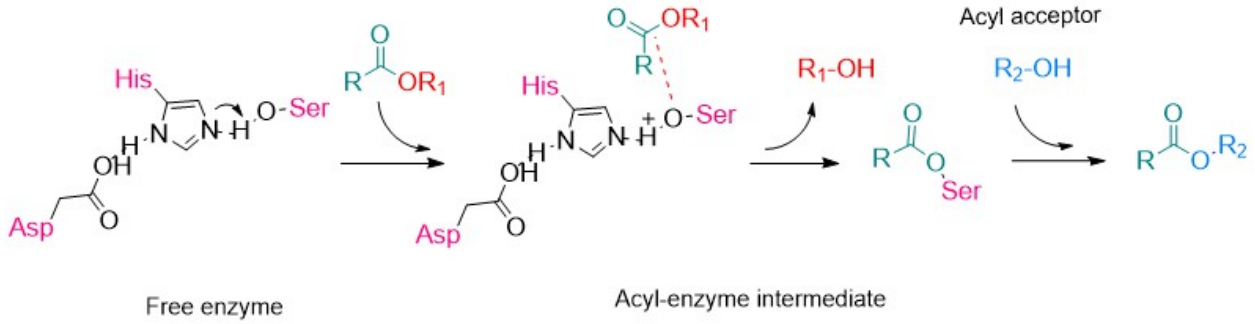


**Figure 4.** Schematic illustration of a lipase-catalyzed transesterification reaction.

Lipase-catalyzed transesterification follows a ping-pong bi-bi mechanism, where the enzyme interacts sequentially with two substrates—typically a triglyceride and an enzyme–substrate intermediate—producing two distinct products. The catalytic function of lipases relies on two key active site residues: a serine residue, which uses its hydroxyl group to carry out nucleophilic addition and form the enzyme–substrate complex, and a histidine residue, which acts as a proton acceptor to facilitate the reaction. These functional groups are essential for the enzyme's transesterification activity [88].

The active center of most lipases is protected by an amphiphilic polypeptide loop, known as the lid. Upon interacting with hydrophobic substrates such as oil droplets, the lid opens, revealing the active site and creating a large hydrophobic pocket [89]. In aqueous media, lipases can form inactive aggregates, reducing their activity [90]. This issue can be addressed by immobilizing the enzyme, which increases surface area and improves lipase efficiency [91].

The commercialization of lipases for bulk chemical production has been hindered by their high cost. Immobilization offers a cost-effective solution by enabling the reuse of lipases, making their application more practical and economical [92]. Biodiesel and other bulk chemicals are typically synthesized in non-aqueous environments, prompting research into lipases with improved activity and stability in organic solvents. The high efficiency of *Candida antarctica* lipase B (CALB) in alcohol-based reactions has established it as a key biocatalyst for biodiesel production [93]. Challenges persist with immobilized lipase in biodiesel production, as hydrophilic carriers can limit oil accessibility and lead to methanol deactivation. In contrast, hydrophobic surfaces stabilize lipase in its active form, enhancing stability and performance [93]. Improving current methods and exploring new approaches for immobilized lipase are essential for industrial applications. Many studies focus on advanced immobilization strategies to produce commercially valuable compounds.

### *3.1. Biodiesel Production*

Biodiesel, composed of fatty acid alkyl esters (FAAE), is a renewable and sustainable alternative to fossil fuels with lower emissions of carbon dioxide, sulfur, and particulates [91].

Biodiesel can be produced from vegetable oils, animal fats, or microbial oils through transesterification with alcohol [93]. Compared to chemical methods, using lipase as a catalyst provides advantages such as easier product separation, reduced wastewater, efficient glycerol recovery, and fewer side reactions [93].

Various strategies for immobilizing lipases on mesoporous and magnetic supports have shown promise for biodiesel production, providing examples of enhanced stability,

reusability, and catalytic efficiency. Immobilized lipases onto magnetic nanoparticles as a carrier can be rapidly separated from the reaction medium and efficiently controlled by applying an external magnetic field [94]. This enables the enzyme to be recycled and reused multiple times, which is a crucial factor for the efficient industrial production of biodiesel.

The mesoporous SPION–silica core–shell ($Fe_3O_4$@$SiO_2$) has recently been synthesized as a promising support for immobilizing *Burkholderia cepacia* lipase, with the high surface area of mesoporous silica for increased enzyme loading and the superparamagnetic properties of SPIONs for easy enzyme recovery. Under optimal conditions—a methanol-to-oil molar ratio of 6:1, 25 wt% immobilized lipase concentration, 10 wt% n-hexane content and 10 wt% water content at 35 °C, and with a reaction time of 35 h—this system achieved a biodiesel conversion rate of 91% from waste cooking oil [63].

Similarly, a new biocatalyst for biodiesel production was developed by immobilizing *Candida rugosa* lipase (CRL) on synthesized wrinkled silica nanoparticles with radially oriented mesochannels. In the esterification of oleic acid with methanol, this biocatalyst demonstrated promising results, achieving an oleic acid conversion rate of approximately 86.4% under optimal conditions [63].

The synthesis of fatty acid methyl ester (FAME) from olive oil as a model feedstock was conducted using *Rhizopus oryzae* lipase immobilized on mesoporous silica-coated magnetic nanoparticles (magnetic M-SiNPs). The magnetic M-SiNPs, functionalized with amine and aldehyde groups to support lipase immobilization, simplified biodiesel production and allowed for easy magnetic separation of the immobilized enzyme from the biodiesel product [63].

Another example is lipase from *Burkholderia sp.* C20 immobilized on core–shell magnetic nanoparticles. These nanoparticles were synthesized by coating a $Fe_3O_4$ core with a silica shell and functionalized with dimethyl octadecyl [3-(trimethoxysilyl) propyl] ammonium chloride for enzyme attachment. The immobilized *Burkholderia sp. C20 lipase* successfully catalyzed the transesterification of olive oil with methanol to produce FAMEs, achieving over 90% FAME conversion within 30 h in batch operation with 11 wt% enzyme loading. Additionally, this immobilized lipase displayed excellent reusability, maintaining high transesterification activity over ten cycles [68].

CALB was covalently immobilized onto epoxy-functionalized $Fe_3O_4$@$SiO_2$ under mild conditions, achieving a high immobilization yield and significantly enhancing its thermal stability and methanol tolerance compared to the free enzyme. The immobilized lipase was considered for biodiesel production through the transesterification of waste cooking oil with methanol. The results showed that the biocatalyst could be simply recovered from the reaction mixture and reused for six cycles without any loss in enzyme activity [75].

*Candida rugosa* lipase immobilized on $Fe_3O_4$/Poly(styrene-methacrylic acid) has been used for biodiesel production from soybean oil. In this study, the lipase was covalently bound to the magnetic support using 1-ethyl-3-(3-(dimethylamino)propyl)-carbodiimide hydrochloride. The results indicate that immobilization improved the pH and thermal stability of the biocatalyst. After 24 h of reaction at 35 °C, an 86% oil conversion was achieved, and the immobilized lipase retained sufficient activity after four reuses [95].

A lipase from *Thermomyces lanuginosus* (TLL) was immobilized on biomimetic silica nanoparticles by two different approaches: in situ entrapment and adsorption/covalent surface immobilization. The entrapped nanobiocatalysts exhibited greater stability and activity compared to soluble TLL, commercial immobilized TLL, and surface-immobilized counterparts. The surface-immobilized lipase achieved a maximum yield of 88% in the synthesis of FAMEs from canola oil and methanol, exceeding the yield of commercial immobilized TL by 10% [77].

The epoxy-functionalized SBA-15 was developed as a novel mesoporous support for covalent lipase immobilization, enabling biodiesel production through the methanolysis of canola oil. Mesoporous SBA-15 nanoparticles were prepared, characterized, and functionalized by 3-3-glycidyloxypropyl trimethoxysilane. Lipases from *Candida antarctica* (CALB), *Thermomyces lanuginosus* (TLL), and *Rhizomucor miehei* (RML) were covalently immobilized onto SBA–epoxy. The immobilized TLL lipase was quite stable and can be reused for 20 cycles without significant loss in activity (6%). RML lipase and CALB lipase also offered excellent reusability, keeping 95% of their initial activities after 7 and 15 cycles of the reaction. Compared with another immobilization method on the SBA-15 support (chemically or physically), epoxy-functionalized silica exhibited higher catalytic activity and reusability [74].

### *3.2. Flavor Esters Production*

Although many flavors and fragrances are produced through chemical synthesis or plant extraction, using biocatalysts offers a safer and more sustainable alternative through more efficient chemical processes. Optimizing variables that affect lipase-catalyzed synthesis, including enzyme formulations, solvent-free media, and acetylating agents, is essential for achieving higher conversion rates [96].

Silica derived from agricultural wastes, particularly rice husks, has gained significant attention for industrial applications due to its low cost, excellent physicochemical properties, and widespread availability in many countries [97]. In this context, $SiO_2$ particles from rice husks were used as a support for immobilizing commercial TLL lipase through adsorption via hydrophobic and ionic interactions, enabling efficient synthesis of cetyl-esters [54].

The synthesis of ethyl valerate, apple flavor, has gained attention due to its commercial value. M-SiNPs MCM-41 coated with polyethyleneimine (MCM-41@PEI) and further modified by chelation of divalent metal ions was used for the immobilization of TLL lipase. Obtained biocatalysts with the best performance were used for the synthesis of ethyl valerate in the presence of valeric acid and ethanol. Immobilizing lipase onto MCM-41@PEI-Co resulted in an esterification yield of up to 60%, outperforming the free enzyme due to the limited activity of non-immobilized lipase in organic solvents [57]. In another study, for the synthesis of the same molecule, CRL lipase was immobilized on ternary biogenic oil palm leaves/silica/magnetite/graphene oxide composite. The obtained immobilized lipase yielded 30% more ethyl valerate compared to the free enzyme, confirming the suitability of $SiO_2/Fe_3O_4$/graphene oxide to hyperactivate and stabilize CRL for satisfactory ethyl valerate production [62]. The synthesis of amyl caproate ester flavor compounds was also performed with immobilized CRL lipase. The type of modification of the fumed silica nanoparticles' surface influences the specificity of the immobilized lipase, since lipase immobilized on the epoxy-functionalized silica nanoparticles showed enhanced properties for ester synthesis [76].

### *3.3. Racemizations*

One of the most difficult and challenging problems in the field of valuable chemicals is the production of optically active compounds [98]. Lipases, thanks to their functional conformation, can resolve racemic mixtures of optically active compounds. Lipase-catalyzed reactions are typically classified into three categories: asymmetric hydrolysis, asymmetric esterification, and asymmetric transesterification.

The pharmacological importance of the (*S*)-enantiomer, in addition to its higher cost compared to racemic ibuprofen, has driven numerous scientific studies focused on the enzymatic resolution of ibuprofen through enantiomeric esterification using lipases as a

biocatalyst [99]. CALB and RML lipases as model enzymes were immobilized on epoxy-functionalized silica and mesoporous silica nanoparticles (SBA-15). Silica–epoxy–RML showed an enantiomeric excess (ee) of 92% and an E-value of 29.9 in the enantioselective esterification of racemic ibuprofen [73]. Also, RML lipase was immobilized on amine-functionalized silica and silica nanoparticles for the catalysis of racemic ibuprofen kinetic resolution [83]. For the same purpose, CRL lipase was immobilized onto silica nanoparticles through adsorption. The catalytic properties of both immobilized and free lipases, such as optimal pH and temperature, were similar [52].

Naproxen is a non-steroidal, anti-inflammatory drug that primarily employs pharmacological activity on (S)-enantiomers; the resolution of racemic naproxen 2,2,2-trifluoroethyl thioester by lipase is useful but has some hindrances, including maintenance of catalytic activity. Song et al. immobilized lipase onto SiNPs using a covalent bonding method and employed it for the enzyme-catalyzed resolution of racemic naproxen 2,2,2-trifluoroethyl thioester. Under optimized conditions, the reaction rate, conversion, and enantioselectivity of the immobilized lipase were significantly enhanced [59].

### *3.4. Synthesis of Antioxidants*

The chemical acylation of natural antioxidants can significantly enhance their oxidative and thermal stability, which is crucial for their effectiveness in various applications, such as in food preservation and cosmetics. Additionally, this modification can alter their hydrophilic–lipophilic balance. However, chemical acylation processes are typically carried out under harsh conditions, often involving the use of strongly corrosive acids, high temperatures, and extended reaction times. In contrast, lipase-catalyzed acylation offers several advantages, including the ability to carry out the reaction under milder conditions, with lower energy requirements, and with greater selectivity [100].

Due to their important medicinal and healthcare benefits, the efficient and rapid synthesis of phytosterol esters has garnered the interest of numerous pharmaceutical and food companies. So far, phytosterol esters have mostly been synthesized by chemical methods; in terms of green methods, enzymatic esterification of phytosterols, especially by immobilized lipases, has become more attractive [101]. Dong et al. used hollow mesoporous silica modified with materials of different hydrophobicity to immobilize CRL lipase. They investigated the esterification of phytosterols with polyunsaturated fatty acid in a solvent-free system for the production of phytosterols esters [67]. Under optimized conditions, a conversion rate of approximately 90% was achieved. These results suggest that CRL immobilized on octadecyl SiNPs is a promising catalyst with potential applications in the production of functional lipids.

### *3.5. Polymer Biodegradation*

The biodegradation of polymers has gained attention as a promising strategy to mitigate environmental pollution from non-biodegradable plastics. In recent years, the number of studies highlighting microorganisms and enzymes as effective agents for plastic degradation has grown significantly [102,103].

Immobilizing lipase on silica nanoparticles is a promising strategy to enhance polymer biodegradation. A more direct and innovative approach involves embedding enzymes, like lipases, directly into the polymer matrix to create self-degradable plastics [23]. To preserve enzyme activity during high-temperature or solvent-based polymer processing, enzymes are immobilized, typically via covalent attachment. This method stabilizes the enzymes within the polymer, enhancing their activity and ensuring sustained functionality. This innovative approach aims to reduce pollution by providing a self-degrading material that retains enzyme activity and offers the potential for recycling. SiNPs were found to be effective

in reinforcing filler interaction with reactive groups of polymers either through hydrogen bonding or covalent bonds during the preparation of polymer nanocomposites [104].

Recently, preparation of self-degradable composites with controlled lifetime was obtained with lipase from *Burkholderia cepacia*, which was covalently attached to the surface of Laponite® layered silicate activated with glycidoxy groups. This modified silicate, when embedded in poly-ε-caprolactone (PCL), allows for the creation of self-degradable biopolymers. The lipase immobilized in this way catalyzes the breakdown of PCL under mild conditions (30–50 °C, near-neutral pH), leading to environmentally safe degradation products [23].

Another study explores a sustainable approach for degrading industrial plastics by immobilizing enzymes (lipase and cutinase) onto $SiO_2$ and $Fe_3O_4$@$SiO_2$ nanoparticles, creating a reusable system for selective depolymerization. Through amino–silane surface modification, the enzymes are covalently bound to the nanoparticles using 3-(aminopropyl)trimethoxysilane and glutaraldehyde linkers, forming a stable imine bond. The immobilized enzymes effectively degraded polycaprolactone (PCL) fiber mats, as shown by morphological changes and weight loss in fibers. Notably, the conjugated enzymes remained highly stable and effective, allowing for repeated use and potential applications in plastic recycling, with magnetic $Fe_3O_4$@$SiO_2$ particles offering straightforward recovery [24]. Interestingly, *Bacillus subtilis* spores were also used as depolymerizing enzyme carriers within PCL material, enabling switchable self-degradation [105]; however, SiNPs provide higher stability and reusability.

### *3.6. Polymerizations*

Polyesters and polycarbonates are key biodegradable and biocompatible polymers that have been widely studied for medical applications [106]. The use of lipases in polymer synthesis has shown great potential, but significant optimization of conditions is required due to enzyme instability at the high temperatures used for polymer synthesis, particularly for PCL. Enzyme immobilization has been recognized as an effective solution. It was reported that native porcine pancreas lipase (PPL) showed low catalytic activity for ε-caprolactone polymerization, while covalently immobilized PPL exhibited better activity but failed to produce PCL below 140 °C within 240 h [107].

The initial use of immobilized PPL on SiNPs of different sizes for the ring-opening copolymerization of 5-benzyloxy-trimethylene carbonate (BTMC) with 5,5-dimethyl-trimethylene carbonate (DTC) revealed that the particle size had a significant impact on catalytic activity and polymer yield. The highest molecular weight of the copolymer was obtained with PPL immobilized on 75–150 μm silica particles [108].

To address the limitations of PPL in polymerization reactions, porous silica particles were modified with surface-active groups to enable its covalent immobilization. The modifications were achieved through silanization using organosilanes with amino or epoxy end groups, as well as polyethyleneimine and long-chain alkyl silane coupling agents. The immobilized PPL (IPPL) demonstrated significantly enhanced catalytic activity compared to native PPL, enabling the successful synthesis of PCL and poly(5,5-dimethyl-1,3-dioxan-2-one) (PDTC) in an ionic liquid medium, which native PPL could not achieve. This immobilization strategy not only improved the enzyme's stability at high temperatures but also optimized polymerization efficiency in ionic liquids, providing a promising approach for designing immobilized enzymes for the synthesis of biodegradable polymers and other applications [86].

### *3.7. Miscellaneous Applications*

Stricter environmental regulations regarding safety and waste disposal have led to changes in many chemical processes.

Covalent immobilization of RML lipase on functionalized SiNPs via random and oriented procedures leads to immobilized derivatives with different properties. The influence of the immobilization procedure on the activity and selectivity of the immobilized preparations was studied in the selective hydrolysis of fish oil to obtain omega-3 fatty acids [72]. In the work of Pota and co-workers, CRL lipase was physically immobilized onto hydrophobic functionalized wrinkled silica nanoparticles to preserve its native conformation and catalytic activity. Immobilization was carried out using a ternary system lipase/water/n-hexane (a micro-oily environment), and the obtained enzyme was compared to free lipase in the reaction of the hydrolysis and the transesterification of sunflower seed oil [69].

## 4. Conclusions and Future Perspectives

This review attempted to cover a wide range of industrially important catalytic applications of lipases immobilized on SiNPs. It also summarized a broad spectrum of modification techniques aimed at enhancing the properties of SiNPs as carriers for lipase immobilization, demonstrating that surface modifications that increase hydrophobicity have a positive impact on both lipase activity and stability. This effect is likely due to the specific structure of these enzymes, which contain a higher proportion of hydrophobic amino acid residues in their primary structure. Also, lipases possess a unique structure characterized by an active site covered by a lid. This lid shifts upon encountering a hydrophobic surface, transforming the lipase into its active form, thereby exposing the active site to the substrate. This transformation can be facilitated by engineering the specific hydrophobic/hydrophilic two-phase interface surface and incorporating specific functional groups on the surface that allow for covalent bonding (e.g., carboxyl, amino, aldehyde groups) to ensure the lipase remains securely attached in its active conformation. This approach not only stabilizes the enzyme but also enhances its catalytic efficiency, making it more effective for various applications. Moreover, researchers can achieve precise and efficient enzyme attachment by utilizing advanced bioconjugation techniques, such as click chemistry or EDC/NHS coupling. These methods can provide better control over the immobilization process and enhance the stability of the enzyme–nanoparticle complex. As a result, these modifications improve the enzyme features, tailoring the support surface properties to optimize enzyme activity.

Recently, studies have indicated that various types of agro-industrial waste can be utilized as sources of SiNPs, presenting a sustainable and cost-effective alternative to traditional synthesis methods. Although this area has been covered by only a limited number of studies so far, the concept is highly promising. Various types of agricultural waste, such as rice husk, wheat straw, sugarcane bagasse, and corn cobs, are rich in silica content, making them suitable feedstocks for producing silica nanoparticles.

In addition to their traditional and well-established role as catalysts for ester bond formation (e.g., in the production of flavor esters, antioxidants, and biodiesel), lipase has attracted significant attention for its applications in various fields of environmental sciences. Building on their catalytic versatility, lipases have also gained recognition in environmental science for their ability to hydrolyze ester bonds, enabling the biodegradation of a broad range of pollutants, including oils, greases, and synthetic polymers such as polyurethanes and polyesters. The ability to decay lipid-rich wastewater from the food industry is a noteworthy property of lipase-catalyzed processes. In this way, not only is the quality

of water improved, but these processes can also contribute to easier industrial waste management and reduce the negative impact on aquatic ecosystems.

The integration of enzyme immobilization techniques into polymer degradation and synthesis represents a transformative approach to addressing environmental challenges posed by non-biodegradable plastics. Immobilizing lipases on SiNPs has proven to be an effective strategy for enhancing enzymatic stability, activity, and reusability, enabling more efficient polymer biodegradation under mild conditions. Recent innovations, such as embedding immobilized enzymes into polymer matrices, have paved the way for self-degradable bioplastics with controlled lifespans. These biopolymers, such as those incorporating lipase-catalyzed degradation of PCL, not only facilitate environmentally friendly degradation but also produce products that are safe by design, offering significant potential for sustainable plastic recycling.

In conclusion, future research should focus on optimizing enzyme immobilization techniques to enhance activity and stability further, particularly in challenging environments such as high temperatures and organic solvents. Additionally, embedding enzymes into smart materials and creating multifunctional biocatalytic systems hold great promise for the next generation of biodegradable polymers and self-degrading plastics. By combining advancements in nanotechnology and enzyme engineering, it is possible to develop innovative solutions for polymer degradation and synthesis, ultimately contributing to the global effort to reduce plastic pollution and promote sustainable materials.

**Author Contributions:** Conceptualization, J.M. and N.Ž.P.; Writing—original draft preparation, J.M. and N.Ž.P.; writing—review and editing, J.M., K.B., J.N., J.N.-R. and N.Ž.P.; funding acquisition, J.N.-R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract Nos. 451-03-65/2024-03/200135 and 451-03-66/2024-03/200287).

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Kulkarni, S. Enzymes as Biocatalysts: Review on Investigations on Synthesis, Mechanism, Kinetics, Applications and Potential. *Lett. Appl. NanoBioSci.* **2022**, *11*, 3049–3064. [CrossRef]
2. Bell, E.L.; Finnigan, W.; France, S.P.; Green, A.P.; Hayes, M.A.; Hepworth, L.J.; Lovelock, S.L.; Niikura, H.; Osuna, S.; Romero, E.; et al. Biocatalysis. *Nat. Rev. Methods Prim.* **2021**, *1*, 46. [CrossRef]
3. Pyser, J.B.; Chakrabarty, S.; Romero, E.O.; Narayan, A.R.H. State-of-the-Art Biocatalysis. *ACS Cent. Sci.* **2021**, *7*, 1105–1116. [CrossRef]
4. Li, C.; Zhang, R.; Wang, J.; Wilson, L.M.; Yan, Y. Protein Engineering for Improving and Diversifying Natural Products Biosynthesis. *Trends Biotechnol.* **2020**, *38*, 729–744. [CrossRef]
5. Du, Y.; Zhao, L.; Geng, Z.; Huo, Z.; Li, H.; Shen, X.; Peng, X.; Yan, R.; Cui, J.; Jia, S. Construction of Catalase@ hollow Silica Nanosphere: Catalase with Immobilized but Not Rigid State for Improving Catalytic Performances. *Int. J. Biol. Macromol.* **2024**, *263*, 130381. [CrossRef]
6. Cao, L. *Introduction: Immobilized Enzymes: Past, Present and Prospects*; Wiley-VCH: Weinheim, Germany, 2005; ISBN 3527312323.
7. Zdarta, J.; Meyer, A.S.; Jesionowski, T.; Pinelo, M. A General Overview of Support Materials for Enzyme Immobilization: Characteristics, Properties, Practical Utility. *Catalysts* **2018**, *8*, 92. [CrossRef]
8. Spasojević, M.; Prodanović, O.; Pantić, N.; Popović, N.; Balaž, A.M.; Prodanović, R. The Enzyme Immobilization: Carriers and Immobilization Methods. *J. Eng. Process. Manag.* **2019**, *11*, 89–105. [CrossRef]
9. Ismail, A.R.; Baek, K.H. Lipase Immobilization with Support Materials, Preparation Techniques, and Applications: Present and Future Aspects. *Int. J. Biol. Macromol.* **2020**, *163*, 1624–1639. [CrossRef]
10. Mihailović, M.; Stojanović, M.; Banjanac, K.; Carević, M.; Prlainović, N.; Milosavić, N.; Bezbradica, D. Immobilization of Lipase on Epoxy-Activated Purolite® A109 and Its Post-Immobilization Stabilization. *Process Biochem.* **2014**, *49*, 637–646. [CrossRef]

11. Prlainović, N.Ž.; Knežević-Jugović, Z.D.; Mijin, D.Ž.; Bezbradica, D.I. Immobilization of Lipase from Candida Rugosa on Sepabeads®: The Effect of Lipase Oxidation by Periodates. *Bioprocess Biosyst. Eng.* **2011**, *34*, 803–810. [CrossRef]
12. Prlainović, N.; Milovanović, J.S.; Milašinović, N.Z.; Bezbradica, D.I.; Mijin, D. Multi-Walled Carbon Nanotubes as Lipase Carriers for Organic Synthesis: Current Trends and Recent Update. *Hem. Ind.* **2024**, *78*, 1–16. [CrossRef]
13. Uddin, M.N.; Desai, F.; Asmatulu, E. Engineered Nanomaterials in the Environment: Bioaccumulation, Biomagnification and Biotransformation. *Environ. Chem. Lett.* **2020**, *18*, 1073–1083. [CrossRef]
14. Ayub, J.; Saeed, M.U.; Hussain, N.; Zulfiqar, I.; Mehmood, T.; Iqbal, H.M.N.; Bilal, M. Designing Robust Nano-Biocatalysts Using Nanomaterials as Multifunctional Carriers—Expanding the Application Scope of Bio-Enzymes. *Top. Cataysis* **2023**, *66*, 625–648. [CrossRef]
15. Bilal, M.; Fernandes, C.D.; Mehmood, T.; Nadeem, F.; Tabassam, Q.; Ferreira, L.F.R. Immobilized Lipases-Based Nano-Biocatalytic Systems—A Versatile Platform with Incredible Biotechnological Potential. *Int. J. Biol. Macromol.* **2021**, *175*, 108–122. [CrossRef]
16. Bitar, A.; Ahmad, N.M.; Fessi, H.; Elaissari, A. Silica-Based Nanoparticles for Biomedical Applications. *Drug Discov. Today* **2012**, *17*, 1147–1154. [CrossRef]
17. Prlainović Nevena, Ž.; Bezbradica Dejan, I.; Knežević-Jugović Zorica, D.; Kozlowska Roksana, T.; Mijin Dušan, Ž. A Kinetic Study of Candida Rugosa Lipase-Catalyzed Synthesis of 4,6-Dimethyl-3-Cyano-2-Pyridone. *J. Braz. Chem. Soc.* **2010**, *21*, 2285–2293. [CrossRef]
18. Prlainović, N.Ž.; Bezbradica, D.I.; Knežević-Jugović, Z.D.; Marinković, A.D.; Mijin, D.Ž. Imobilizacija Enzima Na Ugljenične Nanocevi. *Hem. Ind.* **2011**, *65*, 423–430. [CrossRef]
19. Prlainović, N.Ž.; Bezbradica, D.I.; Knežević-Jugović, Z.D.; Veličković, D.V.; Mijin, D.Ž. Enzymatic Synthesis of a Vitamin B6 Precursor. *J. Serbian Chem. Soc.* **2013**, *78*, 1491–1501. [CrossRef]
20. Milašinović, N.; Jakovetić, S.; Knežević-Jugović, Z.; Milosavljević, N.; Lučić, M.; Filipović, J.; Kalagasidis Krušić, M. Catalyzed Ester Synthesis Using Candida Rugosa Lipase Entrapped by Poly(N-Isopropylacrylamide-Co-Itaconic Acid) Hydrogel. *Sci. World J.* **2014**, *2014*, 142123. [CrossRef]
21. Milašinović, N.; Knežević-Jugović, Z.; Jakovljević, Ž.; Filipović, J.; Kalagasidis Krušić, M. Synthesis of N-Amyl Isobutyrate Catalyzed by Candida Rugosa Lipase Immobilized into Poly(N-Isopropylacrylamide-Co-Itaconic Acid) Hydrogels. *Chem. Eng. J.* **2012**, *181–182*, 614–623. [CrossRef]
22. Tang, K.H.D.; Lock, S.S.M.; Yap, P.S.; Cheah, K.W.; Chan, Y.H.; Yiin, C.L.; Ku, A.Z.E.; Loy, A.C.M.; Chin, B.L.F.; Chai, Y.H. Immobilized Enzyme/Microorganism Complexes for Degradation of Microplastics: A Review of Recent Advances, Feasibility and Future Prospects. *Sci. Total Environ.* **2022**, *832*, 154868. [CrossRef] [PubMed]
23. Hegyesi, N.; Balogh-Weiser, D.; Pukánszky, B. Covalent Immobilization of an Enzyme on a Layered Silicate to Catalyze the Self-Degradation of PCL. *Polym. Degrad. Stab.* **2024**, *229*, 111003. [CrossRef]
24. Krakor, E.; Gessner, I.; Wilhelm, M.; Brune, V.; Hohnsen, J.; Frenzen, L.; Mathur, S. Selective Degradation of Synthetic Polymers through Enzymes Immobilized on Nanocarriers. *MRS Commun.* **2021**, *11*, 363–371. [CrossRef]
25. Gao, R.; Pan, H.; Kai, L.; Han, K. Microbial Degradation and Valorization of Poly(Ethylene Terephthalate) (PET) Monomers. *World J. Microbiol. Biotechnol.* **2022**, *38*, 89. [CrossRef]
26. Dwivedee, B.P.; Soni, S.; Sharma, M.; Bhaumik, J.; Laha, J.K.; Banerjee, U.C. Promiscuity of Lipase-Catalyzed Reactions for Organic Synthesis: A Recent Update. *ChemistrySelect* **2018**, *3*, 2441–2466. [CrossRef]
27. Zhao, L.; Zhang, Y.; Yang, Y.; Yu, C. Silica-Based Nanoparticles for Enzyme Immobilization and Delivery. *Chem. Asian J.* **2022**, *17*, e202200573. [CrossRef]
28. Thakur, K.; Attri, C.; Seth, A. Nanocarriers-Based Immobilization of Enzymes for Industrial Application. *3 Biotech* **2021**, *11*, 427. [CrossRef]
29. Zhong, L.; Feng, Y.; Hu, H.; Xu, J.; Wang, Z.; Du, Y.; Cui, J.; Jia, S. Enhanced Enzymatic Performance of Immobilized Lipase on Metal Organic Frameworks with Superhydrophobic Coating for Biodiesel Production. *J. Colloid Interface Sci.* **2021**, *602*, 426–436. [CrossRef]
30. Shuai, W.; Kumar Das, R.; Naghdi, M.; Kaur Brar, S.; Verma, M. A Review on the Important Aspects of Lipase Immobilization on Nanomaterials. *Biotechnol. Appl. Biochem.* **2017**, *64*, 496–508. [CrossRef]
31. Kuang, G.; Du, Y.; Lu, S.; Wang, Z.; Zhang, Z.; Fan, X.; Bilal, M.; Cui, J.; Jia, S. Silica@lipase Hybrid Biocatalysts with Superior Activity by Mimetic Biomineralization in Oil/Water Two-Phase System for Hydrolysis of Soybean Oil. *LWT* **2022**, *160*, 113333. [CrossRef]
32. Cui, J.; Feng, Y.; Jia, S. Silica Encapsulated Catalase@metal-Organic Framework Composite: A Highly Stable and Recyclable Biocatalyst. *Chem. Eng. J.* **2018**, *351*, 506–514. [CrossRef]
33. Zhong, L.; Jiao, X.; Hu, H.; Shen, X.; Zhao, J.; Feng, Y.; Li, C.; Du, Y.; Cui, J.; Jia, S. Activated Magnetic Lipase-Inorganic Hybrid Nanoflowers: A Highly Active and Recyclable Nanobiocatalyst for Biodiesel Production. *Renew. Energy* **2021**, *171*, 825–832. [CrossRef]

34. Hajareh Haghighi, F.; Binaymotlagh, R.; Palocci, C.; Chronopoulou, L. Magnetic Iron Oxide Nanomaterials for Lipase Immobilization: Promising Industrial Catalysts for Biodiesel Production. *Catalysts* **2024**, *14*, 336. [CrossRef]
35. Li, C.; Zhao, J.; Zhang, Z.; Jiang, Y.; Bilal, M.; Jiang, Y.; Jia, S.; Cui, J. Self-Assembly of Activated Lipase Hybrid Nanoflowers with Superior Activity and Enhanced Stability. *Biochem. Eng. J.* **2020**, *158*, 107582. [CrossRef]
36. Maharramov, A.M.; Hasanova, U.A.; Suleymanova, I.A.; Osmanova, G.E.; Hajiyeva, N.E. The Engineered Nanoparticles in Food Chain: Potential Toxicity and Effects. *SN Appl. Sci.* **2019**, *1*, 1362. [CrossRef]
37. Li, S.F.; Chen, J.P.; Wu, W.T. Electrospun Polyacrylonitrile Nanofibrous Membranes for Lipase Immobilization. *J. Mol. Catal. B Enzym.* **2007**, *47*, 117–124. [CrossRef]
38. Yuan, Y.; Shen, J.; Salmon, S. Developing Enzyme Immobilization with Fibrous Membranes: Longevity and Characterization Considerations. *Membranes* **2023**, *13*, 532. [CrossRef]
39. Kazemzadeh, P.; Sayadi, K.; Toolabi, A.; Sayadi, J.; Zeraati, M.; Chauhan, N.P.S.; Sargazi, G. Structure-Property Relationship for Different Mesoporous Silica Nanoparticles and Its Drug Delivery Applications: A Review. *Front. Chem.* **2022**, *10*, 823785. [CrossRef]
40. Chokkareddy, R.; Redhi, G.G. Green Synthesis of Metal Nanoparticles and Its Reaction Mechanisms. In *Macabresque Humman Violation Hate Genocide, Mass Atrocity Enemy-Making*; Oxford University Press: Oxford, UK, 2018; pp. 113–139. [CrossRef]
41. Choi, Y.; Lee, S.Y. Biosynthesis of Inorganic Nanomaterials Using Microbial Cells and Bacteriophages. *Nat. Rev. Chem.* **2020**, *4*, 638–656. [CrossRef]
42. Ashkan, Z.; Hemmati, R.; Homaei, A.; Dinari, A.; Jamlidoost, M.; Tashakor, A. Immobilization of Enzymes on Nanoinorganic Support Materials: An Update. *Int. J. Biol. Macromol.* **2021**, *168*, 708–721. [CrossRef]
43. Kalska-Szostko, B.; Rogowska, M.; Dubis, A.; Szymański, K. Enzymes Immobilization on $Fe_3O_4$–Gold Nanoparticles. *Appl. Surf. Sci.* **2012**, *258*, 2783–2787. [CrossRef]
44. Sonmez, M.; Georgescu, M.; Alexandrescu, L.; Gurau, D.; Ficai, A.; Ficai, D.; Andronescu, E. Synthesis and applications of $Fe_3O_4/SiO_2$ core-shell materials. *Curr. Pharm. Des.* **2015**, *21*, 5324–5335. [CrossRef] [PubMed]
45. Janjua, T.I.; Cao, Y.; Kleitz, F.; Linden, M.; Yu, C.; Popat, A. Silica Nanoparticles: A Review of Their Safety and Current Strategies to Overcome Biological Barriers. *Adv. Drug Deliv. Rev.* **2023**, *203*, 115115. [CrossRef] [PubMed]
46. Cruz, J.C.; Pfromm, P.H.; Rezac, M.E. Immobilization of Candida Antarctica Lipase B on Fumed Silica. *Process Biochem.* **2009**, *44*, 62–69. [CrossRef]
47. Huang, Y.; Li, P.; Zhao, R.; Zhao, L.; Liu, J.; Peng, S.; Fu, X.; Wang, X.; Luo, R.; Wang, R.; et al. Silica Nanoparticles: Biomedical Applications and Toxicity. *Biomed. Pharmacother.* **2022**, *151*, 113053. [CrossRef]
48. Li, T. Cheng Jianjun Nonporous Silica Nanoparticles for Nanomedicine Application. *Nano Today* **2013**, *8*, 290–312. [CrossRef]
49. Cruz, J.C.; Würges, K.; Kramer, M.; Pfromm, P.H.; Rezac, M.E.; Czermak, P. Immobilization of Enzymes on Fumed Silica Nanoparticles for Applications in Nonaqueous Media. *Methods Mol. Biol.* **2011**, *743*, 147–160. [CrossRef]
50. Pang, J.; Zhou, G.; Liu, R.; Li, T. Esterification of Oleic Acid with Methanol by Immobilized Lipase on Wrinkled Silica Nanoparticles with Highly Ordered, Radially Oriented Mesochannels. *Mater. Sci. Eng. C* **2016**, *59*, 35–42. [CrossRef]
51. Jiang, Y.; Sun, W.; Zhou, L.; Ma, L.; He, Y.; Gao, J. Improved Performance of Lipase Immobilized on Tannic Acid-Templated Mesoporous Silica Nanoparticles. *Appl. Biochem. Biotechnol.* **2016**, *179*, 1155–1169. [CrossRef]
52. Ghofrani, S.; Allameh, A.; Yaghmaei, P.; Norouzian, D. Immobilization of Candida Rugosa Lipase for Resolution of Racimic Ibuprofen. *DARU J. Pharm. Sci.* **2021**, *29*, 117–123. [CrossRef]
53. Wang, C.; Zhou, G.; Xu, Y.; Chen, J. *Porcine pancreatic* Lipase Immobilized in Amino-Functionalized Short Rod-Shaped Mesoporous Silica Prepared Using Poly(Ethylene Glycol) and Triblock Copolymer as Templates. *J. Phys. Chem. C* **2011**, *115*, 22191–22199. [CrossRef]
54. Machado, N.B.; Miguez, J.P.; Bolina, I.C.A.; Salviano, A.B.; Gomes, R.A.B.; Tavano, O.L.; Luiz, J.H.H.; Tardioli, P.W.; Cren, É.C.; Mendes, A.A. Preparation, Functionalization and Characterization of Rice Husk Silica for Lipase Immobilization via Adsorption. *Enzyme Microb. Technol.* **2019**, *128*, 9–21. [CrossRef]
55. Jia, B.; Liu, C.; Qi, X. Selective Production of Ethyl Levulinate from Levulinic Acid by Lipase-Immobilized Mesoporous Silica Nanoflowers Composite. *Fuel Process. Technol.* **2020**, *210*, 106578. [CrossRef]
56. Banjanac, K.; Mihailović, M.; Prlainović, N.; Stojanović, M.; Carević, M.; Marinković, A.; Bezbradica, D. Cyanuric Chloride Functionalized Silica Nanoparticles for Covalent Immobilization of Lipase. *J. Chem. Technol. Biotechnol.* **2016**, *91*, 439–448. [CrossRef]
57. Sadighi, A.; Motevalizadeh, S.F.; Hosseini, M.; Ramazani, A.; Gorgannezhad, L.; Nadri, H.; Deiham, B.; Ganjali, M.R.; Shafiee, A.; Faramarzi, M.A.; et al. Metal-Chelate Immobilization of Lipase onto Polyethylenimine Coated MCM-41 for Apple Flavor Synthesis. *Appl. Biochem. Biotechnol.* **2017**, *182*, 1371–1389. [CrossRef]
58. Ali, Z.; Tian, L.; Zhao, P.; Zhang, B.; Ali, N.; Khan, M.; Zhang, Q. Immobilization of Lipase on Mesoporous Silica Nanoparticles with Hierarchical Fibrous Pore. *J. Mol. Catal. B Enzym.* **2016**, *134*, 129–135. [CrossRef]

59. Song, Y.S.; Lee, H.U.; Lee, J.H.; Park, C.; Kim, S.W. Enzyme-Catalyzed Resolution of Racemate Using Enzyme Functionalized Silica Nanoparticles in the Presence of Surfactants. *Process Biochem.* **2011**, *46*, 817–820. [CrossRef]
60. Thangaraj, B.; Jia, Z.; Dai, L.; Liu, D.; Du, W. Effect of Silica Coating on $Fe_3O_4$ Magnetic Nanoparticles for Lipase Immobilization and Their Application for Biodiesel Production. *Arab. J. Chem.* **2019**, *12*, 4694–4706. [CrossRef]
61. Nikolić, M.P.; Pavlović, K.V.; Stanojević-Nikolić, S.; Maričić, A.; Srdić, V.V. Synthesis and Characterization of Silica Core/Multilayered Cobalt Ferrite-Silica Shell Particles for Lipase Immobilization. *Mater. Res.* **2021**, *24*, e20210130. [CrossRef]
62. Jacob, A.G.; Wahab, R.A.; Mahat, N.A. Ternary Biogenic Silica/Magnetite/Graphene Oxide Composite for the Hyperactivation of Candida Rugosa Lipase in the Esterification Production of Ethyl Valerate. *Enzyme Microb. Technol.* **2021**, *148*, 109807. [CrossRef]
63. Karimi, M. Immobilization of Lipase onto Mesoporous Magnetic Nanoparticles for Enzymatic Synthesis of Biodiesel. *Biocatal. Agric. Biotechnol.* **2016**, *8*, 182–188. [CrossRef]
64. Ranjbakhsh, E.; Bordbar, A.K.; Abbasi, M.; Khosropour, A.R.; Shams, E. Enhancement of Stability and Catalytic Activity of Immobilized Lipase on Silica-Coated Modified Magnetite Nanoparticles. *Chem. Eng. J.* **2012**, *179*, 272–276. [CrossRef]
65. Esmi, F.; Nematian, T.; Salehi, Z.; Khodadadi, A.A.; Dalai, A.K. Amine and Aldehyde Functionalized Mesoporous Silica on Magnetic Nanoparticles for Enhanced Lipase Immobilization, Biodiesel Production, and Facile Separation. *Fuel* **2021**, *291*, 120126. [CrossRef]
66. Sabatini, C.A.; Gehlen, M.H. Enzymatic Hydrolysis of Quinizarin Diester by Lipase in Silica Nanoparticles Investigated by Fluorescence Microscopy. *J. Nanopart. Res.* **2014**, *16*, 2093. [CrossRef]
67. Dong, Z.; Jiang, M.Y.; Shi, J.; Zheng, M.M.; Huang, F.H. Preparation of Immobilized Lipase Based on Hollow Mesoporous Silica Spheres and Its Application in Ester Synthesis. *Molecules* **2019**, *24*, 395. [CrossRef]
68. Tran, D.T.; Chen, C.L.; Chang, J.S. Immobilization of Burkholderia Sp. Lipase on a Ferric Silica Nanocomposite for Biodiesel Production. *J. Biotechnol.* **2012**, *158*, 112–119. [CrossRef]
69. Pota, G.; Bifulco, A.; Parida, D.; Zhao, S.; Rentsch, D.; Amendola, E.; Califano, V.; Costantini, A. Tailoring the Hydrophobicity of Wrinkled Silica Nanoparticles and of the Adsorption Medium as a Strategy for Immobilizing Lipase: An Efficient Catalyst for Biofuel Production. *Microporous Mesoporous Mater.* **2021**, *328*, 111504. [CrossRef]
70. Jin, Q.; Jia, G.; Zhang, Y.; Yang, Q.; Li, C. Hydrophobic Surface Induced Activation of Pseudomonas Cepacia Lipase Immobilized into Mesoporous Silica. *Langmuir* **2011**, *27*, 12016–12024. [CrossRef]
71. Mateo, C.; Abian, O.; Fernández-Lorente, G.; Pedroche, J.; Fernández-Lafuente, R.; Guisan, J.M.; Tam, A.; Daminati, M. Epoxy Sepabeads: A Novel Epoxy Support for Stabilization of Industrial Enzymes via Very Intense Multipoint Covalent Attachment. *Biotechnol. Prog.* **2002**, *18*, 629–634. [CrossRef]
72. Mohammadi, M.; Habibi, Z.; Dezvarei, S.; Yousefi, M.; Samadi, S.; Ashjari, M. Improvement of the Stability and Selectivity of Rhizomucor Miehei Lipase Immobilized on Silica Nanoparticles: Selective Hydrolysis of Fish Oil Using Immobilized Preparations. *Process Biochem.* **2014**, *49*, 1314–1323. [CrossRef]
73. Mohammadi, M.; Gandomkar, S.; Habibi, Z.; Yousefi, M. One Pot Three-Component Reaction for Covalent Immobilization of Enzymes: Application of Immobilized Lipases for Kinetic Resolution of: Rac -Ibuprofen. *RSC Adv.* **2016**, *6*, 52838–52849. [CrossRef]
74. Babaki, M.; Yousefi, M.; Habibi, Z.; Mohammadi, M.; Yousefi, P.; Mohammadi, J.; Brask, J. Enzymatic Production of Biodiesel Using Lipases Immobilized on Silica Nanoparticles as Highly Reusable Biocatalysts: Effect of Water, t-Butanol and Blue Silica Gel Contents. *Renew. Energy* **2016**, *91*, 196–206. [CrossRef]
75. Mehrasbi, M.R.; Mohammadi, J.; Peyda, M.; Mohammadi, M. Covalent Immobilization of Candida Antarctica Lipase on Core-Shell Magnetic Nanoparticles for Production of Biodiesel from Waste Cooking Oil. *Renew. Energy* **2017**, *101*, 593–602. [CrossRef]
76. Banjanac, K.; Mihailović, M.; Prlainović, N.; Ćorović, M.; Carević, M.; Marinković, A.; Bezbradica, D. Epoxy-Silanization—Tool for Improvement of Silica Nanoparticles as Support for Lipase Immobilization with Respect to Esterification Activity. *J. Chem. Technol. Biotechnol.* **2016**, *91*, 2654–2663. [CrossRef]
77. Cazaban, D.; Illanes, A.; Wilson, L.; Betancor, L. Bio-Inspired Silica Lipase Nanobiocatalysts for the Synthesis of Fatty Acid Methyl Esters. *Process Biochem.* **2018**, *74*, 86–93. [CrossRef]
78. Chen, N.; Zhang, C.; Liu, Y.; Dong, X.; Sun, Y. Cysteine-Modified Poly(Glycidyl Methacrylate) Grafted onto Silica Nanoparticles: New Supports for Significantly Enhanced Performance of Immobilized Lipase. *Biochem. Eng. J.* **2019**, *145*, 137–144. [CrossRef]
79. Chen, N.; Zhang, C.; Dong, X.; Sun, Y. Fabrication and Characterization of Epoxylated Zwitterionic Copolymer-Grafted Silica Nanoparticle as a New Support for Lipase Immobilization. *Chin. J. Chem. Eng.* **2020**, *28*, 1129–1135. [CrossRef]
80. Lei, L.; Liu, X.; Li, Y.; Cui, Y.; Yang, Y.; Qin, G. Study on Synthesis of Poly(GMA)-Grafted $Fe_3O_4$/ $SiO_X$ Magnetic Nanoparticles Using Atom Transfer Radical Polymerization and Their Application for Lipase Immobilization. *Mater. Chem. Phys.* **2011**, *125*, 866–871. [CrossRef]
81. Zhong, L.; He, C.; Xiao, C.; Yao, C.; Pyatt, I.H.; Lu, Y. Covalent Immobilization of Candida Antarctica Lipase B on Functionalized Hollow Mesoporous Silica Nanoparticles. *ChemistrySelect* **2021**, *6*, 3453–3460. [CrossRef]

82. Zhu, Y.T.; Ren, X.Y.; Liu, Y.M.; Wei, Y.; Qing, L.S.; Liao, X. Covalent Immobilization of Porcine Pancreatic Lipase on Carboxyl-Activated Magnetic Nanoparticles: Characterization and Application for Enzymatic Inhibition Assays. *Mater. Sci. Eng. C* **2014**, *38*, 278–285. [CrossRef]
83. Mohammadi, M.; Habibi, Z.; Gandomkar, S.; Yousefi, M. A Novel Approach for Bioconjugation of Rhizomucor Miehei Lipase (RML) onto Amine-Functionalized Supports; Application for Enantioselective Resolution of Rac-Ibuprofen. *Int. J. Biol. Macromol.* **2018**, *117*, 523–531. [CrossRef] [PubMed]
84. Jiang, Y.; Liu, H.; Wang, L.; Zhou, L.; Huang, Z.; Ma, L.; He, Y.; Shi, L.; Gao, J. Virus-like Organosilica Nanoparticles for Lipase Immobilization: Characterization and Biocatalytic Applications. *Biochem. Eng. J.* **2019**, *144*, 125–134. [CrossRef]
85. Qian, J.; Huang, A.; Zhu, H.; Ding, J.; Zhang, W.; Chen, Y. Immobilization of Lipase on Silica Nanoparticles by Adsorption Followed by Glutaraldehyde Cross-Linking. *Bioprocess Biosyst. Eng.* **2023**, *46*, 25–38. [CrossRef] [PubMed]
86. Zhang, Z.; He, F.; Zhuo, R. Immobilized Lipase on Porous Silica Particles: Preparation and Application for Biodegradable Polymer Syntheses in Ionic Liquid at Higher Temperature. *J. Mol. Catal. B Enzym.* **2013**, *94*, 129–135. [CrossRef]
87. Kapoor, M.; Gupta, M.N. Lipase Promiscuity and Its Biochemical Applications. *Process Biochem.* **2012**, *47*, 555–569. [CrossRef]
88. Al-Zuhair, S.; Ling, F.W.; Jun, L.S. Proposed Kinetic Mechanism of the Production of Biodiesel from Palm Oil Using Lipase. *Process Biochem.* **2007**, *42*, 951–960. [CrossRef]
89. Brzozowski, A.M.; Derewenda, U.; Derewenda, Z.S.; Dodson, G.G.; Lawson, D.M.; Turkenburg, J.P.; Bjorkling, F.; Huge-Jensen, B.; Patkar, S.A.; Thim, L. A Model for Interfacial Activation in Lipases from the Structure of a Fungal Lipase-Inhibitor Complex. *Nature* **1991**, *351*, 491–494. [CrossRef]
90. Adlercreutz, P. Immobilisation and Application of Lipases in Organic Media. *Chem. Soc. Rev.* **2013**, *42*, 6406–6436. [CrossRef]
91. Sankaran, R.; Show, P.L.; Chang, J.-S. Biodiesel Production Using Immobilized Lipase: Feasibility and Challenges. *Biofuels Bioprod. Biorefin.* **2016**, *10*, 896–916. [CrossRef]
92. Zhong, L.; Feng, Y.; Wang, G.; Wang, Z.; Bilal, M.; Lv, H.; Jia, S.; Cui, J. Production and Use of Immobilized Lipases in/on Nanomaterials: A Review from the Waste to Biodiesel Production. *Int. J. Biol. Macromol.* **2020**, *152*, 207–222. [CrossRef]
93. Idris, A.; Bukhari, A. Immobilized Candida Antarctica Lipase B: Hydration, Stripping off and Application in Ring Opening Polyester Synthesis. *Biotechnol. Adv.* **2012**, *30*, 550–563. [CrossRef] [PubMed]
94. Karimi, M.; Keyhani, A.; Akram, A.; Rahman, M.; Jenkins, B.; Stroeve, P. Hybrid Response Surface Methodology-Genetic Algorithm Optimization of Ultrasound-Assisted Transesterification of Waste Oil Catalysed by Immobilized Lipase on Mesoporous Silica/Iron Oxide Magnetic Core-Shell Nanoparticles. *Environ. Technol.* **2013**, *34*, 2201–2211. [CrossRef] [PubMed]
95. Xie, W.; Wang, J. Enzymatic Production of Biodiesel from Soybean Oil by Using Immobilized Lipase on $Fe_3O_4$/Poly(Styrene-Methacrylic Acid) Magnetic Microsphere as a Biocatalyst. *Energy Fuels* **2014**, *28*, 2624–2631. [CrossRef]
96. Bayout, I.; Bouzemi, N.; Guo, N.; Mao, X.; Serra, S.; Riva, S.; Secundo, F. Natural Flavor Ester Synthesis Catalyzed by Lipases. *Flavour Fragr. J.* **2020**, *35*, 209–218. [CrossRef]
97. Zucca, P.; Sanjust, E. Inorganic Materials as Supports for Covalent Enzyme Immobilization: Methods and Mechanisms. *Molecules* **2014**, *19*, 14139–14194. [CrossRef]
98. Muralidhar, R.; Marchant, R.; Nigam, P. Lipases in Racemic Resolutions. *J. Chem. Technol. Biotechnol.* **2001**, *76*, 3–8. [CrossRef]
99. José, C.; Toledo, M.V.; Briand, L.E. Enzymatic Kinetic Resolution of Racemic Ibuprofen: Past, Present and Future. *Crit. Rev. Biotechnol.* **2016**, *36*, 891–903. [CrossRef]
100. Torres, P.; Reyes-Duarte, D.; Ballesteros, A.; Plou, F. Lipase-Catalyzed Modification of Phenolic Antioxidants. *Methods Mol. Biol.* **2012**, *861*, 435–443.
101. Qianchun, D.; Pin, Z.; Qingde, H.; Fenghong, H.; Fang, W.; Mingming, Z.; Xiao, Y.; Qi, Z.; Chang, Z. Chemical Synthesis of Phytosterol Esters of Polyunsaturated Fatty Acids with Ideal Oxidative Stability. *Eur. J. Lipid Sci. Technol.* **2011**, *113*, 441–449. [CrossRef]
102. Šaraba, V.; Milovanovic, J.; Nikodinovic-Runic, J.; Budin, C.; de Boer, T.; Ciric, M. Brackish Groundwaters Contain Plastic- and Cellulose-Degrading Bacteria. *Microb. Ecol.* **2023**, *86*, 2747–2755. [CrossRef]
103. Spasic, J.; Mandic, M.; Radivojevic, J.; Jeremic, S.; Vasiljevic, B.; Nikodinovic-Runic, J.; Djokic, L. Biocatalytic Potential of Streptomyces Spp. Isolates from Rhizosphere of Plants and Mycorrhizosphere of Fungi. *Biotechnol. Appl. Biochem.* **2018**, *65*, 822–833. [CrossRef] [PubMed]
104. Bikiaris, D.N. Nanocomposites of Aliphatic Polyesters: An Overview of the Effect of Different Nanofillers on Enzymatic Hydrolysis and Biodegradation of Polyesters. *Polym. Degrad. Stab.* **2013**, *98*, 1908–1928. [CrossRef]
105. Tang, C.; Wang, L.; Sun, J.; Chen, G.; Shen, J.; Wang, L.; Han, Y.; Luo, J.; Li, Z.; Zhang, P.; et al. Degradable Living Plastics Programmed by Engineered Spores. *Nat. Chem. Biol.* **2024**. [CrossRef]
106. Jeremic, S.; Milovanovic, J.; Mojicevic, M.; Bogojevic, S.S.; Nikodinovic-Runic, J. Understanding Bioplastic Materials—Current State and Trends. *J. Serbian Chem. Soc.* **2020**, *85*, 1507–1538. [CrossRef]

107. Namekawa, S.; Suda, S.; Uyama, H.; Kobayashi, S. Lipase-Catalyzed Ring-Opening Polymerization of Lactones to Polyesters and Its Mechanistic Aspects. *Int. J. Biol. Macromol.* **1999**, *25*, 145–151. [CrossRef]
108. He, F.; Wang, Y.; Feng, J.; Zhuo, R.; Wang, X. Synthesis of Poly[(5-Benzyloxy-Trimethylene Carbonate)-Co-(5,5-Dimethyl-Trimethylene Carbonate)] Catalyzed by Immobilized Lipase on Silica Particles with Different Size. *Polymer* **2003**, *44*, 3215–3219. [CrossRef]