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Archives of Biotechnology and Pharmaceutical Research

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Vol: 2 & Iss: 2

Super disintegrants in Modern Oral Dosage Forms: A Comprehensive Review

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Citation: Addanki MM, Dasari N, Burri S, et al. Super disintegrants in Modern Oral Dosage Forms: A Comprehensive Review. *Arch Biotech Pharma Res*, 2026;2(2):196-207.

Received: 01 June, 2026; **Accepted:** 05 June, 2026; **Published:** 08 June, 2026

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ABSTRACT

Superdisintegrants are specialized pharmaceutical excipients designed to facilitate rapid tablet disintegration upon contact with biological fluids, thereby enhancing drug dissolution, absorption, and onset of therapeutic action. Their importance has increased considerably with the growing demand for patient-centric dosage forms such as orally disintegrating tablets, fast-dissolving tablets, and other immediate-release formulations intended for conditions requiring rapid pharmacological intervention, including acute cardiovascular, neurological, psychiatric, and gastrointestinal disorders. This review provides a comprehensive overview of the mechanisms underlying tablet disintegration, including swelling, wicking, strain recovery, particle repulsion, heat of wetting, enzymatic action, and deformation theories. Superdisintegrants are systematically classified according to their origin, chemical structure, and ionic properties, highlighting the diversity of available excipients and their functional characteristics. Major commercially available superdisintegrants, including sodium starch glycolate, croscarmellose sodium, crospovidone, low-substituted hydroxypropyl cellulose, and polacrilin potassium, are discussed with respect to their source, physicochemical properties, mechanisms of action, pharmaceutical applications, advantages, limitations, and future potential. Particular emphasis is placed on emerging natural superdisintegrants such as *Plantago ovata* husk, chitosan, fenugreek mucilage, *Lepidium sativum* mucilage, guar gum, and pectin as sustainable alternatives to conventional synthetic materials. Recent advances in co-processed and multifunctional superdisintegrants are also examined, together with emerging technologies involving three-dimensional printing, nanotechnology, continuous manufacturing, and personalized medicine. Furthermore, current research gaps and future opportunities for excipient innovation are critically evaluated. Collectively, the evidence demonstrates that superdisintegrants remain indispensable components of modern oral drug delivery systems and are expected to play an increasingly important role in the development of next-generation pharmaceutical formulations.

Keywords: Superdisintegrants, Tablet disintegration, Sodium Starch Glycolate, Croscarmellose Sodium, Crospovidone, Natural Superdisintegrants, Orally Disintegrating Tablets, Co-Processed Excipients

1. Introduction

Superdisintegrants are specialized pharmaceutical excipients that facilitate the rapid disintegration of tablets and capsules upon contact with saliva or gastrointestinal fluids. They represent an advanced class of disintegrants specifically designed to accelerate tablet breakup and enhance drug dissolution. Conventional disintegrants such as starch are typically employed at concentrations of 5-15% w/w and may require 15-30 minutes to achieve complete tablet disintegration. In contrast, superdisintegrants are generally effective at lower concentrations ranging from 2-8% w/w and produce significantly faster disintegration, thereby improving drug release and therapeutic response[1-4].

The development of superdisintegrants has played a pivotal role in the advancement of immediate-release and orally disintegrating dosage forms. These excipients are particularly valuable in situations where a rapid onset of pharmacological action is desired, including the management of angina pectoris, acute myocardial infarction, hypertensive emergencies, acute migraine attacks, epilepsy, anaphylaxis, acute psychotic episodes, and severe nausea and vomiting[2,5-7]. By promoting rapid tablet disintegration and dissolution, superdisintegrants contribute to improved bioavailability, enhanced patient compliance, and faster therapeutic outcomes. Consequently, they have become indispensable components in the formulation of orally disintegrating tablets (ODTs), fast-dissolving tablets (FDTs), sublingual tablets, buccal formulations, and other patient-centric drug delivery systems[5,6].

1.1. Mechanism of action

Tablet disintegration is a complex process involving the breakdown of a compressed tablet into smaller fragments upon contact with biological fluids. Although several theories have been proposed to explain tablet disintegration, contemporary pharmaceutical science recognizes that disintegration typically results from the simultaneous operation of multiple mechanisms rather than a single process. Superdisintegrants enhance these mechanisms, thereby accelerating tablet breakup, promoting drug dissolution, and facilitating rapid therapeutic action[4,8].

1.1.1. Swelling theory: The swelling theory is the most widely accepted mechanism of tablet disintegration. According to this theory, superdisintegrant particles absorb water and undergo substantial volumetric expansion. As water penetrates the tablet matrix, swelling generates internal pressure within the compact structure. When this pressure exceeds the mechanical strength of the tablet, interparticulate bonds are disrupted, resulting in rapid tablet disintegration[1,3,4].

The effectiveness of this mechanism depends on several formulation variables, including the swelling capacity of the disintegrant, tablet porosity, and compression force applied during manufacturing. Excessive compression may restrict water penetration and limit swelling, whereas excessive concentrations of certain superdisintegrants may promote gel layer formation and retard disintegration. Sodium starch glycolate (SSG) and croscarmellose sodium (CCS) are classical examples of swelling-type superdisintegrants. SSG, in particular, can swell several hundred percent beyond its original volume, making it one of the most effective swelling-based disintegrants available[4,9].

1.1.2. Wicking (Capillary Action) theory: The wicking theory proposes that tablet disintegration occurs through rapid liquid uptake into the porous tablet matrix by capillary forces. Superdisintegrants act as hydrophilic networks that draw water into the tablet structure while simultaneously replacing trapped air within the pores. As hydration progresses, intermolecular forces holding the compact together weaken, leading to tablet breakup[4,8].

Unlike swelling, wicking does not necessarily require significant volumetric expansion. Instead, its effectiveness depends on factors such as pore size distribution, tablet porosity, surface wettability, and liquid viscosity. Crospovidone is regarded as the prototypical wicking-type superdisintegrant because of its highly porous morphology and rapid water uptake without extensive swelling. Croscarmellose sodium also exhibits significant capillary activity, contributing to its superior disintegration performance[1,4,10].

1.1.3. Strain recovery theory: According to the strain recovery theory, particles undergo deformation during tablet compression and store mechanical energy within their structure. Upon contact with water, hydration reduces intermolecular friction and enables the particles to recover their original shape. This recovery generates internal stresses that disrupt the tablet matrix and accelerate disintegration[1,3,8].

This mechanism is particularly useful for explaining the behaviour of certain superdisintegrants that exhibit rapid tablet breakup despite limited swelling capacity. The release of stored elastic energy acts as an additional driving force for disintegration. Crospovidone is the most prominent example of a superdisintegrant exhibiting strain recovery behaviour, which contributes significantly to its rapid disintegration performance[1,4].

1.1.4. Particle repulsion theory: The particle repulsion theory suggests that, upon wetting, particles develop similar electrical charges on their surfaces. These like charges create electrostatic repulsive forces between adjacent particles, causing separation and disruption of the tablet matrix[3,4].

This mechanism was proposed to explain instances where tablet disintegration occurs despite minimal swelling. However, experimental evidence supporting particle repulsion as a dominant mechanism remains limited. Consequently, it is generally regarded as a supplementary mechanism that acts synergistically with swelling and wicking rather than independently[1,3].

1.1.5. Heat of wetting theory: The heat of wetting theory proposes that when water contacts the surface of disintegrant particles, an exothermic wetting process occurs. The heat released may induce localized expansion and generate stresses that contribute to tablet disintegration[3,8].

Historically, this theory represented one of the earliest explanations for tablet breakup. Nevertheless, modern investigations indicate that the amount of heat generated during wetting is generally insufficient to account for rapid disintegration on its own. Consequently, heat of wetting is currently considered a minor contributory mechanism rather than a primary driver of tablet disintegration[1,4].

1.1.6. Enzymatic action theory: The enzymatic action theory is primarily associated with natural disintegrants such as starch and

other polysaccharide-based materials. According to this theory, enzymes present in saliva and gastrointestinal fluids degrade polymeric components within the tablet matrix. Progressive degradation of these structural materials weakens tablet integrity and ultimately results in disintegration[3,4].

Although enzymatic degradation may contribute to tablet breakup, it is generally much slower than physical mechanisms such as swelling and wicking. Therefore, this theory is considered more relevant to traditional natural disintegrants than to modern synthetic superdisintegrants[1].

1.1.7. Deformation theory: The deformation theory is closely related to the strain recovery mechanism. During tablet compression, particles become distorted from their original shape and store deformation energy **(Figure 1)**. Upon hydration, these particles attempt to return to their pre-compression configuration, generating disruptive forces that contribute to tablet breakup[1,3].

In modern pharmaceutical literature, deformation theory and strain recovery theory are frequently discussed together because both involve the release of stored mechanical energy following hydration **(Tables 1-3)**. These mechanisms often act synergistically with swelling and wicking to produce rapid and efficient tablet disintegration[1,4,8].

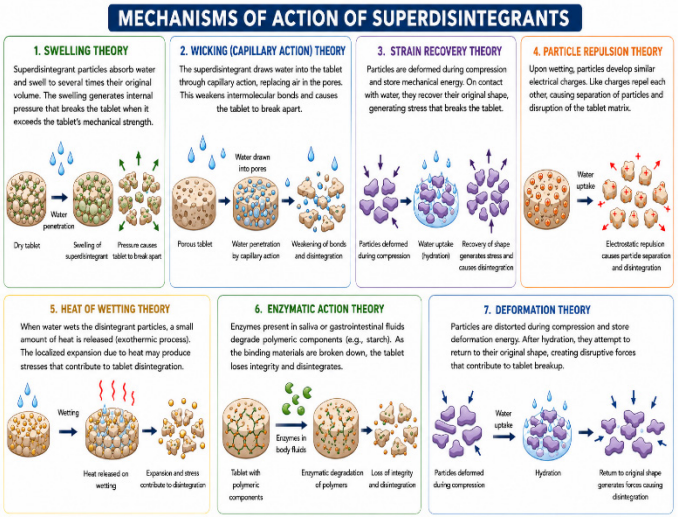

Figure 1: Mechanisms of action of Superintegrants.

Table 1: Classification by Origin.

Origin Class	Description	Examples	Advantages
Natural	Biodegradable, non-toxic polymers extracted from plant, seed, or marine sources.	*Plantago ovata* (Isapghula) husk, *Lepidium sativum* seedmucilage, Chitosan, Soy polysaccharide, Guar gum.	Biocompatible, highly cost-effective, eco-friendly.
Synthetic & Semi-Synthetic	Chemically modified natural polymers designed to improve performance	Crospovidone, Croscarmellose Sodium, Sodium Starch Glycolate.	Improved consistency, enhanced swelling, better functionality
Synthetic	Fully synthetic polymers engineered for rapid disintegration	Crospovidone, Polacrilin Potassium	Excellent batch uniformity, predictable performance
Co-Processed Composite	Composite excipients produced by combining multiple materials at the particle level	Ludiflash® (Mannitol + Crospovidone + PVA), Pharmaburst®, F-Melt®.	Eliminates multiple blending steps, ideal for direct compression of Orally Disintegrating Tablets (ODTs).

Table 2: Classification by Chemical Structure.

Chemical Class	Common Generic Name	Structural Modification	Popular Brand Names	Key Morphological Feature
Modified Starch	Sodium Starch Glycolate (SSG)	Carboxymethylation and cross-linking of potato/corn starch.	Primojel®, Explotab®, Solutab®	Spherical granules that uncoil and swell linearly up to 300%+ in volume.
Modified Cellulose	Croscarmellose Sodium (CCS)	Internal ether cross-linking of sodium carboxymethylcellulose.	Ac-Di-Sol®, Primellose®, Vivasol®	Fibrous micro-structure that balances hydraulic wicking with sponge-like swelling.
Cross-linked PVP	Crospovidone (CP)	Synthetic cross-linked homopolymer of N-vinyl-2-pyrrolidone.	Polyplasdone® (XL/XL-10), Kollidon® CL	Highly porous, "popcorn-like" particle morphology that entirely resists gelling.

Table 3: Classification by Ionic Properties and Surface Charge.

Ionic Category	Surface Charge	Examples	Incompatibility/Formulation Risk
Anionic	Negatively Charged	Sodium Starch Glycolate, Croscarmellose Sodium, *Plantago ovata* mucilage	Can electrostatically bind to cationic (positively charged) drugs, potentially slowing down the dissolution rate.
Cationic	Positively Charged	Chitosan	Can interact with anionic drugs or specific acidic binders.
Non-Ionic (Neutral)	Uncharged / Neutral	Crospovidone, Guar gum	Highly compatible; zero risk of charge-based binding with cationic or anionic APIs.

1.2. Sodium Starch Glycolate (SSG)

Sodium starch glycolate (SSG) is among the most extensively utilized semi-synthetic superdisintegrants in contemporary pharmaceutical formulations. It is produced through the carboxymethylation and subsequent crosslinking of starch obtained from sources such as potato, corn, wheat, or rice. These chemical modifications convert native starch into a highly hydrophilic yet water-insoluble polymer capable of absorbing substantial quantities of water while maintaining structural integrity[4,9,11].

The primary mechanism of action of SSG is swelling, although capillary water uptake also contributes to its disintegration efficiency. Upon exposure to aqueous media, SSG rapidly hydrates and expands several-fold beyond its original volume. This pronounced swelling generates internal stress within the tablet matrix, which eventually exceeds the mechanical strength of the compact and results in rapid tablet disintegration. Owing to its exceptional swelling capacity, SSG is widely regarded as one of the most effective swelling-type superdisintegrants available for oral solid dosage forms[1,4,9].

SSG is extensively employed in immediate-release tablets, orally disintegrating tablets (ODTs), fast-disintegrating tablets, chewable tablets, and direct-compression formulations. It has been successfully incorporated into formulations containing a wide range of active pharmaceutical ingredients, including paracetamol, ibuprofen, diclofenac sodium, metformin, and atenolol. Its widespread use can be attributed to its effectiveness at relatively low concentrations (typically 2-8% w/w), broad compatibility with active pharmaceutical ingredients, ease of formulation, and cost-effectiveness[4,9,11].

A distinguishing characteristic of SSG is its exceptionally high swelling index, which is among the highest reported for pharmacopeial superdisintegrants. This property enables rapid tablet breakup and enhanced drug dissolution, particularly in formulations where fast therapeutic action is desired. However, the performance of SSG may be influenced by formulation and processing variables. Excessive concentrations can promote gel layer formation around tablet particles, potentially delaying drug release, while high compression forces may reduce porosity and restrict water penetration, thereby diminishing its disintegration efficiency[9,11].

Recent research has focused on expanding the applications of SSG beyond conventional immediate-release formulations. Emerging areas of investigation include its incorporation into co-processed multifunctional excipients, nanostructured drug delivery systems, additive manufacturing and three-dimensional (3D)-printed dosage forms, and formulations designed to improve the dissolution of poorly water-soluble drugs. These developments highlight the continued relevance of SSG in the evolving landscape of pharmaceutical formulation science[8,11].

1.3. Croscarmellose Sodium (CCS)

Croscarmellose sodium (CCS) is a widely used semi-synthetic superdisintegrant produced through the crosslinking of sodium carboxymethyl cellulose, a chemically modified cellulose derivative. Crosslinking renders the polymer insoluble in water while preserving its remarkable capacity for water absorption and hydration. As a result, CCS exhibits excellent disintegration efficiency and has become one of the most frequently employed superdisintegrants in modern oral solid dosage forms[4,9,12].

The disintegration performance of CCS is primarily attributed to a synergistic combination of swelling and wicking (capillary action) mechanisms. Its distinctive fibrous structure facilitates rapid water penetration into the tablet matrix through capillary channels, while simultaneous swelling generates internal stresses that weaken interparticulate bonds and promote tablet breakup. In addition, a limited degree of strain recovery may further contribute to the disintegration process following hydration. The combined action of these mechanisms enables CCS to produce rapid and reliable tablet disintegration across a wide range of formulation conditions[4,8,12].

Due to its efficient water transport properties, CCS is extensively utilized in immediate-release tablets, orally disintegrating tablets (ODTs), sublingual tablets, buccal tablets, and direct-compression formulations. It has been successfully incorporated into formulations containing active pharmaceutical ingredients such as aspirin, cetirizine, amlodipine, ondansetron, and loratadine. The widespread adoption of CCS is attributed to its effectiveness at relatively low concentrations, rapid liquid penetration, excellent performance across a broad pH range, and consistent batch-to-batch functionality[9,12].

A notable feature of CCS is its unique fibrous morphology, which allows the simultaneous operation of both swelling and wicking mechanisms. This dual mode of action distinguishes CCS from many other commercially available superdisintegrants and contributes to its versatility in a variety of formulation strategies. Furthermore, CCS remains effective even in relatively hard tablets, making it particularly valuable in direct-compression systems where adequate mechanical strength must be maintained without compromising disintegration performance[4,9,12].

Despite its advantages, the performance of CCS may be influenced by formulation variables. Excessive concentrations of hydrophobic lubricants, particularly magnesium stearate, can reduce water penetration and diminish its disintegration efficiency. Similarly, very high concentrations of CCS may not necessarily improve performance and can occasionally lead to suboptimal tablet properties. Future research is expected to focus on the incorporation of CCS into orally dispersible films, multifunctional co-processed excipients, continuous manufacturing platforms, and advanced patient-centric dosage forms[8,12].

1.4. Crospovidone (CP)

Crospovidone (CP) is a synthetic superdisintegrant produced through the crosslinking of polyvinylpyrrolidone (PVP). Unlike starch- and cellulose-based superdisintegrants, crospovidone exhibits minimal swelling but possesses exceptional water uptake capacity owing to its highly porous, sponge-like particle structure. This unique morphology facilitates rapid liquid penetration into the tablet matrix and contributes significantly to its superior disintegration performance[4,9,13].

The primary mechanisms underlying crospovidone-mediated disintegration include wicking (capillary action), strain recovery, and deformation recovery. Upon contact with aqueous media, water is rapidly drawn into the tablet through capillary channels, while the release of stored elastic energy from compressed particles promotes disruption of interparticulate bonds. Unlike swelling-based superdisintegrants, crospovidone does not form a viscous gel layer during hydration, enabling rapid tablet breakup and often producing faster disintegration than many conventional disintegrants[4,8,13].

Due to these characteristics, crospovidone is extensively employed in orally disintegrating tablets (ODTs), fast-dissolving tablets (FDTs), direct-compression formulations, sublingual tablets, and effervescent dosage forms. It has been successfully incorporated into formulations containing drugs such as rizatriptan, domperidone, meloxicam, zolmitriptan, and sumatriptan. The effectiveness of crospovidone in rapidly disintegrating oral formulations has been demonstrated in several studies involving antimigraine and antiemetic agents[14].

The major advantages of crospovidone include rapid disintegration, absence of gel formation, excellent flow characteristics, low sensitivity to compression force, and suitability for high-dose formulations. Among commercially available superdisintegrants, its most distinctive feature is its pronounced strain recovery behaviour, which contributes substantially to tablet breakup following hydration. Consequently, crospovidone is frequently regarded as the

benchmark wicking-type superdisintegrant in modern pharmaceutical formulation[4,9,13].

Despite its excellent performance, crospovidone exhibits relatively lower swelling capacity compared with sodium starch glycolate and croscarmellose sodium and is generally associated with higher material costs. Nevertheless, its rapid disintegration profile and robust functionality often justify its selection in patient-centric dosage forms where fast drug release is essential. Future research is expected to focus on its application in personalized medicines, three-dimensional (3D)-printed pharmaceutical systems, nanoparticle-based drug delivery platforms, and advanced multifunctional co-processed excipients[8,13].

1.5. Low-substituted hydroxypropyl cellulose (L-HPC)

Low-substituted hydroxypropyl cellulose (L-HPC) is a semi-synthetic cellulose derivative produced through the partial hydroxypropylation of cellulose. The degree of substitution is deliberately maintained at a low level, enabling the material to remain insoluble in water while retaining excellent hydration and swelling properties. Owing to this unique physicochemical profile, L-HPC has gained considerable importance as a multifunctional pharmaceutical excipient, serving both as a superdisintegrant and as a compression aid in solid dosage form development[9,15].

The disintegration performance of L-HPC is attributed to a combination of swelling, wicking, and deformation recovery mechanisms. Upon exposure to aqueous media, the fibrous particles rapidly absorb water and undergo volumetric expansion, generating internal stresses within the tablet matrix. Simultaneously, capillary action facilitates water penetration into the porous structure of the tablet, while recovery of deformation energy stored during compression further contributes to matrix disruption. The synergistic action of these mechanisms promotes efficient tablet disintegration and drug release[8,15].

L-HPC is widely employed in direct-compression tablets, orally disintegrating tablets (ODTs), mini-tablets, multiparticulate dosage forms, and selected modified-release systems. It has been successfully incorporated into formulations containing active pharmaceutical ingredients such as acetaminophen, captopril, theophylline, furosemide, and propranolol. Its excellent compressibility and compatibility with a broad range of excipients make it particularly suitable for direct-compression manufacturing processes[9,15].

One of the most distinctive features of L-HPC is its multifunctionality. Unlike many conventional superdisintegrants that perform a single role, L-HPC can simultaneously function as a disintegrant, binder, and compression enhancer. This dual functionality can simplify formulation design, reduce the number of excipients required, and improve tablet manufacturability. Consequently, L-HPC is especially valuable in formulations where both rapid disintegration and adequate mechanical strength are required[15,16].

Despite these advantages, the disintegration efficiency of L-HPC may be somewhat lower than that of highly efficient superdisintegrants such as crospovidone in certain formulations. Nevertheless, its superior compressibility, versatility, and multifunctional nature continue to support its widespread use in pharmaceutical product development. Future research is expected to focus on its application in pediatric and geriatric dosage forms, three-dimensional (3D)-printed pharmaceuticals, multifunctional co-processed excipients, and advanced drug delivery systems that integrate immediate and modified-release functionalities[8,15,16].

1.6. Polacrilin potassium

Polacrilin potassium is a synthetic, crosslinked ion-exchange resin primarily composed of methacrylic acid–divinylbenzene copolymers. Unlike conventional superdisintegrants, it exhibits both ion-exchange and disintegration functionalities, making it a multifunctional pharmaceutical excipient. The polymer contains exchangeable potassium ions within its crosslinked matrix, enabling unique interactions with drugs and formulation components while maintaining excellent disintegration performance[9,17].

The disintegration mechanism of polacrilin potassium involves a combination of rapid water uptake, swelling, and ionic repulsion. Upon hydration, the resin absorbs water and expands, while electrostatic repulsion generated by the ionized functional groups contributes to the disruption of interparticulate bonds within the tablet matrix. These complementary mechanisms facilitate rapid tablet breakup and subsequent drug release. In contrast to many traditional superdisintegrants that rely predominantly on swelling or wicking, polacrilin potassium benefits from the additional contribution of ion-exchange phenomena, which may further enhance its performance under specific formulation conditions[8,17].

Polacrilin potassium is widely employed in orally disintegrating tablets (ODTs), chewable tablets, and taste-masked formulations. Its ability to bind ionizable drugs through reversible ion-exchange interactions makes it particularly valuable in formulations requiring taste masking while maintaining rapid disintegration characteristics. One of its most established applications is in nicotine replacement therapies, where it improves palatability without compromising drug release. Similar approaches have been explored for bitter-tasting drugs intended for pediatric and geriatric patients[17,18].

A distinguishing feature of polacrilin potassium is its dual functionality as both a superdisintegrant and a taste-masking agent. This multifunctional behavior can reduce formulation complexity, minimize the number of excipients required, and improve patient acceptability. Furthermore, its compatibility with direct-compression manufacturing processes enhances its industrial applicability[9,17].

Despite these advantages, the commercial utilization of polacrilin potassium remains less extensive than that of sodium starch glycolate, croscarmellose sodium, or crospovidone. Factors such as cost considerations and limited familiarity among formulators may contribute to its comparatively restricted use. Nevertheless, its unique ion-exchange properties continue to attract interest for advanced pharmaceutical applications. Future research is expected to explore its potential in controlled-release systems, pediatric dosage forms, multifunctional drug delivery platforms, and novel formulations that combine taste masking with targeted drug release[17,18].

1.7. Natural superdisintegrants

1.7.1. *Plantago ovata* (Psyllium Husk): *Plantago ovata*,

commonly known as psyllium husk or Isapghula husk, is one of the most extensively investigated natural superdisintegrants in pharmaceutical formulations. It is obtained from the outer seed husk of *Plantago ovata* and is composed predominantly of arabinoxylans and other highly hydrophilic polysaccharides. Due to its remarkable water-absorbing capacity and swelling behavior, psyllium husk has emerged as a promising natural alternative to conventional synthetic superdisintegrants[19,20].

The disintegration performance of psyllium husk is primarily attributed to its swelling mechanism. Upon contact with aqueous media, the polysaccharide network rapidly imbibes water and undergoes substantial volumetric expansion, generating internal pressure within the tablet matrix. This swelling force disrupts interparticulate bonds and promotes rapid tablet breakup. In addition to swelling, capillary water uptake may contribute to the overall disintegration process. The exceptionally high swelling index of psyllium husk often rivals or exceeds that of certain synthetic superdisintegrants, making it particularly suitable for orally disintegrating tablets (ODTs) and fast-disintegrating formulations[19-21].

Numerous studies have demonstrated the effectiveness of psyllium husk in formulations containing paracetamol, domperidone, memantine hydrochloride, and various antihistaminic agents. Recent investigations have shown that psyllium husk can produce disintegration and dissolution profiles comparable to those achieved with commercially available synthetic superdisintegrants. Consequently, it has attracted considerable interest for the development of patient-friendly dosage forms intended for pediatric, geriatric, and dysphagicpopulations[20-22].

In addition to its excellent disintegration performance, psyllium husk offers several advantages, including biodegradability, biocompatibility, low toxicity, wide availability, and cost-effectiveness. Its natural origin aligns well with the growing demand for sustainable and environmentally friendly pharmaceutical excipients. Furthermore, its regulatory acceptance and long history of safe use in food and pharmaceutical products enhance its attractiveness for formulation scientists[19,20].

A distinguishing feature of psyllium husk is its exceptionally high swelling capacity, which frequently surpasses that of many other natural superdisintegrants. However, challenges such as batch-to-batch variability, microbial contamination risk, moisture sensitivity, and variability in extraction and processing methods continue to limit its widespread industrial adoption. Standardization of raw materials and quality control procedures therefore remains an important consideration[20,21].

Future research should focus on purification techniques, particle engineering, co-processing with synthetic excipients, and the development of standardized extraction protocols to improve reproducibility and functionality. The incorporation of psyllium husk into advanced drug delivery systems, including co-processed excipients, personalized medicines, and three-dimensional (3D)-printed dosage forms, also represents a promising area for future investigation[21,22].

1.7.2. Chitosan: Chitosan is a naturally occurring cationic polysaccharide obtained through the partial deacetylation of chitin, a structural biopolymer primarily derived from the exoskeletons of crustaceans such as shrimp and crabs. Among natural pharmaceutical excipients, chitosan is unique because of its positive surface charge, which arises from the presence of protonatable amino groups along its polymer backbone. This distinctive characteristic enables chitosan to interact with negatively charged biological membranes, mucosal surfaces, and pharmaceutical ingredients, thereby expanding its utility beyond conventional superdisintegrationfunctions[23,24].

The superdisintegrant activity of chitosan is primarily attributed to a combination of swelling, capillary action, and hydration-induced matrix disruption. Upon exposure to aqueous media, chitosan absorbs water and undergoes moderate swelling, while its porous structure facilitates liquid penetration into the tablet matrix. These processes weaken interparticulate bonds and promote rapid tablet disintegration. Unlike many synthetic superdisintegrants that function predominantly through a single mechanism, chitosan exhibits multifunctional behavior arising from its physicochemical and biological properties[23-25].

Chitosan possesses excellent biocompatibility, biodegradability, low toxicity, and mucoadhesive characteristics, making it particularly attractive for advanced drug delivery applications. In addition to its role as a superdisintegrant, chitosan has been extensively investigated in controlled-release formulations, mucoadhesive drug delivery systems, transdermal preparations, ocular formulations, and nanoparticle-based drug delivery platforms. Its ability to enhance drug residence time at mucosal surfaces has further expanded its pharmaceutical relevance[24-26].

Several studies have demonstrated the successful incorporation of chitosan into orally disintegrating tablets, immediate-release formulations, and multiparticulate drug delivery systems. The polymer has been reported to improve tablet disintegration while simultaneously contributing to enhanced bioavailability and mucoadhesion. These multifunctional attributes distinguish chitosan from most conventional natural and synthetic superdisintegrants[24,25].

A particularly unique feature of chitosan is its dual functionality as both a superdisintegrant and a bioactive carrier. Its cationic nature facilitates ionic interactions with drugs and biological tissues, while its film-forming and nanoparticle-forming abilities provide opportunities for the development of sophisticated drug delivery systems. However, its performance may be influenced by factors such as degree of deacetylation, molecular weight, and environmental pH, necessitating careful formulation optimization[23,25].

Future research is expected to focus on chemically modified chitosan derivatives, nanostructured drug delivery systems, co-processed multifunctional excipients, and personalized pharmaceutical applications. Advances in chitosan engineering may further enhance its disintegration efficiency while preserving its valuable biological and pharmaceutical functionalities[25,26].

1.7.3. Fenugreek mucilage: Fenugreek mucilage is a natural polysaccharide obtained from the seeds of *Trigonellafoenum-graecum* and has gained considerable attention as a promising natural superdisintegrant owing to its remarkable hydration and swelling characteristics. The mucilage is composed predominantly of galactomannan polysaccharides, which possess a strong affinity for water and undergo rapid volumetric expansion upon hydration. These properties make fenugreek mucilage highly effective in promoting tablet disintegration and enhancing drug release[27,28].

The disintegration mechanism of fenugreek mucilage is primarily governed by swelling and water uptake. Upon contact with aqueous media, the galactomannan-rich polymer rapidly absorbs water and expands, generating internal stresses within the tablet matrix that facilitate the disruption of interparticulate bonds. In addition, capillary water penetration may contribute to the overall disintegration process. Several investigations have demonstrated that fenugreek mucilage can achieve disintegration performance comparable to that of established synthetic superdisintegrants such as sodium starch glycolate and croscarmellose sodium[27,28].

Fenugreek mucilage has been successfully incorporated into a variety of orally disintegrating tablets (ODTs), fast-dissolving tablets (FDTs), and immediate-release formulations. Studies involving drugs such as loperamide, paracetamol, and other model pharmaceutical compounds have reported rapid tablet disintegration and improved dissolution profiles when fenugreek mucilage was employed as a superdisintegrant. Its natural origin, low toxicity, biocompatibility, and cost-effectiveness further enhance its attractiveness as an alternative to synthetic excipients[28-30].

One of the most notable advantages of fenugreek mucilage is its ability to provide efficient disintegration at relatively low concentrations while maintaining acceptable tablet hardness and friability. Furthermore, the widespread availability of fenugreek seeds and the simplicity of mucilage extraction support its potential use in economically viable pharmaceutical formulations. Compared with many synthetic excipients, fenugreek mucilage offers an environmentally sustainable and patient-friendly alternative[27,29].

Despite these advantages, several challenges continue to limit its large-scale industrial utilization. Variability in plant source, extraction procedures, and purification methods may influence the physicochemical characteristics and performance of the mucilage. In addition, susceptibility to microbial contamination and moisture-induced instability necessitates careful processing and storage conditions. Consequently, standardization and quality control remain important considerations for pharmaceutical applications[28,29].

Future research should focus on the development of standardized extraction and purification protocols, physicochemical characterization of different fenugreek varieties, and co-processing approaches designed to enhance functionality and batch-to-batch consistency. The incorporation of fenugreek mucilage into multifunctional excipient systems, personalized dosage forms, and advanced drug delivery platforms also represents a promising area for future investigation[29,30].

1.7.4. *Lepidium sativum* mucilage: *Lepidium sativum*, commonly known as garden cress, has emerged as a promising source of natural superdisintegrant material for pharmaceutical applications. The mucilage obtained from its seeds is rich in hydrophilic polysaccharides and exhibits excellent swelling and hydration characteristics, which are essential for rapid tablet disintegration. Owing to its natural origin, biodegradability, and widespread availability, *Lepidium sativum* has attracted increasing attention as an alternative to conventional synthetic superdisintegrants[31,32].

The disintegration performance of *Lepidium sativum* mucilage is primarily attributed to its ability to absorb water rapidly and undergo substantial swelling. Upon hydration, the mucilage expands within the tablet matrix, generating internal stresses that weaken interparticulate bonds and promote tablet breakup. In addition to swelling, capillary water uptake may contribute to the disintegration process by facilitating rapid penetration of dissolution media into the compact structure. The combined effects of swelling and water absorption enable efficient disintegration and enhanced drug dissolution[31-33].

Several studies have demonstrated that *Lepidium sativum* mucilage can provide disintegration performance comparable to that of established synthetic superdisintegrants such as sodium starch glycolate and croscarmellose sodium. Its effectiveness has been reported in orally disintegrating tablets (ODTs), fast-dissolving tablets, and immediate-release formulations, where rapid tablet breakup is desirable. These findings highlight its potential as a cost-effective and sustainable excipient for patient-centric dosage forms[32,33].

The major advantages of *Lepidium sativum* mucilage include its natural origin, low toxicity, biodegradability, ease of availability, and economic feasibility. Furthermore, the material can often be extracted using relatively simple processing techniques, making it attractive for pharmaceutical applications in both developed and resource-limited settings. Its high swelling capacity and compatibility with a variety of active pharmaceutical ingredients further support its utility as a natural superdisintegrant[31,33].

Despite these promising characteristics, industrial application of *Lepidium sativum* mucilage remains limited by challenges associated with variability in plant sources, extraction procedures, and physicochemical properties. In addition, comprehensive stability studies and large-scale manufacturing evaluations remain relatively scarce. Addressing these limitations will be essential for broader pharmaceutical acceptance and commercialization[32,33].

1.7.5. Guar gum: Guar gum is a naturally occurring galactomannan polysaccharide obtained from the endosperm of *Cyamopsistetragonoloba* seeds. Owing to its excellent hydration capacity, swelling behavior, and biocompatibility, guar gum has been extensively investigated as a pharmaceutical excipient and natural superdisintegrant. The polymer consists primarily of mannose and galactose units arranged in a highly hydrophilic structure, enabling rapid water absorption and expansion upon contact with aqueous media[34,35].

The superdisintegrant activity of guar gum is primarily mediated through a swelling-based mechanism. Upon hydration, guar gum rapidly imbibes water and undergoes volumetric expansion, generating internal stresses within the tablet matrix that facilitate the disruption of interparticulate bonds and promote tablet disintegration. In addition to swelling, improved water penetration into the tablet structure may contribute to enhanced disintegration and drug release. The efficiency of this mechanism has led to the successful application of guar gum in a variety of immediate-release and orally disintegrating tablet formulations[34-36].

Several studies have demonstrated the utility of guar gum as a natural alternative to synthetic superdisintegrants in pharmaceutical dosage forms. It has been employed in formulations containing analgesics, antihistamines, and other immediate-release therapeutic agents, where rapid

tablet disintegration and enhanced dissolution are desired. Its widespread availability, low cost, and favorable safety profile further contribute to its attractiveness for large-scale pharmaceutical manufacturing[35,36].

Among its notable advantages, guar gum is biodegradable, non-toxic, renewable, and economically feasible. Its natural origin aligns with the growing interest in sustainable pharmaceutical excipients and green formulation strategies. Furthermore, guar gum exhibits good compatibility with many active pharmaceutical ingredients and commonly used excipients, facilitating its incorporation into diverse formulation platforms[34,35].

Despite these advantages, guar gum is associated with certain limitations. At higher concentrations, the polymer may produce increased viscosity and the formation of a gel-like layer around tablet particles, which can impede water penetration and potentially retard drug release. Variability associated with natural sources and processing conditions may also influence its performance. Consequently, careful optimization of concentration and formulation parameters is necessary to achieve the desired disintegration profile[35,36].

Future research should focus on the development of modified guar gum derivatives, chemically engineered galactomannan systems, and co-processed excipients that retain the excellent swelling characteristics of guar gum while minimizing viscosity-related limitations. Additional opportunities exist in personalized medicine, orally disintegrating dosage forms, and advanced drug delivery platforms incorporating natural multifunctional excipients[36,37].

1.8. Pectin

Pectin is a naturally occurring polysaccharide primarily obtained from citrus peels and apple pomace and has attracted considerable interest as a natural pharmaceutical excipient owing to its biocompatibility, biodegradability, and favorable hydration properties. Structurally, pectin consists mainly of partially esterified galacturonic acid residues that form a highly hydrophilic polymer network capable of absorbing substantial amounts of water. These characteristics have led to its investigation as a natural superdisintegrant in various oral solid dosage forms[38,39].

The superdisintegrant activity of pectin is predominantly attributed to its rapid water uptake and swelling behavior. Upon contact with aqueous media, pectin absorbs water and expands within the tablet matrix, generating internal swelling forces that weaken interparticulate bonds and promote tablet disintegration. In addition to swelling, enhanced water penetration into the compact structure may further facilitate tablet breakup and drug dissolution. The effectiveness of pectin in accelerating disintegration has been demonstrated in several immediate-release and orally disintegrating tablet formulations[38-40].

Pectin is particularly attractive for pediatric and geriatric dosage forms due to its excellent safety profile, non-toxic nature, and widespread regulatory acceptance. Its natural origin aligns well with the growing demand for sustainable and patient-friendly pharmaceutical excipients. Furthermore, pectin has been explored in formulations containing analgesics, antihistamines, and other drugs requiring rapid onset of action, where it has demonstrated satisfactory disintegration and dissolution performance[38,39].

One of the most important advantages of pectin is its multifunctionality. Beyond its role as a superdisintegrant, pectin has been extensively employed as a gelling agent, stabilizer, film-forming polymer, and controlled-release matrix material. This versatility provides formulation scientists with opportunities to develop multifunctional dosage forms while reducing excipient complexity. Moreover, its biodegradability and renewable origin support the principles of green and sustainable pharmaceutical manufacturing[38,40].

Despite these advantages, certain limitations may restrict the broader application of pectin as a superdisintegrant. Variability associated with source materials, degree of esterification, and extraction methods can influence its physicochemical properties and performance. Additionally, excessive swelling or gel formation under certain conditions may affect drug release characteristics and tablet robustness. Consequently, careful optimization of formulation variables remains essential[39,40].

Current research is increasingly focused on chemically modified pectins, pectin-based co-processed excipients, and multifunctional delivery systems that combine rapid disintegration with controlled-release capabilities. Future investigations may also explore the incorporation of pectin into personalized medicines, three-dimensional (3D)-printed dosage forms, and advanced natural polymer-based drug delivery platforms[39,40].

1.9. Co-Processed and multifunctional superdisintegrants

Co-processed superdisintegrants represent one of the most significant advances in modern excipient technology. Unlike simple physical mixtures, co-processed excipients are engineered at the particle level to combine the desirable characteristics of multiple materials within a single multifunctional system. Through particle engineering and optimized excipient interactions, these systems exhibit improved flowability, compressibility, dilution potential, and disintegration performance while simultaneously simplifying manufacturing processes[41-43].

Ludiflash® is a commercially available co-processed excipient composed primarily of mannitol, crospovidone, and polyvinyl acetate. This combination provides excellent mouthfeel, rapid disintegration, and superior compressibility, making it particularly suitable for orally disintegrating tablets (ODTs). Similarly, Pharmaburst® is specifically designed for direct-compression ODT formulations and contains a proprietary blend of sugars, disintegrants, and flow-enhancing agents that facilitate rapid tablet disintegration while maintaining adequate mechanical strength[41,42].

F-Melt® is another multifunctional excipient platform developed for fast-disintegrating tablets. It consists of carbohydrates, inorganic excipients, and superdisintegrating components that collectively provide excellent compressibility and rapid disintegration without the need for specialized manufacturing equipment. Likewise, Prosolv® ODT combines microcrystalline cellulose, colloidal silicon dioxide, and superdisintegrating agents to produce tablets with enhanced hardness, improved flow characteristics, and rapid disintegration behavior. These systems have significantly expanded the capabilities of direct-compression technology and have facilitated the development of robust patient-centric dosage forms[42-44].

The principal advantage of co-processed superdisintegrants lies in their ability to integrate multiple functionalities within a single excipient system. This multifunctionality reduces formulation complexity, minimizes excipient-excipient incompatibilities, improves manufacturing efficiency, and enhances batch-to-batch consistency. Furthermore, co-processed systems often demonstrate superior performance compared with the simple physical blending of individual excipients because the engineered particle architecture promotes synergistic functionality[41-44].

With the increasing emphasis on personalized medicine, continuous manufacturing, and additive manufacturing technologies, co-processed superdisintegrants are expected to play an increasingly important role in future pharmaceutical formulation development. Current research efforts are focused on designing next-generation multifunctional excipients capable of simultaneously providing rapid disintegration, improved drug dissolution, enhanced mechanical strength, and compatibility with advanced manufacturing platforms such as three-dimensional (3D) printing and continuous processing systems[43-45].

1.10. Comparative evaluation of commercial superdisintegrants

Although numerous superdisintegrants have been developed for oral solid dosage forms, sodium starch glycolate (SSG), croscarmellose sodium (CCS), crospovidone (CP), and low-substituted hydroxypropyl cellulose (L-HPC) remain the most extensively utilized in commercial pharmaceutical products owing to their proven efficacy, regulatory acceptance, and versatility in formulation development. Their performance varies considerably depending on physicochemical properties, tablet composition, manufacturing method, compression force, and the desired disintegration profile[46-48].

SSG is primarily a swelling-type superdisintegrant and exhibits one of the highest swelling capacities among commercially available excipients. This characteristic makes it particularly suitable for formulations in which strong swelling forces are required to disrupt compact tablet matrices. However, excessive concentrations may lead to gel layer formation around the tablet particles, potentially delaying drug dissolution and release[46,47]. In contrast, crospovidone functions predominantly through wicking and strain recovery mechanisms. Its highly porous, sponge-like structure facilitates rapid water uptake without substantial swelling, thereby preventing gel formation and producing exceptionally rapid tablet disintegration[47-49].

Croscarmellose sodium occupies an intermediate position between SSG and crospovidone. Its fibrous morphology promotes both capillary action and swelling, providing a balanced mechanism that ensures reliable performance under a wide range of formulation conditions. Consequently, CCS is frequently regarded as a benchmark superdisintegrant for immediate-release formulations because of its consistent performance across varying compression forces and formulation compositions[46-48]. Low-substituted hydroxypropyl cellulose differs from the other superdisintegrants due to its multifunctional nature. In addition to facilitating tablet disintegration, L-HPC can act as a binder and compression aid, thereby reducing formulation complexity and improving manufacturability[48,49].

Selection of an appropriate superdisintegrant should therefore be based on formulation requirements rather than disintegration efficiency alone. Factors such as tablet hardness, drug solubility, manufacturing method, moisture sensitivity, excipient compatibility, and the desired dissolution profile must be carefully considered during excipient selection. A comprehensive understanding of the mechanisms and performance characteristics of individual superdisintegrants enables rational formulation design and optimization of oral drug delivery systems[46-49].

Table 4: Comparative Evaluation of Major Superdisintegrants.

Superdisintegrant	Source	Primary Mechanism	Typical Concentration (%)	**Major Advantages**	**Major Limitations**
Sodium Starch Glycolate (SSG	Semi-synthetic starch	Swelling	2–8	High swelling capacity, economical	Gel formation at high concentrations
Croscarmellose Sodium (CCS)	Semi-synthetic starch	Swelling + Wicking	0.5–5	Rapid water uptake, versatile	Lubricant sensitivity
Crospovidone (CP)	Synthetic PVP	Wicking + Strain Recovery	2–5	No gel formation, rapid disintegration	Higher cost
L-HPC	Semi-synthetic cellulose	Swelling + Wicking	2–10	Multifunctional, excellent compressibility	Moderate disintegration efficiency
Polacrilin Potassium	Synthetic ion-exchange resin	Swelling + Ionic Repulsion	2–5	Taste masking and disintegration	Limited commercial use
Plantago ovata Husk	Natural	Swelling	2–10	High swelling index, biodegradable	Batch variability
Chitosan	Natural	Swelling + Wicking	1–8	Mucoadhesive, biocompatible	pH-dependent performance
Fenugreek Mucilage	Natural	Swelling	2–10	Low cost, effective disintegration	Extraction variability
Lepidium sativum Mucilage	Natural	Swelling	2–10	Emerging natural alternative	Limited industrial data
Guar Gum	Natural	Swelling	2–10	Economical, readily available	Increased viscosity at high levels
Pectin	Natural	Swelling	2–8	Safe, biodegradable	Lower mechanical robustness

2. Emerging Trends in Superdisintegrant Technology

Recent advances in pharmaceutical technology have expanded the role of superdisintegrants beyond conventional tablet formulations. The growing demand for patient-centric dosage forms, particularly orally disintegrating tablets (ODTs), pediatric medicines, geriatric formulations, and personalized drug delivery systems, has accelerated the development of innovative superdisintegrant technologies. These advancements aim not only to achieve rapid tablet disintegration but also to improve manufacturability, patient compliance, and therapeutic outcomes[50-52].

One of the most significant developments is the emergence of co-processed superdisintegrants, wherein two or more excipients are engineered at the particle level to achieve synergistic functionality. Commercial platforms such as Ludiflash®, Pharmaburst®, F-Melt®, and Prosolv® ODT exemplify this approach. These multifunctional systems provide enhanced flowability, compressibility, dilution potential, and disintegration efficiency while reducing formulation complexity and manufacturing variability. Consequently, co-processed excipients have become increasingly important in the development of robust direct-compression ODT formulations[41-45,50].

Another rapidly evolving area is the integration of superdisintegrants into additive manufacturing and three-dimensional (3D) printing technologies. The highly porous architectures generated by 3D printing create unique opportunities to optimize tablet disintegration through controlled placement, concentration, and distribution of superdisintegrants within printed dosage forms. Such technologies support the production of personalized medicines with customized drug doses and release profiles. Although preliminary studies have demonstrated promising results, systematic investigations into the behavior of superdisintegrants within printed pharmaceutical matrices remain limited and warrant further exploration[51-53].

Nanotechnology-based approaches are also attracting considerable attention. Surface modification of superdisintegrants using nanomaterials and nanoscale engineering techniques has the potential to enhance water uptake, swelling kinetics, wettability, and drug dissolution. These strategies may be particularly beneficial for poorly water-soluble drugs, which continue to present significant formulation challenges. Furthermore, nanostructured superdisintegrants may facilitate the development of multifunctional excipients capable of simultaneously improving disintegration, dissolution, and bioavailability[52-54].

More recently, artificial intelligence (AI) and machine learning (ML) have begun to influence pharmaceutical formulation development. Predictive computational models can assist in optimizing superdisintegrant selection, concentration, and formulation variables, thereby reducing experimental workload and accelerating product development. Integration of AI-driven formulation design with continuous manufacturing technologies may facilitate the development of next-generation oral dosage forms characterized by improved quality, efficiency, and reproducibility[54,55].

Collectively, these emerging technologies highlight the transition of superdisintegrants from conventional tablet excipients to multifunctional materials that play a central role in advanced pharmaceutical manufacturing and personalized medicine. Continued innovation in excipient engineering, digital formulation design, and advanced manufacturing technologies is expected to further expand the applications and capabilities of superdisintegrants in future drug delivery systems[50-55].

3. Research Gaps and Future Perspectives

Despite significant advances in superdisintegrant technology, several challenges remain unresolved. Although commercially available superdisintegrants such as sodium starch glycolate, croscarmellose sodium, and crospovidone have demonstrated excellent performance and regulatory acceptance, most of these excipients were introduced decades ago. Relatively few fundamentally new superdisintegrants have achieved widespread industrial adoption in recent years, highlighting the need for innovative materials with enhanced multifunctionality, sustainability, and formulation versatility[56-58].

Natural superdisintegrants represent one of the most promising avenues for future research. Numerous plant-derived materials have demonstrated excellent swelling, hydration, and disintegration properties comparable to those of conventional synthetic superdisintegrants. However, large-scale industrial implementation remains limited owing to variability in botanical sources, extraction procedures, physicochemical composition, and quality control parameters. The development of standardized extraction protocols, robust characterization techniques, and clear regulatory guidelines will be essential to facilitate broader pharmaceutical acceptance and commercialization of natural superdisintegrants[24,26-29,56].

Another important research gap involves understanding the relationship between superdisintegrant particle morphology and disintegration performance. Although swelling, wicking, and strain recovery mechanisms are well established, the influence of particle architecture, pore structure, and hydration dynamics remains incompletely understood. Advanced analytical tools such as micro-computed tomography (micro-CT), confocal laser scanning microscopy, synchrotron imaging, and machine-learning-assisted image analysis may provide deeper insights into water penetration pathways and tablet breakup mechanisms, thereby enabling more rational excipient design[57,58].

The growing adoption of continuous manufacturing presents additional opportunities and challenges. Most published studies have been conducted using conventional batch-processing techniques, whereas the behaviour of superdisintegrants under continuous blending, feeding, and tableting conditions remains insufficiently characterized. Future investigations should focus on establishing process-structure-performance relationships to facilitate evidence-based excipient selection and process optimization in continuous manufacturing environments[59].

Furthermore, the integration of superdisintegrants into personalized medicine platforms, including three-dimensional (3D)-printed tablets, on-demand pharmaceutical manufacturing systems, and digitally enabled drug production technologies, represents an emerging field with substantial potential. Optimization of superdisintegrant type, distribution, concentration, and interaction with advanced dosage-form architectures may contribute significantly to the development of next-generation oral drug delivery systems tailored to individual patient needs[51-53].

Overall, future progress in superdisintegrant research is expected to focus on the development of multifunctional excipients, sustainable natural materials, advanced characterization methodologies, and compatibility with emerging pharmaceutical manufacturing technologies. Such advances will further strengthen the role of superdisintegrants in improving drug delivery performance, patient compliance, and formulation efficiency[56-60].

4. Summary

Superdisintegrants play a critical role in modern oral drug delivery systems by promoting rapid tablet disintegration and enhancing drug dissolution. Their performance is governed by multiple mechanisms including swelling, wicking, strain recovery, particle repulsion, heat of wetting, enzymatic action, and deformation recovery. Among commercially available superdisintegrants, sodium starch glycolate, croscarmellose sodium, crospovidone, and low-substituted hydroxypropyl cellulose remain the most extensively utilized owing to their proven efficacy and regulatory acceptance. Emerging trends such as co-processed excipients, natural superdisintegrants, nanotechnology-based modifications, and 3D-printed dosage forms are expected to shape future developments in this field. Continued research focusing on multifunctionality, sustainability, and personalized drug delivery will further expand the applications of superdisintegrants in pharmaceutical formulation science.

5. Conflict of Interest

The authors declare that there is no conflict of interest.

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