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Nanoparticle Enhanced edible coating and their applications in food packaging

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Abstract
Ediblecoatingsarethethinlayersoffood-gradematerialswhicharedirectlyappliedtofoodto extendtheproduct'sfreshnessperiod.The coatingsprotectfoodsfromoxidationandmicrobial growth and moisture loss and all other changes which take place during storage. Theconventionalediblecoatingswhichuseproteinsandlipidsandpolysaccharidesastheirmainmaterialsshowenvironmentallyfriendlypropertiesbecausetheycanbebrokendownnaturallybut their mechanical strength has several limitations because they let too much water vapor escape and they provide insufficient protection against harmful microorganisms.The researchers in this field have started to develop methods which can enhance the coating capabilities because of the deficiencies which exist in the current system. The edible coatings have received significantimprovementsthroughtheimplementationofnanotechnologyduringthelastfewyears.The combination of nanomaterials which include nanocellulose, nano clays, Nanoemulsions,liposomes,andmetaloxidenanoparticleshasresultedinthecreationofstrongercoatingswhich offer improved barrier performance and antimicrobial capabilities. The coating structure gainsstrengthfromnanofillerswhichincludecellulose nanocrystalsandnano claysbecausetheycreate more complex diffusion pathways which obstruct gas and moisture movement and theynanoscaledeliverysystemsallowfortargetedreleaseofnaturalbioactivesubstances whichincludeessentialoilsandantioxidants.Thenanoenhancedediblecoatingshavebeeneffectively utilized to control microbial growth and respiration patternsand maintain sensory attributesand postpone lipid oxidation in fruits and meat and seafood and dairy products and vegetables. The advantages of the technology face challenge because of two important issues which deal with how nanoparticles travel through systems and their risk of causing health problems and howpeopleperceivethem.Thecurrenttechnologyneedsboththoroughsafetytestsandregulatory body permissions before it can be used in widespread commercial operations. The nano-enhancedediblecoatingswillserveasaneffectiveandenvironmentallyfriendlysolutionto enhance food storage methods and contemporary packaging technologies.

Keywords
Ediblecoatings;Nanotechnology;Nanoemulsions;Activefoodpackaging; Shelf-lifeextensions.

I. Introduction
Food waste results in substantial economic damages because spoiled food creates global food wasteproblemswhichendangerbothfoodsafetyandfoodquality.Theentireworldnowtreats this problem as a major international emergency. Food products spoil during storage anddistribution because of several factors which include oxidative damage, moisture loss, bacterial growth, enzymatic processes and gas exchange variations. Conventional packaging methods establish delays for these processes because sustainable packaging solutions have emerged as a responsetogrowingenvironmentalproblemswhichstemfromplasticwastethatdoesnotbreak down in nature [1]. Edible coatings have generated a lot of interest withinthese substitutes since they can be coated directly to the food surfaces and can be consumed without risk. Food-grade biopolymers serve as the base material for edible coatings which producethinfilmsthatdecreasebothoxygenpermeabilityandmoisturetransferandbacterial contamination [2]. The internal atmosphere of fresh fruits andvegetablescanbemodifiedtoextendtheirshelflifebecausethismodificationdelaysthenatural deterioration process. The material exhibits multiple challenges which include brittleness,excessivewatervaporpermeability,insufficientmechanicalstrengthandunpredictableantibacterialagentdischarge.Researchershaveinvestigatedadvancedmodificationtechniquesto address these challenges which emerged from their attempts to enhance coating performance [3].

Thelimitationsofcurrentsystemscanbesolvedthroughtheimplementationofnanotechnology inediblecoatingsystems.Nanotechnologyallows scientiststochangematerialproperties atthe nanoscale which results in improved mechanical performance and functional attributes andphysicochemical characteristics. The researcher group established complex matrix structures accordingtotheir findings[4].Researchershave extensivelystudiedcellulose nanocrystalsandnanoclaysasnanofillersbecausethesematerialspossessextensivesurfacearea and deliver reinforcement capabilities and they match the characteristics of biodegradablepolymers[21]. Nanotechnologyenablesthecreationofthe nano-delivering system,likeliposomesandNanoemulsions,whichprotectthenaturallyoccurring bioactivecompounds and to enhancetheirstability, solubility, and controlled release.Thecombination of plantcomponentswiththeirextractedessentialoilsproducesbetterantibacterialandantioxidantresultswhile minimizingnegativesensoryeffectsinfoodproducts[5,6].

Theactivefoodpackagingsystemsusemetalandmetaloxidenanoparticles which include zinc oxide to provide dual functions that protect against ultraviolet radiation andrangeofmicrobialthreat.Themainchallengesforthesematerialsstemfromtheir advantageswhichaboutconsumeracceptanceandtheir potentialfortoxiceffectsandthewaynanoparticles scatter through the environment [7]. The European Food Safety authorityrequirescontrol authoritiesto obtain completephysicochemical characterization and exposure assessmentandtoxicologicalevaluationbeforetheycanusenanoparticlesinfoodapplications [8].

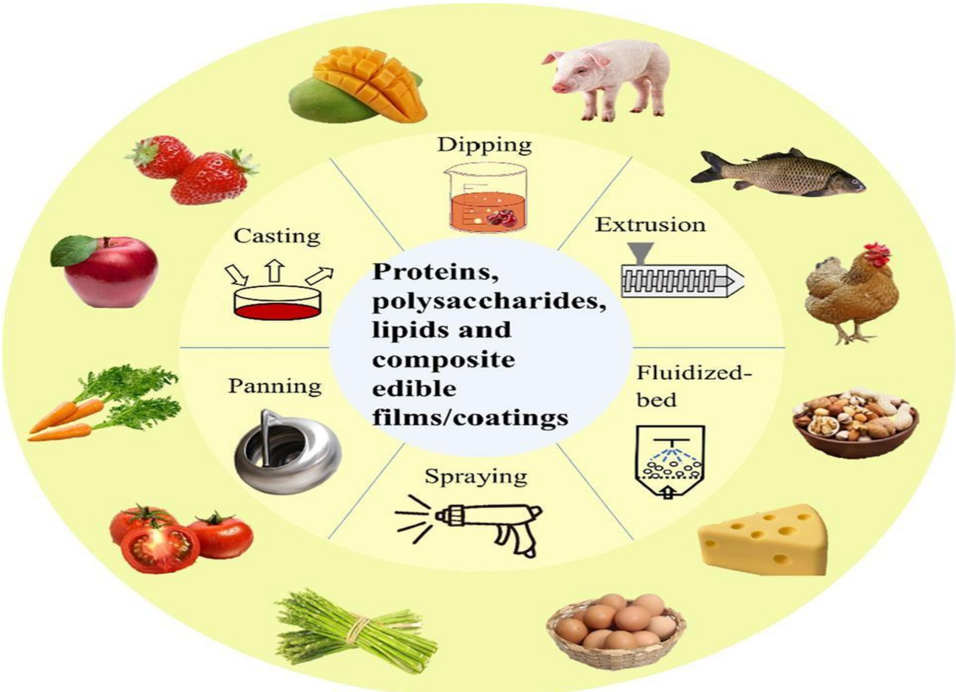

Figure1: Majorbiopolymermaterialsusedinediblecoatings,includingpolysaccharides, proteins, and lipids, and their functional roles in food preservation.

2.EdibleCoating Materials

Theproductionofedible coatingsusesfood-gradebiopolymerswhichderivefromnaturalsources through protein and lipid and polysaccharide extraction methods [3]. The biopolymer materials receive widespread adoption because they have biodegradable properties andnon-toxicnatureandtheirabilitytocreatesafefoodcontactthinprotectivefilms.Theproper selection of coating materials establishes the foundation for determining coating performance,whichaffectsitscapabilitytopreservefooddqualityandshelflife[9].

2.1. Polysaccharide-BasedMaterials

Theediblecoatingcompositionscommonlyusepolysaccharidesastheirmaincomponentbecausethesematerials possessexceptionalfilm-

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formingcharacteristicsandprovideclearfilms which function as carbon dioxide and oxygen barriers. Chitosan starch alginate pectin andcellulosederivativeswhichincludehydroxypropyl methylcelluloseHPMCandcarboxymethyl cellulose CMC represent the significant polysaccharides used in this study. The researchersdevelopedpolysaccharidecoatingswhichsuccessfullyreducedgasexchangewhileextendingthe shelflifeoffoodproductsbyminimizingoxidativedamage[10].Chitosanwhich derives from chitin exists as a natural material that scientists value because its antibacterialpropertiesandbiocompatibilityanditscapacitytobuildstrongflexiblefilms.Chitosanfunctions through its cationic properties which enable it to connect with microbial cell membranes that carryanegativecharge[11].Starch-basedcoatingswhichpeoplecanobtainatalow-cost face excessive water vapor permeability problem due to their hydrophilic nature whichneeds either modification or blending with additional materials [12].Alginate andpectincoatingswhichmostcommonlyusecalciumionsforcross-linkingdevelopmentcreate standard gel networks which strengthen structural stability while improving food adherence [13].

2.2. Protein-BasedMaterials

Theprotein-basedediblecoatingsaremadeofanimalortheplantproteinslikewheyproteins, casein, gelatin, soy protein, and zein. The components show exceptional oxygen barrierperformancecombinedwithstrongmechanicalattributes.Theproteinfilmscontaindensemolecularstructureswhichprovideeffectiveprotectionfordelicatefooditemsaccordingtotheir claims [14; 9].Thehigheradhesionandclarityofwheyproteincoatingsmakethemsuitableforuseincheese and fruits and nuts. The gelatin-based coatings maintain film integrity through their flexiblepropertieswhichalsoprotectagainstmoisturedamage [16]. Thefilm- forming abilities of zein coatings and soy protein function as plant-based alternatives whichresearchersarestudyingtocreatesustainablefoodpackagingsolutions.The proteincoatingsrequireplasticizerstoimprovetheirflexibilityandtodecreasetheirbrittlenesswhenexposedto dry conditions according to research by [17] in 2012 and [18] in 2002.

2.3. Lipid-BasedMaterials

Thelipid-basedediblecoatingscontaintheoil,fattyacids,monoglyceridesanddiglyceridesand natural waxes such as carnauba and beeswax. These materials are the excellent moisturebarriersduetotheirhydrophobiceffect.Wax-basedcoatingseffectivelyreducetheshrivelingof the fresh food and water loss during the food storage[2].In spite of their outstanding moisture barrier characteristics, lipid coatings mostly show poor mechanical strength and limited gas barrier performance [9].As a result, the lipids are mostly mixed with the proteins or polysaccharides to form compositecoatingsthatequalizemoistureresistanceand mechanicaldurability [20].

2.4. Composite-BasedMaterials

Inordertoovercomethelimitationsofindividualbiopolymers,compositeediblecoveringsare prepared from proteins, lipids, and polysaccharides are being carefully studied. The combined advantages of these composite systems improve the mechanical strength, barrier performance, and functional stability. The composite coatings serve as efficient matrices for combining thenano-enhancedcompoundsandsurpasssingle-componentsystems[4].Ingeneral,theselectionandoptimizationoftheediblecoatingcomponentsareessential tosuccessfulfoodpreservation.Understandingthephysicochemicalcharactersofproteins,lipidsandpolysaccharidesallowsfortheimprovementofthealteredediblecoatingswhicharemost suitedforavarietyofdietaryuses [1,9]

3. Nano-EnhancementStrategies

Bycombiningthenanotechnologyintoediblecoatingsystemshasefficientlysolvedthedrawbacksoftheconventionalbiopolymercoatings,particularlytheirlowmechanicalstrength, high water vapor permeability, and poor stability of the active ingredients. The nanofillers,nanodeliverysystems,andactivenanoparticlesarefrequentlyusedinthenano-enhancement approaches to develop the structural, functional, and bioactive properties of edible coatings [4,1]

3.1. Nanocellulose-BasedReinforcement

As asustainable nanofiller for edible coatings, nanocellulose—including cellulose nanocrystals (CNCs)andcellulosenanofibrils(CNFs)—haveattractedalotofattentionduetoits highaspect ratio, enormous surface area, higher mechanical strength, and biodegradability. By making adensehydrogen-bondednetwork,nanocelluloseconsiderablyimprovestensilestrengthand reduces oxygen permeability in biopolymer matrices [21]. By forming aconvolutеddiffusionchannelthatlimitstheflowofgasesandmoisture,nanocelluloseincreases barrier

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qualities [4].Nanocellulose increases edible coatings structural integrity and thermal stability in addition to providingmechanicalsupportwhilemaintainingtheirflexibilityandtransparency.Nanocellulose is a perfect reinforcing ingredient for edible and biodegradable packaging materials since it is verycompatiblewithmatricesbasedonproteinsandpolysaccharides [22].

3.2. NanoclaysForBarrier Enhancements

Layeredsilicatemineralscalledthenanoclays,mainlyhalloysiteandmontmorillonitenanotubes, are largely used as nanofillers in the food packaging applications.These components increase the mechanical strength, thermal stability, and barrier properties of the edible coatings by forming many convoluted diffusion routes for gases and water vapor. When they disperse uniformlythroughoutthepolymermatrix,nanoclaysprovideintercalatedorexfoliatedstructures that specifically decrease permeability [23].Enhanced resistancetobothoxygenandmoisturetransferhasbeenshown byNanoclay-reinforcedbiopolymerfilms,whichisimportantforincreasingtheshelflifeofthefoodproducts [4]. Furthermore, essential oils and antimicrobial substances can be transferred through nanoclays, increasing the coating functionality and allowing their gradual release [19].

3.3. NanoemulsionsForControlledDeliveryofBioactiveCompounds

Thehydrophobicbioactivematerials,likeantioxidants derivedfromtheplantsandessentialoils, aremostcommonlyencapsulatedinNanoemulsions,whicharecolloidalsystemswiththedroplet sizes generally less than 200nm. Nanoemulsions-based edible coatings reduce volatility andsensoryproblemswhileimprovingthesolubility,stability,antibacterialefficiencyoftheessential oils [5].constantbioactivematerialsdispersiononthefoodsurfacesisproducedbynanoemulsioncoatings,whichalsoallowcontrolleddispersiontoincreaseantioxidantandantibacterialactivity [6]. Since they reduce the down ripening, block the microbial growth and maintain sensory quality, these techniques are especially effective on fresh fruits and vegetables [24].

3.4. LiposomesAsNano-Delivery Systems

Liposomesarevesicularstructuresbasedonthephospholipidsthatcancontainbothhydrophilic and hydrophobic molecules. They are suitable for edible coating applications because of theirabilitytosafeguardthesensitivebioactivesandtheir biocompatibility.Antimicrobialsareenclosedinliposomeshaveimprovedstabilityandcontrolledrelease,whichenhancesthe efficacy of preservation during storage [25].When added together with edible coatings, liposomes slow down the rapid breakdown of bioactivematerialsandprovidelong-lastingantibacterialandantioxidantactivitywithout severely affecting the flavor of the food [26].

3.5. MetalAndMetalOxide Nanoparticles

Metal and metal oxide nanoparticles, including zinc oxide (ZnO) and titanium dioxide (TiO_2) are used in edible coatings because of them because of their excellent antibacterial and UV- blocking properties. By breaking the membranes and manufacturing reactive oxygen species, zincoxidenanoparticlesshowbroad-spectrumantibacterialactionagainstbacteria,yeasts,and molds [27].consideringtheirpotency,metalnanoparticleshavetobeutilizedwiselyintheedible coatingsbecauseoftheirpotentialtoxicityandmigrationintofoodmatrices.TheRegulatoryorganization stress that an extensive safety review, including the physicochemical characterization andexposureassessment,isnecessarypriortotheirusein foodsystems[28; 29].

4. ApplicationsInFoodPackaging

Nano-enhanced edible coatings are becoming increasingly essential in food packaging,even thoughtheycanimprovefoodsafety,shelflife,andqualitywhilereducingtheneedforplasticpackagingandartificialpreservatives.Theadditionofnanoparticlestoediblecoatingsallowsfor better control over gas exchange, moisture transfer.And the release of antibacterial chemicals and antioxidant, making them compatible for a range of food systems [1; 30].

4.1. FruitsAndVegetables

Rawfoodismorepronetopostharvestlossesfrom respiration,transpiration,microbialdeterioration,and enzymaticbrowning.Nano-enhanced ediblecoatingshaveshowneffectivereductioninrespirationrateanddelayedsenescencebyformingasemi-permeablebarrieronthe produced surface. On regulating the exchange of carbon dioxide and oxygen, edible coatingslowermetabolicactivityandextendtheshelflife [10].

Therecentstudieshaveshowedthatthecoatingsthatarereinforcedwithantimicrobialsenclosed in nanoparticles particularly inhibit the microbial growth on fruits and vegetables. Essential oils were found to increase the antibacterial stability and effectiveness of the Nanoemulsions, which helped in the preservation of the fresh food. Further, it has been showed that during the coldstorage,nano-reinforcedpolysaccharidecoatingsmaintaincolor,stiffness,reduceweightloss [31].

4.2. MeatAndSeafoodProducts

The meat and seafood products are significantly prone to rotting because of lipid oxidation, fast microbialgrowth,andproteindegradation.Andnano-enhancedediblecoatingseffectivelysolve these issues by forming oxygen barriers and carefully dispersing the antioxidants andantimicrobials.Ediblecoatingscontainingbioactive compoundsparticularlylowertheoxidative reactions and microbiological growth of animal-based diets [1].Lipid peroxidation and total volatile basic nitrogen (TVB-N), the two decaying signals in the seafoodsystems,havebeenshowntohavedelayedbythe nano-basedcoatings.Demonstrated that the employed nano-structured edible coatings, fish quality was satisfactorily maintainedthroughoutchilledstorage.Similarly,coatingscontainingnanoparticleshaveincreasedthe microbiological safety and shelf life of the beef products without sacrificing their sensory attributes [32].

4.3. BakeryProducts

Bakeryproductsareparticularlysusceptibletomoldimprovedandmoisturemigration,whichdecreasestheshelflifeanddeterioratestheirtexture.Nanotechnology-enhancedediblecoatings have been applied to baked products to regulate the moisture transportand stop the growth of fungi.Theantimicrobial packaging techniquescan significantly delay the growth of the mold innanotechnology have long-lasting antibacterial action that efficientlydecreasesthefungalinfectionwhilestillpreservingthefoodsuppleness.Theyshowedthatnano- based antimicrobial solutions may successfully battle typical bakery rotting organisms, boosting the storage stability and shelf life [34].

4.4. DairyProducts

Dairyproducts,especiallycheese,arevulnerabletooxidativedeterioration,moistureloss,and surface mold growth during storage and ripening. Nontechnology-enhanced edible coatings produce barriers against moisture evaporation and microbiological contamination. Ediblecoatingscontainingantimicrobialcomponentsparticularlypreventfungalgrowthonthecheese surfaces [35].utilizingthenano-structureddeliverymethods,antimicrobialscanbeadministeredgradually, limiting the sensory changes and doing away with the requirement for high quantities ofpreservatives.Theyfoundthatthedairyproducts microbiologicalstabilitywasdevelopedbyadditionofediblecoatingswhilepreservingtheirflavor,texture,andoverallappeal[36]

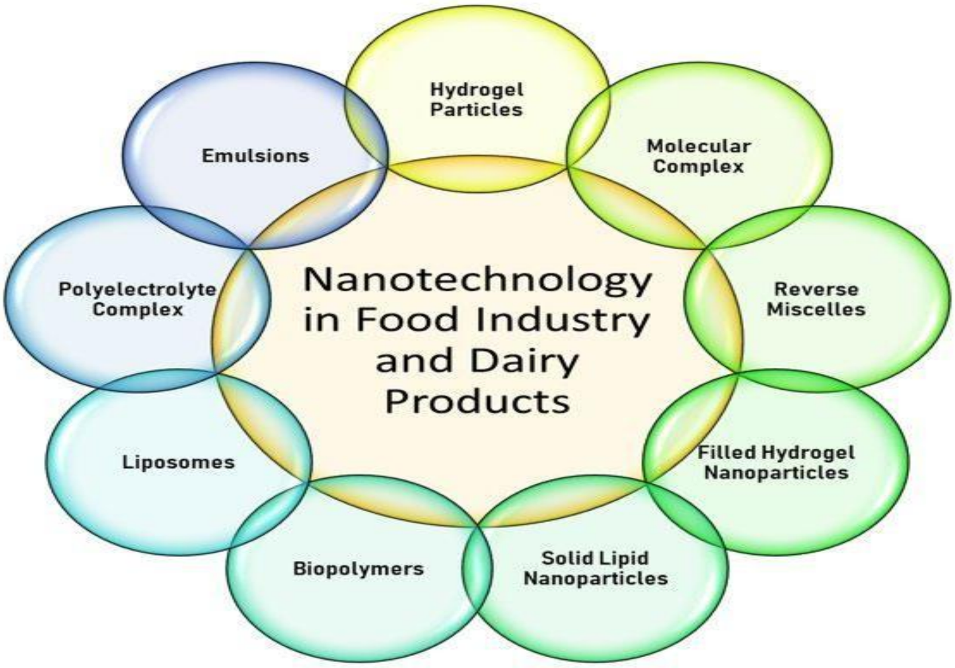

Figure2: Nanotechnologyinfoodindustryanddairyproducts.[41]

5. SafetyAndRegulatoryAspects

The incorporation of nanoparticles into edible coatings introduces distinct safety and regulatory concerns,particularlybecausethesematerialsaredeliberatelyconsumedalongwithfood.Unlike conventional packaging materials, edible coatings are applied directly to food surfaces and are ingestedbyconsumers,makingcomprehensivesafetyevaluationessential.Factorssuchastoxicologicalcharacteristics,migrationpotential,andpossiblelong-termhealthimpactsmustbe carefully examined. Owing to their nanoscale dimensions, these particles may display alteredphysicochemical properties and biological interactions compared to their bulk forms, which couldinfluencetheirbehaviorwithinthehumanbody[28,38].

5.1. NanoparticleMigrationandConsumerExposure

Themainissuewithediblecoatingsthatusenano-enhancementsarisesfromtheirpotentialto allow nanoparticles and their dissolved ionic forms to penetrate into food products. Themigration process with food products depends on various factors which include the food categoryaseitherfattyoracidicorwateryandthecharacteristicsofcoatingmaterialsandparticledimensionsandsurfacechargepropertiesandtheirsolubilityandtheconditionsusedfor storage. The study showed that nanoparticles which exist in a polymer matrix can move out ofthematrixincertainsituationsespeciallyunderconditionswherecoatingsexperiencehigh moisture or fat content.

Thesafetyassessmentprocessrequiresexposureassessmentasitsfundamentalcomponent.The assessment of consumer exposure requires researchers who need to study actual consumptionpatternstogetherwiththe specificnanoparticle concentrationsandthetypicalrangeofnanoparticleconsumptionthroughouttheday.Thestandardmethodforassessing nanoparticlereleaseandexposurelevelsinvolvestwocomponentswhichincludemigrationexperimentsthat use standardized food simulants and analytical techniques which include electron microscopy and inductively coupled plasma mass spectrometry (ICP-MS) [37].

5.2. ToxicologicalEvolutionofNanoparticles

Thetoxicologicaltestsofnanoparticleswhichareusedinediblecoatingsassessmultipletoxicity aspects including acute toxicity, chronic toxicity genotoxicity, oxidative stress, immunologicalresponsesandbioaccumulation.Thehigherreactivityandlargersurfaceareaofnanoparticles enablethemtointeractwithbiologicalsystemsinways whichdiffer fromstandardmaterials.Researchdemonstratedthatnanoparticlespossesstheabilitytopenetratebiological barrierswhichresultsinintracellularabsorptionthat requiresadditionalresearch[29].Thescientists conducted studies through both in vitro and in vivo methods to determine toxicity levels; however there exists a complete lack of long-term toxicity assessment for multiple food-relatednanomaterials.Regulatoryagenciesfacedifficultiesinapprovinginorganicnanoparticles because of their ability to persist throughout biological systems. Toxicological testing mustincludedoseassessment,exposuredurationassessmentandassessmentofsensitivepopulations which includes youngsters and people with immunocompromised conditions [37].

5.3. InternationalRegulatory Framework

Theworldwide regulatoryagencieshaveestablishedacautiousframeworkforevaluatingnanomaterialsusedinfoodpreparationactivities.Thenovelfoodregulation,whichregulates synthetic nanoparticles in the EU, requires clear labeling and individual risk assessment Manufacturersneedtosubmitcompletephysicochemicaldetailstogether with migration information and toxicological data before they can receive product approval according to McClements and Xiao 2017.The Food and DrugAdministration (FDA) encourages companies to seek their guidance when theyworkwithnanoscalematerialsbecausetheFDAassessesnanoparticlesaccordingtocurrent foodsafety regulations.TheFDAadvisory statement stressesthat variationsin particle sizemay affect safety and functionality even if the bulk item has already been approved. The FDA2014documentshowsthatprecautionaryregulationsestablishedinotherfieldsdemonstratewidespreadenvironmentalprotectionconcernsaboutthepotentialdangersofnanotechnologyin food systems [39].

5.4. RiskAssessmentandSafety-By-DesignStrategies

Incurrentregulatoryscience,a"safety-by-design"approachthatminimizespotentialrisksinthe early stages of material making is gaining attraction. By modifying the size, concentration, and surface chemistry of nanoparticles, toxicity can be particularly decreased while preservingfunctionaladvantages.Forediblecoatings,thismethodencouragestheuseoffood-grade, biodegradable nanostructures rather than persistent inorganic nanomaterials, such asNanoemulsions and biopolymer-based nanoparticles [40]. Weighing the advantagesoftechnologyagainstanypotentialhealthrisksisanotheraspectofriskassessment. Open reporting, consistent testing, and interdisciplinary collaboration between food scientists,toxicologists,andregulatoryagenciesareessentialtoensuringsafeinnovation[41].

5.5. ConsumerPerceptionANDFutureRegulatory Challenges

Thepublicneedstounderstandediblecoatingsthatusenanotechnologybecausecustomersupportisessentialfortheirmarketsuccess.Publicapprehensionabouttheterm"nano"arises from two main factors which include the perceived health dangers and the general lack ofknowledgeaboutnanotechnology.Theprocessofwinningclienttrustrequireseffectivecommunicationofriskinformationthatneedstobeunderstoodbyclients.Theglobalacceptance of the product remains obstructed because international standards remain uncoordinated andanalyticalmethodslackproperestablishment[38]. Thefutureregulatoryactivitiesshouldbeginwiththeestablishmentofstandardizedtesting methods which will increase research on long-term effects of nanomaterials and ongoingregulatoryupdatesthatwilladdressnewmaterialdevelopments.Allofthese issues requiresolutionstoachievesafeethicalandsustainable practiceswithnano-enhancedediblecoatingsin food packaging systems.

6. Conclusion

The technology which produces edible coatings through nano-enhancements provides an environmentallyfriendlysolutionforfoodpackagingbyimprovingfoodproductsandextending their storage time and ensuring their safety. The coating system achieves better performance throughtheincorporationofnanoclaysandnanocelluloseandnanoemulsionsandliposomesandmetaloxidenanoparticlesintoediblebiopolymermatriceswhichsolvemultipleissuesthataffect traditional edible coatings which show weak mechanical properties and high permeability andrestrictedantimicrobialperformance.Thematerialsfunctioneffectivelyaspackagingforvarious types of food products because they manage gas flow and moisture movement and chemical oxidation and bacterial growth. The implementation of nanoparticles in edible coatings bringsscientificadvantageswhilerequiringevaluation ofhowconsumersperceivetheirsafetyandtheir compliance with food safety regulations. The assessment process requires physicochemicalcharacterizationandexposureassessmentandtoxicologicalevaluationbecausenanoparticlescan migratefromtheirsource andbuildupinlivingorganismsandcreatelong-termhealthproblems. Regulatoryauthoritiesworldwideimplementaprecautionarymethodwhichexamines risksindividually using safety-by-design methods to better control potential hazards to public health andenvironmentalsafety.Researchshoulddeveloptestingmethodswhichestablishstandardized procedures for testing food-grade and biodegradable nanostructures and which improve publicunderstandingofriskcommunication.Thecorrectregulatory monitoringtogetherwithresponsibleinnovationpracticeswillenablenano-enhancedediblecoatingstocreatesustainable food packaging systems which secure global food available.

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