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Can additives enhance cassava starch bioplastics for prospective dental applications? A systematic review

Abstract

Objectives: To identify methods reported in the literature for improving the mechanical and barrier properties of cassava starch bioplastics and to discuss their potential application in dentistry.

Methods: A systematic search was conducted in five major electronic databases: PubMed, Ovid, Scopus, Web of Science and Cochrane. In vitro studies on cassava starch that compared the mechanical, physical, thermal or water barrier properties of modifications with additives or reinforcing materials to those of a control were considered. Review articles, opinion articles, letters, commentaries, and non-peer reviewed literature were excluded.

Results: Out of the 884 articles identified in the search, 132 were included in the qualitative synthesis. Nanoparticles, nanofibrils, fibres, essential oils, animal products and various other substances were among the common additives. All the suggested modifications were summarized along with the corresponding observations.

Conclusion: Most of the additives and reinforcers suggested in the literature improved the properties of the cassava starch bioplastic. There is a potential for further research in this area to expand the use of these bioplastics in dentistry. The need to replace conventional plastics with biodegradable alternatives extends beyond the food packing industry to other fields as well.

Clinical Relevance: In the future, if the properties of cassava starch bioplastics are customized for dental use, this material has a scope to replace the acrylic used for temporary purposes. Thus, we can introduce biodegradable alternatives and encourage green dentistry.

Introduction

Dental acrylics are synthetic resins widely used in dentistry for fabricating dentures, crowns, and orthodontic appliances due to their versatility, ease of manipulation, biocompatibility and durability.[1] Most commonly used material used in dental acrylics is polymethyl methacrylate, a type of plastic polymer that is synthesized from petroleum-derived monomers.[2] While dental acrylics offer great functional advantages in dental field, their petroleum origin cause environmental concerns as other plastics.[1-6] Some environmental hazards associated with acrylics include non-biodegradability, fossil fuel dependency, waste generation, toxicity concerns during production, microplastic pollution and challenges in disposal and recycling.[1-6] As there is a growing need to reduce the consumption of these non-biodegradable plastics, research is advancing toward the development of biodegradable and bioplastic polymers.[6]

Now-a-days, in dentistry, the biodegradable application is limited to guided tissue/bone regeneration, tissue scaffolds for tissue engineering, sutures, drug delivery, bone grafts and implants.[4] Materials like polylactic acid, polycaprolactone, polyhydroxyalkanoates, chitosan, polyglycolic acid, collagen-based materials, calcium phosphate based bioceramics, hyaluronic acid, fibrin and gelatin based materials.[4] However, the substitute to dental acrylics is not being explored till now.

In literature, there are reported sustainable materials derived from renewable biological sources, such as plants or microorganisms, designed to reduce reliance on fossil fuels and minimize environmental impact through biodegradability or compostability.[7] The production of low- cost, carbohydrate-based polymer from starch is one proposed method, as starch is a naturally abundant and essential raw material.[7] Starch is granular in form and consists of a combination of amylose and amylopectin. Amylose is a linear molecule with D-glucopyranosyl units connected by α(1,4) bonds, while amylopectin is a branched molecule with D-glucopyranosyl units connected by both α(1,4) and α(1,6) bonds. The amylose and amylopectin content of starch varies depending on its source.[8]

Native starch lacks plastic properties, but when subjected to temperature and pressure in the presence of a plasticizer, it forms thermoplastic starch. The membrane forming properties are due to the formation of hydrogen bonds between hydroxyl groups of two chains.[8] Starch for industrial use is obtained from sources such as wheat, potato, rice, maize, corn, cassava, amaranth, and quinoa. These starches are colorless, odorless, tasteless and non-toxic.[9] However, a significant drawback is their high water vapor permeability, which compromises the barrier properties, and in turn, the mechanical properties of the films produced. Among the various sources, cassava (also known as manioc, mandioca, tapioca, and yuca) is a promising material for bioplastic production due to its low cost and abundant availability.[10]

To overcome disadvantages such as poor mechanical and barrier properties, various additives and coating materials have been reported in the literature.[11-142] The properties of the cassava starch based bioplastics have been enhanced using a range of additives, including nanoparticles,[11,18,29,38,40,41,46,49,65] fibres,[12-14,16,19,22,23,27,34,35] flours,[20] synthetic fibres/materials,[24] essential oils,[28,63,68,96] shells,[73,74] nanoclay[90] and other materials. There is a need to systematically review the existing literature to identify potential methods for reinforcing these bioplastics for dental applications. Therefore, this review focuses on the modifications tested for the cassava starch based bioplastics, along with the properties analyzed.

Methods

The research question formulated for this review was "Can additives improve the mechanical and barrier properties of cassava starch bioplastics for prospective dental application?" This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

A comprehensive search was performed through March 2024 in the Medline via PubMed (https://pubmed.ncbi.nlm.nih.gov/advanced/), Ovid (https://ovidsp.ovid.com/), Scopus (https://www.elsevier.com/en-in/products/scopus/search), Web of Science (https://webofscience.help.clarivate.com/en-us/Content/advanced-search.html) and Cochrane (https://www.cochranelibrary.com/advanced-search/search-manager) electronic databases using specific medical subject headings (MeSH): "bioplastics," "cassava starch," "tapioca starch," and "modification/additives/fillers/blend," combined with the Boolean operators "OR" and "AND". The reference lists of the selected articles were also searched for additional studies.

All studies on cassava starch published in English up to March 2024 that compared the properties of cassava starch modifications with those of a control were considered. Studies reporting mechanical, physical, thermal or water barrier properties in an in vitro study design were selected. Review articles, opinion articles, letters, commentaries, and non-peer reviewed literature were excluded. Any disagreements among reviewers regarding inclusion or exclusion were discussed to reach a consensus.

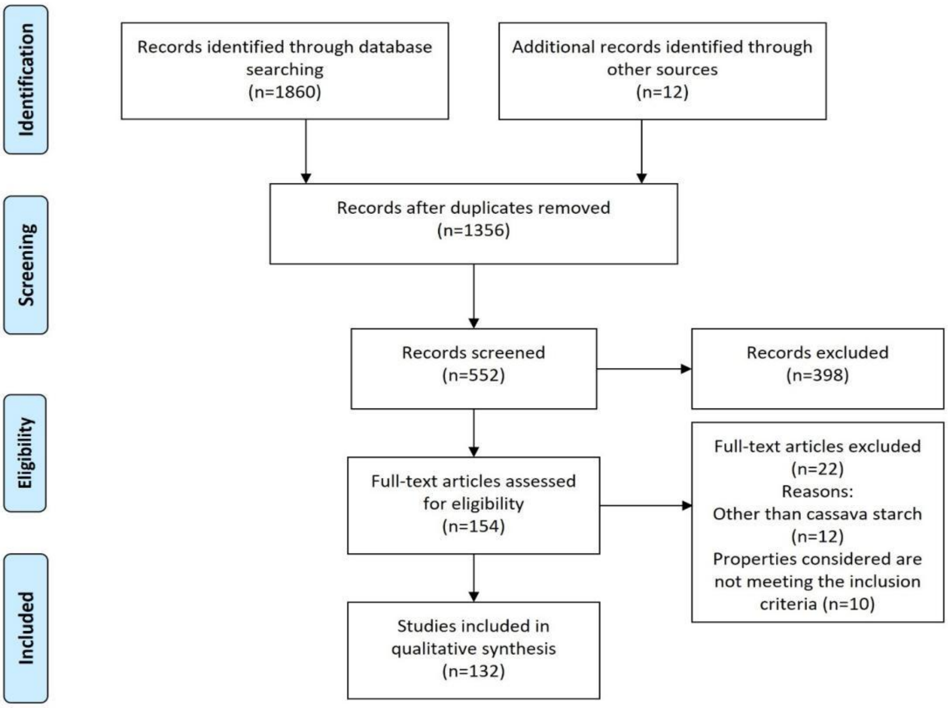
The outcome variables considered were structural, physical, mechanical, thermal and water barrier properties. Three reviewers (DV,RK,HK) independently selected the studies to be included in the review. The kappa score for inclusion and exclusion of articles was 0.96. The selection process involved reading and evaluating the articles in three phases: titles, abstracts and full articles. All papers found in the search results were first screened by title and then by abstract. If the abstracts did not provide sufficient information to determine inclusion or exclusion, the full text of the articles was reviewed. All full texts were retrieved and considered for qualitative synthesis based on the specified criteria.

The quality assessment of the included in vitro studies was done using modified CONSORT checklist of items for reporting in vitro studies.[143] The items considered were structured abstract, specific background, explanation of rationale, intervention, outcome, sample size, randomization, statistical methods, outcomes in results section and limitations in discussion.

The information collected from the studies included the author(s) and year of publication, the modification tested, the properties analyzed and the conclusions reported in the article.

Results

Of the 884 articles identified in the search, 132 were included in the qualitative synthesis.[11-142] The number of records identified, screened, and assessed for eligibility, and finally included is represented in a flow chart (Figure). The methods of modification and the conclusions reported by the authors of the included studies are detailed in Table. Because of lack of sample size determination and randomization of samples in all the reported studies, there is a minimal possibility of bias in the included studies.



Discussion

Starch from cassava (scientifically known as Manihot esculenta; family Euphorbiaceae) has been considered for review because it is extensively produced starch product in the world after maize, potato and wheat.10 Cassava is a perennial plant, easy to harvest and is available throughout the year in regions like Africa (72%), Asia (18%) and North and South America (10%). Nigeria, Thailand and Indonesia account for 50-60% of the global cassava market.10 The production of starch involves extrusion and/or molding under controlled temperature and pressure.

Research has been conducted on improving the properties of cassava based bioplastics. Among the articles included in the qualitative analysis, the properties evaluated included physical,[11,23,32,41,46,50-52,55,69,70,73,74,81,85,91,92,111,133,134] mechanical,[11,12,14-20,22,24-29,31-35,37-47,49,50,52,54,60,61,62,64,65,67-71,73-80,83,84,86,87,89,90,92-98,100-105,107-108,110-132,135-138,140,141,142] thermal,[22,26,27,33,35,36,42,43,49,50,53,55,57,62,69,70,76] and water barrier properties (such as hydrophobicity, water resistance, water solubility and moisture absorption),[13,18,19,21,24,25,27,28,30,33,37-40,42,44-49,52-54,57,59,61,67,68,72,75] as well as morphology,[22,43,49,52,55,95,109,117,122,133,136] structure,[20,35,41,53] antimicrobial[28,30,63,66,115,125,127] and anti-oxidative activities.[30] Of these, mechanical and water barrier properties are the most commonly considered parameters. Through this systematic review, it is evident that nanoparticles from various sources are frequently used as additives/ reinforcers. Among the suggested materials are cellulose nanofibrils derived from cassava bagasse, sisal, bamboo, and ramie fibres as well as cellulose nanocrystals from kenaf fibres, licuri leaves, rice husk fibre and Dendrocalamus sericeus Munro. Additionally, nanofibres from straw, nanocellulose from coconut fibre, lucuri fibre, corn stover, as well as pulp from eucalyptus, bamboo nanofibrils, bixin nanocapsules, zinc oxide nanofiller, TiO_2 nanoparticles, nanoclay/clay nanotubes and nano precipitated calcium carbonate, have been reported in literature.[11,12,18,29,38,40,41,46,49,65,69,71,90,95,96,98,108,109,124,133,139,141,142] The effectiveness of these nanoparticles as barriers to moisture, water, light, and environmental gas enhances the sturdiness, abrasion resistance, and overall efficiency of typical polymers. Similarly, several cassava starch nanocomposites made using blends of polymers and nanofillers have demonstrated improved properties like mechanical strength and resistance to humidity.

Another aspect that has been reported in literature is the usage of fibres. Numerous authors have suggested various fibres for reinforcing the bioplastics.[12,13,14,16,19,22,23,27,34,35,38,51,52] These fibres come from sources such as sugarcane, sugarcane bagasse, banana, banana leaf, banana inflorescence waste, kraft, jute, kapok, carrageenan, cotton, Brazillian coconut, sugar palm, sisal, bamboo, empty fruit brunch, coir, pine apple leaf, newspaper pulp fibre, and the residuals from starch extraction.

Various essential oils like Geranium, rosemary, oregano, cinnamon essential oils and epoxidized soyabean and palm oil were employed with beneficial results in several studies.[28,63,68,96] In recent years, there has been a growing interest in research on plant-based essential oils due to the active and useful compounds they contain. These oils are derived from various plant parts, including roots, flowers, leaves, and stems. They possess a distinctive odour and are hydrophobic in nature. Due to their natural origins, essential oils are generally considered safe for human ingestion and are recognised as 'generally recognised as safe' by the US Food and Drug Administration. To maximise efficiency and reduce volatility, essential oils are typically incorporated to films by entrapping or encapsulating them within a polymeric matrix.

A few authors have employed animal products such as chicken skin gelatin, shrimp shell waste, chitosan and fermented cheese.[74,108,125] The use of animal-derived ingredients in bioplastics poses a significant issue for vegetarians, as it conflicts with their dietary and ethical principles, limiting their ability to accept such products. They also have concerns regarding animal welfare and cruelty towards animals. The scope of these additives is limited.

Miscellaneous additives like chlorhexidine gluconate, kappa carrageenan, palm wax, agar, gallic acid, maltol, rice husk ash, graphene oxide, borax, tannia, grapheme oxide, calcium carbonate, Nicotiana tabacum xylan, raw kaolinite, passion fruit peel, pineapple shell, soyabean hulls, corn husk, malt bagasse, orange bagasse, anthocyanin rich bay berry extract, Cabernet Sauvignon grape stalks, soyaprotein concentrate and rice flour have been used with positive results.[14,57,110,114,117,138]

Synthetic materials such as carboxymethyl styrene-butadiene rubber, poly (L-lactide) co polymer, poly (butylene adipate-co-terephthalate, poly(lactic acid), polyethylene, polycaprolactone, polyvinyl alcohol, polyethylene and Betazeolite have also been added to bioplastic to increase their strength.[24,34,36,41,43,44,60,61,76,80,103,105,118,122] The advantage of using synthetic additives is enhanced mechanical properties, improved processbility, cost effectiveness and increased stability. However, the disadvantages include environmental impact, toxicity concern, regulatory resistance and compatibility issues.

Therefore, there are many reported methods to enhance the properties of cassava starch. In dentistry, there is scope for the possible use of these materials as a substitute to disposable or one-time-use resin. Further studies can be planned comparing the mechanical properties of these bioplastics with that of various dental acrylics.

Conclusion

The review highlights the growing trend of research on biodegradable plastics. While these plastics may not perform as good as conventional plastics in terms of cost, strength and water resistance, their positive environmental impact has driven research in this field. This review discusses various methods reported in the literature for improving the mechanical and water resistance properties of cassava starch based bioplastics. By incorporating these modifications, there is significant potential to explore the use of these bioplastics in dentistry and encourage green dentistry.

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Ref.	Modification tested	Key conclusion
11	Waxy starch nanocrystals	Increase of the rubbery storage modulus; decrease in water vapor permeability
12	Cellulose cassava bagasse nanofibrils	Increase of elongation at break and reduction of glass transition temperature and hydrophilic character
13	Sugarcane bagasse fibres and polyvinyl alcohol	Increased expansion index and reduced water adsorption at low levels of addition
14	Banana fiber	Increased tensile strength and reduced elongation at break
15	Acetobacter xylinum bacterial cellulose, before/after Trichoderma reesei endoglucanases treatment	Increased tensile strength; eightfold with treated fibres and almost double with untreated
16	Fibre from ethanol–water fractionation of bagasse	Increased tensile strength and elastic modulus
17	Poly(butylene adipate co-terephthalate) and soybean oil	Improved hydrophobicity and polymer compatibility
18	Cellulose nanocrystals; sucrose and inverted sugar plasticizers	Increased tensile strength, elastic modulus, mechanical and water stability
19	Kraft fiber and chitosan	Density, tensile strength and elongation similar to polystyrene foam; water absorption and solubility greater
20	Rice flour	Increased crystallinity and tensile strength; decreased breaking strain
21	Raw kaolinite and DMSO-intercalated kaolinite	Improved transparency and water uptake; significantly reduced UV transmission
22	Cassava bagasse fibre and poly(lactic acid)	Low miscibility of thermoplastic starch with PLA; cassava bagasse increased strength
23	Sugarcane fibers and Na-montmorillonite	Decreased rigidity
24	Beta zeolite and Na-beidellite synthetic fillers	Increased mechanical properties
25	Mercerized bacterial cellulose	Improved properties and reduced water absorption
26	Soybean oil maleate mixed with poly(lactic acid)	Improved compatibility, surface appearance and mechanical properties
27	Jute or kapok cellulosic fibers	Increased maximum-load stress and Young's modulus; decreased thermal degradation temperature
28	Cinnamon essential oil	Inhibited microbial growth; decreased tensile strength but increased elongation, water vapor permeability
29	Cellulose nanocrystals from kenaf fibers	Increased tensile strength and elastic modulus
30	Cellulose nanocrystals from licuri leaves	Increased mechanical strength; reduced water permeability and water activity
31	Zein, gluten, soy protein, kraft fiber and palm oil	Kraft fiber increased flexural/compressive strength; palm oil gave the lowest; zein/gluten decreased water absorption and solubility
32	Malt bagasse	Decreased hygroscopicity and initial water adsorption rate
33	Green tea and palm-oil carotenoid extracts	Improved mechanical, water-vapor barrier, functional and antioxidant properties

Table: Methods of modification and conclusions reported

Ref.	Modification tested	Key conclusion
34	Polyethylene modified with carrageenan and cotton fibers	Improved mechanical properties
35	Brazilian coconut fibers	Improved maximum-load break and tensile strength; decreased elongation and water absorption
36	Poly(lactic acid), methylenediphenyl diisocyanate and acetyl tributyl citrate	Increased tensile strength and elongation at break
37	Residue remaining from starch extraction	Increased mechanical resistance; UV-barrier capacity and adequate water-vapor barrier
38	Nanofiber straw and ZnO	Increased tensile strength and elongation; lowered water absorption with 9% ZnO
39	Soy protein concentrate with 20% glycerol	Lowered water-vapor permeability
40	Nanocellulose from coconut, licuri, corn-stover and eucalyptus	Reduced water-vapor permeability and increased Young's modulus
41	Polyvinyl alcohol and bamboo nanofibrils	Improved tensile strength and elongation; reduced tensile modulus, water-vapor permeability and water solubility
42	Eucalyptus-pulp cellulose fibers	Improved tensile strength and reduced moisture adsorption
43	Poly(butylene succinate)	Good biodegradability, improved strength and high water resistance
44	Polyvinyl alcohol	29 wt% PVA improved tensile strength and stiffness; highest elongation increase after water immersion
45	Microcrystalline cellulose	Improved tensile strength; decreased elongation, density and water uptake
46	Bixin nanocapsules	Higher concentrations decreased tensile strength and water solubility and increased elongation and water-vapor permeability
47	Pectin particles and cotton fibers	Increased maximum-load stress and Young's modulus; cotton fibers reduced water uptake
48	Recycled newspaper pulp fibre	30% gave lowest water absorption; 50% gave highest tensile strength; elongation increased as fibre content decreased
49	Cellulose nanofibers from sisal	Reduced water-vapor permeability and increased tensile strength; elongation decreased
50	Fibrous residual of starch extraction (cassava bagasse)	Increased thickness, water solubility, water absorption, modulus and tensile strength; reduced water content and density
51	Cassava bagasse and sugar palm fiber	Increased thickness; decreased density, water content, solubility and water absorption
52	Cellulose fibers and/or nanoclay	Increased tensile strength and decreased water-vapor permeability
53	Cellulose nanocrystals from rice-husk fiber	Increased storage modulus, tensile properties and thermal stability; decreased water uptake
54	Passion fruit peel	4% improved mechanical properties and reduced water solubility; increased water-vapor permeability
55	Cotton fiber and concentrated natural rubber latex	Increased hydrophobicity, moisture resistance and dimensional stability; decreased bending modulus
56	Zinc oxide nanofiller	Improved tensile strength; decreased elongation at break

Table: Methods of modification and conclusions reported

Ref.	Modification tested	Key conclusion
57	PVA gels with bacterial cellulose fibers	Fibers increased thermal and moisture resistance and tensile strength in the sonicated blend
58	Electrochemical-mechanical liquid exfoliation graphene	Increased tensile strength and Young's modulus; decreased elongation; 9% graphene was superior
59	Graphene oxide filler	Increased tensile strength, elongation and Young's modulus
60	Polybutylene succinate	Improved strength properties and thermal stability
61	PLA blended with starch and functionalized with commercial graphene	Improved elongation and toughness; water barrier properties did not improve

62	Bamboo cellulose nanofibrils with PVA and modified starch	Improved physical, thermal and mechanical properties
63	Sugarcane bagasse fiber with oregano essential oil	8 wt% OEO achieved minimum inhibitory concentration against E. coli and S. aureus
64	Thermoplastic starch–PVA–cellulose nanocomposite films	Nanocellulose increased tensile strength
65	Chitosan/cassava starch nanostructured with montmorillonite or bamboo nanofibers	Increased tensile strength and elongation at break at 1.0 g/100 g
66	Chitosan	Confirmed antimicrobial activity
67	Polylactic acid	Improved tensile strength and reduced water absorption; no significant elongation improvement
68	Rosemary oil	Increased mechanical strength and Young's modulus; lowered water-vapor transmission and solubility
69	Nano-precipitated calcium carbonate and ramie cellulose nanofibers	Increased tensile strength, moisture absorption, crystallinity and thermal stability
70	Ramie cellulose microfibrils	Enhanced crystallinity index, thermal stability and tensile strength
71	Nanoclay	Increased tensile strength and complete degradation
72	Zinc oxide and bacterial cellulose	Changed diffraction pattern and decreased water absorption
73	Pineapple shell	Improved tensile strength but showed high water absorption
74	Shrimp shell waste	Improved physical and mechanical properties
75	Cabernet Sauvignon grape stalks	Improved mechanical and humidity-related properties
76	Poly(butylene adipate-co-terephthalate)	Increasing TPS:PBAT ratios decreased tensile strength, modulus and flexibility
77	Carnauba wax and sisal fiber	7.5% sisal fiber and 10% carnauba wax showed the best properties
78	Nicotiana tabacum xylan	Increased mechanical strength
79	Soybean-oil-ester-modified cellulose nanocrystals	Promising hydrophobic effects and increased tensile strength

Table: Methods of modification and conclusions reported

Ref.	Modification tested	Key conclusion
80	Polyethylene, polyethylene-grafted-maleic anhydride and poly(lactic acid)	Improved tensile properties and water resistance
81	Cellulose fibers	Increased expansion compared with control
82	Soybean hulls or microcrystalline cellulose	Lowered solubility, water-vapor permeability and hygroscopicity; improved film flexibility
83	Carboxymethylcellulose with turmeric oil	Increased tensile strength and hydrophobic surface
84	Calcium carbonate	0.4% increased tensile strength; 0.5–1.0% decreased strength; best elongation at 0.8%
85	Linear low-density polyethylene and green tea	Reduced surface hydrophobicity; increased water-vapor permeability and solubility
86	Bamboo fiber treatment with lime juice and epoxidized waste cooking oil	Optimum: plain woven bamboo fibre, 0.25% v/v lime juice and 0.75% v/v EWCO
87	Short banana fibre	Superior mechanical properties
88	Carrageenan	XRD peak shifting and FTIR spectral changes
89	Carrageenan (0–10%)	Increased elastic modulus and tensile strength
90	Lignocellulose nanofibers and commercial nanoclay	Reduced water-vapor permeability; improved thermal stability and tensile stress; decreased elongation
91	Anthocyanin-rich bayberry extract	Improved water-vapor barrier and tensile strength
92	Microcrystalline cellulose	Enhanced physical, mechanical and biodegradability properties
93	Empty fruit bunch fibres in PB succinate with modified tapioca starch	Lowered mechanical properties without significant thermal change

94	Thermoplastic cassava starch/PLA blend with coir fibre	Improved stiffness and hardness but lowered extensibility, tensile and impact strength; increased shear viscosity
95	Halloysite clay nanotubes in starch/PBAT blend	Increased tensile strength and Young's modulus; improved compatibility
96	ZnO nanorods with PVA-rosemary polyphenol electrospun layer	Increased Young's modulus, stress/strain at break and toughness; decreased water-vapor permeability
97	Sugarcane bagasse, cornhusk, malt bagasse or orange bagasse	Cornhusk, malt and orange bagasse reduced hygroscopicity; cornhusk increased rigidity
98	Malic-acid and KH-550 modified cellulose nanofibrils	Increased tensile strength and improved barrier properties
99	Lactic acid bacteria/probiotics and sodium carboxymethylcellulose	Enhanced antioxidant activity and qualitatively improved banana shelf life
100	Carboxylated styrene-butadiene rubber and cellulose fiber	Decreased tensile value; improved water resistance and moisture content
101	Polyvinyl alcohol	Improved tensile strength, decomposition temperature and thermal stability
102	Carboxymethyl cellulose with quercetin and TBHQ	Improved tensile strength; reduced elongation and water solubility

Table: Methods of modification and conclusions reported

Ref.	Modification tested	Key conclusion
103	PBAT and nano-zinc oxide	Improved mechanical properties
104	Tannia	Increased tensile strength; decreased elongation, pores, density and water absorption
105	Polycaprolactone	Appropriate extrusion/injection processability and low water susceptibility
106	Borax	Increased thermal conductivity
107	Banana leaf fibre	Highest strength and modulus at 40 wt%; increased thermal stability
108	Chicken-skin gelatin and zinc oxide nanoparticles	Increased tensile strength; decreased elongation with increasing ZnO; 3% was optimal
109	TiO2 nanoparticles in starch/PBAT blend	5% TiO_2 gave least permeability, highest tensile strength and oxygen-scavenging
110	Rice husk ash	Increased tensile strength and Young's modulus and decreased swelling
111	Dialdehyde starch and silica solutions	Improved moisture content, solubility and tensile strength
112	Empty fruit bunch modified with epoxidized palm oil or citric-acid-epoxidized palm oil	Increased tensile strength and Young's modulus; slightly reduced water sensitivity and permeability
113	Tapioca starch as filler in PLA	Starch initially improved tensile strength, but strength decreased with further addition
114	Graphene oxide	10% improved tensile strength, Young's modulus and elongation; decreased residual weight and water uptake
115	Chitosan/pineapple leaf fiber/zinc oxide	Improved physical, mechanical and antibacterial properties
116	Elephant-grass cellulose and oyster-shell CaCO3	Cellulose + CaCO3 produced lower mechanical properties than cellulose alone
117	Rice husk ash	Improved flexural tensile strength, thermal stability, density and biodegradation; decreased water absorption
118	Poly(lactide)/poly(butylene succinate)	Improved strength and flexibility considerably
119	Silicon dioxide with PBAT	Increased tensile strength; decreased elongation; enhanced oxygen and water-vapor permeability
120	Banana inflorescence waste fibre	Improved water resistance and mechanical/thermal performance; optimum filler 10 wt%
121	1–10% maltol in acetylated starch	Extended bakery shelf life; 1% decreased tensile strength; 3% improved strength
122	Gallic acid (1–10%) and linear-low-density polyethylene	Increased water-vapor permeability and oxygen scavenging; 5% GA gave homogeneous film with high mechanical/barrier properties

123	Poly(L-lactide)-b-poly(ethylene glycol)-b-poly(L-lactide)	Decreased tensile stress/strain at break and increased hydrophilicity
124	Silica nanoparticle, glycerol and rosemary essential oil	0.6% SNP increased tensile strength and thermal stability; lowered water absorption and water-vapor transition
125	Fermented cheese whey	Good mechanical and barrier properties

Table: Methods of modification and conclusions reported

Ref.	Modification tested	Key conclusion
126	Hydroxypropyl starch blended with PBAT	Reduced water-vapor permeability and improved mechanical/barrier properties
127	Geranium essential oil	Decreased water content, water-vapor permeability and tensile strength; increased roughness, opacity and antibacterial properties
128	Duckweed biomass in PLA–starch blend	Increased tensile strength, Young's modulus and hardness; reduced glass transition, crystallization and melting temperatures
129	Native, acetylated, octenyl-succinated and hydroxypropylated starch with PBAT	Modified starches altered mechanical/barrier properties; hydrophobic OS starch improved compatibility and interaction
130	Starch/PVA matrices with Kepok banana-bunch cellulose	7:3 cassava starch:cellulose gave highest tensile strength, strain, modulus and optimum thermal stability
131	Agar–cassava-starch blends	Superior tensile strength, elongation and water resistance
132	Cellulose, PVA and zinc oxide	Superior quality, environmental performance and hydrophobicity
133	Titanium dioxide nanoparticles	Fast degradation with improved mechanical resistance
134	Palm wax blends with Cymbopogon citratus fibre	Improved impact strength and water resistance
135	PBAT and poly(butylene succinate)	Synergistic mechanical properties with optimal balance of strength and elongation
136	Cassava starch in ZnO/SiO2 semi-refined kappa-carrageenan film	Increased surface morphology, thickness and mechanical properties
137	Poly(L-lactide)-b-poly(ethylene glycol)-b-poly(L-lactide) with citric-acid compatibilizer	Citric acid improved phase compatibility and mechanical properties
138	Chlorhexidine gluconate	Improved tensile strength, elongation and thermal stability; increased hydrophobicity
139	Cellulose nanocrystals from Dendrocalamus sericeus Munro	Decreased water solubility and water-vapor permeability; 0.4 g CNC gave highest tensile strength
140	3-aminopropyl trimethoxy silane modified starch with epoxidized soybean oil	Higher thermal stability and tensile strength
141	Montmorillonite-filled starch bionanocomposites	Increased hydrophobicity and tensile strength/Young's modulus; reduced solubility and water/oxygen permeability
142	Locust bean galactomannan and cellulose nanofibers	No change in mechanical properties; enhanced vapor barrier

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